Multi-Channel Wireless Sensor Networks: Protocols, Design and Evaluation

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MULTI-CHANNEL WIRELESS SENSOR NETWORKS: PROTOCOLS, DESIGN AND EVALUATION

DISSERTATION

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Abstract

Pervasive systems, which are described as networked embedded systems integrated with everyday environments, are considered to have the potential to change our daily lives by creating smart surroundings and by their ubiquity, just as the Internet. In the last decade, "Wireless Sensor Networks" have appeared as one of the real-world examples of pervasive systems by combining automated sensing, embedded computing and wireless networking into tiny embedded devices.

A wireless sensor network typically comprises a large number of spatially distributed, tiny, battery-operated, embedded sensor devices that are networked to cooperatively collect, process, and deliver data about a phenomenon that is of interest to the users. Traditionally, wireless sensor networks have been used for monitoring applications based on low-rate data collection with low periods of operation. Current wireless sensor networks are considered to support more complex operations ranging from target tracking to health care which require efficient and timely collection of large amounts of data. Considering the low-bandwidth, low-power operation of the radios on the sensor devices, interference and contention over the wireless medium and the energy-efficiency requirements due to the battery-operated devices, fulfilling the mentioned data-collection requirements in complex applications becomes a challenging task.

This thesis focuses on the efficient delivery of large amounts of data in bandwidth-limited wireless sensor networks by making use of the multi-channel capability of the sensor radios and by using optimal routing topologies. We start with experimenting the operation of the sensor radios to characterize the behavior of multi-channel communication. We propose a set of algorithms to increase the throughput and timely delivery of the data and analyze the bounds on the data collection capacity of the wireless sensor networks. The main contributions of the thesis are listed as follows:

- **Contribution 1 - Characteristics, challenges and the use of multi-channel communication in wireless ad hoc networks and wireless sensor networks:** We review the state of the art channel assignment protocols in wireless multi-hop networks, particularly in wireless ad hoc networks and wireless sensor networks. We classify the existing solutions according to the number of transceivers required per node and according to the dynamics of the channel assignment. Since the channel assignment methods designed for general wireless ad hoc networks may not be directly applicable to wireless sensor networks, we give brief comparisons of them and discuss the additional challenges and requirements for wireless sensor networks.

- **Contribution 2 - Characterization of multi-channel interference:** The assumption of perfectly orthogonal, interference-free channels, which is adopted in most of the multi-channel communication studies, may fail in practice. Radio signals are not limited to their allocated frequency band, but cause interference in adjacent bands as well — how much depends on the filtering characteristics of the transceivers. We conduct an extensive set of experiments, using NrF905 radio, to investigate the properties of multi-channel communication in wireless sensor networks. Based on these experi-

ments, we explore an analytical model on the interference characteristics and by using the analytical model we discuss the impact of channel orthogonality on the network performance with extensive simulations.

- **Contribution 3 - Design and implementation of a multi-channel MAC protocol for wireless sensor networks:** We design a multi-channel MAC protocol, namely MC-LMAC (Multi-Channel Lightweight Medium Access Control), which is a schedule-based multi-channel MAC protocol that takes advantage of interference and collision-free parallel transmissions over different channels. MC-LMAC is designed to provide high throughput and high delivery ratio during high-rate traffic whereas it also meets the traditional requirements of wireless sensor networks such as energy efficiency and scalability.

- **Contribution 4 - Enhancing the rate of aggregated data collection:** We consider enhancing the data collection rate of *aggregated convergecast*, which is one of the fundamental communication patterns in wireless sensor networks. We focus on the problem of finding the fastest rate of aggregated data collection with TDMA scheduling which is equivalent to minimizing the TDMA schedule length. We explore different techniques to address this question, such as transmission power control and multi-channel communication. We show that, once multiple frequencies are employed along with spatial-reuse TDMA, the aggregated data collection rate often becomes no longer interference-limited, but rather topology-limited. Accordingly, we show that the final step to enhance the rate of periodic aggregated data collection is to use an appropriate *degree-constrained tree* topology.

- **Contribution 5 - Fast convergecast scheduling in wireless sensor networks:** We focus on data delivery models where data cannot be aggregated and raw sensor readings need to be relayed towards the sink node. We study the minimum time to complete the delivery of the messages in a convergecast operation. Similar to the *aggregated convergecast* problem, we investigate the benefits of transmission power control and multiple channels to eliminate the effects of interference. Once the interference is completely eliminated, we show that with half-duplex single-transceiver radios, the achievable schedule length is lower-bounded by $\max(2n_k - 1, N)$, where n_k is the maximum number of nodes on any subtree and N is the number of nodes in a network organized as a tree. We study a distributed time slot assignment algorithm to achieve this bound when a suitable routing scheme over a *capacitated minimal spanning tree* is employed.

Samenvatting

Pervasive systems zijn via een netwerk verbonden embedded systemen die geïntegreerd zijn in onze dagelijkse omgeving. Algemeen wordt aangenomen dat pervasive systems, net zoals het internet, ons dagelijks leven kunnen beïnvloeden doordat ze met hun wijdverspreide aanwezigheid een “intelligente” omgeving kunnen. In het afgelopen decennium zijn “Draadloze Sensornetwerken” naar voren gekomen als een praktijk voorbeeld van pervasive systems. Zij combineren automatische metingen met embedded gegevensverwerking en draadloze embedded apparaten van beperkte omvang.

Een draadloos sensornetwerk bestaat normaal gesproken uit een groot aantal verspreide, kleine, door een batterij gevoede en met sensoren uitgeruste apparaten. Deze apparaten werken samen en verzamelen en verwerken gegevens over een fenomeen waarin een gebruiker is genteresseerd. Oorspronkelijk werden draadloze sensornetwerken toepast in applicaties waarbij, over een korte periode geobserveerd kon worden met beperkt dataverkeer. Van huidige draadloze sensornetwerken wordt aangenomen dat ze complexere taken kunnen ondersteunen, variërend van het volgen van een doelobject tot en met medische zorg. Bij deze laatste worden op efficiënte en tijdsgebonden wijze grote hoeveelheden data verzameld. Deze taken zijn uitdagend vanwege factoren zoals: eisen op het gebied van energie-ëfficiëntie vanwege het gebruik van batterijen, het lage vermogen van de radio op de sensorapparaten, de lage bandbreedte en interferentie en conflicten over het gedeelde gebruik van het draadloze medium.

Dit proefschrift richt zich op het efficiënt afleveren van grote hoeveelheden gegevens in een draadloos sensornetwerk, beperkt door bandbreedte limieten en interferentie. Dit kan door gebruik te maken van meerdere kanalen op de sensorradio en het gebruik van optimale routes in het netwerk. Onze experimenten starten met experimenten met de aansturing van de sensorradio’s om het gedrag van communicatie over meerdere kanalen te beschrijven. Verder stellen we een verzameling van algoritmes voor om de doorvoer en het tijdsgebonden afleveren van gegevens te verbeteren en we analyseren de grenzen van de capaciteit om data te verzamelen. De belangrijkste bijdrages van dit proefschrift zijn als volgt:

- **Bijdrage 1. Karakteristieken, obstakels en het gebruik van communicatie over meerdere kanalen in draadloze ad-hoc netwerken en draadloze sensornetwerken:** We beschrijven recente protocollen om kanalen toe te kennen in draadloze sensornetwerken, met name in multi-hop ad-hoc netwerken. We delen de bestaande oplossingen in, op basis van het aantal benodigde transceivers per apparaat en volgens de dynamiek van de kanaaltoekenning. Aangezien methodes om kanalen toe te kennen voor draadloze ad hoc netwerken niet in het algemeen toepasbaar zijn voor sensornetwerken presenteren we een korte vergelijking tussen deze twee groepen en bespreken we de eisen en obstakels voor draadloze sensornetwerken.

- **Bijdrage 2. Beschrijving van interferentie tussen meerdere kanalen:** De meeste onderzoeken naar communicatie over meerdere kanalen nemen aan dat kanalen volledig orthogonaal en interferentievrij zijn; dit kan in de praktijk onjuist blijken. Radio signalen beperken zich niet tot de hun toegewezen frequentieband, maar beïnvloeden ook de naastgelegen banden. Hierdoor kan er, afhankelijk van de filter eigenschappen van de transceivers, interferentie tussen naburige kanalen ondervonden worden. Om de eigenschappen van communicatie over meerdere kanalen te onderzoeken hebben we een uitvoerige verzameling experimenten uitgevoerd. Op basis van deze experimenten onderzoeken we een analytisch model van interferentie eigenschappen. Gebruikmakend van dit model en uitvoerige simulaties bespreken we de gevolgen van de orthogonaliteitsaanname van de kanalen op de prestaties van het netwerk.

- **Bijdrage 3. Ontwerp en implementatie van een meer-kanaals MAC protocol voor draadloze sensornetwerken:** We ontwerpen MC-LMAC (Multi-Channel Lightweight Medium Access Control), een meer-kanaals MAC protocol. MC-LMAC is een meer-kanaals MAC protocol gebaseerd op een "schedule" dat gebruik maakt van interferentie- en collisie-vrije parallelle transmissies over verschillende kanalen. MC-LMAC is ontworpen om een hoge doorvoersnelheid en en een hoog afleveringspercentage te behalen, rekeninghoudend met de traditionele eisen voor een draadloos sensornetwerk, zoals energie efficiëntie en schaalbaarheid.

- **Bijdrage 4. Het verbeteren van de verzamelsnelheid van gespreide gegevens:** We bestuderen de data verzamelsnelheid voor *aggregated convergecast*. Aggregated convergecast is één van de fundamentele communicatiemethoden in draadloze sensornetwerken. Ons doel is het vinden van de kortste verzamelsnelheid van alle gedistribueerde data met behulp van *TDMA scheduling*. Dit komt neer op het minimaliseren van de duur van het TDMA schedule. We onderzoeken verschillende technieken om dit schedule te vinden, zoals het regelen van het transmissie vermogen en het gebruik van communicatie over meerdere kanalen. We tonen aan dat, zodra er meerdere frequenties worden gebruikt en deze in verschillende gebieden worden hergebruikt, de snelheid van het verzamelen van samengestelde data niet meer beperkt wordt door interferentie, maar door de topologie van het netwerk. Daaruitvolgend laten we zien dat de laatste stap om de snelheid van het periodiek verzamelen van gedistribueerde data te verbeteren bestaat uit het afgestemd toepassen van een zogenaamde *degree-constrained tree* topologie.

- **Bijdrage 5. Snelle convergecast scheduling in draadloze sensornetwerken:** We richten ons op data afleveringsmodellen waar de data niet kan worden samengevoegd en waarbij de ruwe sensormetingen verzonden moeten worden naar een afvoerpunt. We bestuderen de minimale tijd om het afleveren van de berichten met behulp van *convergecast* te voltooien. Net zoals met de convergecast voor gedistribueerde data, onderzoeken we de voordelen van het regelen van het transmissievermogen en het gebruik van meerdere kanalen om interferentie te elimineren. Hierna laten we zien dat voor half-duplex radio's met een enkele transceiver de ondergrens voor de minimale overdrachtstijd van de gedistribueerde data gelijk is aan $\max(2n_k-1, N)$, waarin n_k het maximale aantal apparaten is binnen de sub-bomen en N het aantal apparaten binnen een als boom geörganiseerd netwerk. We onderzoeken een gedistribuëerd tijdsslottoekenningsalgoritme om deze grens te halen met een geschikt routeschema over een capaciteitsgebonden minimaal opspannende boom.

Acknowledgements

In the first year of my Phd life, I remember seeing a graph on the Phd-comics website about a graduate student's motivation level versus years, full of ups and downs. Definitely, road to a Phd is not always smooth, is sometimes hilly and has bends but it's a pleasant journey with the help of the guides who know about the road, the other fellow travelers and the supporters.

Before I start with acknowledging the wonderful people who have been part of this journey, I'd like to tell a bit how my journey started. Why do I do a Phd? Everything started with this question, I think. I like researching, I like teaching and I wanted (and still want) to become an academician. I have been always fascinated with the continuous learning/teaching cycle and the information flow in the academic world. If I go 6-7 years back, when I was at the end of my Bsc. studies, I had the opportunity to work in the Networking Lab of Yeditepe University. I also had internship experiences in the industry before and I came to a conclusion that academic life, despite all the struggles, attracts me more than a career in the industry. So, this is how the story started. I continued my Msc. studies in the same lab working with wonderful people. *Prof. Şebnem Baydere* and *Dr. Yaşar Safkan* always encouraged me to go further. I guess those are the ones that I should start acknowledging with for their support at the very beginning of the story. Professor Baydere's guidance taught me a lot about conducting good research. I'd like to thank her for her guidance, support and being the first role model before starting my Phd journey.

Next step was the Phd towards the academic life. My colleague from the same lab, *Ömer Sinan Kaya*, was at the same time applying for Phd positions. He encouraged me to apply to the University of Twente after an enthusiastic discussion about the group's activities on wireless sensor networks. After the interviews, the positive answer came back the other day. I was admitted as a phd student to work for the Smart Surroundings project. This answer started my Phd journey.

Over the past 4 years, I had opportunities to work with different advisors/supervisors. My promotor, *Sape Mullender* (although he was mostly on the other side of the world), always supported me that I can do it. I remember complaining to him at the very beginning "but I'm not a radio guy, I'm from computer science, how can I progress in RF communication research?", but everything was doable. I thank Sape for guiding me at the very beginning to learn a lot about different aspects of wireless communication. He encouraged me to make my hands dirty with the experimentation on real radios which at the end taught me a lot about the practical aspects of the wireless world. Without his support, this research couldn't have reached this far.

Pierre Jansen, my daily advisor, had always time to listen to me about any topic from wireless sensor networks to my complaints about the obstacles in the Phd journey. Without any complaints he reviewed all my writings where he was discovering the rules of Turkish grammar through my English texts! I was impressed with the breadth of his knowledge about any topic from politics to history, from food culture to novels. I guess none of our meetings ended less than 1 hour. I thank Pierre for his mentorship and continuous support during all the periods of this journey.

During the past 4 years, I have been involved in the Smart Surroundings project which was leaded by *Paul Havinga*. Although I didn't know about my supervisor and my promotor before, I knew about Paul and the innovative research he was conducting in his group through the Eyes and the Embedded WiSeNts projects. Paul has been always supportive. He was the one to advise me to look at the multi-channel communication aspects of wireless sensor networks. There was not much research done on the topic at that time and I was not so much eager to work on wireless communication below the routing layer. I thank Paul for orienting me towards a timely topic which received quite a lot of attention during my Phd studies and for providing me the opportunity to work in his group.

In the last 2 years of my Phd studies, I had a great opportunity to work in *Dr. Bhaskar Krishnamachari*'s research group, Autonomous Networks Research Group (Anrg) in USC. First of all, I'd like to thank *Prof. Pieter Hartel* for agreeing to support me during my first visit to USC. Bhaskar has been a great supervisor and definitely one of the most important role models for my future planned career. I am impressed by his enthusiasm and passion for research and teaching, the care and support that he gives for each of his students. My second visit to Anrg was as fruitful as the first time where I was surrounded with great people to work with. I'd like to thank Bhaskar for providing this opportunity, for his kindness, for helping me to regain my confidence and for being just a great advisor. I hope my collaborations with Anrg will continue so many years in the future.

I'd like to thank all of the committee members for reading my manuscript. Without the help of *Prof. Langendoen* and *Prof. Smit* my thesis couldn't have reached this far. Their comments and proposals helped me a lot to improve my manuscript and to express my ideas better.

When I came to Twente for an interview for the first time, I remember telling myself "this place looks very nice but I don't know anyone here, all my friends will be left back in Turkey". I was wrong. *Sinan*, my friend/colleague from Turkey, started his Phd studies in the same group a couple of months before me and helped me a lot with settling and making a lot of friends. I will always be grateful to him.

During my phd journey, I met a lot of nice people. Especially, the multi-cultural, international environment in the university has taught me a lot about different cultures and different stories.

Raluca and Mihai, not only colleagues at the university but neighbors living in the same building and travel mates, have been very close friends. I will never forget you guys standing with flowers on my door early in the morning, on my first birthday in the Netherlands and your kind hospitality during our visit in Romania. Thanks for all the unforgettable moments...

Kavitha has been my office mate throughout the 4 years. We always had something to talk, sometimes about the gossips in the university, sometimes about how to manage with the ups and downs of the Phd life. She introduced me to the colorful world of Indian culture, I even own an Indian dress which is a gift from her. In the 2nd year, we organized a small dancing group, performing Indian dances, and Kavitha instructed us with passion during those days. The performances of our dancing group were the main attraction in our parties and even in Diwali celebrations. Many thanks for the very warm friendship (also to *Kiran*) and your support and most importantly for accepting to be my paranymph during my defence.

Ayşegül, being my colleague and one of the closest friends, joined our group 2 years after me. We are both alumni of the Yeditepe University and this has formed a sisterhood between us. We shared a lot of great memories from the daily lunch discussions to celebrating birthdays together. That was funny that we attended a class on “Turkish” folklore dance in “the Netherlands”! Our picture with the traditional costumes is still hanging on the board in the Pervasive Systems corridor. I’d like to thank Ayşegül for the great memories, for her care and support during this journey and for her help by being my paranymph.

Ştefan and Ileana, the other Romanian couple, have also been very good friends to have very nice time together. The parties, gaming gatherings, volleyball sessions wouldn’t have been this lively without their presence. Ştefan helped me a lot to progress in my research studies especially at the very beginning. He is a great Matlab master and taught me how to collect fast and efficient simulation results. I’d like to thank both of them for their warm friendship.

Supriyo... We both still complain that we couldn’t have collaborated enough, so far, but I believe that we will continue interacting in the future. His enthusiasm, being always ready to help or discuss about anything have made a very lively and positive office environment. His reviews on my introduction chapter helped me how to restructure the rest of the thesis. He was the one who proposed to visit Bhaskar’s group when we went to California in 2007. This visit gave me the opportunity to clarify my research visit to Anrg. I’d like to thank Supriyo, accompanied with *Anindita* and little *Samhita*, for making the life more livelier.

Nirvana, I call her the problem solver. If you ask her a question about anything, about the group, management issues, etc., she always has the answer or she knows who can answer it. I thank her many times for making things easier and for her continuous support and for her positiveness with her warm smile.

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As I mentioned, I had the opportunity to visit Anrg two times. All the members of the Anrg made me feel at home. I thank *Amitabha*, listening to all my dumbest questions on theorem proving and explaining theoretical issues with a great detail. I thank *Avinash* who was always ready to talk about any technical or research stuff, *Scott, Ying* and *Hua*, for their care, *Pai-Han, Sundeep, Marjan, Joon, Yi Wang* and *Yi Gai*.

Besides the members of the research groups, I also had the opportunity to meet a lot of nice people outside the office hours. *Michel* has been the best Dutch friend both for me and for Mustafa. He not only showed the patience in teaching Dutch to spoiled foreigners, like us, but also introduced us to the world of board games. Many thanks to Michel for making things easier to get used to the life here. Hoping not to forget any of the names I’d like to acknowledge *Ayşe, Andreea, Eugen, Mohammed, Anka, Ari, Ha, Malohat, Vasughi, Chiara, Laura* and *Ricardo*, for the wonderful memories that we shared especially during those joyful parties.

I was away from home but I always felt at home by the support of my Turkish friends. Actually, Mustafa and I managed to convince some of our friends from Turkey to move to the Netherlands. *Cem* (the most faithfull friend that I’ve had so far), *Seçkin*, *Kamil*, who were my former friends from the Yeditepe University, and *Murat* have been great sources of support to manage in a foreign country.

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My parents, not only during the Phd journey but throughout my life, always believed in me and supported me. Thanks to Skype that we could speak almost every day. I'd like to thank my parents for their committed support, love and prayers which made me to quickly recover from disappointments and discouragements during my Phd journey. I thank my sister, *Didem*, for being always there when I need her and for being a source of happiness and positiveness in my life. I also thank *my mother-in-law* for her support and care.

Without hesitation, my greatest thanks are for my love, my best friend and my husband, *Mustafa (Mincel)*. Starting from the very beginning, by accepting to move with me to the Netherlands, he always supported me. I know, it's hard to thank enough but thanks a million for being always next to me. I couldn't have sailed through this journey alone without your help, support, patience, sacrifices, encouragement, simply without you! Before forgetting, I should mention that the wonderful photo on the cover page of my thesis is taken by him. Thanks for everything...

Finally, to summarize this non-ending story, After being in the learning side of the fascinating learning/teaching cycle for almost 25 years, I'm really excited to take part also on the other side. Thanks everyone for being a part of my journey in the last 4 years.

Özlem Durmaz Incel
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Contents

CHAPTER I

Introduction

We are living in the digital revolution era, unconsciously witnessing the concept of the “disappearing computer” [110, 263]. Computers are becoming much smaller, much cheaper, yet more powerful which makes it easier to embed computing power into everyday devices.

In the last decade, *Wireless Sensor Networks (WSNs)* [34] have appeared as one of the emerging technologies that combine automated sensing, embedded computing and wireless networking into tiny embedded devices. Although these individual enablers of WSNs are themselves not new ideas, technological improvements, particularly in micro-electro-mechanical systems (MEMS), enabled their integration [94] on miniaturized embedded computers that corroborate the concept of the disappearing computer.

The earliest research efforts on WSNs date back to the late 1990’s, when a research project funded by DARPA (the US Defense Advanced Research Projects Agency) focused on developing low-power devices to enable large scale WSNs [33]. Traditionally, WSNs were deployed for monitoring applications based on low-rate data collection [187]. However, current WSN applications can support more complex operations ranging from target tracking to health care. This thesis is motivated by the communication problems in WSNs that appear with the evolution from the low-rate, data-collection-based monitoring applications to more complex applications that require *fast* and *efficient* delivery of *large amounts* of data. The aim of the thesis is to identify the barriers to fulfill these requirements in the wireless domain and in the organization of the network and provide solutions to overcome these barriers.

The outline of this chapter is as follows. First, we present WSNs as the context of this thesis. We describe the general properties of sensor devices and continue with a survey of examples of WSN applications. Next, we discuss the topics related with networking wireless sensors as the focus of this thesis. We explain the characteristics and challenges of communication in WSNs and present the data collection models which lead us to the research question addressed in the thesis. Finally, we introduce our contributions and conclude with the organization of the studied topics.

1.1 Wireless Sensor Networks

A WSN typically comprises a large number of spatially distributed, tiny, embedded sensor devices that are networked to cooperatively collect, process, and deliver data about a phenomenon that is of interest to the users. Being embedded into the physical world and being able to detect the physical properties, such as temperature, light, etc., at a close proximity have distinguished the WSNs from traditional computing, which usually exists in a virtual world [94].

A typical WSN device (Figure 1.1) consists of the following components:

- *Sensor/Actuator Boards* include different types of sensors and actuators. The types of the sensors vary according to the application requirements. Typical examples of

Figure 1.1: *MICAz [22] - An Example Sensor Node Platform*

sensors are temperature, light, humidity, acoustic, pressure, chemical sensors and accelerometers. Examples of actuators can be speakers, LEDs, buzzers.

- *The Wireless Transceiver* available on sensor nodes is usually a low-rate, low-power, short-range radio. The transceivers mostly operate on unlicensed bands like the 868-915MHz or 2.4 GHz industrial, scientific and medical (ISM) bands. Typical data rates supported by the radios are 50-250 kbits per second. Some common examples of the radios used on sensor nodes are Chipcon CC1000 [15] and CC2420 [16], and Nordic NrF905 [24].
- *The Processor* used on the sensor nodes is required for processing the sensed data, running the system software and the networking protocol stack. Mostly, 8-bit or 16-bit processors (e.g., Texas Instruments MSP430 [20]) are used. Nodes usually run specialized operating systems to meet the resource constraints. Examples of operating systems include AmbientRT [127], TinyOS [32] and Contiki [92].
- *Memory/Storage* capabilities are also quite limited. Usually a few kBytes of RAM and a few tens of kBytes of flash RAM are available for storing data and code.
- *The Power Supply* of the sensor nodes generally consists of batteries. In many WSN applications it is impractical or impossible to replace/recharge the batteries of the nodes. Although energy harvesting methods or continuous power sources can be available on the nodes in some cases, energy is the most critical resource.

The small, embeddable size of WSN devices (mainly due to the cost and invisible-deployment constraints), wireless and untethered/unattended mode of operation (often without human intervention) and large-scale, dense deployments make WSNs attractive for numerous applications [34]. Traditionally, WSNs are deployed for monitoring applications based on low-rate data collection [187]. However, current WSN applications can support more complex operations ranging from target tracking to health care. In the following, we briefly survey some examples of WSN applications according to the context of operation:

- **Environmental/Habitat Monitoring:** Networked sensors can be deployed to collect detailed information about an environment/habitat such as temperature, pollution, agricultural data, etc. *Great Duck Island* [187] is an example project where the behavior of the bird species living in the environment are monitored. Monitoring toxic substances in rural areas [217], monitoring the sources of drinking water [206], precision agriculture [48] are some other examples of environmental monitoring applications using WSNs.

- **Military:** WSNs are used in military applications for information collection, enemy tracking and battlefield surveillance. Target (enemy) classification and tracking are the key battlefield tactical applications [192]. Other examples include chemical (nuclear, biological) attack detection [34], counter-sniper tactics [249], etc.

- **Emergency/Surveillance:** Surveillance applications consider the problem of tracking unexpected conditions/situations by a WSN. Border protection/intruder detection [44], coal mine surveillance [171], detection of abnormal animal behavior in farms [247], tracking of patients and first responders in a disaster scenario [177] are some typical applications to mention.

- **Disaster Early Warning Systems:** Disaster monitoring applications use WSNs as an early-warning system. Forest fire detection [298], flood detection [19], volcano eruption monitoring [282], hazardous substance detection [211] are the major examples of such applications.

- **Industrial/Structural Monitoring:** Equipment-health monitoring is a typical industrial application that can benefit from WSNs. Sensors attached to the critical equipment can proactively detect and prevent future equipment problems [200, 216]. WSNs are also used for structural health monitoring to detect damage to bridges [70], buildings, etc.

- **Transport and Logistics:** Inventory control and warehouse monitoring are the challenging tasks in transport and logistics applications. Using WSNs, assets can be monitored from production until the delivery to the end user. The CoBIs (Collaborative Business Items) project [17] aims the usage of smart sensor technology in industrial supply chain settings. Other projects to mention in this field are *Smart Dust Inventory Control* [30] and flower warehouse monitoring [99].

- **Health Care:** Health care applications use WSNs for monitoring physiological data, tracking and monitoring of doctors and patients inside a hospital, etc. Example applications of this type include *Body Area Sensor Networks* [50], preventing cardio-vascular diseases [29] and tracking doctors and patients inside hospitals [123].

We presented example applications targeted for different contexts but the list of the applications can certainly be extended since the number of existing and visionary applications of WSNs is probably inexhaustible with the growing interest both within the research and industrial communities. In the next section, we continue with explaining the networking characteristics of WSNs.

1.2 Networking Wireless Sensor Devices

The networking of sensor devices is possible by wireless RF (radio frequency) communication through the radios available on the nodes[†]. WSNs share the challenges of traditional wireless networks, including limited energy available on each node and bandwidth-limited, error-prone channels [268]. The wireless medium is a shared/broadcast channel. Simultaneous transmissions on the same channel and in the same spatial domain may cause conflicts on each other. Therefore, conflict-free, spatial reuse of the wireless medium is an important requirement in WSNs which has been the case for other wireless networks.

WSNs are characterized as ad hoc and multi-hop networks where the nodes self-organize into a network without an infrastructure. The most common form of communication pattern in WSNs is called *convergecast* where the sensor nodes report the collected data to a sink, a basestation, node. Usually the sink node is not directly reachable by all the sensor nodes due to the deployments over large areas and limited transmission power available on the sensor radios. This results in *multi-hop* network structures where nodes relay each other's data towards a sink node. Another communication pattern is *multicast*, which is the opposite of convergecast. The data is disseminated from the sink node to the sensor nodes in the network. The other common communication patterns are *unicasts* and *local broadcasts* or *local gossip* operations where data is exchanged among the neighbors, for instance, for collaborative processing of data instead of sending raw readings [158].

Due to the energy efficiency requirements and the size of the sensor nodes, the sensor radios are more limited than the radios used for other wireless devices, for example, compatible with Wireless Local Area Networks (WLAN) [54] or GSM [31]. Table 1.1, presents the characteristics of the radios that are available on common sensor node platforms. The last column displays the specifications of an IEEE 802.11b compliant WLAN radio for comparisons. Most of the transceivers operate on licence-free ISM bands, which are reserved for industrial, scientific and medical applications. Due to the requirement of low power consumption, radios transmit with low power and the achievable data rates are limited. The radios provide half duplex communication such that they cannot transmit and receive at the same time.

Newer generations of commercially available radios support multi-channel communication in order to comply with the emerging IEEE 802.15.4 standard [201]. The IEEE 802.15.4 standard, which is used as a basis for the ZigBee [28], WirelessHART [255], and MiWi [23] specifications, provides a framework for low data rate communications systems. It has been originally designed for low-rate wireless personal area networks (WPANs). The standard is then adopted by WSNs, interactive toys, smart badges, remote controls and home automation, operating on license-free ISM bands. IEEE 802.15.4 makes use of multi-channel communication to reduce the effects of interference due to co-existing networks that share same parts of the spectrum [61]. Interference and contention on the wireless medium are inherent limitations. Multi-channel communication is an efficient method to eliminate interference and contention on the wireless medium by supporting parallel transmissions over different frequency channels [162]. We study different aspects of multi-channel communication in WSNs throughout this thesis.

[†] There can be other communication methods, such as infrared or microwave communication. In this thesis we focus on WSNs with RF communication.

Table 1.1: *Characteristics of Typical Sensor Radios versus a WLAN Radio*

	Nordic NrF905	**Chipcon CC1000**	**Chipcon CC2420**	**RFM TR1001**	**Infineon TDA5250**	**Cisco HWIC-AP**
Operating Frequency	433/868/ 915MHz	315/433/ 868/915MHz	2.4GHz	868.35MHz	868MHz	2.4GHz
Modulation	GFSK	FSK	O-QPSK	ASK/OOK	ASK/FSK	BPSK, QPSK, 16-QAM, 64-QAM
Data Rate	50kbps	76.8kbps	250kbps	115.2kbps	64kbps	54Mbps
Max Tx. Power	10dBm	10dBm (433MHz)	0dBm	1.5dBm	13dBm	20dBm
Receiver Sensitivity	-100dBm	-107dBm (868MHz)	-94dBm	-106dBm	-109dBm	-73dBm (54Mb/s)
Tx. Current	30mA	26.7mA	17.4mA	12mA	9mA	-
Rx. Current	12.5mA	9.6mA	19.7mA	3.8mA	12mA	-
Tx. Range (indoors)	50m		50m	100m	30m	24-90m
Tx. Range (outdoors)	125m	>100m	125m	300m	80m	90m-610m
Multi-Channel Support	+	-	+	-	-	+
Nr. of Channels	512	-	16	-	-	11
Channel Width	200kHz	-	5MHz	-	-	22MHz

Designing communication protocols for WSNs is closely related with the application requirements [227]. For instance, an application may require low latency or real time responsiveness whereas an other requires reliable communication. Therefore it is difficult to generalize the aspects of communication protocols in WSNs. In the following, we describe the common requirements that need to be addressed in designing networking protocols for WSNs:

- *Energy efficiency* is the biggest challenge for the development of long-lived sensor networks. As a major energy consumer, radio communication needs to be optimized. The most common method is to operate the radio with duty cycles with periodic switching between sleep and wake-up modes. However, long sleep periods may reduce the responsiveness of the network [157]. There exists an extensive literature on energy-efficient networking protocols for WSNs. The reader can refer to [35, 134, 165, 186, 278] for detailed surveys on the topic.

- *Scalability* is another required property due to the large-scale and dense deployments. The number of deployed sensor nodes may be in the order of hundreds or thousands. Protocols designed for WSNs should be able to work with this number of nodes.

- *Ad hoc networking* and *self organization* are the other challenging requirements due to a lack of infrastructure and network dynamics, for instance, due to unreliable communication links or unreliable sensor nodes. Similarly, *adaptivity* to the network changes is a related requirement. Moreover, *distributed* solutions are favored due to the *self organization* and *adaptivity* issues in WSNs [281].

As we mentioned, expected properties of networking protocols for WSNs heavily depend on the application specifications but besides the stated requirements, responsiveness, robustness or fault tolerance, reliability, support for mobility and quality-of-service parameters such as latency may be listed as some other important topics.

In the next section, we explain the data delivery models and the corresponding requirements of these models in the WSNs domain. These lead us to define the research question and the contributions of the thesis.

1.3 Data Delivery Models in WSNs

Sensor nodes are designed to collect data about a phenomenon and transmit their readings to a sink node. In this section we present a classification of data delivery models in WSNs and the corresponding requirements. Depending on the application requirements, there are three basic data delivery models: continuous model, query-driven model, and event-driven model [268]. In the following, we explain the characteristics of these models:

- **Continuous Data Delivery:** In this model, sensor nodes transmit the collected data at periodic intervals. It is the basic model for traditional monitoring applications based on data collection. The data rates are usually low and to save energy the radios can be turned on only during data transmissions.

- **Query-Driven:** In this model, sensors only report data in response to an explicit request from the sink. The response to the query provides the user with a snapshot of the monitored conditions or a stream of data for a short interval [63]. The sink may also initiate a query to reconfigure/reorganize the sensor nodes such as upgrading the system software running on the nodes.

- **Event-Driven:** In this model, sensor nodes report data only if an event of interest occurs. Usually, the events are rare. Yet, when an event occurs, a burst of packets is often generated that needs to be transported reliably, and usually in real-time, to a base station. The success of the network depends on the efficient detection and notification of the event that is of interest to the user.

In different applications, the data delivery models described above may coexist in the network which is called the *hybrid model*.

In the continuous data delivery mode, which is the fundamental data delivery method in traditional data-collection applications, delay and loss of data may be tolerated. If the sensors report data in larger intervals, such as once per hour, the network mostly operates under a light load, and is mostly idle. Accordingly, throughput and bandwidth utilization do not usually pose a concern for the network. On the other hand, if the application requires frequent reports, then higher amounts of data may need to be streamed towards the sink node. In the query-driven model, tolerance of delay depends on the query characteristics. If the query requests streams of data to be collected quickly, large amounts of data may need to be delivered in a short period. Throughput, timely delivery of data and bandwidth may become important concerns. In the event-driven model, bursty-traffic generated in case of an event needs to be delivered to the sink node as quickly and as reliably as possible. In this model, the network should be able to provide high throughput and timely delivery of the data. In the next section, we introduce the research question addressed in this thesis. Then, we explain our contributions followed by the structure of the thesis.

1.4 Research question

As we briefly surveyed in Section 1.1, the broad range of emerging applications requires more complex operations like detection of events in real-time or responsive querying of the network by collecting streams of data in a timely manner. During bursty traffic, the large number of packets generated within a short period leads to a high degree of channel contention and thus a high probability of packet collision. Limited channel capacity and the influence of interference among the sensor radios or the interference due to external networks or electronic devices, that share the same parts of the spectrum, result in a competitive communication environment. Besides these challenges the traditional challenges of WSNs such as *energy efficiency* and *scalability* remain as important concerns in networking wireless sensors.

In this thesis, we focus on *high-rate* data collection that requires *timely* and *efficient* delivery. Limited bandwidth, increased levels of interference and contention, half-duplex nature of the sensor radios are identified as the primary barriers on the successful delivery of large amounts of data in short intervals. However, the sensor radios can operate on different channels by adjusting their operating frequencies to overcome the limitations of contention and interference. This thesis focuses on the following question:

> *How much efficiency can be achieved in the delivery of large amounts of data in bandwidth limited WSNs by making use of the multi-channel capability of the sensor radios and by using appropriate routing topologies?*

We approach the problem by studying methods to efficiently utilize the limited bandwidth and organize appropriate network topologies. The thesis addresses the question by following a bottom-up approach in three main parts. In the first part, we focus on the use and characteristics of multi-channel communication in WSNs. Typical sensor radios have multi-channel communication capabilities, however the effects of adjacent channel interference and dynamic channel switching make multi-channel communication challenging. First, we study the advantages and challenges of multi-channel communication.

Having explored the characteristics of multi-channel communication, we focus on protocols in the second part. We introduce a multi-channel MAC protocol that utilizes multi-channels and also meets the traditional requirements of WSNs such as energy efficiency and scalability.

In the third part, we explore a fundamental question: *how fast can information be collected from a wireless sensor network?* We investigate the effects of interference reduction mechanisms such as transmission power control and multi-channel communication and study optimal routing topologies for fast data collection in WSNs. Initially, we focus on data delivery with message aggregation [158] and next we investigate raw data collection mechanisms.

1.5 Contributions

- **Contribution 1: Characteristics, challenges and the use of multi-channel communication in wireless ad hoc networks and WSNs**
  We review the state of the art channel assignment protocols in wireless multi-hop networks, particularly in wireless ad hoc networks and wireless sensor networks. We classify the existing solutions according to the number of transceivers required per node and according to the dynamics of the channel assignment. Since the channel assignment methods for general wireless ad hoc networks may not be directly applicable to wireless sensor networks, we give brief comparisons of them and discuss the additional challenges for wireless sensor networks.

- **Contribution 2: Characterization of multi-channel interference**
  The research community working on multi-channel protocols either assumes that channels are perfectly orthogonal (interference-free) or considers the use of only orthogonal channels. The assumption of perfectly orthogonal, interference-free channels may fail in practice. Radio signals are not limited to their allocated frequency band, but cause interference in adjacent bands as well — how much depends on the filtering characteristics of the transceivers. On the other hand, the use of only orthogonal channels cannot utilize the spectrum efficiently. Considering the mentioned facts, in order to design good protocols we first need to understand the multi-channel interference behavior with typical WSN radios. We conduct an extensive set of experiments, using Nordic NrF905 radio, to investigate the properties of multi-channel communication in WSNs. Based on the experiments, we explore an analytical model on the interference characteristics and by using the analytical model we discuss the impact of channel orthogonality on the network performance with extensive simulations. Different parts of this work appear in the following papers:

  - *Multi-Channel Interference Measurements for Wireless Sensor Networks*, O. Durmaz Incel, S. Dulman, P. Jansen and S. Mullender, in Proceedings of the 31st IEEE Conference on Local Computer Networks, LCN 2006, pages 694-701, Tampa/USA, November 2006.
  - *Measurements on the Efficiency of Overlapping Channels*, O. Durmaz Incel, S. J. Mullender, P. G. Jansen and S. O. Dulman, in Proceedings of the Fourth Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, Secon 2007, pages 689-690, San Diego/USA, June 2007 (poster session).
  - *Capacity analysis of interfering channels*, O. Durmaz Incel, P. Jansen, S. Dulman and S. Mullender, in Proceedings of the 2nd ACM workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks, pages 11-18, Crete Island/Greece, October 2007.
  - *Characterization of multi-channel interference*, O. Durmaz Incel and P. Jansen, in Proceedings of the 6th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks and Workshops, Wiopt 2008, pages 429-435, Berlin/Germany, March 2008.

- **Contribution 3: Design and implementation of a multi-channel MAC protocol for WSNs**
  We design a multi-channel MAC protocol, called MC-LMAC, which is a schedule-based multi-channel MAC protocol that takes advantage of interference and collision-free parallel transmissions on different channels. MC-LMAC is designed to provide high throughput and high delivery ratio during high-rate traffic whereas it also meets the traditional requirements of WSNs such as energy efficiency and scalability. We evaluate the performance of MC-LMAC with extensive simulations and compare its performance with two other multi-channel MAC protocols that are designed for WSNs. We implement MC-LMAC and demonstrate a proof-of-concept on real sensor nodes. This work appears in the following papers:
  - *Multi-channel Support for Dense Wireless Sensor Networking*, O. Durmaz Incel, S. O. Dulman and P. G. Jansen, in Proceedings of the First European Conference on Smart Sensing and Context, EuroSSC 2006, pages 1-14, Enschede/the Netherlands, October 2006.
  - *MC-LMAC: A Multi-Channel MAC Protocol for Wireless Sensor Networks*, O. Durmaz Incel, P. G. Jansen and S. J. Mullender, Technical Report TR-CTIT-08-61, Enschede/the Netherlands, 2008.
- **Contribution 4: Enhancing the rate of aggregated data collection**
  Data aggregation is a form of in-network processing where data can be combined coming from different sources en route to the sink- eliminating redundancy, minimizing the number of transmissions and thereby saving energy and improving network performance. We consider the convergecast process under aggregation, referred to as *aggregated convergecast*, in which every node sends exactly one packet (aggregating its own as well as data from its children) on a tree-based routing topology. We focus on the following question: *What is the fastest rate at which we can collect a stream of aggregated data from a set of wireless sensors organized as a tree?* We consider time division multiple access (TDMA) scheduling. In our framework, maximizing the data collection rate corresponds exactly to minimizing the TDMA schedule length. We explore a number of techniques to address this question, such as transmission power control and multi-channel communication. With the extensive simulations we observe that, once multiple frequencies are employed along with spatial-reuse TDMA, the aggregated data collection rate often becomes no longer interference-limited, but rather topology-limited. Accordingly, we show that the final step to enhance the rate of periodic aggregated data collection is to use an appropriate *degree-constrained tree* topology. This work appears in the following paper:
  - *Enhancing the Data Collection Rate of Tree-Based Aggregation in Wireless Sensor Networks*, O. Durmaz Incel and B. Krishnamachari, in Proceedings of the Fifth Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, Secon 2008, pages 569-577, San Francisco/USA, June 2008.
- **Contribution 5: Fast convergecast scheduling in WSNs**
  In some applications, such as phenomena modeling where algorithms rely on individ-

ual data from each sensor, aggregation operations may not be possible or may not be desirable; instead raw-data from each source should be collected. We focus on data delivery models where data is not aggregated and explore the following fundamental question: *How fast can information be collected from a WSN?* Similar to the *aggregated convergecast* problem, we investigate the benefits of transmission power control and multiple channels to eliminate the effects of interference. Once the interference is completely eliminated, we show that with half-duplex single-transceiver radios the achievable schedule length is lower-bounded by $\max(2n_k - 1, N)$, where n_k is the maximum number of nodes on any subtree and N is the number of nodes on a tree network. We study a distributed time slot assignment algorithm to achieve this bound when a suitable routing scheme over a *capacitated minimal spanning tree* is employed. Finally, we also demonstrate possible further improvements when the sink is equipped with multiple transceivers or when there are multiple sinks to collect data. This contribution appears in the following technical report:

  - *Multi-Channel Scheduling for Fast Convergecast in Wireless Sensor Networks*, O. Durmaz Incel and A. Ghosh and B. Krishnamachari and K. Chintalapudi, USC-Ceng Technical Report CENG-2008-9, Los Angeles/USA, 2008.

The following relevant contributions are not directly included in this thesis but are cited throughout the thesis:

- *Using TinyOS Components for the Design of an Adaptive Ubiquitous System*, O. S. Kaya, O. Durmaz Incel, S.O. Dulman, R. Gemesi, P.G. Jansen, and P.J.M. Havinga, in Proceedings of the International Workshop on Wireless Ad-hoc Networks, Iwwan 2005, London/UK, May 2005.
- *Impact of Network Density on Bandwidth Resource Management in WSN*, O. Durmaz Incel, L.F.W. van Hoesel, P.G. Jansen and P.J.M Havinga, Technical Report TR-CTIT-05-43, Enschede/the Netherlands, 2005.
- *Algorithms for Fast Aggregated Convergecast in Sensor Networks*, A. Ghosh, O. Durmaz Incel, V.S Anil Kumar, and B. Krishnamachari, USC-Ceng Technical Report CENG-2008-8, Los Angeles/USA, 2008.

1.6 Organization of the Thesis

We begin by describing the state of the art in multi-channel protocols in general wireless ad hoc networks and particularly in WSNs in Chapter 2 which corresponds to **Contribution 1**. The rest of the chapters are blocked into 3 groups:

- **Chapter 3 and 4:** In this part of the thesis, we explain the characteristics of multi-channel communication in WSNs which corresponds to **Contribution 2**. We experiment the behavior of multi-channel communication with real sensor motes and explain our findings in Chapter 3. Then, based on the experimental observations, we develop an analytical model on the interference characteristics in Chapter 4. Moreover, we discuss the impact of channel orthogonality on the network performance with extensive simulations.

- **Chapter 5:** In this chapter, we explain our insights in designing multi-channel MAC protocols for WSNs and introduce MC-LMAC. This corresponds to **Contribution 3**. We compare the performance of MC-LMAC with single-channel MAC protocols as well as two different multi-channel MAC protocols designed for WSNs.
- **Chapter 6 and 7:** In this part of the thesis, we focus on fast convergecast scheduling in WSNs. In Chapter 6, we begin by a simpler version of the problem where data is aggregated such that each link on the routing tree is scheduled once which corresponds to **Contribution 4**. In Chapter 7, we describe a general version of the problem and discuss the possible tradeoffs that correspond to **Contribution 5**.

In Chapter 8, we summarize our contributions and conclusions. Furthermore, we highlight the possible future research directions for the problems and solutions discussed in the thesis.

Introduction

CHAPTER II

Background

As described in Chapter 1, this thesis focuses on efficient delivery of large amounts of data in wireless sensor networks (WSNs) by using multi-channel[†] communication capabilities of the sensor radios. This chapter introduces the existing work on the general concepts studied in the thesis, while the other chapters present the existing work specific to the topics studied.

In the first part of the chapter, we investigate the achievable data delivery capacity in WSNs over multi-hop topologies. We identify the limiting factors on the capacity and accordingly explain the existing methods to overcome those limitations. Interference and contention on the wireless medium, which are the major limiting factors on the data delivery capacity, can be eliminated by multi-channel communication that is studied throughout this thesis. Accordingly, in the second part of the chapter, we present a survey of existing channel assignment methods, particularly for general wireless ad hoc networks and WSNs that are based on multi-hop communication techniques. We classify the methods according to their requirements and mode of operation. To determine whether the existing channel assignment methods for traditional wireless ad hoc networks can be used in WSNs, we present a list of comparisons and conclude with the requirements and a classification of existing work on multi-channel communication in WSNs.

The organization of the chapter is as follows: Section 2.1 presents the many-to-one data delivery capacity in WSNs. The limiting factors on the achievable capacity are explained in Section 2.1.1 together with the existing solutions to overcome the limitations. In Section 2.2, we present a survey and a classification of channel assignment methods in wireless ad hoc networks. Section 2.3 concludes the chapter with a survey of existing work on multi-channel communication in WSNs.

2.1 Capacity of Wireless Sensor Networks

In this section, we first review the existing work on the capacity of general wireless multi-hop networks and next study the data delivery capacity of WSNs.

In their seminal work, Gupta and Kumar study the asymptotical transport capacity in general wireless multi-hop networks [120]. The analysis is based on the assumptions that communications are one-to-one, and sources and destinations are randomly or arbitrarily (optimally) chosen. Accordingly, they show that if the nodes are randomly placed and the destinations are randomly chosen, then the achievable throughput per node is bounded by:

$$\Theta\Big(\frac{W}{\sqrt{nlog(n)}}\Big) \tag{2.1}$$

[†] A channel is defined to be a frequency range over which two nodes communicate. We use the terms “channel” and “frequency” interchangeably in the text.

where W is the transmission capacity, n is the number of nodes in the network and Θ represents the asymptotic notation[‡]. They also show the results for arbitrary (optimal) node placement and communication patterns. In this case the achievable per node throughput is:

$$\Theta\left(\frac{W}{\sqrt{n}}\right) \tag{2.2}$$

Grossglauser *et al.* [117] extend this work and show that the capacity can be improved by the mobility of the nodes which can reduce the number of hops between the source and the destination and in turn reduce the contention in the network. Gastpar *et al.* [109] show further improvements on the obtained capacity bounds by introducing relay nodes which do not generate traffic but act as routers to deliver data to the destination.

When we switch to WSNs, the traffic is usually towards (a) sink node(s) which results in many-to-one communications, as we have discussed in Chapter 1. Duarte-Melo *et al.* study the capacity of WSNs in many-to-one data gathering scenarios [91]. The trivial upper bound per node is presented as W/n which can be achieved when the sink is 100% busy in receiving, equipped with a single radio and shared by n source nodes each of which generate the same amount of data. They further show under which circumstances this bound is achievable. For instance it is achieved when all the sources can directly transmit to the sink node. On the other hand, if each source cannot directly communicate with the sink, such that the communication takes place on a multi-hop network, it may or may not be achieved depending on the transmission and interference ranges of the nodes. These affect the reuse possibilities of the medium and the schedule that the nodes are transmitting with.

2.1.1 Constraints on the Capacity of WSNs

In this section, we present the constraints on the achievable capacity in WSNs. We identify the following major constraints:

- the limited bandwidth and the half-duplex capability of the radios on the nodes,
- interference and contention on the wireless medium,
- the topology of the network.

In the following sub-sections, we discuss the details of these limitations on the capacity of WSNs together with the existing solutions. Since some of the constraints, such as interference and contention, are the inherent limitations in wireless networks, we not only mention the existing work on WSNs but also present the important solutions in other wireless networks.

Bandwidth-Limited and Half-Duplex Transceivers

As we have reviewed in Chapter 1, sensor nodes are equipped with bandwidth-limited and half-duplex radios. The radios can transmit with limited power on channels with a limited bandwidth. The achievable data rates are around a few tens of kilobits per second (kbps). Newer radios such as CC2420 can transmit with 250kbps with spread spectrum capabilities [16] using larger bands of 5MHz allocated to each channel. Additionally, most of the

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[‡] $f(n) \in \Theta(g(n))$: f is bounded both above and below g asymptotically

commercially available radios operate on the 868/915MHz or 2.4GHz unlicensed worldwide ISM bands. The regulations usually allow low transmitted power where the transmissions span distances from 30 to 100 meters, depending on the environmental conditions.

As we have briefly mentioned in Chapter 1, the IEEE 802.15.4 standard [28] provides a framework for low data rate communications systems, typically for WSNs. Originally, the standard defined three bands to support low bit rate operations (20kbps for the 868MHz band, 40kbps for the 915 band and 250kbps for the 2.4GHz band). Later, the IEEE 802.15.4a Task Group [12] was created with the goal of defining a new physical layer, that is able to provide higher data rates and high-accuracy ranging capabilities. New releases of the standard focus on using Ultra Wide Band (UWB) and chirp signals as alternative physical layer technologies to overcome the bandwidth limitations. UWB can achieve bit rates varying approximately between 0.1Mbps and 26Mbps. New radios that are based on the mentioned technologies with low power consumption capabilities have been released recently [79, 89]. In a recent work [240], the capacity of UWB-based WSNs is studied.

Another limitation is due to the half-duplex nature of the transceivers on the sensor nodes. The transceivers cannot transmit and receive simultaneously and cannot receive from more than one sender at a time. This was defined as the “destination bottleneck” constraint in [162], meaning that the capacity of a wireless network is constrained by the amount of the data that can be received by a destination node. Depending on the application, there may be multiple sink nodes deployed in a WSN to improve the data collection rate. Alternatively, the sink node may be equipped with multiple radios. However, sensor nodes equipped with a single radio, that relay the data towards the sink node, may still constrain the achievable capacity. Equipping the sensor nodes with multiple radios is usually not desirable due to the energy constraints. Nevertheless, there exist recent studies on deploying sensor nodes with multiple radios [41, 161, 180]. Scenarios with multiple sinks are studied in [85, 147, 166, 207] with the objective of increasing the lifetime and the scalability of a WSN by selecting different sinks to collect data from different sources.

Regarding the topics studied in this sub-section, we assume the sensor nodes are equipped with commercially available radios, such as CC2420 [16] or Nordic nRf905 [24], that are commonly used on current sensor node platforms. UWB-based WSNs are out of the scope of this research study, yet they can further improve the capacity of WSNs when employed together with the improvements studied in this thesis. We evaluate the impact of deploying multiple sink nodes and deploying sink nodes with multiple radios on the achievable capacity in Chapters 5 and 7.

Interference

As we mentioned, WSNs inherit the challenges of traditional wireless networks, including interference. Wireless medium is a shared, broadcast medium. When simultaneous transmissions are performed on the same channel in the same spatial domain, all the unwanted transmissions contribute to the interference on the desired signal. If the transmissions do not conflict with each other, parallel transmissions can simultaneously take place on the shared medium. However, a collision, i.e., a packet loss, occurs if the received signal is too weak compared to the interfering signals.

In this section, before presenting the existing solutions to eliminate interference in wireless networks, we focus on analytical models of interference. These models are extensively used in simulations and analytical studies while evaluating the performance of wireless networks [136]. There are two common models: the *protocol interference model* and the *physical interference model*. We briefly explain them in the following:

- Protocol Interference Model: It was first introduced in [120]. It can be summarized as follows: Suppose node X_i (this denotes the node itself and also denotes the location of the node) transmits over a channel to a node X_j. Then this transmission is successfully received by X_j if the intended destination X_j is sufficiently apart from the source of any other simultaneous transmission such that:

  $$|X_k - X_j| \geqslant (1 + \Delta)|X_i - X_j| \tag{2.3}$$

  for every other node X_k transmitting in parallel over the same channel.

  The constant $\Delta > 0$ specifies a guard zone to prevent a neighboring node from transmitting on the same channel at the same time. The advantage of this approach is that it enables the use of simple graph-coloring based scheduling algorithms. In [116], Grönkvist *et al.* analyze the performance of the protocol interference model and indicate that the model does not always provide a comprehensive view of reality due to the aggregate effect of interference in wireless networks [280]. The model can also be pessimistic in the sense that two nearby communications that could take place together with a tolerable level of interference are considered to be not possible. Other models such as RTS/CTS model [37] or hop count based models [237] are the extensions or special cases of the protocol interference model.

- Physical Interference Model (SINR Model): This is a richer model that can capture the interference from multiple simultaneous senders. It is summarized as follows [120]: Let $\{X_k; k \in T\}$ be the subset of nodes transmitting simultaneously at some time instant over a certain channel. Let P_k be the power level chosen by node X_k for $k \in T$. Then the transmission from a node X_i, $i \in T$, is successfully received by a node X_j if

  $$\frac{\dfrac{P_i}{|X_i - X_j|^{\alpha}}}{N + \displaystyle\sum_{k \in T, k \neq i} \dfrac{P_k}{|X_k - X_j|^{\alpha}}} \geq \beta \tag{2.4}$$

  where β represents the minimum signal-to-interference-noise ratio (SINR) for successful receptions, α represents the exponent for signal loss due to distance and N represents the level of the ambient noise.

  Moscibroda *et al.* [197] study the impact of physical interference model on the achievable capacity in wireless multi-hop networks and they show that protocols designed with the SINR model can surpass the theoretically achievable performance of graph-based scheduling protocols. In [254], Son *et al.* evaluate the physical interference model by experiments on real sensor nodes. They also confirm the inadequacy of the simplistic interference-range-based protocol model. They observe that the measured interference from multiple transmitters is generally less than what is theoretically predicted by the assumption of additive interference. Additionally, they find that SINR threshold is not a constant value, but it depends on the transmitter hardware and the signal strength level. Furthermore, in [305], Zhou *et al.* study the radio interference detection during run time for WSNs. They show that the interference-connectivity assumption of the protocol interference model, which states that interference always comes from connectivity, is not always maintained.

Enabling interference-free spatial reuse of the medium has been an important research topic in the wireless networks domain. There exist many different multiple access (medium access or MAC) methods in the literature designed for coordinating communications. *Time division multiple access* (TDMA), *frequency division multiple access* (FDMA), *code division multiple access* (CDMA) and *carrier sense multiple access* (CSMA) are the major techniques to share the wireless medium by alleviating the conflicts. In TDMA, interfering transmissions are scheduled in different time units. In FDMA, the idea is to schedule the simultaneous transmissions on different frequencies without interfering with each other. CDMA allows multiple users to simultaneously access the same physical channel by assigning different spreading codes. CSMA, on the other hand, is a probabilistic MAC scheme in which a node verifies the absence or presence of other traffic before transmitting by listening on a shared medium. We review the MAC protocols for WSNs in Chapter 5 and the reader can refer to [134, 161, 165] for detailed survey studies.

Other than the MAC protocols, *transmission power control* is a well-studied method to alleviate interference [93, 159, 253, 299] in wireless networks. Excessive levels of interference can be eliminated if the signals are transmitted with sufficient power instead of maximum power. The motivation for transmission power control studies is twofold: limiting the interference increases the throughput and reduces power consumption to prolong the network lifetime. In the WSNs domain, for instance Moscibroda [196] shows that unbounded improvements in the asymptotic capacity of data collection can be achieved by employing non-linear power assignment at sensor nodes. In [170], Li *et al.* study the throughput efficiency of WSNs by using topology control methods. They define topology control as the mechanism for computing a sufficient transmission range for each node by power control methods. In Chapters 6 and 7, we evaluate the impact of transmission power control on the performance of WSNs under realistic settings and compare transmission power control method with multi-channel communication methods in term of their efficiency in eliminating interference.

Use of *directional antennas*, instead of omnidirectional antennas, can also improve the spatial reuse of the wireless medium. With directional antennas more than one pair of nodes located in close proximity can communicate in parallel, depending on the directions of transmissions. Capacity improvements with directional antennas for general wireless ad hoc networks are discussed in [296]. MAC protocols that are designed for wireless ad hoc networks where nodes are equipped with directional antennas are presented in [43, 78, 155, 276]. In this thesis, we do not consider the use of directional antennas in WSNs but the reader can refer to [232, 290, 303] for the existing work.

We observe a trend towards using *cognitive radios* in wireless networks. A cognitive radio is defined as a software defined radio (communication functions are implemented on software instead of hardware) that additionally senses its environment, tracks changes, and reacts upon its findings [141] by efficiently avoiding interference. To the best of our knowledge, the current example radio platforms used for WSNs are not cognitive radios and the channel sensing needed for cognitive radio operation would be incompatible with the energy-efficiency requirements of WSNs [261].

In [272], Vakil *et al.* study the effect of cooperation in an interference limited, narrowband WSN by using *relay nodes* which do not generate traffic but only forward data from sources to the sink node. They show that cooperation with relay nodes leads to significant capacity improvements. However, with asynchronous transmissions the relay nodes cause more interference to other sensors. They investigate the optimal tradeoff between the amount of cooperation and the amount of interference introduced to the network. In this thesis, we do not consider the availability of the relay nodes but in Chapter 6 we discuss the impact of cooperation with aggregation operations on the performance of WSNs.

Different from the previous work, we consider to use *multi-channel communication* to reduce the effects of interference on the capacity of WSNs. The existing work on channel assignment methods and multi-channel MAC protocols on wireless ad hoc networks and WSNs are presented with a greater detail and with comparative remarks in Sections 2.2 and 2.3.

So far, we have explored the interference issues among the transmissions in the same network. However, *co-existence* of different networks operating on the shared medium may also cause performance degradations. Considering the growing demand for the use of the ISM bands, there are many scenarios where different systems operate simultaneously in the same spatial domain, such as IEEE 802.15.4 Low-Rate Wireless Personal Area Network (LRW-PAN), IEEE 802.11b Wireless Local Area Network (WLAN), Bluetooth, etc. Adaptive use of frequency channels to solve the co-existence issues has received a lot of attention from the research community. Example experimental studies and the methods to solve the co-existence problems (mostly based on transmission power control and channel switching) are presented in [39, 199, 245, 286] for the co-existence of IEEE 802.11 and IEEE 802.15.4 networks, and in [77, 241, 248] for the co-existence of IEEE 802.15.4 and Bluetooth networks.

Topology

Due to the many-to-one communication paradigm, data from sensors to the sink is usually relayed over tree-type routing topologies. On a multi-hop tree topology whenever there are multiple senders (children) assigned to the same receiver (parent), each of these senders have to wait for each other's transmission since a single half-duplex transceiver can receive from only one node at a time. Therefore the topology of the network impacts the data collection performance in WSNs and, as emphasized in [76], routing trees that allow more parallel transmissions do not always result in higher capacity. For example, in a network of nodes with identical and omnidirectional radio ranges, changing the topology from a single hop star topology to a multi-hop line topology, where all the nodes are sources and are in the transmission/interference range of each other, degrades the throughput since the wireless interference and multi-hop forwarding limit the reuse of the medium and accordingly limit the number of parallel transmissions. On the other hand, multi-hop communication is favorable and commonly used in WSNs due to the deployments over large areas and due to the limited transmission capabilities of the sensor radios.

To the best of our knowledge, impact of routing trees on the capacity of WSNs have not been addressed before. In this thesis, we study the impact of routing topologies on the data collection rate of WSNs. In Chapters 6 and 7, we present the appropriate routing topologies for fast data collection operations.

Interference-aware topology construction can reduce the impact of interference on the achievable capacity in WSNs. A greedy algorithm called *Low Interference Forest Establisher (LIFE)* is proposed in [59]. *LIFE* constructs an interference-optimal topology while maintaining the connectivity of a given network. We use *LIFE* to study the impact of interference-aware topology control on fast aggregated convergecast operations in WSNs [2].

2.2 Multi-Channel Communication in Wireless Ad Hoc Networks

A wireless ad hoc network is a collection of wireless devices that self-configure to form a network without the aid of any established infrastructure [114]. WSNs are considered as a sub-class of wireless ad hoc networks and the existing studies on multi-channel communication in wireless ad hoc networks can guide us while designing protocols for WSNs.

The use of multi-channel communication is a well-studied research topic in wireless ad hoc networks, particularly in packet radio networks [143] and wireless mesh networks [81]. Kyasanur *et al.* [162] study the capacity of multi-channel wireless ad hoc networks by extending the analysis of Gupta and Kumar [120], that we discussed in Section 2.1. They investigate the impact of the number of channels and the number of radio interfaces on the network capacity by studying the relationship between them. They show that, even if the number of interfaces is smaller than the number of available channels, multi-channel communication can enhance the network's capacity.

In the next sub-sections, we survey the existing protocols on channel assignment and multi-channel MAC protocols for wireless ad hoc networks. We classify the existing approaches according to their requirements on the number of radios available on the nodes. In Section 2.2.1, we present the single-radio multi-channel approaches whereas in Section 2.2.2 multi-radio multi-channel methods are presented. In each section, we initially present the existing protocols and then discuss the advantages and the challenges. In Section 2.2.3, we present comparisons on the explained methods. Other classifications of channel assignment algorithms and multi-channel MAC protocols can be found in [81, 195, 246, 279].

We further discuss the requirements and challenges of multi-channel communication in WSNs. We explain how the problem differs from the multi-channel communication in other classes of wireless ad hoc networks and present the existing work with comparisons in Section 2.3.

2.2.1 Single-Radio Multi-Channel Wireless Ad Hoc Networks

In this section we present the existing work in single-radio multi-channel wireless ad hoc networks. We classify the protocols according to the channel assignment methods: *fixed assignment*, *semi-dynamic assignment* and *dynamic assignment*. In fixed assignment approaches, radios are assigned channels for permanent use. Although the assignment of the channels can be renewed, for instance due to changing interference conditions, radios do not change the operating frequency during communication. In semi-dynamic approaches, the radios are assigned constant channels, either for receiving or transmitting, but it is possible to change the channel for communicating with the radios that are assigned different channels.

In dynamic approaches, nodes are not assigned static channels and can dynamically switch their interfaces from one channel to another between successive data transmissions.

Fixed Channel Assignment

At first glance, fixed channel assignment approaches seem contradictory with the idea of multi-channel communication: "If the nodes are assigned fixed channels then how can they exploit the advantages of multi-channel communication?". The basic motivation of fixed channel assignment approaches is to cluster the nodes into different frequencies such that each cluster only uses a single channel which is different from the channels that are assigned to the clusters which may cause interference. An example of this type of channel assignment is presented in [297].

Different from the idea of clustering the nodes into different frequencies, Vedantham *et al.* [275] introduce the concept of *component-based channel assignment*. In this approach, all links in a connected component, induced by a flow graph between sources and destinations, are assigned a single channel and operate on the same channel.

The main advantage of fixed channel assignment approaches is the ease of implementation since the dynamics due to channel switching and variations in the network topology are not considered. However, fixed channel assignment enforces the nodes to keep their interfaces on a particular channel and this may cause the following problems:

- Being inadaptive to dynamic network conditions: Network conditions may change over time such as topology changes due to unstable links or traffic requirements.

- Network partitions: Related to the previous item, if transceivers of two nearby nodes are fixed on different frequencies and if communication is required between these peers, they cannot communicate with each other. During channel assignment, it is required to identify the nodes that need to communicate with each other. Alternatively, the channel assignments need to be renewed frequently due to changing requirements in the network.

Semi-Dynamic Channel Assignment

In semi-dynamic approaches, fixed channels are assigned either to the senders or receivers and the nodes can switch their interfaces on the selected channels to communicate with other nodes.

Usually the channel assignment problem is solved by graph-based approaches. Vertices represent the nodes and the edges represent the communication links. Interference links can also be included in case of the parallel communications on edges [116]. The solutions can benefit from the extensive research on graph coloring algorithms [56].

Examples of semi-dynamic assignment are presented in [183] for wireless mesh networks and in [235] for multi-hop packet radio networks where receivers are assigned fixed channels and the transmitters switch to those channels for communication.

An advantage of semi-dynamic approaches over the fixed channel assignment is that nodes can switch to the different channels to communicate with different neighbors such that partitions can be eliminated. On the other hand, with semi-dynamic channel assignment approaches a detailed coordination of channel switching is required between the senders and receivers in order to be on the same channel at the same time. The problems that arise due to the channel switching are listed as follows:

- *Multi-channel hidden terminal problem:* This problem [250] is associated with the CSMA/CA (carrier sense multiple access with collision avoidance) based protocols where RTS/CTS (request to send / clear to send) mechanism is used. It occurs when the control packets (RTS/CTS) sent on a given channel cannot be received by the nodes communicating on different channels. The nodes that miss the control packets, start transmission of control packets on the destination's channel which causes a collision.
- *Deafness problem:* The deafness problem [183] is also associated with the RTS/CTS based protocols. The problem occurs when a transmitter sends a control packet to initiate a transmission and the destination is tuned to another channel. After sending multiple requests, if the transmitter does not get any response it may conclude that the receiver is not reachable anymore.
- *Broadcast support:* When the nodes are switching between channels dynamically, it might be problematic to support broadcasts.

Dynamic Channel Assignment

In dynamic channel assignment approaches, every data transmission takes place after a channel selection. The channel selection can be measurement based or status based. In measurement based approaches, the communicating parties measure the SINR values on a channel before transmitting. In status-based approaches nodes keep track of the status of the channels, such as busy or idle, according to the received control packets.

Dynamic channel assignment approaches share the problems of multi-channel hidden terminal, deafness and broadcast support that we introduced for semi-dynamic channel assignment. Dynamic channel assignment is further classified into four categories based on the methods of coordination:

- **Dedicated Control Channel:** With this approach, nodes synchronize by exchanging control packets on the dedicated control channel and negotiate for the channel to be used for data exchanges. Examples of dedicated control channel approaches are presented in [138, 169]. *Multiple channel carrier sense multiple access* is presented in [138] where channels are selected according to power sensing. In [169], the channels are selected according to *preferable channel lists*. The dedicated control channel approaches do not require time synchronization and are easy to implement. However, they suffer from deafness and multi-channel hidden terminal problems. The control channel can only be used for exchanging control messages and data exchange proceeds over the data channels. This causes the control channel bottleneck problem [140]. For instance, in the 2.4 GHz band, there are three orthogonal channels used by IEEE 802.11b. This means, one third of the channels are consumed for control purposes.
- **Split Phase:** In split phase protocols, nodes access the medium in 2 phases: a control and a data exchange phase. During the control phase, all the nodes switch to a common control channel and negotiate with their intended receivers for the channel(s) to be used during the data exchange phase. Usually, during the control phase,

access to the medium is contention based. Protocols differ according to the channel access mechanisms they support during the data exchange. An example of contention-based protocols is *Multi-Channel MAC* (MMAC), which is presented in [250]. *Multi-Channel Access Protocol* (MAP) [67] and TMMAC [302] are examples of protocols that are based on scheduled access. The main advantage of the split phase protocols are the elimination of multi-channel hidden terminal and deafness problems. On the other hand, the protocols require time synchronization and during the control phase the non-control channels remain idle. Channel switching time may affect the performance depending on the hardware used but the problem can be amortized by extending the duration of the data exchange phase. Broadcasts can be supported by periodic switching to the common control channel.

- **Frequency Hopping:** In frequency-hopping approaches, nodes switch, or in other words hop, between different channels. There are two basic variations of this method: *common hopping* and *independent hopping*. In common hopping approaches, all the nodes hop according to the same pattern and remain on the same channel if they agree to exchange data packets and rejoin the hopping sequence after the transmission. Examples of the common hopping approach are presented in [266, 270]. In the independent hopping approach, nodes follow their own hopping sequence. Nodes usually hop to a common channel after following their sequence which enables the exchange of hopping sequences. If a node wants to transmit data to a destination, it switches its interface to the next channel according to the destination's hopping sequence. McMAC [195] and *Slotted Seeded Channel Hopping* (SSCH) [49] are examples of independent hopping. The main advantage of frequency hopping approaches over dedicated control channel and split phase approaches is to eliminate the channel-negotiation process. Nodes simply follow their hopping pattern in order to exchange packets. On the other hand, the protocols require tight time synchronization and channel switching time is an important overhead. It is difficult to support broadcast operations and, if the nodes have limited memory, keeping the hopping sequence of each neighbor may bring extra overhead [81].

2.2.2 Multi-Radio Multi-Channel Wireless Ad Hoc Networks

In this section, we discuss multi-radio multi-channel networks and present the existing relevant studies and the comparisons. Coordination of communication is simpler with multi-radio and multi-channel wireless ad hoc networks compared to the single-radio variant. The multi-radio multi-channel wireless ad hoc networks are classified according to channel assignment approaches as follows [81]:

- **Fixed Channel Assignment:** Fixed channel assignment methods assign a permanent channel to each radio. Similar to the semi-dynamic channel assignment for single radio networks, channels are assigned usually following graph-based approaches. For instance in [190], the channel assignment is formulated as a topology control problem with the objective of minimizing link conflicts and still keeping the network connected. Similarly, Draves *et al.* [90] approach the problem by introducing a connectivity layer. In [264] the objective is to minimize the channel interference among links. Other examples of fixed channel assignment with topology control are presented in [86, 87].

In [152] the problem is formulated as a multi-commodity flow problem [80] with a fixed data rate on each link. In [151], a distributed channel assignment algorithm is presented which is based on local information.

The advantage of the fixed channel assignment is that the problem is easier to solve since the conditions are not considered dynamic. Graph-coloring methods can be used to solve the channel assignment. Since there are multiple radios, solving the connectivity problem is easier compared to the single-radio wireless ad hoc networks. On the other hand, the fixed assignment cannot adapt the use of channels according to the varying conditions such as interference, load, etc.

- **Semi-Dynamic Channel Assignment:** Semi-dynamic channel assignment also assigns fixed channels to the radios. However, channel assignment is repeated periodically according to changing conditions. The advantage of semi-dynamic channel assignment over the fixed channel assignment is that most of the algorithms are load-aware which means that the data rates over links are considered to be dynamic. Examples of load-aware assignment are presented in [37, 213, 221, 288]. A common point about these studies is that they address channel assignment together with routing such that routes are selected according to the capacities of the links. There exist other studies based on semi-dynamic channel assignment where the load is not considered but the external interference from other networks together with the interference within the network is considered during channel assignment [215].

  Load-aware channel assignment enhances the performance when the nodes transmit with variable data rates. On the other hand, estimation of the dynamic traffic patterns may be quite challenging. External interference-aware assignment can change the channel use according to the level of interference which is an important property considering the intensive use of the ISM bands.

- **Dynamic Channel Assignment:** Most of the multi-radio multi-channel wireless ad hoc network protocols favor to keep some of the interfaces fixed while some of the interfaces switch over different channels to keep the network connected. There are not many examples of dynamic channel assignment protocols where nodes switch their interfaces dynamically from one channel to another between successive data transmissions. An example is presented in [202] which is a dynamic multichannel CSMA-MAC protocol. It is assumed that the number of available radios is equal to the number of channels which can be expensive when there is a large number of channels. Before transmitting a packet, a node listens on all the channels in parallel to find a free channel to transmit.

- **Hybrid Channel Assignment:** In hybrid channel assignment, some interfaces are assigned fixed channels whereas others switch between different frequencies. The examples of hybrid channel assignment are presented in [163] where the receivers have fixed assignment and in [173, 289] where a dedicated control channel is used. Hybrid channel assignment has the advantage of preserving the connectivity of the network. Simultaneous transmissions can be performed while the channel switching delay is avoided.

2.2.3 Comparisons

In Table 2.1, we summarize the general aspects of the multi-channel algorithms that we presented for wireless ad hoc networks. The table also presents comparisons of the discussed algorithms and it is sorted according to the classification that we have presented in Sections 2.2.1 and 2.2.2 with different features. The *Year* column shows the year when the algorithm was proposed/published. The column entitled *#of Radios* presents the number of radios required per node. The *Implementation* column indicates whether the channels are assigned with a distributed, centralized or peer-to-peer method. *Interference Estimation* specifies how interference is estimated. The *Coordination* field indicates how frequently the channel assignment is performed. The *Synchronization* column shows whether the algorithm requires time synchronization or not. The *Channel Orthogonality* field specifies whether the channels are assumed to be orthogonal or overlapping. The last column *Medium Access* shows whether the channel assignment is combined with a medium access protocol. Some channel assignment strategies are designed for specific MAC protocols whereas some of them can work with any medium access control protocol. On the other hand, some of them are tested with specific protocols.

Most of the algorithms were proposed after 2000. Multi-channel protocols and channel assignment topics are still under investigation to improve the communication in multi-hop wireless ad hoc networks. Channels are usually considered to be orthogonal or only the orthogonal channels are used. However, the use of overlapping channels can better utilize the spectrum once they are assigned carefully [193]. We discuss the improvements with the use of overlapping channels on the capacity of WSNs in Chapter 4.

Most of the protocols are either designed for or tested on IEEE 802.11 protocols. Some protocols estimate the interference by power sensing before channel selection or by keeping a list of free channels in the neighborhood. On the other hand, some protocols assume simple interference models, such as interference disks or hop-based interference, and avoid the cumulative interference due to the parallel transmissions. We investigate the correctness of graph-based interference models in Chapters 6 and 7 and propose a "receiver-based channel assignment" protocol by using the realistic interference model.

Table 2.1: *Comparison of Channel Assignment Methods for Wireless Ad Hoc networks*

Reference	**Year**	**# of Radios**	**Implementation**	**Interference Estimation**	**Coordination**	**Synchronization Requirement**	**Channel Orthogonality**	**Medium Access**
CMMP [297]	2007	Single	Clustered	Neighboring clusters interfere	Fixed	Required	Orthogonal	CMMP (Cluster-based multi-channel management protocol)
Component level assignment [275]	2006	Single	Centralized	Hop Count Based (2-Hops)	Fixed	Not required	Orthogonal	-
LCM MAC [183]	2006	Single	Peer-to-Peer	Power Sensing (Busy Tone)	Semi-Dynamic	Not required	Orthogonal	IEEE 802.11
RDT [235]	1987	Single	Localized	Circular Interference Range	Semi-Dynamic	Required (Slotted Aloha)	Orthogonal	Slotted Aloha, CSMA
M-CSMA [138]	2001	Single	Peer-to-peer	Power Sensing (At the receiver)	Dynamic Dedicated Control Channel	Not required	Orthogonal	IEEE 802.11
[169]	2003	Single	Peer-to-peer	Idle/Busy Status	Dynamic Dedicated Control Channel	Not required	Orthogonal	IEEE 802.11
MMAC [250]	2004	Single	Peer-to-peer	Free Channel List 1-hop neighbors	Dynamic Split Phase	Required	Orthogonal	IEEE 802.11
MAP [67]	2003	Single	Peer-to-peer	Free Channel List	Dynamic Split Phase	Required	Orthogonal	IEEE 802.11 (with scheduled communication)
TMMAC [302]	2007	Single	Peer-to-peer	Free Channel List	Dynamic Split Phase	Required	Orthogonal	IEEE 802.11 (with slotted communication)
HRMA [266]	1999	Single	Distributed	RTS/CTS	Dynamic Common Hopping	Required	Orthogonal	-
CHMA [270]	2000	Single	Distributed	Carrier Sensing	Dynamic Common Hopping	Required	Orthogonal	CHMA (Channel hopping multiple access)
McMAC [195]	2005	Single	Distributed	RTS/CTS	Dynamic Independent Hopping	Required	Orthogonal	IEEE 802.11 (modified)
SSCH [49]	2004	Single	Distributed	Interference Range	Dynamic Independent Hopping	Required	Orthogonal	IEEE 802.11
CLICA [190]	2005	Multiple	Centralized	Protocol interference model	Fixed	Not required	Orthogonal	IEEE 802.11 (Used in the simulations)
MR-LQSR [90]	2004	Multiple	Peer-to-peer	Measurement Based	Fixed	Not required	Orthogonal	IEEE 802.11
[264]	2005	Multiple	Centralized	Interference Disk (Graph based)	Fixed	Not required	Orthogonal	IEEE 802.11
[86]	2005	Multiple	Centralized	Connectivity Graph	Fixed	Not required	Orthogonal	-
[87]	2006	Multiple	Centralized	Link Conflict Graph	Fixed	Not required	Orthogonal	IEEE 802.11 (Only channel assignment is discussed)

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Table 2.1

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Reference	Year	# of Radios	Implementation	Interference Estimation	Coordination	Synchronization Requirement	Channel Orthogonality	Medium Access
[152]	2005	Multiple	Centralized	Protocol interference model	Fixed	Required	Orthogonal	IEEE 802.11 (Only channel assignment is discussed)
[151]	2007	Multiple	Distributed	Hop Count Based (3-Hops)	Fixed	Not Required	Overlapping	IEEE 802.11
[221]	2004	Multiple	Centralized	Interference Range (Double the comm. range)	Semi-Dynamic	Not required	Orthogonal	IEEE 802.11
[37]	2005	Multiple	Centralized	Interference Range (Protocol interference model)	Semi-Dynamic	Required	Orthogonal	IEEE 802.11
JOCAC [213]	2006	Multiple	Centralized/ Distributed	Physical interference model	Semi-Dynamic	Not required	Overlapping	IEEE 802.11
JCAR [288]	2006	Multiple	Distributed	Interference Range (Equal to the comm. range)	Semi-Dynamic	Required	Orthogonal	IEEE 802.11
[215]	2006	Multiple	Centralized	Measurement Based and Conflict Graph	Semi-Dynamic	Not Required (Used in the simulations)	Orthogonal	IEEE 802.11 (Used for simulations and implementation)
[202]	1999	Multiple	Distributed	Power Sensing	Dynamic	-	Orthogonal	IEEE 802.11
HMCP [163]	2006	Multiple	Distributed (Receiver fixed)	Free Channel List	Hybrid	Not required	Orthogonal	IEEE 802.11
DCA [289]	2000	Multiple	Distributed	Idle/Busy Status	Hybrid	Not required	Orthogonal	DCA (Extension of IEEE 802.11)
DCA-PC [173]	2001	Multiple	Distributed	Idle/Busy Status	Hybrid	Not required	Orthogonal	DCA-PC (Extension of IEEE 802.11)

2.3 Multi-Channel Communication in WSNs

In this section we discuss the differences between multi-channel communication in wireless ad hoc networks and WSNs. As we mentioned, WSNs are defined as a sub-class of wireless ad hoc networks. However, general wireless ad hoc networks are usually composed of nodes (laptop computers, palmtops, personal digital assistants (PDA) or other information devices) with more complex radios and can run protocols such as IEEE 802.11, which is costly in terms of energy consumption for the resource constrained sensor nodes. In the following we summarize the main differences:

- Sensor nodes are equipped with simple radios and usually a single radio is available at each node.
- Bandwidth is limited on sensor radios, e.g. 50kbps, whereas the nodes in a wireless ad hoc network can transmit with much higher rates.
- Most of the channel assignment protocols in wireless ad hoc networks are based on a variant of the IEEE 802.11 protocol which cannot be supported by the simple radios of the WSN devices.
- Energy efficiency is an important concern for WSNs. Sensor nodes are limited in power, computational capacity, and memory. On the other hand, in other wireless ad hoc networks, a terminal can be fairly powerful such as a PDA or a laptop. Both types of networks have energy as a scarce resource but WSNs have tighter requirements on the lifetime and replacing or recharging the batteries may not be always possible.
- Sensor nodes are usually densely deployed and the number of sensor nodes in a WSN can be several orders of magnitude higher than the nodes in a wireless ad hoc network [34]. These facts make scalability an important concern for WSNs.

Considering these differences, multi-channel protocols that are developed for wireless ad hoc networks may not be directly applied to WSNs since the traditional requirements of WSNs, such as energy-efficiency and scalability, remain important concerns. On the other hand, the fundamentals of the presented channel assignment strategies can guide the protocol design since WSNs share the challenges of single-radio wireless ad hoc networks, such as broadcast support and avoiding network partitioning.

2.3.1 Existing Work

In this thesis, we focus on the use of multi-channel communication to alleviate the impact of interference on the network's performance in terms of throughput and timely delivery of data. There also exist studies that utilize multi-channel communication for other objectives. For instance, the use of multi-channel communication against jamming is discussed in [38, 287, 294]. Channel surfing mechanisms have been introduced such that the jammed nodes dynamically change their operating frequency. Multi-channel clustering is discussed in [119] where the nodes that hold correlated data are clustered together and communicate on the same frequency, which is different from the communication frequency of the other clusters. Cluster heads are assumed to be the aggregation points to process raw data before relaying towards the sink node. The key objective in this work is to minimize energy consumption within the network by reducing the effects of collisions that may occur if the clusters operate on the same frequency. Multi-channel communication is also used in reliable data dissemination from the sink to the sensor nodes [172, 293]. The Typhoon protocol [172] uses channel switching to reduce contention in the broadcast medium which, in turn, reduces the completion time of data dissemination. Multi-channel communication can also be used to overcome the congestion that can occur due to contention and interference in the network. Examples of joint channel assignment and congestion control do exist in wireless ad hoc networks [112, 213]. However, in WSNs, congestion avoidance with multi-channel communication is very briefly addressed in [291].

In the following, we survey the channel assignment strategies in WSNs. All of the existing studies are based on the availability of a single radio per node. We follow the same classification that we used for wireless ad hoc networks:

- **Fixed Channel Assignment:** In this method, the nodes are clustered into different frequencies. The examples are presented in [5, 60, 119, 291]. The IEEE 802.15.4 standard also uses fixed channel assignment but it is possible that the beacon node can change the operating frequency of its network if the nodes report excessive levels of interference. In [291], it is argued that very frequent channel switching may cause potential packet losses. However, once channel switching is done synchronously, as we will explain for semi-dynamic and dynamic channel assignment methods in the following, the channel switching overhead can be eliminated.

- **Semi-Dynamic Channel Assignment:** In semi-dynamic approaches nodes are assigned fixed channels but they can switch between channels in order to communicate with other nodes. Examples are presented in [7, 10, 69, 166, 167, 191, 307].

- **Dynamic Channel Assignment:** Y-mac [149] is the first example that uses dynamic channel assignment in WSNs. A combination of a dedicated control channel and a frequency hopping method is used. In [277], Voigt extends the D-MAC protocol [179] and proposes to use multi-channel communication to reduce interference problems.

We explain the details of the mentioned examples in Chapter 5, where we survey multi-channel MAC protocols for WSNs.

2.3.2 Comparisons

In Table 2.2, we summarize the general aspects of the multi-channel algorithms that we have discussed for WSNs. The table is sorted according to the method of channel assignment, i.e. how often the channel assignment needs to be performed. The columns with the same titles that have been presented in Table 2.1 have the same meaning. Additionally, we have the columns *objective* and *broadcast support*. The column *objective* indicates the objective of the protocol such as increasing throughput, minimizing interference, etc. The *broadcast support* shows whether the protocol can support multi-channel communication, which can be quite challenging with a single radio.

Most of the algorithms have been introduced recently, during the course of the research reported in this thesis. Mostly, they rely on scheduled medium access and require synchronization due to the coordination of the interfaces switching between the channels. Overlaps between channels are not usually addressed except the receiver-based channel assignment which is presented in Chapter 6. The protocols that are based on clustered fixed channel assignment do not support broadcasts.

Research on multi-channel WSNs is more recent compared to the research in other classes of wireless ad hoc networks. There exist a few multi-channel MAC protocols and some channel assignment strategies. This thesis makes one step forward by extensively studying the potential improvements that can be achieved with multi-channel communication in WSNs. In Chapters 3 and 4, we study the characteristics of multi-channel communication. We show that the assumption of perfect orthogonal channels may fail in practice and the use of overlapping channels can better utilize the spectrum and increase network capacity once they are assigned carefully. In Chapter 5, we introduce a multi-channel MAC protocol designed to provide high throughput and high delivery ratio during high-rate traffic whereas it also meets the traditional requirements of WSNs. In Chapter 6, we introduce a receiver-based channel assignment algorithm to enable fast convergecast operations and evaluate its performance both in Chapter 6 and Chapter 7.

Table 2.2: *Comparison of Channel Assignment Methods for WSNs*

Reference	**Year**	**Implementation**	**Interference Estimation**	**Coordination**	**Synchronization**	**Channel Orthogonality**	**Medium Access**	**Broadcast Support**	**Objective**
[60]	2002	Centralized	Neighboring cells interfere	Fixed	Required	Orthogonal	IEEE 802.11 (Used in the simulations)	Inside clusters	Timely delivery of data
[5]	2005	Centralized	Hop count based (2-hops)	Fixed	Required	Orthogonal	LMAC (Used in the simulations)	Inside clusters (Branches of the tree)	Improve the reuse of the medium, reduce contention
[119]	2006	Distributed	-	Fixed	Not required	Orthogonal	TDMA/CSMA	Inside clusters	Improve the energy efficiency
TMCP [291]	2008	Centralized	Interference disk	Fixed	Not required	Orthogonal	-	Inside branches of the tree	Efficient data collection
MMSN [307]	2006	Distributed	Hop count based (2-hops)	Semi-dynamic	Required	Orthogonal	Slotted CSMA	Supported	Increase parallel transmissions, full multi-channel MAC design
[7]	2006	Distributed	Hop count based (2-hops)	Semi-dynamic	Required	Orthogonal	LMAC	Partially Supported	Enhance the communication performance in densely deployed WSNs
[69]	2006	Centralized	-	Semi-dynamic	Required	Orthogonal	TDMA	Supported	Improve the parallel transmissions and throughput
HyMAC [191]	2007	Centralized	Hop count based (2-hops)	Semi-dynamic	Required	Orthogonal	TDMA	-	Improve parallel transmissions and increase the network throughput
[166]	2007	Distributed	-	Semi-dynamic	Not required	Orthogonal	-	-	Throughput optimization by load balancing over multiple sink nodes
[167]	2008	Distributed	Interference Range / Measured with packet loss	Semi-dynamic	Not required	Orthogonal	-	-	Utilize multiple channels efficiently

Continued on the next page

Table 2.2

Continued from previous page

Reference	Year	Implementation	Interference Estimation	Coordination	Synchronization	Channel Orthogonality	Medium Access	Broadcast Support	Objective
Receiver Based Channel Assignment [4]	2008	Centralized	Physical interference model	Semi-dynamic	Required	Orthogonal/ Overlapping	Slotted	-	Fast Convergecast in WSNs
MC-LMAC [10]	2008	Distributed	Hop count based (2-hops)	Semi-dynamic	Required	Orthogonal	LMAC	Supported	Improve the achievable throughput of WSNs
Y-MAC[149]	2008	Distributed	Channel Polling	Dynamic	Required	Orthogonal	TDMA	Supported	Handling bursty traffic, energy efficiency
[277]	2008	Distributed	-	Dynamic	Required	Orthogonal	Slotted	-	Reduce interference problems

CHAPTER III [*]

Experimentation of Multi-Channel Interference

Abstract This chapter presents experiments to investigate the characteristics of multichannel communication in wireless sensor networks using an example sensor platform. By varying distances between the sensor nodes and operating frequencies of the radios we get a measure of the interference caused by parallel transmissions on the same channel and on adjacent bands. Our observations show that not only co-channel interference but also adjacent spectrum interference significantly influences the data delivery. Transmissions should be separated in the spatial or in the frequency domains if interference is to be avoided. In addition, we show that the distances between simultaneous transmitters and the number of simultaneous transmissions are highly correlated with channel distances. Therefore, channel assignments should be performed according to spatial distances for interference-free transmissions. We also give proposals for further investigation on the usage of this correlation that are relevant to the design of future multi-channel protocols.

3.1 Introduction

Wireless Sensor Networks (WSNs) is an evolving technology that is the fundament of various ubiquitous applications [11]. A WSN is embedded into the real world and enables monitoring, inspection and analysis of unknown, untested environments. It typically comprises a large number of battery operated, tiny sensor devices. Sensor nodes are designed to collect sensor data and to transmit readings by wireless communication.

With the growing interest, in the near future, WSNs are expected to be deployed in large numbers everywhere [308] — perhaps on the order of hundreds or thousands [34]. Besides the deployments in large numbers, the limited channel capacity and the influence of interference, due to external networks or electronic devices that share the same parts of the spectrum, are the other factors which will cause a competitive communication environment.

Multi-channel communication is an efficient method to eliminate interference and contention on the wireless medium by enabling parallel transmissions over different frequency channels [162]. Newer generations of commercially available radios used on the sensor nodes support multi-channel communication. For example, the Nordic NrF905 radio [24] used on Ambient μNodes [13] and the CC2420 radio [16] for MICAz [22] and TelosB [26] sensor nodes can be tuned to operate on different frequencies[†]. Hence, there exists the potential to use multi-channel communication for alleviating the effects of competitive communication environment in WSNs.

Use of multi-channel communication in multi-hop wireless mesh networks has been shown to be able to improve the network performance significantly [220]. Examples of multi-

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[*] This chapter is a minor revision of the paper published with the title "Multi-Channel Interference Measurements for Wireless Sensor Networks" in the Proceedings of the 31st IEEE Conference on Local Computer Networks, LCN 2006 [6].

[†] The terms "channel" and "frequency" are used interchangeably in the text.

channel MAC and routing protocols were introduced in [138, 173, 250]. Moreover, multi-channel MAC protocols especially designed for WSNs have been recently presented [7, 307].

There exist several practical experiments to test the link layer characteristics of WSNs for single-frequency systems [205, 304, 306]. Kurth *et al.* [160] and Mishra *et al.* [194], have presented experiments and observations about the behavior of IEEE 802.11b-compliant, multi-frequency systems for wireless mesh networks. When we look into the WSNs, characteristics are quite different. A typical sensor device is usually equipped with a single half-duplex radio transceiver, which can not perform simultaneous transmission and reception, but can work on different channels separately. On the other hand, traditional wireless mesh networks usually assume more powerful radio hardware and multiple transceivers per node. For instance, the typical bandwidth offered by WSNs is usually very limited, e.g., 50kbps, whereas an IEEE 802.11b-compliant radio can transmit with 54Mbps.

In this chapter, we experiment the characteristics of multi-channel communication in WSNs with an example platform: Ambient μNode [13] sensor platform equipped with Nordic NrF905 radio [24]. To the best of our knowledge, this is the first proposal that gives observations and discusses some possible implications about the interference behavior of multi-channel communication in the WSNs domain. Recently, Wu *et al.* [291] also presented a set of experiments to investigate the multi-channel interference in WSNs but on a different hardware (Micaz nodes equipped with the CC2420 radio [16]). Moreover, there is no standard protocol for multi-channel communication in WSNs so far and our observations can have implications for the design of future multi-frequency WSN protocols.

The primary objective of our experiments is to observe the level and the effect of adjacent spectrum interference. If the channels are orthogonal, simultaneous transmissions can take place on different channels without interference. However, radio signals are usually not limited to their allocated frequency band. Therefore, channel overlaps, that may cause interference, may be examined between adjacent bands depending on the filtering characteristics of the transceiver. Another issue is the spatial reuse of the channels. If the interference level is tolerable, simultaneous transmissions in close proximity can take place on the same channel or on adjacent bands. We investigate the relationship between these factors: "*What is the correlation between spatial distances and required channel distances to eliminate excessive interference in the presence of simultaneous transmissions?*". This correlation can be used for interference-free channel assignment. For instance, if two channels f_i and f_j have a large separation, they could be assigned to nodes that are closer. If they are close on the spectrum, they should be assigned to nodes that are far apart, to efficiently allocate the channels and maximize the spectrum utilization.

We show that there is a high correlation between channel distances and spatial distances: channel distances can be adjusted according to the spatial distances so that multiple concurrent transmissions can be performed without interference. Hence, the channels that can be used simultaneously change according to the spatial distances between the transmissions. Moreover, the number of simultaneous transmissions on different channels may change the level of interference on the wireless links. This relationship is also investigated with different numbers of simultaneous transmissions.

The rest of the chapter is organized as follows: Section 3.2 explains the methodology, the hardware and the parameters that are used during the experiments. Section 3.3 introduces the experiments related with physical distance and channel distances, and also the correlation between these factors. Section 3.4 presents the experiments about the number of simultaneous transmissions and its effects on the required channel distances to avoid interference. Section 3.5 includes the conclusions.

3.2 Preliminaries

3.2.1 Hardware and Transceiver Platform

The "Ambient μNode" sensor node platform [13] is used during the experiments. The platform has been used in various WSN applications [14, 17, 18, 25] and has the typical characteristics of a sensor node: a Texas Instruments MSP430F169 processor with 48 kB Flash memory (code) and 10kB of RAM (data). It operates on a 32 kHz clock and 4Mb EEPROM memory is available for permanent storage.

The sensor platform is equipped with a Nordic NrF905 [24], single-chip radio transceiver that can operate on the 868/915 MHz ISM band. The modulation of the transceiver is Gaussian Frequency Shift Keying (GFSK) and the data is internally Manchester coded. The transceiver automatically generates preamble and CRC (cyclic redundancy check). An onboard dipole antenna is integrated. The radio frequency of the platform is adjustable. It provides 512 channels with 200kHz channel width and 200 kHz channel spacing.

3.2.2 Environment and Topology

Tests are performed in a large office corridor which is about 150m long and 2m wide (University of Twente Campus, Zilverling Building, 4th floor corridor). The floor is carpeted. The nodes are not directly put on the ground but elevated by placing on 20cm-high boxes. We place the nodes on a line topology with 15m distance between each other.

3.2.3 Methodology

In the experiments, there are three different roles of the nodes: transmitter, receiver, and jammer. The transmitter sends out packets with sequence numbers every $1/8$ second. The number of packets is set to be 256 packets for each run. The receivers maintain a log of the received packets in their EEPROM and operate on the same frequency as the transmitter. At the end of the tests, the data from the loggers of the receivers are downloaded to a laptop. The jammer node is a transmitter whose operating frequency is adjusted to a different channel at each run. The transceiver provides 512 channels, thus in each turn both the transmitter and the jammer are set to send $512*256$ packets. They simultaneously[‡] transmit packets allowing us to observe the level of interference among different channels. The jammer's position is changed to observe the relationship between the physical distance and channel distance. Each run takes 8 seconds, and each turn takes approximately 68 minutes for each position of the jammer. To prevent variations due to different battery status, all the sensor nodes are equipped with brand-new batteries. The level of interference is used as an indicator for the link quality, i.e. the packet loss rate[§].

[‡] We use a gateway node attached to the laptop which transmits a start message for the transmitters. The gateway also sends "poll" messages to collect the data from the receivers stored in their EEPROM. All the nodes can directly communicate with the gateway node.

[§] Other measures of interference, such as the received signal strength indicator (RSSI), can certainly be used. However, the example radio platform does not provide the values of the received signal strength but can directly measure the packet loss rate.

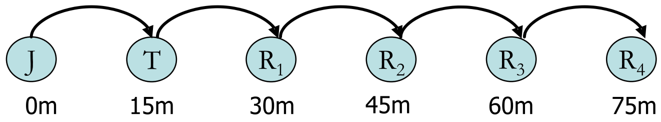

Figure 3.1: *Positions of the Nodes during the Experiments*

There are various factors that can influence the data delivery performance in wireless networks: the environment, the network topology, traffic patterns, hardware characteristics, etc. Environmental characteristics and obstacles cause signals to be reflected, diffracted and scattered. Background noise, human activity, temperature, humidity are all external factors that can influence the data reception. Also the activity of other networks sharing the same unlicensed portions of the radio spectrum may affect the results. Hardware characteristics such as antenna type, antenna gains, transmission power, receiver sensitivity, battery status, modulation schemes are the other factors that may affect the performance. External factors, such as the topology, the indoor environment, and the sensor nodes are the same for all the experiments. We perform the experiments during evenings to reduce the effect of human activity on the results. In order to see the stability of the links over time, we repeat the experiments on different days. Results of the experiments are averaged for different sets which are performed on different days.

3.3 Spatial Distance versus Channel Distance

We investigate the interference level versus channel distances with respect to the distance of a receiver to the jammer and the transmitter. By varying the position and the operating frequency of the jammer, the amount of interference is measured on adjacent bands for different spatial distances. In the rest of the chapter, we use the following symbols for the parameters:

- Δ represents the physical distance between the transmitter and a receiver.
- Γ represents the physical distance between the jammer and a receiver.
- Ψ represents the channel distance between the jammer's channel and a receiver's channel.

Note that these parameters can take negative values. For instance, when the jammer is positioned to the left of a receiver, Γ is negative and when it is to the right of a receiver it has a positive value. When the jammer is transmitting on channel 134 (in decimal) and a receiver is receiving on frequency 144, Ψ equals -10[¶].

There are four receivers, located at 30m, 45m, 60m, and 75m from the jammer's initial position (Figure 3.1 shows how the nodes are located during the experiments, J:Jammer, T:Transmitter, R:Receiver). The transmitter has a fixed position at 15m, during all the experiments. We do not use more nodes that are located further than 75m. This is because,

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[¶] The channel distances can also be represented in MHz. For instance the mid frequency of the first channel is at 844.6MHz, the second channel is at 844.8MHz. We use the decimal values for ease of presentation.

our aim is to investigate multi-channel interference within a single-hop (the link quality, i.e., the packet reception rate, at a further located receiver is found to be very low without the presence of a jammer). The jammer is placed at a different position for each run:

- At 0m.
- At 15m, next to the transmitter (in the text, when we refer "the jammer is next to", this means that the distance to the jammer is 20cm, due to width of the boxes on which the nodes are placed. However, we present Γ=0, in these cases).
- At 30m, next to the first receiver.
- At 45m, next to the second receiver.
- At 60m, next to the third receiver.
- At 75m, next to the fourth receiver.

The transmitter and receivers always operate on a base frequency of 873.6MHz (channel 144) and the jammer adjusts its transmitting frequency over 512 channels at each run. The operating frequency of the receivers and the transmitter is also changed to test whether the interference behavior is the same. This behavior is found to be similar for different operating frequencies of the transmitter and the receivers.

3.3.1 Observations

Figures 3.2, 3.3, 3.4, 3.5 show the results for the interference level at the receivers versus the channel spacing. In the figures only a subset of the channels are shown instead of all the 512 channels. For the channels not shown, the interference level at the receivers is 0%.

We observe that the level of interference changes according to spatial and frequency distances. There is a high correlation between channel spacing and spatial spacing. Hence, the channel spacing and, in turn, the number of channels that can be used simultaneously, changes according to the spatial distances between the transmitters. The correlation between these factors is computed in Section 3.3.2 and the use of this correlation is investigated. First, we explain our observations and discuss possible reasons for the observations.

A general observation is that, as channel distance (Ψ) changes, the level of interference changes as a function of the spatial distance at every receiver. For instance, independent from the location of a receiver, if Δ=Γ, every receiver experiences interference by the jammer when it operates on the same channel as the transmitter and/or on adjacent channels ($-1 \leq \Psi \leq 1$) at different interference levels. According to this observation, when both the jammer and the transmitter are using the same channel, co-channel interference occurs. In addition, when they are using adjacent channels, adjacent channel interference occurs. The level of interference varies at different receivers since Γ is different for each receiver. Non-perfect receiver selectivity can result in adjacent channel interference between consecutive channels. Imperfections in the transmit filter also cause the signal energy to spread over the adjacent spectrum (out-of-band emission). For the experimental radio platform, the 1^{st} adjacent channel transmission power is -27 dBc and 2^{nd} adjacent channel transmission power is -54 dBc. Also receiver selectivity values are given as follows: for the 1^{st} adjacent channel -7dB, for 1the 2^{nd} adjacent channel -16dB, respectively.

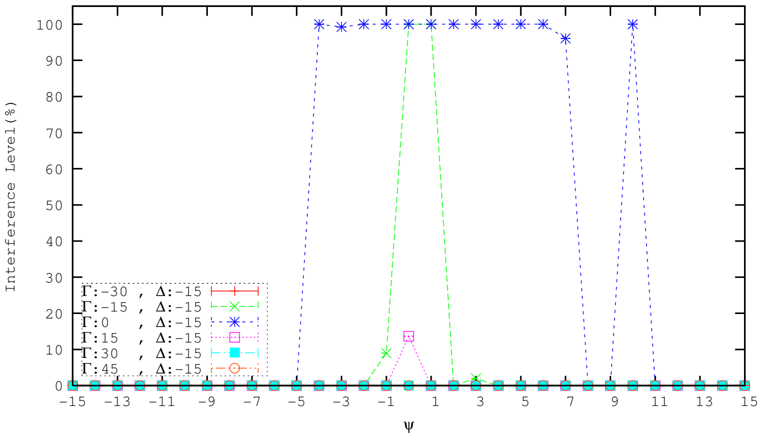

Figure 3.2: *Interference level at Receiver 1 (15m from the transmitter)*

According to our observations, when the jammer is getting closer to a receiver, the interference over the adjacent spectrum spreads over a larger interval, thus the channel distances should be larger to prevent interference. For example, in Figure 3.3, the receiver at 45m does not experience any interference when $\Gamma = -45$. When $\Gamma = -30$, there is interference if $-1 \leq \Psi \leq 1$. When the jammer is closer, such that $\Gamma = -15$, the interference occurs if $-1 \leq \Psi \leq 1$ and $\Psi = 4$. When the jammer is just next to the receiver ($\Gamma = 0$), the receiver experiences interference if $-5 \leq \Psi \leq 7$ or $\Psi = 10$. The same observation holds for all the receivers.

When the jammer is closer than the transmitter, there is always packet loss at all receivers.

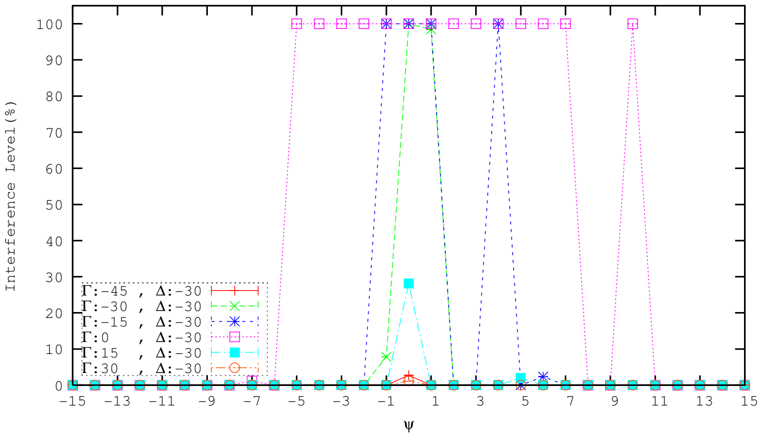

Figure 3.3: *Interference level at Receiver 2 (30m from the transmitter)*

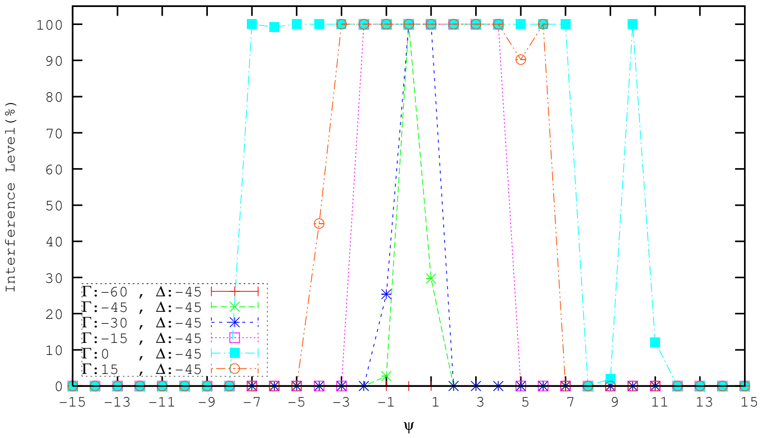

Figure 3.4: *Interference level at Receiver 3 (45m from the transmitter)*

However, when the distance between a receiver and both the jammer and the transmitter is the same, in most of the cases there is interference but there are also cases with no interference effect. For instance, when $\Delta = -15$ and $\Gamma = 15$, the receiver at 30m is at the same distance to the jammer and the transmitter (Figure 3.2). According to the protocol interference model that we have described in Chapter 2, one would expect a higher level of interference implying that neither of the packets or few of the packets are received correctly. However, the receiver loses only 15% of the packets when Ψ=0 and it is not interfered when $\Psi \neq 0$. This observation shows that, the idealized collision model –when transmissions are simultaneous and initiated from the same distance, packets are lost due to collision– is not always correct but

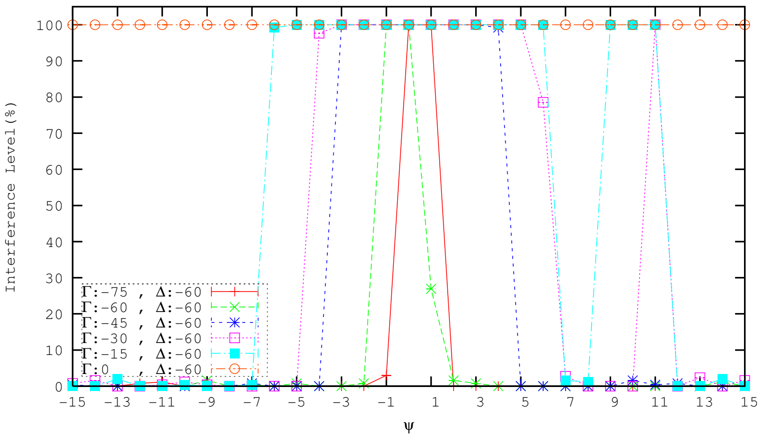

Figure 3.5: *Interference level at Receiver 4 (60m from the transmitter)*

simultaneous transmissions can successfully be decoded. In other words, one packet may be corrupted while the other is received correctly. One possible explanation of this observation is that signal strength is not isotropic, so it varies on different directions [205, 306].

When the transmitter is closer than the jammer, in most of the cases there is no interference at the receivers. However, there is an exception: when Γ = -75, the receiver at 75m is interfered when the jammer is on the same channel or on the adjacent channels (Figure 3.5). Therefore the receiver cannot receive any packets from the transmitter, although the jammer is positioned further. This can be explained by environmental factors such as the multipath effect. The shape of the corridor allows the wireless signals to be reflected by the walls so that multiple copies of the jammer's signals may be received stronger than the transmitter's. Thus, signals initiated from a further position are not always weaker than the signals that are initiated from a closer distance. On the other hand, we do not observe other examples of this conflict in this result set.

Another observation is about the symmetry of the channel distances. The interference level is asymmetric with respect to the operating frequency, such that different levels of interference occur between $-n \leq \Psi \leq n$, due to the asymmetric blocking values (a measure of how much interference can be tolerated due to the parallel transmissions on different channels) of the transceiver specified in the data sheet [24].

3.3.2 Correlation between Physical Distance and Channel Distance

According to the results explained above, we investigate the correlation between the physical distances and channel distances, namely, Γ, Δ and Ψ. The term "interference interval" is used to indicate the number of channels on which the receiver is interfered by the jammer. One could say that the interference interval should be two times the required channel distance to avoid interference. However, the interference level with respect to channel spacing is not always symmetric around the mid operating frequency. Computations on the interference interval are given in Section 3.6.

As the signals propagate through the wireless medium, the signal power decreases. The ratio of the transmitted signal power to the received power is called the path loss. The received signal power decreases in inverse proportion to the distance between the transmitter and the receiver [259]. Path loss is also influenced with wavelength of the transmitted signal, propagation medium, height and gain of the antenna, environment, etc. The received signal power is computed as:

$$P_R = \frac{P_T}{Path\_Loss} \tag{3.1}$$

where P_T represents the transmitted signal power and P_R represents the received signal power. We adopt Equation 3.1, to calculate the relative signal strengths of the transmitter and the jammer with respect to distance. Let SIR represent the received signal strength ratio (signal-to-interference ratio) of the transmitter and the jammer at the receiver with respect to distance. Then,

$$SIR = \frac{P_{RT}}{P_{RJ}} \tag{3.2}$$

where P_{RT} and P_{RJ} represent the power of the signals received from the transmitter and the jammer respectively. We simplify SIR as follows:

$$SIR = \frac{\left(\frac{P_{RT}}{Path\_Loss_T}\right)}{\left(\frac{P_{RJ}}{Path\_Loss_J}\right)} \tag{3.3}$$

where P_T and P_J represent the transmission power of the transmitter and the jammer, $Path\_Loss_T$ and $Path\_Loss_J$ represent the path loss values of the transmitter and the jammer, respectively. Since both the transmitter and the jammer send out packets with the same power[‖], SIR is then the ratio of the path losses. We simplify Equation 3.3 as:

$$SIR = \frac{Path\_Loss_J}{Path\_Loss_T} \tag{3.4}$$

According to the log-distance path loss model[**], loss is calculated as follows:

$$Path\_Loss = L_0 \left[\frac{d}{d_0}\right]^{\alpha} \tag{3.5}$$

where d is the distance between antennas, d_0 is the reference distance for the antenna far field, L_0 is the path loss at distance d_0 and depends on the antenna characteristics, and α is the path loss factor. Since both of the senders have the same values for L_0 and d_0, SIR is the ratio of the distances to the power of α. Simplifying Equation 3.4:

$$SIR = \left(\frac{\Gamma}{\Delta}\right)^{\alpha} \tag{3.6}$$

SIR in decibels is:

$$SIR_{dB} = 10\alpha \log_{10} \frac{\Gamma}{\Delta} \tag{3.7}$$

After computing the interference interval and SIR_{dB} we obtain the correlation coefficients[††] for each receiver. Table 3.1 shows the correlation coefficients according to the positions of the receivers. Computations of interference intervals, SIR_{dB} and correlation coefficients are presented in Figure 3.10, in Section 3.6.

[‖] The transmit power of the radios might vary due to the improper calibration of the devices, battery status, etc. We assume that these factors are negligible.

[**] The log-distance path loss model is a generalized free-space path loss model. The path loss exponent α varies between 2 (free-space path loss) and 5 to 6 according to the environment. More complicated path loss models can also be used but the model can capture the essence of signal propagation [114] and we are only interested in finding an approximation of relative received signal strengths from the transmitter and the jammer reduced by distance.

[††] A correlation coefficient is a number between -1 and 1 which measures the degree to which two variables are linearly related. If there is perfect linear relationship with positive slope between the two variables, we have a correlation coefficient of 1; if there is positive correlation, whenever one variable has a high (low) value, so does the other. If there is a perfect linear relationship with negative slope between the two variables, we have a correlation coefficient of -1. A correlation coefficient of 0 means that there is no linear relationship between the variables.

Receiver's Position	Correlation Factor
30m	-0.985
45m	-0.967
60m	-0.911
75m	-0.977

Table 3.1: *Correlation coefficients*

According to the results, the correlation between two parameters for all receivers is close to -1. This means that there is a negative relationship between SIR_{dB} and the interference interval, when one increases, the other decreases. In other words, when the received signal strength from the transmitter decreases at the receiver due to jammer's position, the number of channels on which the receiver's performance is degraded, increases. Besides computing the correlation coefficients for the individual receivers, we computed the coefficients for all the results. The overall correlation is found to be -0.857. These results show that, with a high probability, one can predict the value of one parameter by knowing the value of the other.

With the knowledge of this correlation, channel distances can be adjusted according to the spatial distances so that multiple concurrent transmissions can be performed without interference. For instance, when a WSN is deployed, the positions can be adjusted such that the interference interval is smaller and more frequencies can be used for simultaneous transmissions. Moreover, proper channel assignment can be performed by the sensors locally by collecting interference data and infer the value of the proper channel to be used. This relationship is an important information for the MAC layer at the channel assignment phase.

The correlations can also be used to estimate the relative positions of sensor nodes. For instance, three sensor nodes can estimate their relative positions by using the same methodology in our experiments: assign roles (jammer, transmitter, receiver), perform transmissions, collect data and infer the relative positions. They can further exchange their roles to provide more accurate results.

Moreover, these results can be used to calculate the optimal throughput with perfect knowledge of position and channel spacing requirements. For instance, if two channels mostly overlap and the throughput is reduced, for example by 15% on each channel, we still have 1.7 times the bandwidth of one channel. These calculations can represent the upper bound which is a maximum that can be achieved, with global knowledge. The performance of multi-channel MAC algorithms can be compared with this maximum.

To summarize, besides the co-channel interference adjacent channel interference also plays an important role on the data delivery rate. The observations expressed so far have an important impact on multi-channel protocol design for WSNs. If the channels are assigned properly, simultaneous transmissions can take place without disturbing each other.

3.4 Spatial Distance versus Channel Distance - Multiple Jammers

The number of simultaneous transmissions in the environment is another important factor which may affect the results. In this set of experiments, the effect of the number of jammers is

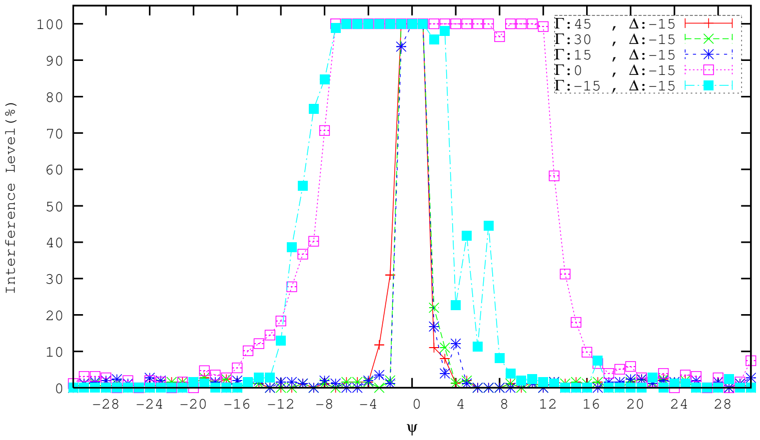

Figure 3.6: *Interference level at Receiver 1 (15m from the transmitter)*

investigated. We experiment with double jammers and also with triple jammers[‡‡]. However, to eliminate repetitions and redundancy, the results for double jammers are not presented. Instead, the results for triple jammers are presented where the data delivery rate is worse than the results for the double jammers. The results of this set can be compared with the results in Section 3.3 where only a single jammer is active. The transmitter and the receivers operate on 873.6MHz (144 Decimal) and the jammers adjust the operating frequency over 512 channels at each run and send out packets simultaneously with the transmitter. Since the jammers are always positioned together[*], Γ has the same meaning.

Figures 3.6, 3.7, 3.8, 3.9 show the results on the interference level at the receivers. In Section 3.3 we mentioned that, when Γ=Δ, independent from the location of a receiver, there is interference when the jammer operates on the same channel or on the adjacent channels. However, when triple jammers are positioned next to the transmitter, all the receivers experience interference when $-12 \leq \Psi \leq 8$. The interference level with more jammers is similar compared to the interference with a single jammer. However, interference is observed over a wider adjacent spectrum with more jammers. Moreover, all the receivers are interfered the most in this setting compared with the other positions of the jammers except when the jammers are located next to a receiver.

When there are 3 jammers located next to the receiver at 30m (Γ=0), there is interference when $-16 \leq \Psi \leq 16$, over 32 channels in Figure 3.6 whereas the interference interval is $-5 \leq \Psi \leq 8$ with a single jammer as shown in Figure 3.2. When triple jammers are transmitting next to the receiver at 45m ($\Gamma = 0$, Figure 3.7), the interference level is over

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[‡‡] The experiments can certainly be extended with more jammers. According to the data specifications of the example radio platform, the channels become orthogonal after 50 channels of spacing (10MHz). With 3 jammers, we already observed that the receiver located at the furthest position (75m) was jammed within 50 channels distance and not beyond.

[*] Different positioning of the jammers can certainly be experimented. The motivation for putting the jammers together is to test the worst-case scenarios, where multiple jammers with strong additive interference may disrupt the communication at a nearby receiver.

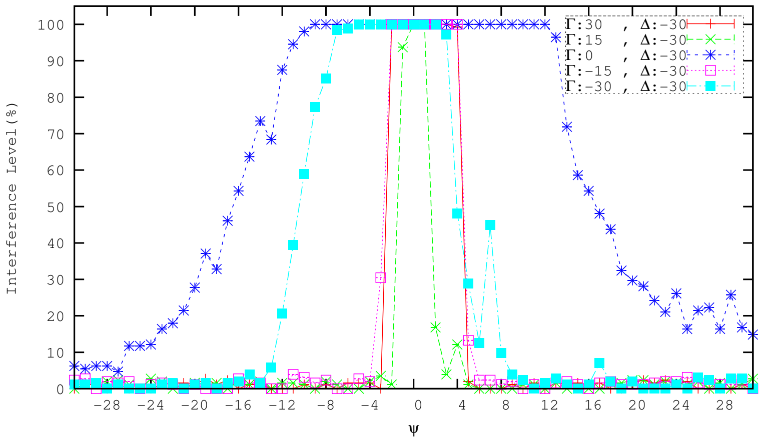


Figure 3.7: *Interference level at Receiver 2 (30m from the transmitter)*

20% within the $-24 \leq \Psi \leq 24$ interval. Triple jammers next to the receivers at 60m and at 75m create interference on all channels shown in Figures 3.8 and 3.9 when $\Gamma = 0$.

According to the results of this set, the channel spacing between simultaneous transmitters in the same spatial domain should be larger with more jammers. The required channel spacing to avoid interference for the receivers varies with respect to the spatial distances to the transmitters.

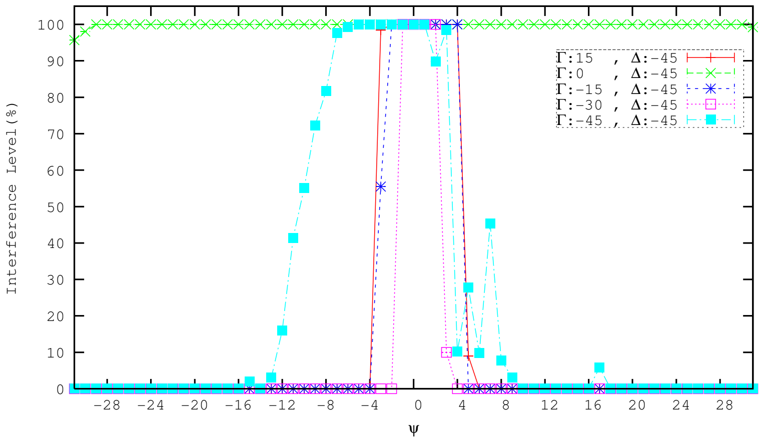


Figure 3.8: *Interference level at Receiver 3 (45m from the transmitter)*

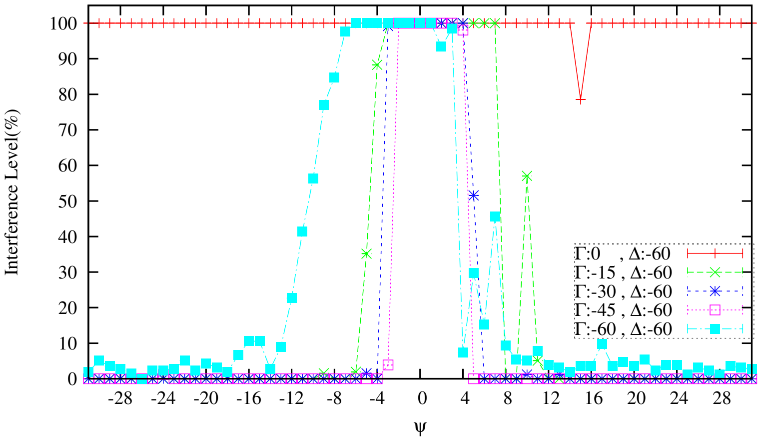


Figure 3.9: *Interference level at Receiver 4 (60m from the transmitter)*

3.4.1 Correlation Calculations with More Jammers

The number of simultaneous transmissions clearly affects the interference level. When there are more jammers, the interference signal is stronger and if the transmitter's signal is weaker than the interference, packets might be corrupted.

In Section 3.3, SIR is used to mention the ratio of the signal strengths of the transmitter and the jammer with respect to distance for a single jammer (Equation 3.4). When there are multiple jammers, SIR can be computed as;

$$SIR = \frac{P_{RT}}{\sum P_{RJ}} \tag{3.8}$$

where the total interference is calculated as the sum of the interference of individual jammers, according to the physical interference model discussed in Chapter 2 (in [184], it is shown that additive interference assumption is valid for low power sensor radios). We compute the correlation coefficients for triple jammers as given in Table 3.2. These coefficients imply a similar correlation between the spatial distances and the channel distances. Hence, these results support our conjecture about the correlation. Computations of interference intervals, $SIR_{d_{dB}}$ and correlation coefficients are presented in Figure 3.11, in Section 3.6.

Receiver's Position	Correlation Factor
30m	-0.881
45m	-0.915
60m	-0.966
75m	-0.988

Table 3.2: *Correlation coefficients for triple jammers*

3.5 Conclusions

We have investigated the data link interference behavior of a multi-channel WSN system with an example radio platform. When there are simultaneous transmissions operating on the adjacent spectrum in the same spatial domain, not only co-channel interference but also adjacent spectrum interference is observed. We have tested the required channel distances between simultaneous transmissions for a specific indoor environment. There is a high correlation between the spatial distances and channel distances. Therefore, channel spacing can be adjusted according to the spatial distances so that multiple concurrent transmissions can be performed without interference. Channel distances and in turn the number of channels that can be used simultaneously change according to the spatial distances between the transmissions. Implications about where and how this correlation can be used have been presented.

The ability of the transceiver to reject the adjacent spectrum interference is a hardware-specific property. Advanced radios, for instance used for cellular networks, can successfully eliminate the adjacent spectrum interference. However, sensor nodes are usually equipped with much simpler radios. In [291], it is also shown that adjacent channel interferences may greatly impact radio reception on the CC2420 radio which confirms our observations. Before implementing a multi-channel protocol on sensor nodes, the characteristics of multi-channel communication on the radio platform should be investigated. In [8], we took a further step towards the systematic usage of overlapping channels and show that while having an acceptable level of interference (packet loss) with smaller channel distances, we can enhance the spectral efficiency compared with larger channel distances that result in no packet losses.

Despite the hardware-specific results, the work in this paper opens up an interesting direction for further investigation. As an extension, it would be interesting to extract the interference information from the active traffic in a real network instead of measuring the interference separately. In this chapter, we have experimented the impact of adjacent spectrum interference on packet losses of individual nodes. In Chapter 4, we evaluate the impact of overlapping channels on the overall performance of a network.

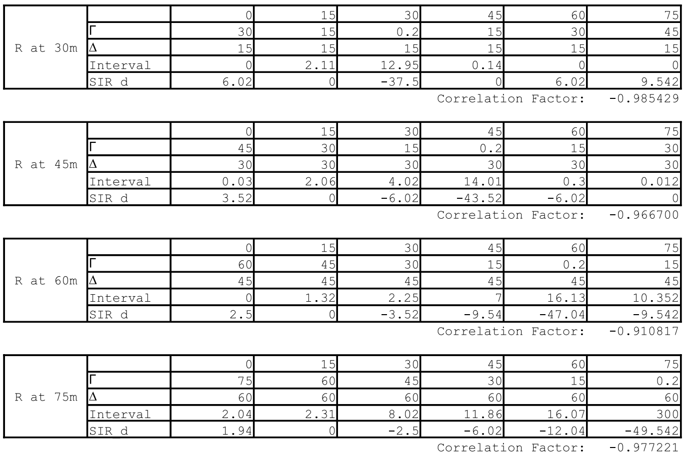
3.6 Correlation Computations

3.6.1 Interference Interval Calculation

When the jammer is transmitting on a specific channel, if the interference level at a receiver is above 0%, that channel is included in the interference interval. For instance, if the interference level is 100%, this means that 1 channel is totally affected. If the interference level is 40%, the receiver is affected by $40/100 = 0.4$ on this channel. Then, we sum the number of channels that the receiver is affected for a specific position of the jammer. Figures 3.10 and 3.11 show the values of the calculated interference interval for the results shown in Figures 3.2 to 3.9.

3.6.2 SIR Calculation

The SIR is computed in dB (Equation 3.7) and $\alpha = 2$. Results are shown in Figures 3.10 and 3.11. The columns represent the positions of the jammer: at 0m, 15m, 30m, 45m, 60m, 75m.



R at 30m		0	15	30	45	60	75
	Γ	30	15	0.2	15	30	45
	Δ	15	15	15	15	15	15
	Interval	0	2.11	12.95	0.14	0	0
	SIR d	6.02	0	-37.5	0	6.02	9.542

Correlation Factor: -0.985429

R at 45m		0	15	30	45	60	75
	Γ	45	30	15	0.2	15	30
	Δ	30	30	30	30	30	30
	Interval	0.03	2.06	4.02	14.01	0.3	0.012
	SIR d	3.52	0	-6.02	-43.52	-6.02	0

Correlation Factor: -0.966700

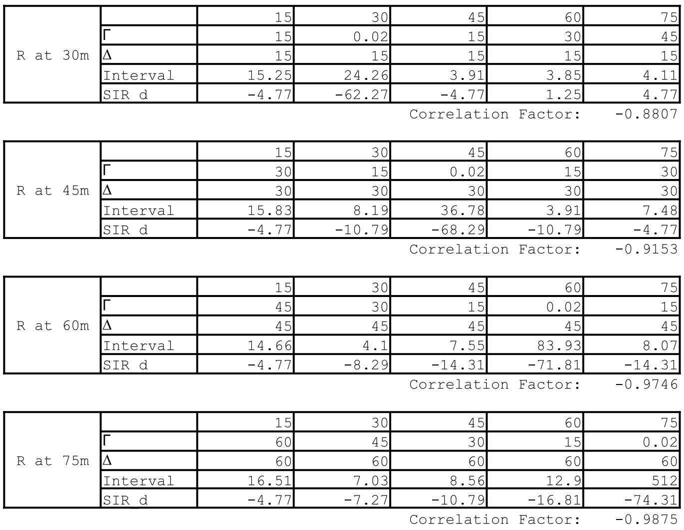
R at 60m		0	15	30	45	60	75
	Γ	60	45	30	15	0.2	15
	Δ	45	45	45	45	45	45
	Interval	0	1.32	2.25	7	16.13	10.352
	SIR d	2.5	0	-3.52	-9.54	-47.04	-9.542

Correlation Factor: -0.910817

R at 75m		0	15	30	45	60	75
	Γ	75	60	45	30	15	0.2
	Δ	60	60	60	60	60	60
	Interval	2.04	2.31	8.02	11.86	16.07	300
	SIR d	1.94	0	-2.5	-6.02	-12.04	-49.542

Correlation Factor: -0.977221

Figure 3.10: *Correlation coefficients for a single jammer*



R at 30m		15	30	45	60	75
	Γ	15	0.02	15	30	45
	Δ	15	15	15	15	15
	Interval	15.25	24.26	3.91	3.85	4.11
	SIR d	-4.77	-62.27	-4.77	1.25	4.77

Correlation Factor: -0.8807

R at 45m		15	30	45	60	75
	Γ	30	15	0.02	15	30
	Δ	30	30	30	30	30
	Interval	15.83	8.19	36.78	3.91	7.48
	SIR d	-4.77	-10.79	-68.29	-10.79	-4.77

Correlation Factor: -0.9153

R at 60m		15	30	45	60	75
	Γ	45	30	15	0.02	15
	Δ	45	45	45	45	45
	Interval	14.66	4.1	7.55	83.93	8.07
	SIR d	-4.77	-8.29	-14.31	-71.81	-14.31

Correlation Factor: -0.9746

R at 75m		15	30	45	60	75
	Γ	60	45	30	15	0.02
	Δ	60	60	60	60	60
	Interval	16.51	7.03	8.56	12.9	512
	SIR d	-4.77	-7.27	-10.79	-16.81	-74.31

Correlation Factor: -0.9875

Figure 3.11: *Correlation coefficients for triple jammers*

CHAPTER IV *

Estimation and Analysis of Multi-Channel Interference

Abstract Multi-channel communication protocols in wireless networks usually assume perfect orthogonality between wireless channels or consider only the use of interference-free channels. The first approach may overestimate the performance whereas the second approach may fail to utilize the spectrum efficiently. Therefore, a more realistic approach would be the careful use of interfering channels by controlling the interference at an acceptable level. We explore a simple method to estimate the packet error rate (PER) due to adjacent channel interference in a wireless network. The method experimentally characterizes the multi-channel interference and analytically estimates it based on the observations from the experiments. Furthermore, the analytical estimation is used in simulations to derive estimates of the capacity in larger networks. Simulation results show that the achievable network capacity, which is defined as the number of simultaneous transmissions, significantly increases with realistic interfering channels compared to the use of only orthogonal channels. When we consider the same number of channels, the achievable capacity with realistic interfering channels can be close to the capacity of idealistic orthogonal channels. This shows that overlapping channels which constitute a much smaller band, provides more efficient use of the spectrum. Finally, we explore the correctness of channel orthogonality and show why this assumption may fail in a practical setting.

4.1 Introduction

The research community working on multi-channel protocols either assume that channels are perfectly orthogonal (interference-free) or consider the use of only orthogonal channels. Assumption of perfect orthogonal channels fails in practice since radio signals are usually not limited to their allocated frequency band so that channel overlap/interference may be examined between adjacent bands. On the other hand, the use of only orthogonal channels cannot utilize the spectrum efficiently. For instance, the 802.11b standard define 11 channels (in the 2.4GHz band) of which only 3 are orthogonal. Most users configure their wireless interfaces to use one of these 3 channels. However, careful use of not only 3 channels but all 11 channels with a tolerable level of interference can significantly improve the system performance [193].

In Chapter 3, we have presented experiments to investigate the impact of inter-channel interference on individual nodal performances according to varying physical and channel distances among parallel transmissions. We have shown that there is a high correlation between channel distances and spatial distances according to the level of interference among simultaneous transmissions.

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[*] This chapter is an extension of the paper published with the title “Characterization of Multi-Channel Interference” in the Proceedings of the 6th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, WiOpt 2008 [3].

Experimentation of wireless networks is a valuable approach since it overcomes the unrealistic assumptions of idealistic RF models [156]. However, experimentation usually takes long and it is difficult to generalize/reproduce the results due to the large variety of settings. Therefore, it is difficult to evaluate the results which would be easy with an analysis or simulation.

In this chapter, we are interested in exploring the effects of inter-channel interference on the general performance of a wireless sensor network instead of the individual nodal performances. The first question that we try to answer is: "*Can we analytically estimate the interference such that the estimations comply with the results of the experiments?*". We explore a simple method to analytically estimate the multi-channel interference. The method calculates Signal-to-Interference-Noise Ratio (SINR) according to the spatial distances between the nodes. Based on the SINR values, the bit error rate (BER) is calculated as a function of the channel distances between the nodes and the transceiver characteristics. Finally, packet error rate (PER) is calculated in terms of BER. As mentioned, the analytical method should be simple but also should comply with the experimental observations. We verify the estimation by comparing the analytical results with the experimental results: on average, 90% of the results are found to be similar. We explain the comparisons in Section 4.4.

Furthermore, the analytical estimation is used in simulations to derive the performance in larger networks. The second question that we focus on is: "*How can we enhance the network performance and achieve better utilization of the spectrum with the use of overlapping channels while keeping the interference level at an acceptable level?*". First, we investigate the performance gains with the usage of overlapping channels over using only the orthogonal channels. In this case, the network can make use of more channels and the capacity increase is inevitable [194]. Then, we investigate the relationship between channel orthogonality and network capacity. In particular, we compare the achievable capacity with the same number of interference-free (orthogonal) channels and interfering (overlapping) channels. Simulation results show that, given the same number of channels, the achievable network capacity with realistic interfering channels can be close to the capacity of idealistic orthogonal channels. This implies that, if the transceiver is designed firm enough against adjacent channel interference, channel overlaps do not have a major impact on the achievable capacity. Overlapping channels which constitute a much smaller band, provides more efficient use of the spectrum. Finally, we investigate the correctness of schedules generated with the orthogonal frequencies assumption by comparing the values of the signal strength with the blocking values of the transceiver.

The rest of the chapter is organized as follows: in Section 4.2 we explain the experimentation of the interference behavior between overlapping channels. Section 4.3 introduces the analytical estimation of packet error rate caused by adjacent channel interference. Section 4.4 includes the comparisons between the analytical estimation and the mentioned experiments to verify the estimation. Section 4.5 presents the simulation results on the capacity of overlapping channels. Section 4.6 draws the conclusions.

4.2 Experiments

We have investigated the multi-channel interference behavior with an example radio platform [6, 8]. The primary objective of the experiments is to observe the level and the effect of adjacent spectrum interference. The experiments have been presented in Chapter 3.

As a result of the experiments, we show that not only co-channel interference but also adjacent channel interference significantly impacts the packet reception on the sensor radios. In this chapter, instead of individual nodal performances, we are interested in exploring the effects of adjacent channel interference on the general performance of a wireless sensor network.

4.3 Analytical Estimation

As we mentioned, experimentation is a valuable tool for testing the performance of wireless networks since it prevents the assumption of unrealistic/idealistic RF models [156]. On the other hand, due to the large variety of settings, it is usually difficult to generalize/reproduce the results which would be easy with an analysis or simulation. Simulations have the advantage of evaluating the scalability of the new solutions. Considering the advantages/disadvantages of the different methods, we describe a simple analytical model which is verified by experimentation and tested with simulations in larger networks.

In this section, we explain the steps to estimate the packet error rate caused by interference due to a jammer or jammers that simultaneously operate on a different channel in the same spatial domain. The method incorporates the parameters that impact the adjacent channel interference: distances between transmitter(s), jammer(s) and receiver(s), channel distance between the transmitter(s) and the jammer(s), transmission power and the transceiver characteristics.

The method is briefly composed of the following steps:

- Given the values of transmission power and the distance between the nodes, we calculate the signal to interference ratio (SINR) at the receiver using a log-distance path loss model [259].
- We calculate the bit error rate (BER) as a function of the SINR according to the blocking values (a measure of how much interference can be tolerated due to the parallel transmissions on different channels) of the transceiver with the given channel distance between the transmissions.
- We calculate the packet error rate (PER) as a function of the BER.

Analytical estimation enables us to calculate the PER caused by interference according to the spatial and channel distances between the parallel transmissions. A similar analytical method was discussed in [238]. The packet errors caused by interference due to the coexistence of different networks were investigated. We follow the same steps, but we also give comparisons with actual measurements on the sensor devices.

4.3.1 Single Jammer

In this section, we explain the details of the analytical calculations in the presence of a single jammer and in the next section we consider the case with multiple jammers.

SINR Calculation

We first calculate the received signal strength at the receiver with respect to the background noise and interference due to the jammer's transmissions, which is defined as:

$$SINR = \frac{P_{RT}}{N + P_{RJ}} \tag{4.1}$$

where P_{RT} and P_{RJ} represent the power of the signals received from the transmitter and the jammer after the signal have attenuated due to path loss and N represents the noise level at the receiver. We use the log-distance path loss formula given in Equation 3.5.

BER calculation

In communication systems, BER is simply defined as the ratio of the number of erroneous bits received divided by the total number of bits transmitted. It is used as a performance metric for the evaluation of the digital modulation techniques. Error probability is parameterized by the energy metric called energy per bit, E_b. The SNR or SINR values are often expressed in terms of the signal energy per bit as follows:

$$SINR = \frac{P_R}{N_o B + P_I} = \frac{E_b}{N_o B T_b} \tag{4.2}$$

where P_R is the received signal strength, P_I is the power of the interference, N_o represents the spectral noise density, B is the bandwidth of the transmitted signal and T_b is the time to transmit a bit. The quantity E_b/N_o is often called the SINR per bit, and $SINR = E_b/N_o$ for binary signalling. For performance specification, we are interested in the bit error probability P_b as a function of E_b/N_o. For frequency shift keying modulation, P_b is computed as [114]:

$$P_b = Q(\sqrt{E_b/N_o}) = Q(\sqrt{SINR}) \tag{4.3}$$

where Q-function represents the tail probability of the Gaussian distribution. On the other hand, in a fading environment the signal power varies randomly over distance or time due to the shadowing and multipath fading. Thus, SINR or E_B/N_o is a random variable with a fading distribution $p_{E_b/N_o}(\gamma)$. Therefore, $P_b(E_b/N_o)$ is also random. The average probability of error is computed by integrating the bit error probability over the fading distribution [114]:

$$\overline{P_b} = \int P_b(\gamma) p_{E_b/N_o}(\gamma) d\gamma \tag{4.4}$$

where $\overline{P_b}$ is the average error probability. We use the log-normal fading model in the calculations.

Given the SINR values, we can predict whether the receiver can demodulate the target signal based on the threshold values of "co-channel rejection" and "blocking" parameters. Co-channel rejection is a measure of the receiver's capability to demodulate a target signal in the presence of an unwanted signal, if both signals are on the frequency of the receiver [144]. Blocking indicates how much power the receiver can tolerate on a nearby frequency/channel,

Frequency	Blocking
1st adjacent channel (200kHz)	-7dB
2nd adjacent channel (400kHz)	-16dB
+1MHz	-40dB
-1MHz	-50dB
-2MHz	-63dB
+5MHz	-70dB
-5MHz	-65dB
+10MHz	-69dB
-10MHz	-67dB

Table 4.1: *Blocking values for the example transceiver*

and still can receive on a desired channel. It is the lower bound for the difference between the signal powers at the receiver. The example platform used during the experiments has a co-channel rejection of 13dB. This means if the wanted signal is 13dB or higher in magnitude than the unwanted signal, correct demodulation is performed. Correct demodulation typically means a BER (P_b) smaller than 10^{-3}. The blocking values of the example transceiver that we use are given in Table 4.1. These values are taken from the data sheet of the Nordic NrF905 radio [24].

PER Calculation

In the next step, we calculate the PER as a function of the BER, i.e., $\overline{P_b}$. The probability of not having a bit error is the probability that all the bits are received correctly. Therefore the conditional probability of PER is one minus the the probability of no bit errors and is computed as follows:

$$PER = 1 - (1 - \overline{P_b})^N \tag{4.5}$$

where N represents the number of bits in a packet. For the experimental setting each packet is composed of 32 bytes. If there is an error correction mechanism, then the PER utilizing the BER should be computed differently. However, the experimental platform does not provide an error correction mechanism and Equation 4.5 is the final form of the PER.

4.3.2 Multiple jammers

The number of simultaneous transmissions in the environment is another important factor which affects the level of interference. In the preceding sections we calculate the BER in the presence of a single jammer. In the case of multiple jammers, which is more likely to occur in a large set of nodes, a wireless signal is decoded by treating the sum of all the other transmissions as interference [136, 184]. The SINR in the presence of multiple jammers is calculated as follows:

$$SINR = \frac{P_{RT}}{N + \sum P_{RJ}} \tag{4.6}$$

	R1 @ 30m.	R2 @ 45m.	R3 @ 60m.	R4 @ 75m.
J @ 0m	96.8	96.8	90.3	96.8
J @ 15m	100	100	100	100
J @ 30m	87.1	96.8	100	83.9
J @ 45m	93.5	67.7	93.5	71.7
J @ 60m	96.8	93.5	74.2	64.5
J @ 75m	100	90.3	80.6	100

Table 4.2: *Ratio of matching between calculated and experimented results*

	R1 @ 30m.	R2 @ 45m.	R3 @ 60m.	R4 @ 75m.
J @ 15m	73.1	66.6	69.8	33.3
J @ 30m	73.1	90.5	96.8	93.6
J @ 45m	95.2	88.8	98.4	96.8
J @ 60m	96.8	95.2	100	87.3
J @ 75m	93.6	96.8	96.8	100

Table 4.3: *Ratio of matching between calculated and experimented results (multiple jammers)*

The rest of the calculations on BER and PER for multiple jammers is performed the same as in the case of a single jammer.

4.4 Evaluation with the Experimental Results

As we mentioned in the introduction, unrealistic/idealistic models may not always be reliable to estimate the real performance of wireless networks and should be verified with experimentation. In this section we present the comparisons of the analytical estimation and the experiments presented in Chapter 3, Sections 3.3 and 3.4.

The comparisons are based on a binary matching. If the PER for a given channel spacing is larger than 0, then we consider it as 1 which indicates that interference causes packet loss. Otherwise, there is no interference effect (0). For different positions of the jammer that are mentioned in Section 3.2.3 and different channel spacings we repeat the same process. Finally, we compute in how many cases the experimented and calculated results are the same i.e., in how many cases the experimented and the calculated PER is the same, which is either 0 or 1.

The comparisons are given in Tables 4.2 and 4.3. Topology and abbreviations are the same as in Figure 3.1 (J:Jammer, R:Receiver). The average matching is found to be 90% in the case of a single jammer and 87% for multiple jammers between the experimental and analytical results. In the case of multiple jammers, the worst values of matching are observed when the jammers were positioned at 15m, next to the transmitter. The estimated results, based on the distance metric, are more optimistic to predict the number of channels where interference causes packet loss. On the other hand, the experimented results report packet loss between $-12 \leq \Psi \leq 8$ for all the receivers. The reason for this might be that jammer signals originated from the same distance cause the receiver's signals not to be received properly and the variance in the SINR values at the receivers cause variable levels of packet

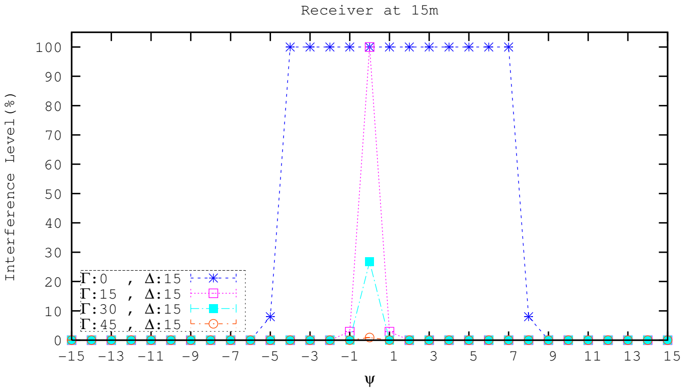

Figure 4.1: *Calculated PER versus channel spacing (15m from the transmitter)*

losses.

Figure 4.1 presents the analytical results for an example setting from the experiments presented in Chapter 3 with a single jammer whereas Figure 4.2 (same graph was presented in Figure 3.2) shows the experimented results for the same set. The x-axis (Ψ) shows the channel spacing between the transmitter and the jammer. Different lines stand for different values of Γ, the physical distance between the jammer and the receiver.

The difference between the analytical results and the experimental results may be due to various factors. In the experiments, we notice that the results differ when the jammer is located to the left of a receiver or to the right of a receiver at the same distance, since signal strength is not isotropic. The analytical estimation does not differentiate these 2 cases. We calculated the BER with log-normal fading. However, complex multipath effects in the

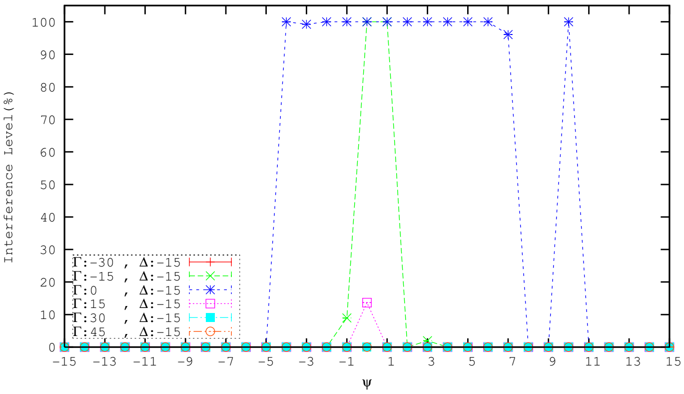

Figure 4.2: *Experimented PER versus channel spacing (15m from the transmitter)*

corridor, that degrade the signal strength in some locations and amplify in others, may not be captured. In the case of multiple jammers, we sum the interference values from the individual jammers according to the physical interference model which has been described in Chapter 2. However, as it was identified in [254], the measured interference from multiple transmitters can be less or more than what is theoretically predicted by the assumption of additive interference.

To summarize the results, the analytical estimation cannot perfectly predict the packet loss in all the experimented cases which is mostly due to the inaccurate calculation of the signal strength that is impacted by various factors. However, on the average the analytical estimation can capture the experimented level of interference at an acceptable level where the average matching is around 90%.

A question may arise whether the obtained conclusions can be generalized to different multi-channel systems. The blocking values and selectivity of the transceiver, basically how much the transceiver is prone to the interference, are the important factors to characterize the performance of such a multi-channel system. We discuss the impact of those factors with the simulations in Section 4.5. We also considered the fact that the actual received signal strength may vary from the computed value. This variance can be different for different platforms and environmental factors. Likewise, different signal propagation models can be used. What we aim to show is that the analytical computations may not always be realistic due to the idealistic assumptions [156]. Analytical estimations verified with actual implementation can avoid the errors before generalizing the results, for instance with simulations.

4.5 Capacity Estimation Simulations

We have investigated the individual node packet-loss/delivery capacities by experimental measurements. Based on the analytical estimation method, we develop a simulation model in Matlab [21] to analyze the overall capacity of the network with orthogonal channels and overlapping channels in a larger setting. The aim of the simulations to explore the performance of concurrent neighbor communications.

4.5.1 Simulation Settings

Fixed simulation parameters are tabulated in Table 4.4. A terrain of size 100*100 m^2 is used to simulate a dense network. A topology generator is used to randomly distribute the nodes within the terrain according to a uniform distribution. We have created 5000 random topologies. We run the simulation for each topology with overlapping channels and orthogonal channels. By changing the number of nodes but keeping the terrain size and the transmission range fixed, we simulate different levels of neighbor density. We vary different parameters: the number of nodes, number of channels and transmission power.

For each simulation, we assume all the nodes have a packet to transmit to a randomly selected neighbor[†]. A node can transmit to the selected neighbor if the neighbor is not addressed by another node or the node itself is not selected as a destination. The other constraint is due to the interference among concurrent transmissions. According to the analytical estimation, that is presented in Section 4.3, the interference among simultaneous transmissions

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[†] We should note that, the traffic is based on a single-hop communication between a pair of neighbor nodes. It may be argued that, this traffic model does not represent a typical communication pattern for WSNs but it provides an abstract model to test the performance of concurrent communications with orthogonal and overlapping channels.

Parameter Name	Value
Terrain Size	100*100 m^2
Number of nodes	50 – 500
Number of Channels	10 – 50
Transmission Power	-10dBm, 10dBm
Number of Runs	5000

Table 4.4: *Simulation Parameters*

is computed. A channel is assigned to a node if the PER due to co-channel and adjacent channel interference is 0 and if the destination or the node itself is not addressed by another node. The model can be considered as a one-shot, pairwise scheduling scenario.

We define the capacity as the number of nodes that can successfully be assigned a channel and can access the media. If the usage of orthogonal channels is assumed, the interference levels on the same channel are considered for a successful packet delivery. On the other hand, if the interfering channels are considered, then the interference levels also on the adjacent channels are checked for successful transmissions. At the end of the simulation we report:

- how many nodes can communicate successfully and simultaneously,
- how many nodes cannot communicate due to interference,
- how many nodes cannot communicate because possible destinations are selected by other transmitters or the destinations are themselves transmitters.

4.5.2 Capacity with Overlapping Channels and Orthogonal Channels

In the first set of the experiments we analyze the capacity with the usage of overlapping channels and using only the orthogonal channels. In this setting, the transmission power is set to 10dBm.

As we mentioned, the transceiver provides 512 channels with a 200kHz channel width. According to the experimental values and the data sheet of the example platform, channel spacing should be 10MHz (channel spacing should be 50) to guarantee interference-free communication. Considering this, we compare the performance with 10 orthogonal channels and 512 overlapping channels. Both the overlapping channels and orthogonal channels occupy the same spectrum between 868-915 MHz. Figure 4.3 presents the results. The x-axis shows the number of nodes and the y-axis shows the ratio of the nodes that can simultaneously access the media.

If the transceiver operates on a single channel, a limited number of nodes can communicate simultaneously. As the number of nodes increases, the density increases and this results in less chance to access the media due to higher interference and contention. If the nodes use only orthogonal channels, the performance is pessimistic in the sense that two nearby communications can simultaneously take place on closer channels if the interference level is tolerable. If the nodes use overlapping channels by controlling the interference at an acceptable level, the number of simultaneous transmissions is significantly increased: in the

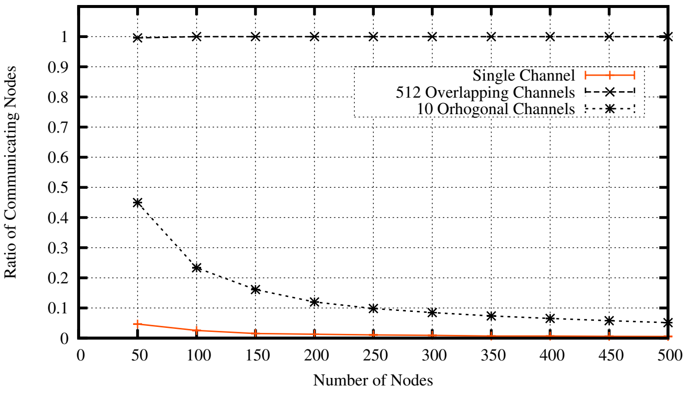

Figure 4.3: *Capacity with Overlapping Channels (512) versus Orthogonal Channels (10)*

example simulations all the nodes can communicate even if the network gets denser. Increasing the number of simultaneous transmissions improves the network performance by increasing the throughput [162].

4.5.3 Capacity with Equal Number of Overlapping and Orthogonal Channels

In the first set of the experiments, the capacity increase was guaranteed since the network can make use of more channels. In this set, we analyze the capacity with the same number of orthogonal and overlapping channels. Orthogonal channels constitute a wider spectrum. For instance 10 orthogonal channels require 500MHz-wide band whereas 10 overlapping channels make up a 2MHz-wide band.

Figure 4.4 shows the ratio of communicating nodes as a function of the number of chan-

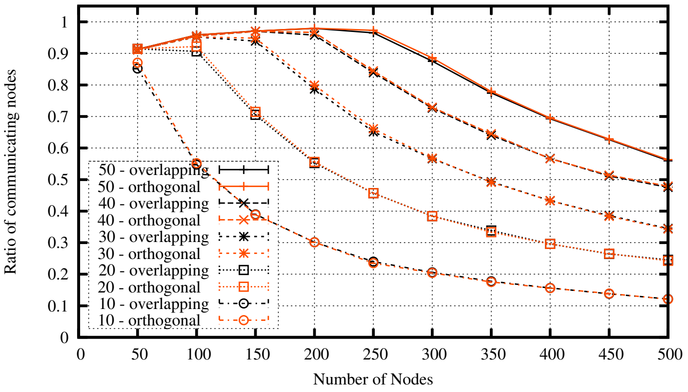

Figure 4.4: *Capacity with the Same Number of Overlapping and Orthogonal Channels*

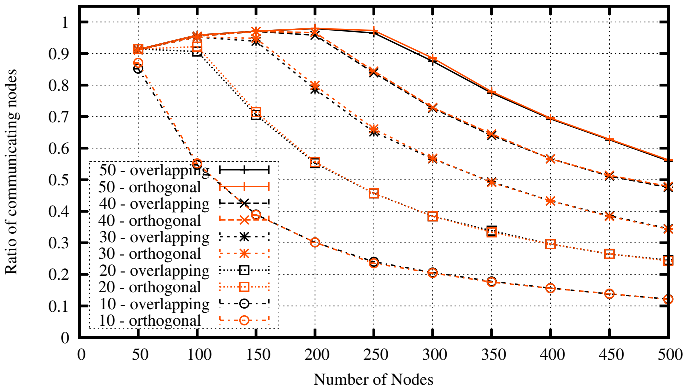

Figure 4.5: *Capacity with the Same Number of Overlapping and Orthogonal Channels, transmission power:-10dBm*

nels. Terrain dimensions and the transmission power parameters have the same values as in the previous set. The capacity results of the orthogonal channels are on the average 1-3% better than the results of the overlapping channels. The ratio of the nodes that create adjacent channel interference over the nodes that create co-channel interference is quite small. Therefore, hardly a difference is observed and the adjacent channel interference hardly affects the achievable capacity.

Another factor that can affect the capacity is the transmission power. In the following set of the simulations the transmission power is set to -10dBm, which is the minimum value for the example platform, to simulate a sparser network. Figure 4.5 shows the results of this set. When the transmission power is -10 dBm, the network is much sparser in terms of connectivity and interference. Similar to the previous results shown in Figure 4.4, whether the channels are overlapping or orthogonal, the capacity results differ only 1-3%. Although the network is sparser, the capacity with 50 nodes and 20 or more channels is lower than the capacity results presented in Figure 4.4, since some of the nodes cannot find a free destination to transmit due to the lower connectivity.

Careful use of interfering channels provides better utilization of the spectrum. Although the overlapping channels span a narrow band of the spectrum, the achievable capacity is similar to the capacity with orthogonal channels which constitute a wider band. By careful analysis of interference in terms of distance, transmission power, etc., the transmitters can be assigned channels with less distance. This allows the use of much more channels over a given band.

4.5.4 Impact of Transceiver Characteristics

In this set of the simulations, we discuss the impact of blocking values on the capacity. The default interference blocking value of the transceiver for the 1st adjacent channel (200kHz) is -7dB. This means if there is a jammer operating on the 1st adjacent channel, the signal from the jammer can be maximum 7dB stronger than the signal power of the transmitter on the

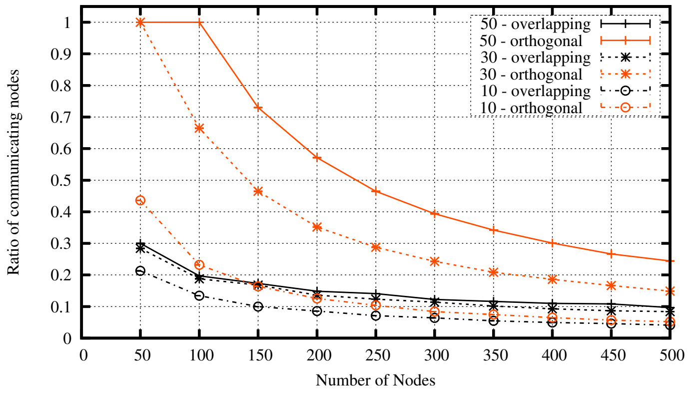

Figure 4.6: *Impact of Blocking Values on the Capacity (Blocking values are reduced by a factor of 10)*

same channel for none-interfering communication. If we decrease the default interference blocking values then a receiver will be more prone to interference from adjacent channels.

Figure 4.6 shows the capacity results when the interference blocking values are reduced by a factor of 10. The results for the orthogonal channels are not different from the results of the default values shown in Figure 4.4. On the other hand, the capacity differs with the overlapping channels. Much lower capacity is achieved since the interference from the nodes in the adjacent channel interference region is less tolerable at the receiver since the receivers are more prone to the interference. The difference of the capacity between overlapping channels and orthogonal channels varies up to a factor of 0.7 in sparser deployments. However, when the number of nodes increases, the ratio of the capacity values tends to be similar since the main limiting factor is the number of channels. However, we still observe almost a half factor of performance with overlapping channels compared to the orthogonal channels.

The results of the simulations show that adjacent channel interference has an impact on the capacity if the transceiver is prone to the adjacent channel interference. This should not be ignored when developing realistic protocols and algorithms on multi-channel wireless networks. However, if interference blocking values of the transmitters are firm enough against the adjacent channel interference, the achievable overall network capacity does not significantly differ from the capacity of orthogonal channels. The overall network capacity is found to be similar with the default settings of the example platform in terms of orthogonal and overlapping channels.

4.5.5 Correctness of Orthogonal Channels Assumption

As we mentioned, one of the general assumptions in multi-channel protocols is the perfect orthogonality of the channels. In this section, we investigate the correctness of this assumption. In particular, we investigate what if we treat the overlapping channels as orthogonal. In the simulations, we assume n number of orthogonal channels that constitute the same band as the overlapping channels. We investigate how many nodes are scheduled incorrectly.

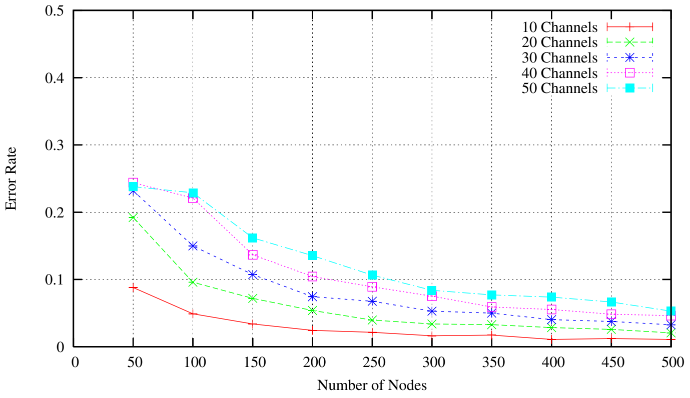

Figure 4.7: *Incorrectness of Orthogonal Channels Assumption*

This means incorrectly scheduled nodes select a channel according to the orthogonality assumption by only checking the interference on the selected channel. However, interference from the simultaneous transmissions on nearby channels may still disturb the transmission. Figure 4.7 presents the results. The y-axis shows the ratio of the nodes that are incorrectly scheduled for transmission, over the total number of nodes. The error rate is much higher in sparser scenarios and decreases with density since the ratio of simultaneous transmissions (ratio of communicating nodes) decreases. Although the capacity with orthogonal channels and overlapping channels is observed to be the same (Section 4.5.3), we cannot treat the channels as orthogonal and the channel selection by the orthogonality assumption may not always be correct. Thus, the protocols based on the orthogonal channels assumption may fail in a practical setting.

4.6 Conclusions

We have presented a methodology that experimentally characterizes the multi-channel interference and analytically estimates the interference based on the observations from an experimental work. Analytical estimation of interference is then used in simulations to investigate the impact of channel orthogonality on the network capacity and to show the improvements on the network performance. Furthermore, we have shown how the estimation methodology can be used for deriving estimates of the performance of a larger network by simulations. Simulation results support the previous experimental conclusion on the use of overlapping channels: the overall network capacity significantly increases with the use of overlapping channels. When we investigate the impact of orthogonality, we observe that the overall network capacity by using overlapping channels is close to the capacity of orthogonal channels. This shows that overlapping channels which constitute a much smaller band, provides more efficient use of the spectrum. If overlapping channels are assigned carefully in the same spatial domain, the spectrum is utilized more efficiently compared to the use of only orthogonal channels. In the last set of the simulations, we explore the assumption of treating the channels as orthogonal. Simulations results show that the transmission schedules based on orthogonal channel assumption is not always correct.

In Chapters 6 and 7, we investigate the effects of our findings by proposing a channel assignment algorithm that considers channel overlaps.

CHAPTER V [*]

MC-LMAC: A Multi-Channel MAC Protocol for Wireless Sensor Networks

Abstract In traditional wireless sensor network (WSN) applications, energy efficiency may be considered to be the most important concern whereas utilizing the bandwidth and maximizing the throughput are of secondary importance. However, recent applications, such as structural health monitoring, require high amounts of data to be collected at a faster rate. We present a multi-channel MAC protocol, MC-LMAC, designed with the objective of maximizing the throughput of WSNs by coordinating transmissions over multiple channels. MC-LMAC takes advantage of interference and contention-free parallel transmissions on different channels. It is based on scheduled access which eases the coordination of nodes, dynamically switching their interfaces between channels and makes the protocol operate effectively free of collisions during peak traffic. Time is organized into time slots and each node is assigned control over a time slot to transmit on a particular channel. We analyze the performance of MC-LMAC with extensive simulations. MC-LMAC exhibits significant bandwidth utilization and high throughput while ensuring an energy-efficient operation. Moreover, MC-LMAC outperforms the contention-based multi-channel MMSN protocol, a cluster-based channel assignment method and the single-channel CSMA in terms of data delivery ratio and throughput for high data rate, moderate-size networks of 100 nodes.

5.1 Introduction

In typical wireless sensor network (WSN) applications it is of interest to extend the network lifetime due to battery limitations of the sensor devices. As an important source of energy consumption, wireless communication in WSNs has received a lot of attention. Especially the MAC protocols [165] have been extensively studied with the objective of energy efficiency whereas throughput, bandwidth utilization, fairness and latency were considered as the secondary objectives [134].

It is usual that bandwidth is not the main concern in traditional low duty cycle, low data rate applications. However, it becomes an important concern during certain periods of time when a large burst of packets is generated, for instance, due to a change in the monitored conditions. Bursty data needs to be transported to a base station in a reliable and efficient manner. Emerging applications, such as intruder detection [45] or structural health monitoring [70], require data transfer at a higher rate by utilizing the limited bandwidth. Moreover, it becomes more common to use sensor nodes that run multiple concurrent applications which also results in higher data rate requirements. The common use of WSNs will further result in overlapping and co-existing networks which will make the bandwidth an important concern

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[*] Some parts of this chapter appear in the paper published with the title “Multi-channel Support for Dense Wireless Sensor Networking” in the Proceedings of the First European Conference on Smart Sensing and Context, EuroSSC 2006 [7] and in the technical report presented in [10].

for WSNs [308].

As mentioned in Chapter 2, the fundamental limitations on the achievable throughput are the limited reuse and/or the wastage of bandwidth due to interference and the half-duplex operation of the radios on the sensor nodes. In general wireless networks, multiple channels have been provisioned to mitigate the effects of interference by performing interfering transmissions on different frequency channels.

In this chapter we investigate the use of multi-channel MAC protocols to improve the achievable throughput of WSNs. Although the typical WSN radios operate on a limited bandwidth, the operating frequency of the radios can be adjusted over different channels. Once different channels are assigned to previously interfering or contending links, more simultaneous transmissions can take place and more data can be delivered to the sink node in shorter intervals.

We first present the challenges and requirements of multi-channel communication from the perspective of WSNs. Next, we introduce the Multi-Channel Lightweight Medium Access Control (MC-LMAC) protocol which is a schedule-based multi-channel MAC protocol that takes advantage of interference and collision-free parallel transmissions on different channels.[†]

MC-LMAC is designed to provide higher throughput over multiple channels whereas it also meets the traditional requirements of WSNs such as energy efficiency and scalability. The main design is based on the single channel LMAC (lightweight medium access control) which has been proven to be an efficient and energy-aware MAC protocol for WSNs [165, 274]. A node selects a time slot and a channel on which it is allowed to transmit. Time slot and channel selection is fully distributed and guarantees the same slot/channel pair not to be used within a 2-hop neighborhood. A time slot consists of a control period and a data transmission period. During the control period, all the nodes switch their interfaces to a common channel. The control period is used for notifying the destination about the incoming packet and the channel on which the data transmission will take place such that the receiver switches its interface. The following are some of the key highlights of this work:

- We present a review of existing multi-channel MAC protocols for WSNs and discuss the requirements and challenges of multi-channel communication.

- MC-LMAC not only supports many-to-one communication towards the sink node but broadcasts and local-gossip operations are also supported. This can be quite challenging in a multi-channel communication environment [162].

- We evaluate the performance of the MC-LMAC protocol with extensive simulations in Glomosim [300] and present a large study of comparisons with the MMSN [307] protocol which is a recently proposed multi-channel MAC protocol for WSNs. Different from the scheduled communication in MC-LMAC, MMSN provides contention-based channel access. The protocols with completely different designs allow us to study a large set of tradeoffs between different performance metrics. The MC-LMAC protocol achieves better delivery ratio and throughput during high data rate scenarios whereas

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[†] A channel is defined to be a frequency range over which two nodes communicate. We use the terms “channel” and “frequency” interchangeably in the text.

the MMSN protocol may fail to successfully allocate the medium. Moreover, we compare the performance MC-LMAC with CSMA and with a clustering mechanism where the branches of the routing tree are assigned different channels.

- To show the advantages of multi-channel protocols, we compare MC-LMAC and the mentioned techniques with an alternative where the communication takes place on a single-channel but over a larger bandwidth. For further comparisons, we investigate single-channel scenarios with multiple sink nodes.
- We implement MC-LMAC on the Ambient μNode [13] platform as a proof of concept.

The remainder of the chapter is organized as follows: Section 5.2 presents the related work. Section 5.3 motivates the use of multiple channels in WSNs. Section 5.4 introduces the MC-LMAC protocol with the details on channel and time slot selection, and medium access. Section 5.5 presents the performance of the protocol for typical WSN traffic patterns in terms of different factors such as throughput and latency. Finally, Section 5.6 draws the conclusions.

5.2 Related Work

5.2.1 Use of Multiple Channels in General Wireless Networks

The channel assignment problem and multi-channel MAC protocols in wireless networks are well-studied topics for both cellular and wireless ad hoc networks. In cellular networks [146], basestations use different frequency domains within a cell, while clients share the time domain to access the wireless medium. However, this approach is based on single-hop, or infrastructure, channel assignment and is not suitable for multi-hop networks that are deployed over large geographical regions due to high energy consumption to reach the basestation.

Multi-channel communication has been extensively used in multi-hop ad hoc networks to increase the system throughput [138, 228, 250]. Most of these approaches are based on the IEEE 802.11 protocols; for instance, IEEE 802.11b allows 11 channels that are spaced 5MHz apart. However, the IEEE 802.11 protocols are very expensive in terms of energy consumption and do not meet the requirements of WSNs [307], as we have discussed in Chapter 2. Protocols in [220] either assume multiple radios on the nodes or consider radios that can listen on multiple frequencies simultaneously. Protocols in [266, 270] can operate with frequency-hopping spread spectrum wireless cards. However, in WSNs, usually nodes are equipped with much simpler radios and there is only a single radio available on each node. Additionally, typical bandwidth used by WSN radios is limited. Although these protocols perform well in general wireless multi-hop networks, due to the mentioned constraints, they may not be directly applicable to WSNs.

5.2.2 Use of multi-channel communication in WSNs

In the WSNs domain, there are many MAC protocol proposals which consider single channel communication [122, 179, 210, 214, 224, 273, 295]. These protocols exhibit good performances in single channel scenarios where the primary design goals are energy efficiency [165], scalability and adaptability to changes [134].

There are other single channel MAC protocols that aim to provide high throughput especially with scheduled communication, such as Z-MAC [224] and Burst-MAC [226]. While these protocols function well in single channel scenarios, parallel transmissions over multiple channels can further improve the throughput by eliminating contention and interference on a single channel.

Challenges and Requirements

In this section we explain the challenges and requirements of multi channel communication from the perspective of WSNs and how we address them in our protocol:

- Synchronization: If the channel assignment is done dynamically, i.e. the radios are switching between channels instead of being fixed on one channel, a detailed coordination of channel switching is required between the senders and receivers in order to be on the same channel at the same time. Scheduled access overcomes this complexity and that is where we benefit from the time-slotted communication of single channel LMAC.
- Partitions: If transceivers of two nearby nodes are fixed on different frequencies, they cannot communicate with each other[‡]. MC-LMAC uses a common channel during the control period of each time slot to let the receivers be informed about the requests and about the channels on which the data will be sent.
- Joining the network: A new node joining the network may disrupt the channel organization or may be required to scan all the channels to find the suitable channel to transmit on. In MC-LMAC, communication on a common channel at the beginning of each time slot lets the new node to collect full information about its neighborhood before starting transmission.
- Broadcast support: If the nodes are switching between channels dynamically, it might be problematic to support local broadcasts. However, local broadcasts are important for WSN traffic since sensor nodes may require in-network processing before they transmit the data towards the sink node. In MC-LMAC all the receivers of a broadcast are informed on the common channel at the beginning of each slot.
- Channel switching: The radio can not switch between the channels immediately but takes some time, for instance it is around $650\mu sec$ for Nordic Nrf905 [24] radio. The time slot size in MC-LMAC is large enough to accommodate the switching time and the overhead of switching time can be considered negligible.

Existing Work

There exist recent proposals for multi-channel usage in WSNs. In this section we discuss the differences between the existing work and our work. One point worth mentioning is that the performance of existing protocols have been compared against single channel protocols. In this work, we compare our protocol with example multi-channel protocols via simulations.

Zhou *et al.* [307], recently introduced the MMSN multi-frequency MAC protocol especially designed for WSNs. It is a slotted CSMA protocol and at the beginning of each time slot nodes need to contend for the medium before they can transmit. On the other hand, in the

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[‡] This is actually a design decision. Because the nodes that do not require to communicate with each other may be placed in different clusters. We refer to the nodes on different channels that require to communicate.

MC-LMAC protocol we assume scheduled access where each node is granted a time slot and performs its transmissions in this time slot without contention. Contention-based protocols are known to have a lower delay and promising throughput potential at lower traffic loads, which generally happens to be the case in WSNs [134]. However, when the network load is high, there is a higher waste of bandwidth from collisions and backoffs. On the other hand, schedule-based communication has the inherent advantage of collision-free medium access.

MMSN assigns channels to the receivers. When a node intends to transmit a packet it has to listen for the incoming packets both on its own frequency and the destination's frequency. A snooping mechanism is used to detect the packets on different frequencies which causes the nodes to switch between channels frequently. MMSN uses a special broadcast channel for broadcast traffic and the beginning of each time slot is reserved for broadcasts. Different from MMSN, MC-LMAC does not require a dedicated broadcast channel. On the other hand, at the start of each time slot, all the nodes are required to listen on a common channel in order to exchange control information which simply adds to the protocol overhead. But doing so provides many advantages [274]: collision-free addressing, maintaining synchronization, allowing distributed operation of the medium access. Moreover, the control period is much smaller compared to the data period and during the data period the nodes can transmit multiple packets to minimize the overhead.

TMCP [291] is a tree-based multi-channel protocol for data collection applications. The goal is to partition the network into multiple subtrees while minimizing the intra-tree interference. The protocol partitions the network into subtrees and assigns different channels to the nodes residing on different trees. TMCP is designed to support convergecast traffic and it is difficult to have successful broadcasts due to the partitions. Contention inside the branches is not resolved since the nodes communicate on the same channel.

Similar to TMCP, the protocol in [167] uses a control-theory approach to assign channels to the clusters of nodes. Initially all the nodes communicate on the same channel and when a channel becomes overloaded, nodes migrate to new channels based on the feedback information from the neighbors around.

Y-MAC [149] is another recent multi-channel MAC protocol designed for WSNs. Similarly, it is based on scheduled access. However, time slots are not assigned to the senders but to the receivers. At the beginning of each time slot, potential senders for the same receiver contend for the medium. Each time slot is long enough to transmit one data message. If multiple packets need to be transmitted, then the sender and the receiver hop to a new channel according to a predetermined sequence. Other potential senders also follow the hopping sequence of the receiver. As we mentioned, increased contention especially around the sink node with high data rate scenarios is hard to solve with contention-based protocols as we further discuss in the rest of the chapter.

Another multi-channel MAC protocol proposed for WSNs is HyMAC [191]. Similar to our protocol, HyMAC is also a combination of TDMA and FDMA. However, time slots and frequencies are assigned according to the *Breadth First Search (BFS)* algorithm [80] on a tree topology. However, there remain open questions such as how to maintain time-synchronized communication, how to resolve collisions and how a new node joins the network.

Table 5.1: *Comparisons of Multi-Channel MAC Protocols for WSNs*

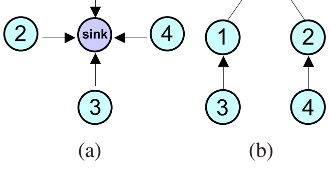
	MC-LMAC	**Y-MAC**	**MMSN**	**TMCP**	**HyMAC**	**[167]**
Broadcast Support	+	+	+	No Information	No Information	No Information
Partitions	-	-	-	+	-	-
Medium Access	Scheduled	Scheduled	Slotted Contention	No Information	Scheduled	No Information
Channel Assignment	Senders	Dynamic	Receivers	Clusters	Senders	Receivers (Home Channel)
Channel Switching	Once per time slot	Once per time slot	Multiple times per time slot	No	Once per time slot	If needed
Joining Network	Anytime	Anytime	At Channel Assignment	At Channel Assignment	At Channel Assignment	Anytime (With-Scanning)

Following the classification presented in Chapter 2, we present a semi-dynamic channel assignment that benefits from the ”*split phase*” approaches. The protocol keeps a list of busy channels and requires only a single transceiver. Moreover, the *multi-channel hidden terminal* [250] and the *deafness* [183] problems are eliminated. Table 5.1 illustrates a classification of the existing MAC protocols on the discussed topics in this section.

5.3 Motivation

Theoretically speaking, the throughput capacity of a WSN with n nodes under a many-to-one communication pattern can not exceed W/n per node where W is the transmission capacity of the radio [91]. Practically, this bound is usually not achieved due to the half-duplex nature of the radio and due to the increased amounts of contention and interference in dense deployments with multi-hop topologies. In this section, we study a simple benchmark scenario to show the efficiency of multiple channels.

In Figure 5.1(a) we present a topology where all the source nodes can directly reach the sink node. Let W represent the capacity of the shared medium. In an idealized setting, aggregate throughput would be W, and each source node should transmit with a capacity of $W/4$. When we switch to a multi-hop scenario, which is shown in Figure 5.1 (b), if there is no interference then, with a suitable scheduling mechanism, we can achieve the $W/4$ throughput per node. However, if all the transmissions interfere with each other, then each node can get



(a) (b)

Figure 5.1: (a) *Single-hop topology used in the benchmark scenario*; (b) *Multi-hop topology used in the benchmark scenario*;

only $W/6$ capacity. On the other hand, if nodes can use different channels to transmit then interference can be eliminated and the nodes can reach the $W/4$ capacity.

In Section 5.5.1, we present simulation results on the efficiency of multi-channel communication for the capacity improvements in WSNs, using the presented topologies in Figure 5.1.

5.4 MC-LMAC Protocol

MC-LMAC is a schedule-based multi-channel MAC protocol. The main design is based on the single-channel LMAC [274] (lightweight medium access control) which is an energy-efficient medium access protocol designed for WSNs. The LMAC protocol enables the communicating entities to access the wireless medium on a schedule basis in which each node periodically uses a time slot to transmit. The main aspects of the protocol are:

- *Self-configuration*: LMAC can operate in a fully-distributed, ad hoc manner and does not require a central scheduler.

- *Energy-efficiency*: the time-scheduling method has the natural advantage of collision-free medium access, which avoids wasting energy.

Moreover, time-scheduled communication eases the coordination of multi-channel communication. Since nodes switch their interfaces between different channels, a detailed coordination of channel switching is required between the senders and receivers in order to be on the same channel at the same time. Scheduled access overcomes this complexity.

Another key aspect of the time-slotted communication is the robustness during high peak loads [230]. Alternative carrier-sense protocols may fail to successfully allocate the medium and result in collisions when the number of sources or the source rates increase. On the other hand, scheduled communication has the advantage of collision-free access. Since we focus on the scenarios with a high demand on the medium, we consider LMAC to be an optimal choice. In the following, we explain the properties of the time slot assignment and medium access and how we extend the LMAC protocol to a multi-channel domain.

5.4.1 Time slot and Channel Selection

In this section we present the localized scheduling algorithm of LMAC. It allows nodes to choose a time slot autonomously, such that a node's transmissions in that slot does not interfere with the transmissions of other nodes in the same slot.

Each node periodically gets a time interval, called a time slot, during which it is allowed to control the wireless medium and transmit its data. Time slots are organized into frames. If there is no conflict (we explain the causes and resolution of conflicts in the next subsection), the node uses the same time slot in the upcoming frames. Each frame has a fixed number of time slots (required number of time slots depends on the density of the deployment). Due to the multi-hop nature of WSNs, reuse of time slots is possible. We assume all the nodes control one time slot per frame but the algorithm can be extended to allocate more time slots, i.e. allocate more rate, if needed [64]. Nodes are notified when they are intended receivers and if they are not addressed, they can turn off their transceivers to save energy.

The time slot selection process takes place either at the network initialization or whenever a conflict occurs and a node is required to select a new time slot to eliminate the conflict. If the time slots are selected during network initialization, the sink node starts the selection process by getting the control of a time slot. When a node joins a network, first it has to discover a "free" time slot to transmit its data. A free slot is defined as a slot:

- which is not used by direct neighbors of the node: in the opposite case, the node would not be able to exchange messages with those neighbors.
- which is not used by the nodes whose transmissions may be interfered with or may interfere with the transmissions of this node.

To guarantee that the first constraint holds, a node that is searching for a free time slot should exclude all time slots during which a message is received (or a carrier is detected) from the list of potential slots. The other constraint should be fulfilled by the potential receivers such that they should transmit a list of the time slots during which they are already receiving (or detecting a carrier). This lets the new node determine the list of free slots that can be used without interference. With this information, the nodes get a view of the time slot usage in their 2-hop neighborhood and this lets them make a list of potential free slots. We assume a node randomly selects its time slot from the set of free slots (for other methods of time slot selection the reader can refer to [274]).

Time slot selection is implemented as follows: All the nodes keep a bit vector called "occupied slot vector" with a length equal to the number of time slots. It is used for storing the information about the slots occupied by the neighbors and the vector is transmitted during the node's time slot to share this information with potential transmitters. Initially it is filled with 0's, meaning all the slots are free. When a packet is received or a carrier is detected during a time slot, the node inserts a "1" in the vector at the respective position of the time slot. To get a 2-hop view of the network, a node is required to collect transmitted bit vectors. After a complete frame has passed, the node can make a list of the free slots by executing an 'OR' operation on all the received occupied slot vectors and the local occupied slot vector.

Figure 5.2 shows the time slot selection. Here, the number of time slots per frame is 7 and the node marked with "?" is searching for a time slot. All the other nodes control the time slot represented by the number inside the circles. The "?"-marked node receives the occupied slots information (the position of a bit in the vector is the time slot number: 1 means the time slot is occupied and 0 means free) from the neighbors, next it executes the OR operation and finds time slot 7 as free and grabs it.

In order to keep the list of the occupied slots up to date, nodes clear their occupied slot vectors after their transmissions and collect new information on the usage of time slots until their next transmissions in the upcoming frame. This makes the protocol to be robust against the variations over the wireless links which may cause the topology and the connectivity of the network change and also helps the nodes to keep an up to date neighbor list for routing purposes. Moreover, a new node joining the network does not disrupt the already established time slot organization.

The number of required time slots per frame depends on the connectivity of the network topology. If the number of time slots is larger than what is required, the bandwidth may get wasted during empty slots and nodes have to wait longer before they can access the medium. On the other hand, when there are not enough slots (i.e. the local connectivity is higher than expected), the node remains in the initialization state, periodically monitoring frames

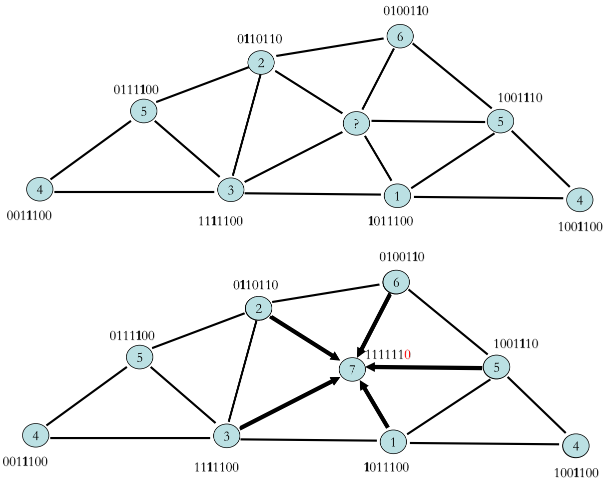


Figure 5.2: *LMAC time slot selection*

for an empty time slot. In single-channel LMAC, the number of transmissions is limited by the number of time slots in a frame. However, in MC-LMAC time slots are selected with frequencies. A node can use the same time slot that is used by a 2-hop neighbor on a different frequency so that parallel transmissions are not disturbed at the common neighbors. Consequently, more transmissions can take place with the same number of time slots.

In MC-LMAC, nodes keep occupied slot vectors per channel and select a time slot to be used on a particular channel. A node which is trying to get a control of a time slot, executes an “OR” operation over each occupied slot vector per channel and discovers the free slots on different channels. Similar to single channel LMAC, this method guarantees that the same “time slot/channel” pair is not used in the 2-hop neighborhood. Note that the nodes do not select the time slots used by their direct neighbors on any frequency, due to the limitation of the half-duplex radio[§].

Figure 5.3 shows an example for time slot and channel selection. The node marked with “?” is searching for a time slot and other nodes are marked by time slot/frequency pair that they are using. The number of time slots per frame is 5 and the number of frequencies is 2. The node without a time slot receives the occupied slots information (the position of a bit in the vector is the time slot number: 1 means the time slot is occupied and 0 means free) from the neighbors, executes the OR operation and finds that all the slots are occupied on F1 (frequency 1), however there are free slots on F2. The node selects time slot 5 (which is not occupied by the direct neighbors) on F2.

[§] In our design, the nodes keep a list of the free channels in the 2-hop neighborhood. For other methods of channel selection mechanisms, such as power sensing or measurement based, the reader can refer to [81].

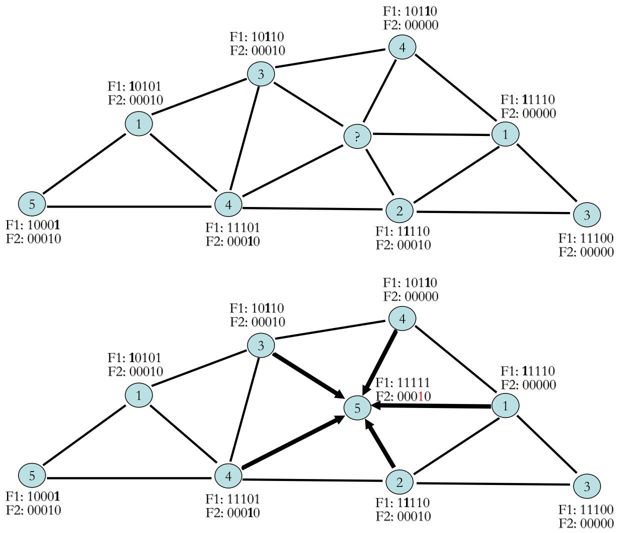


Figure 5.3: *MC-LMAC time slot and channel selection*

Conflict Resolution

Nodes always use the same time slot in each frame unless a collision occurs. Collisions can occur when two or more nodes in close proximity choose the same time slot to control[¶]. This can happen during network setup or when network topology changes due to for instance variations in link quality. When a collision has been detected at a time slot, the node records the number of the time slot and reports this during its own time slot. If the reported number matches with the time slot of a node, the node releases its time slot and restarts the time slot selection procedure. To reduce the number of collisions, especially at the start up, nodes wait random times, i.e. random number of frames, to start with the time slot selection.

Time Synchronization

Multi-hop time synchronization is achieved by a hierarchical scheme such that every node synchronizes with its parent (every node selects a parent node from the set of the nodes which are closer to the sink node in terms of number of hops). Synchronization details can be found in [274] and are out of the scope of this thesis.

5.4.2 Medium Access

As we mentioned, nodes transmit information during their time slots. A time slot consists of a control message (CM) section and a data transmission (DATA) section. The DATA section has a fixed maximum length. Depending on the amount of data, the node can send only a single packet or multiple packets or the DATA section can be omitted.

[¶] Besides the collisions, temporal variations in signal strength or interference from external networks or electronic devices that share the same parts of the spectrum may result in packet losses. In LMAC, nodes should be able to distinguish between collisions and other causes of packet loss. In [274], a method for identifying these causes is presented.

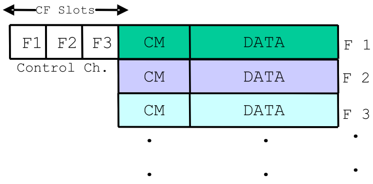


Figure 5.4: *MC-LMAC time slot structure*

In the CM section, nodes transmit control information prior to the data transmission. It provides collision-free addressing, maintaining synchronization and neighbor discovery. The contents of the control message transmitted during the CM section and they are as follows: *ID* represents the node id of the sender, *Destination ID* is the receiver's id or it can be a broadcast address. *Occupied Slots* represents the bit vector for the occupied slots in the neighborhood, which was explained in Section 5.4.1. *Collision in Slot* represents the slot number during which a collision has been detected. *Current Slot* represents the slot number and it is used for synchronization by the new joining nodes. *Hops to Gateway* field lets the nodes announce their hop distance to the sink node and it is used for synchronization. The *acknowledgement bit vector* has a length equal to the number of time slots per frame. Nodes keep track of the slots during which they receive data. Initially the vector is filled with 0's. If a message is received, a logical 1 is inserted at the position of the respective time slot in the acknowledgement field.

To support multi-channel communication, nodes select a time slot together with a channel. Parallel data transmissions take place on the selected frequencies but the receivers are notified on the common frequency first. The time slot structure of LMAC is extended as presented in Figure 5.4 in MC-LMAC by adding a common frequency (CF) section. During the CF section, only the intended destination ID is transmitted. This enables the sender to notify the destination and invite the destination to switch its radio to the sender's channel.

Communication during the CF section is also based on scheduled access and takes place in small slots called CF slots. The number of CF slots is equal to the number of channels and each slot is indexed by a channel number. A sender controlling the current time slot addresses the destination during the CF slot which is reserved for the channel number it controls.

Receivers listen during the whole CF section in order to be informed about the intended destinations. If a receiver is addressed during a CF slot, it switches its transceiver on the sender's associated frequency. If not, the node switches its transceiver to standby for the remainder of the time slot to conserve energy. Note that the common frequency can also be used by the nodes for data transmission and it has the same characteristics as the other channels.

After the CF section the receiver switches to the sender's channel and the time slot owner transmits CM, followed by the DATA section. Contents of the CM are the same as the single channel LMAC with the exception of the *Destination id*. The occupied slot vector includes information per channel and *Collision in frequency* field is added to distinguish the channel on which a collision has been detected.

An example of the overall medium access coordination is shown in Figure 5.5. The initial

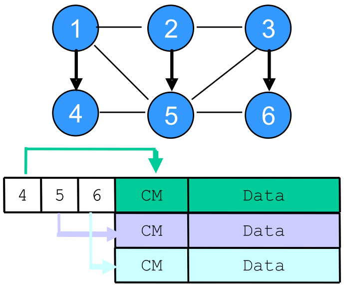


Figure 5.5: *MC-LMAC coordination scheme*

part shows the topology: the numbers inside the circles represent the id's of the nodes. It is assumed that there are 3 channels available (represented as $F1$, $F2$ and $F3$) and accordingly there are 3 CF slots. Sender 1 addresses node 4 in the first CF slot to communicate on channel $F1$, sender 2 addresses node 5 in the second CF slot to communicate on $F2$ and sender 3 addresses node 6 in the third CF slot to communicate on $F3$. CF section takes place on the control channel which is $F1$. In the CM and data sections, the nodes tune their transceivers on the associated channels: node 1 and 4 on $F1$, node 2 and 5 on $F2$, node 3 and 6 on $F3$. Note that, due to interference these three parallel transmissions would not be possible if there was only a single channel available.

5.4.3 Discussion

An issue to be solved is a receiver's response if it is addressed by multiple senders in the same time slot but on different channels. We define this situation as a clash. An option would be to select a sender randomly or select a sender according to a priority mechanism. In the simulations, we use a priority mechanism during time slot selection by prioritizing the selection of the time slots that are not used by the other children of the parent node on the convergecast tree. This efficiently reduces the probability of clashes. To inform the unselected senders in the case of a clash, the acknowledgement field, which is modified to include the acknowledgement frequency, in the CM is used. Besides convergecasts, we also evaluate the impact of clashes on the performance when the nodes use broadcasts, i.e. for local gossip operations, in Section 5.5.5.

Another issue is the overhead of the CF section at the beginning of each time slot. We try to keep this section as small as possible: the nodes transmit only the destination id. The overhead is compensated by allowing the transmission of multiple data packets during the DATA section. In Section 5.5 we show that the CF section does not add an overhead in terms of energy consumption compared with other protocols, but it enables higher throughput at the sink node by coordinating transmission over different channels.

5.5 Performance Analysis

In this section, we analyze the performance of the MC-LMAC protocol by extensive simulations with Glomosim [300]. Different simulation scenarios are studied according to four different performance metrics: aggregate throughput, delivery ratio, latency and energy effi-

Terrain Size	150*150 m^2
Number of Nodes	100
Node Placement	Random
Number of Frequencies	1 - 10
Bandwidth	250kbps
Transmit Power	1dBm
Radio Model	RADIO_ACCNOISE
Radio Range	40m
MAC Protocol	MC-LMAC, MMSN, CSMA
Routing Protocol	GF

Table 5.2: *Simulation Parameters*

ciency. Aggregate throughput is calculated as the total amount of data delivered to the sink node per unit time by the MAC protocol.

We study the performance according to different system loads, different source rates, different numbers of frequencies, different node densities and different traffic patterns. Simulation parameters are presented in Table 5.2. We use the RADIO_ACCNOISE model, which simulates the behavior of the physical interference model [120] such that interference from multiple senders is captured, as we have discussed in Chapter 2. According to the radio parameters, the transmission range of the nodes is around 40m. The sink node is positioned in the center of a square area. In the simulations, we assume that the packet losses occur due to collisions from concurrent packet transmissions in the same time slot on the same channel. Testing the performance of the protocols with other causes of packet loss is planned as a future work on a real testbed. In most of the simulations, the Geographic Forwarding (GF) [145] routing protocol is used but we also study the performance of a gossip traffic pattern without GF.

Performance of MC-LMAC is compared with the MMSN protocol [307]. Compared with the other protocols explained in Section 5.2.2, MMSN fulfills most of the requirements/challenges about the multi-channel usage. Its performance has been deeply studied from different aspects [307] and it is a representative of the slotted, contention-based, multi-channel MAC protocols designed for WSNs.

Moreover, we simulate a previously introduced channel assignment algorithm [5] based on LMAC where each branch of the convergecast tree is assigned a different channel; in other words, each branch is clustered into different channels. Inside the clusters, nodes communicate according to the single-channel LMAC protocol and we refer to this as clustered LMAC. The operation of clustered LMAC is similar to TMCP [291] which was mentioned in Section 5.2.2. In TMCP the level of interference that a node creates on the nodes of a branch is considered. However, in clustered LMAC, nodes join the branches according to the minimum hop count to the sink node or randomly in case of a tie. We also compare the performance of MC-LMAC with clustered LMAC and CSMA. All the results are averaged over 1000 simulation runs.

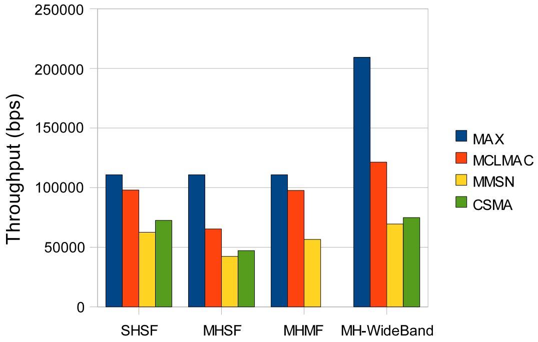


Figure 5.6: *Benchmark Results*

5.5.1 Benchmark Results

Before presenting the results with 100-node deployments, for which the simulation parameters are shown in Table 5.2, in this section we discuss the results of the benchmark scenario. The benchmark was discussed in Section 5.3 with the illustrated topologies in Figure 5.1. Figure 5.6 shows the simulation results. The vertical axis shows the aggregate throughput in total bits per second received at the sink node, and the abbreviations are as follows: SHSF: Single-hop, single-frequency, MHSF:Multi-hop, single-frequency, MHMF:Multi-hop, multi-frequency. In the multi-hop scenario, we assume all the nodes are in the transmission range of each other. Therefore, parallel transmissions on different links, unless they are assigned different channels, interfere with each other. Nodes transmit 32-byte packets continuously (every 2msec) to the sink node (effective data rate is 250kbps). The maximum aggregate throughput, i.e. total amount of data that the sink can receive per unit time from all sources, is approximately calculated as 104 Kbits per second. When the topology is single hop and there is a single channel (SHSF), slotted MC-LMAC performs close to the maximum. The only overhead is that of the control messages sent at the beginning of time slots. Contention-based protocols CSMA and MMSN perform worse. MMSN performs worse than CSMA since some part of the time slot is spent to listen on the broadcast frequency. In the single hop scenario, having multiple channels does not improve the results since senders transmit to the same sink node and have to wait for each other's transmission. When the topology is multi-hop and there is a single frequency (MHSF), transmissions of all the nodes interfere with each other. All the protocols perform quite poorly. However, MC-LMAC still performs better than the others since collisions are eliminated but it takes 6 time slots to deliver all the data compared to the 4 time slots in the single hop scenario due to relaying of the messages. When there are multiple frequencies available (MHMF), MC-LMAC performs similar to the SHSF scenario achieving a performance very close to the maximum. On the other hand, MMSN performs better than the MHSF scenario but cannot achieve the throughput of the SHSF scenario.

If throughput is the issue, instead of using multiple channels, using a more powerful radio with a higher data rate could work better than the multi-channel scenario. In the last column of Figure 5.6, we present the results where the nodes can transmit over a double size band, i.e. with an effective data rate of 500kbps. Compared with the results of MHSF and MHMF, all protocols achieve higher throughput. However, most of the band is still not utilized due to the interference experienced on the same channel. Moreover, contention based protocols, CSMA and MMSN, over a wider band perform worse than the MC-LMAC protocol with 2 channels presented in the MHMF scenario. Additionally, using a radio that can transmit over a wider band may consume more energy which is not desired by WSNs due to the limited battery on the sensor nodes.

Observations from the benchmark results are two-fold: Due to the common destination problem with the many-to-one traffic pattern, aggregate throughput is limited by the reception capacity of the sink node. However, this throughput is usually not achieved in multi-hop scenarios due to contention, interference and collisions that increase with relaying of data. Multi-channel communication can cope with interference and collisions and improve the throughput and delivery performance. Next, we conclude that schedule-based medium access can better cope with high peak loads [230] since the contention and collisions are eliminated.

5.5.2 Impact of the Number of Channels

In this section we analyze the impact of the number of channels on the network performance. All the nodes initiate CBR streams towards the sink node and each node generates a packet every 2 seconds (if nodes transmit more frequently, buffer overflows start to occur). The number of channels varies between 1 and 10. The terrain size is 150*150m^2.

Figure 5.7 presents the results in terms of aggregate throughput. The x-axis shows the number of available channels; the y-axis shows the aggregate throughput in terms of the number of bytes per second received by the sink node. Maximum aggregate throughput at the sink node is 1584 bytes/sec (99 sources generate 32 byte packets every 2 seconds). Different lines present the results collected with different protocols: MC-LMAC, MMSN, Clustered LMAC and CSMA. In MC-LMAC, the number of time slots per frame is 32[‖] and each time slot is approximately 50msec long. This allows the nodes to transmit multiple packets. In contrast, a time slot in MMSN is only long enough to send one broadcast packet and one data packet.

Aggregate throughput increases when the number of channels increases from 1 to 10 (although the example radios, such as Nordic Nrf905, provide more channels, the number of orthogonal channels is rather limited) with all the protocols except CSMA where the number of channels is fixed to 1. MC-LMAC achieves lower throughput than MMSN with 1-3 frequencies since some of the nodes cannot get a free time slot, due to the dense 1-hop and 2-hop neighborhood, and cannot start transmissions. As the number of channels increases, more nodes can control a time slot. After 6 channels, MC-LMAC performs very close to the maximum throughput, and with 8 or more channels, the maximum throughput can be achieved. On the average, the achievable throughput is 99% of the maximum throughput. Loss is due to the clashes that may occur. In the implementation of the protocol we reduced the probability of the clashes by prioritizing the selection of the time slots that are not used

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[‖] The number of time slots is adapted according to the expected node density. According to the example deployment, average number of first hop neighbors per node is around 24 nodes. Moreover, in order to have efficient forwarding during convergecasts, the nodes that have the same parent node should not select the same time slot to prevent the clashes. Accordingly, 32 slots per frame is an experimented, suitable value for the given density in the example deployment.

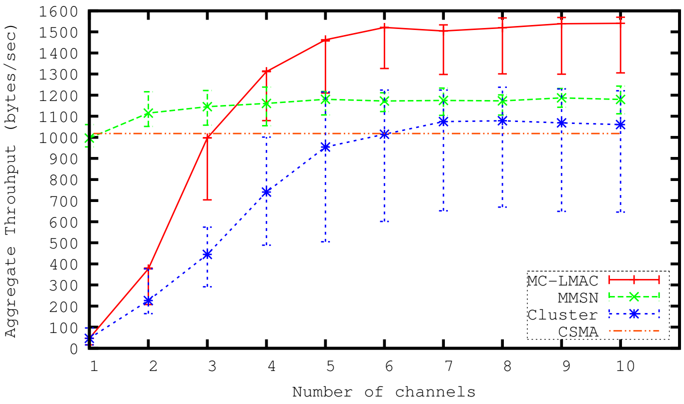

Figure 5.7: *Aggregate throughput with different number of channels*

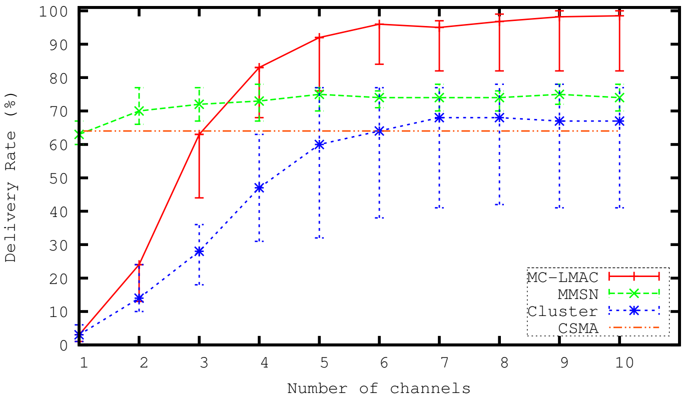

Figure 5.8: *Packet delivery rate with different number of channels*

by the other children of the parent node on the convergecast tree.

Aggregate throughput with MMSN is observed to be limited and does not increase beyond 6 channels. This is due to the failure of the nodes around the sink to successfully sense the channel and prevent collisions. Achievable throughput with clustered LMAC is rather limited due to the single-channel communication inside the clusters. Nodes need to select time slots that are not used in the 2-hop neighborhood to prevent collisions and interference. On the average, single channel CSMA achieves an aggregate throughput of 64% of the maximum throughput. Due to the high contention, the protocol fails to successfully allocate the medium to the nodes. Compared to CSMA, MMSN achieves slightly lower throughput on a single channel which is due to the time spent on sampling the broadcast channel at the beginning of each slot.

Figure 5.8 presents the results in terms of delivery ratio. The x-axis shows the number of available channels; the y-axis shows the delivery ratios. The figure has a very similar

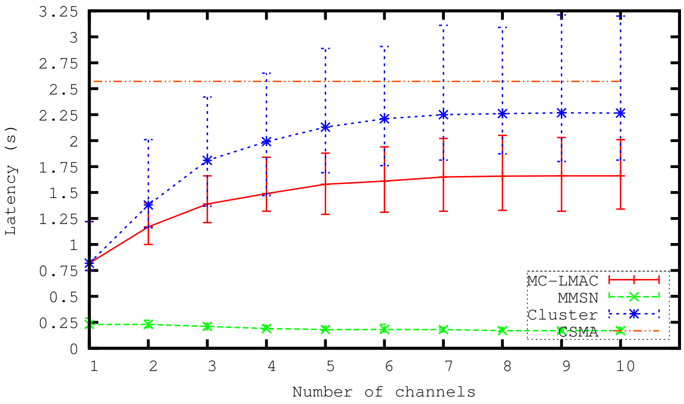

Figure 5.9: *Latency with different number of channels*

shape with the aggregate throughput graph presented in Figure 5.7. With sufficient channels, MC-LMAC achieves to deliver 99% of the packets on average. As we mentioned, the small percentage of losses is due to clashes. However, with a smaller number of channels, the delivery ratio is more limited since most of the nodes cannot get a free time slot. On the other hand, contention-based MMSN protocol saturates around 70% delivery ratio with an increasing number of channels and CSMA delivers only 64% of the packets.

Figure 5.9 shows the results in terms of end-to-end latency between the transmission of a packet at the source node and reception at the sink node. Although MC-LMAC achieves lower latency than clustered LMAC and CSMA, MMSN has much lower delay compared to the MC-LMAC protocol. Higher latency is a characteristic of the schedule-based protocols[**]. If a node has a packet to transmit it has to wait untill its assigned slot. The average delay from source to sink is equal to a frame size which is approximately 1.6 seconds (the selection of the time slots that are before the parent node's slot are prioritized). A simple solution to decrease the latency would then be to decrease the frame size. However, in that case, the number of packets that can be delivered per time slot will also decrease and the packets will be buffered to be transmitted later. The best option then is to assign the relaying nodes consecutive time slots according to their hop distance to the sink node. CSMA also experiences higher delay than MMSN which is due to the exponential and higher number of backoffs due to the high contention. In contrast, MMSN uses a different backoff algorithm.

Figure 5.10 shows the results in terms of energy consumed per successfully delivered packet. We consider both the energy spent to receive and transmit as well as the energy spent for relaying the packet towards the sink node. To calculate the consumption, we use the energy values used in the datasheet of the CC2420 radio [16] and the time to transmit and receive packets. Current consumption in the receive mode is given as 19.7 mA, and in the transmit mode it is 17.4 mA. Energy spent per delivered packet is quite high with MC-LMAC when there is only a single channel. This is due to the very low delivery rate. As the number

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[**] If the nodes can be assigned multiple time slots per frame according to their requirements, or give up their time slots when they do not have data to transmit, the latency can be reduced since the empty slots are not wasted and utilized by the other nodes. We design a time slot scheduling algorithm in Chapter 7 according to these improvements.

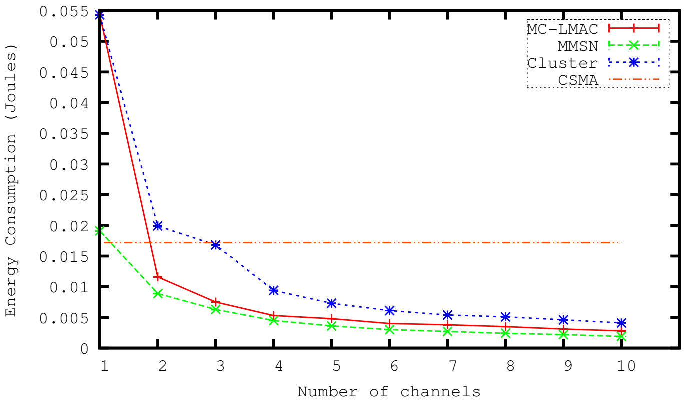

Figure 5.10: *Energy consumption per delivered packet with different number of channels*

of channels increases, both MC-LMAC and MMSN spend much less energy than CSMA. MC-LMAC can provide higher throughput while meeting the energy efficiency constraints of WSNs.

5.5.3 Impact of Load

In this section, we analyze the impact of the load on the network performance. In particular we vary the number of sources. The aim is to investigate the performance of the protocols with different levels of contention.

Figure 5.11 shows the results in terms of the active sources. We vary the number of sources from 10 to 100. The number of channels for both MC-LMAC and MMSN is 10. Since MC-LMAC assigns slots to all of the nodes, whether they are the sources or not, the performance of MC-LMAC is close to the maximum aggregate throughput in all cases. However, MMSN and CSMA suffer from contention. When more sources are active, the contention mechanism cannot sense the incoming packets at the destination's frequency with MMSN particularly around the sink node.

In this set of simulations, the nodes generate packets every 2 seconds. We also investigated scenarios where nodes generate packets more frequently. In that case, all the protocols experience buffer overflows with higher data rates and the achievable throughput gets much lower than the maximum.

5.5.4 Impact of Density

In this section, to test the scalability we evaluate the impact of density on the performance of the protocols. We vary the terrain size between $50 * 50m^2$ and $225 * 225m^2$ (beyond 225m, unconnected nodes appear with random deployment). Figure 5.12 presents the results. The x-axis shows L, the side length of the deployment area whereas y-axis shows the aggregate throughput. The number of channels is 10 for both MMSN and MC-LMAC. Aggregate throughput with MC-LMAC is lower when $L \neq 150$ since 32 slots per frame is lower in denser scenarios and higher in sparser scenarios than required. During unused time slots in sparser scenarios the sink stays idle. We repeat the experiments with different num-

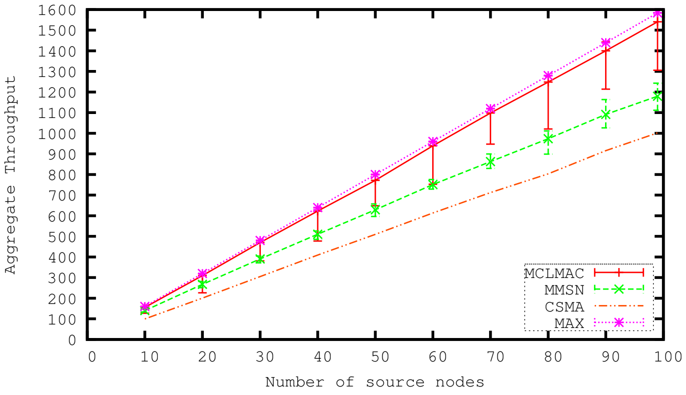

Figure 5.11: *Aggregate throughput with different number of sources*

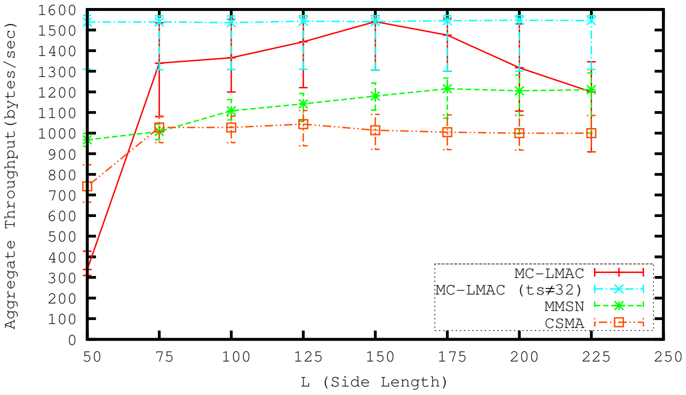

Figure 5.12: *Aggregate throughput with different densities*

bers of time slots that are adjusted according to the expected connectivity and the results are presented with the second line where the maximum throughput is achieved. Aggregate throughput with MMSN continues to increase when the network gets sparser since the contention is lower and the nodes can successfully sense the incoming packets. However, the performance of MMSN is still lower than MC-LMAC.

5.5.5 Impact of Traffic Patterns

In this section we evaluate the network performance with a different traffic pattern: local gossip. We can think of this scenario as in-network processing such that the source nodes exchange packets before they decide to transmit the data towards the sink node. The nodes in the center of the terrain are assumed to be the sources and they exchange broadcast packets.

We assume a 30*30m^2 (such that all nodes are within the transmission range of each other) area where the source nodes are located. We vary the density by changing the terrain size and the number of channels is 10 for MC-LMAC and MMSN. Figure 5.13 shows the re-

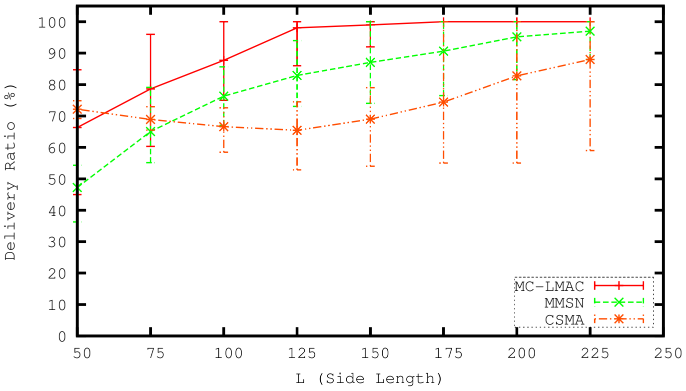

Figure 5.13: *Delivery Ratio with different densities*

sults in terms of delivery ratios. When the network is dense, the rate of successful deliveries is low. MC-LMAC suffers from the clashes whereas CSMA and MMSN suffer from collisions. Additionally, the number of time slots with MC-LMAC is 32 which causes some of the source nodes not to be able to get a slot. In order to achieve higher delivery ratios in denser deployments, the number of time slots should be increased as we discussed in Section 5.5.4. When $L \geq 125$ MC-LMAC can deliver more than 98% of the broadcast packets. In contrast, MMSN and CSMA protocols need more sparseness to mitigate the effects of contention.

5.5.6 Multiple Sinks versus Multiple Channels

As we discussed in Section 5.3, the limiting factor is the reception capacity of the sink node. Contention-based protocols fail to successfully allocate the medium during high contention around a single sink node. In this section, as an alternative to single-sink multi-channel scenario, we discuss the impact of deploying more sink nodes using single-channel communication on the achievable throughput.

Multiple sink nodes are randomly deployed in a $150 * 150\ m^2$ area. Source nodes transmit packets every 2 seconds to the closest sink node (geographic forwarding is used). Figure 5.14 shows the results. In this set, the nodes communicate on a single channel. Our aim is to compare the results of n sink nodes with 1 channel with the results of 1 sink node with n channels which were presented in Figure 5.7. Compared to the results in Figure 5.7, both CSMA and MMSN a chieve higher throughput since the contention around the sink nodes has lower impact compared to the contention around a single sink. Beyond 4 sink nodes, MMSN starts to perform better than MMSN with 4 channels and a single sink node. However, around 9 sink nodes the aggregate throughput starts to saturate.

In contrast, the single channel LMAC has a constant lower performance with a single channel and 32 time slots since most of the nodes cannot get a free slot on a single channel. However, if the number of time slots is increased to 48, a higher performance is achieved. Although the packet delivery ratio with 48 time slots is 100%, the aggregate throughput is on the average 75% of the maximum aggregate throughput since the nodes cannot choose the time slots that are used by their 2^{nd} hop neighbors on the same channel and this reduces

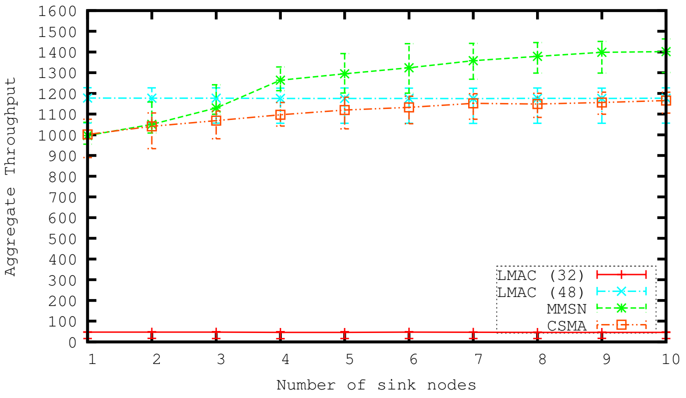

Figure 5.14: *Aggregate throughput with different number of sink nodes*

the number of parallel transmissions. Compared with the results in Figure 5.7, MMSN and CSMA perform better with multiple sinks but still they cannot achieve the performance of MC-LMAC with multiple channels which has the advantage of collision free medium access over multiple channels.

Multiple sink nodes can be used as a complementary solution together MC-LMAC which can further improve the achievable throughput for higher data rate scenarios. We evaluate the performance with multiple sink nodes and multi-channel communication in Chapter 7.

5.5.7 Implementation

The single channel LMAC protocol has been implemented and previously tested [274] on Ambient μNode sensor platform. We added the MC-LMAC extension and performed a simple test as a proof of concept using a simple topology where 2 pairs of nodes are communicating in parallel. The aim of the experiments is to investigate the impact of channel switching on the synchronization of the nodes.

The sensor platform is equipped with Nordic Nrf905 radio that can operate on the 868/915 MHz ISM band. Channel switching time is around $650\mu sec$. Nodes continuously transmit 32-byte packets every 1/8 second. The conclusion of the experiments is that nodes can change their operating frequency without loosing the synchronization. The aggregate throughput with parallel communication over different channels is doubled, as expected.

As a future work, that would be interesting to compare the performance of different protocols on real sensor nodes on a larger testbed.

5.6 Conclusions

We have presented MC-LMAC, designed for wireless sensor networks with high throughput requirements. MC-LMAC takes advantage of both scheduled and multi-channel communication. Scheduled communication has the advantage of minimizing collisions whereas the multi-channel communication overcomes the increased contention and interference on the limited bandwidth and improves the throughput and bandwidth utilization. Nodes can transmit in parallel on different channels without disturbing each other.

Simulation results show that, MC-LMAC achieves a throughput very close to the maximum with the increased number of channels and outperforms the MMSN protocol and the channel clustering method for moderate-size, 100-node networks. While MC-LMAC supports higher throughput, it also meets the typical characteristics of WSNs such as energy efficiency and scalability. Besides convergecast traffic MC-LMAC supports broadcasts and local gossip operations are performed efficiently. As a proof of concept, a simple test case of MC-LMAC demonstrates that nodes do not loose synchronization while switching between frequencies.

Acknowledgments

We gratefully acknowledge Dr. Gang Zhou for sharing the source code of the MMSN protocol on Glomosim.

CHAPTER VI *

Enhancing the Data Collection Rate of Tree-Based Aggregation in WSNs

Abstract What is the fastest rate at which we can collect a stream of “aggregated” data from a set of wireless sensors organized as a tree? We explore a hierarchy of techniques using realistic simulation models to address this question. We begin by considering TDMA scheduling on a single channel, reducing the original problem to minimizing the number of time slots needed to schedule each link of the aggregation tree. The second technique is to combine the scheduling with transmission power control to reduce the effects of interference. To better cope with interference, we then study the impact of utilizing multiple frequency channels. We define a receiver-based channel assignment problem, and prove it to be NP-complete on general graphs and introduce a simple receiver-based frequency scheduling heuristic. We find that for networks of about a hundred nodes, the use of multi-frequency scheduling can suffice to eliminate most of the interference. The data collection rate then becomes limited not by interference, but by the maximum degree of the routing tree. Therefore we consider finally how the data collection rate can be further enhanced by the use of degree-constrained routing trees. Considering deployments at different densities, we show that these enhancements can improve the streaming aggregated data collection by as much as 10 times compared to the baseline of single-channel data collection over non-degree-constrained routing trees. In addition to our primary conclusion, in the frequency scheduling domain we evaluate the impact of different interference models on the scheduling performance and give topology-specific bounds on time slot and frequency channel requirements.

6.1 Introduction

Periodic collection of aggregated data from sensors to a common sink over a tree topology is a fundamental operation in wireless sensor networks (WSNs). Many WSN applications require periodic summaries or aggregates of the data rather than raw sensor readings. In such cases, data coming from different sources can be aggregated at each hop en-route to the sink [158]. In this chapter, we consider the aggregated data collection process where data is periodically streamed from a set of sources to a common sink over a tree-based routing topology.

In many WSN applications, it is of interest to maximize the rate at which the sink can receive aggregated data from the network [196]. For instance, it has been noted that in networked structural health monitoring more than 500 samples per second are required to efficiently detect damages [70].

Time division multiple access (TDMA) scheduling is a natural solution for such periodic

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[*] This chapter is a revision of the paper with the same title published in the Proceedings of the Fifth Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, SECON 2008 [4].

data collection applications [188, 214]. Consider a repeated frame of k time slots in which each link of the data gathering tree is scheduled once. In steady state (once a pipeline is established), the sink will receive aggregated information from all nodes in the network once per frame, i.e. once every k slots. In this framework, maximizing the data collection rate corresponds exactly to minimizing the frame length. This is the focus of our work[†].

We explore a number of techniques in order to address the basic question: "How fast can aggregated data be streamed to the sink"? These techniques provide a hierarchy of successive improvements. The simplest approach is to do some form of interference-aware, minimum frame length TDMA scheduling that enables spatial reuse. The second step is to combine the scheduling with transmission power control. The third step is to consider the use of multiple frequency channels. We show that once multiple frequencies are employed along with spatial-reuse TDMA, the aggregated data collection rate often becomes no longer interference-limited, but rather topology-limited. Thus, the final step to enhance the rate of periodic aggregated data collection is to use an appropriate degree-constrained tree topology. Our primary conclusion is that combining these techniques can provide an order of magnitude improvement in the rate compared to the simple approach of TDMA scheduling on a single channel with minimum-hop routing trees.

We evaluate different design choices using simulations that use realistic channel models and radio parameters typical of WSN radio devices. The following are some of the key contributions and findings of this work:

- Evaluation of power control in a realistic setting: Moscibroda [196] has shown in a recent theoretical study that under idealized settings (unlimited power, continuous range) power control mechanisms can provide unbounded improvements in the asymptotic capacity of aggregated data collection. We employ the optimal power control algorithm proposed by El Batt and Ephremides [93] in a practical setting where we take into account the limited discrete power levels available in today's radios. We find that for moderate size networks of 100 nodes, power control can reduce the number of time slots by 15-20 percent.

- Comparison of interference models: In the literature, there are two common approaches to model interference. The protocol model is a graph theoretic approach with the assumption that a message is correctly received if no other sender transmits at the same time in close proximity. The advantage of this approach is that it enables the use of simple graph-coloring-based scheduling algorithms. On the other hand, the protocol model may fail in practice since interference is not a binary phenomenon [116]. The model can also be pessimistic in the sense that actually two nearby communications can simultaneously take place if the interference level is tolerable. A richer model that can capture the interference from multiple senders is the physical model also named as SINR (signal to interference and noise ratio) model. We evaluate the impact of both models on the scheduling performance. We find that the use of the graph-based model

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[†] While we do not focus on minimizing energy usage directly, we note that the formulation we explore provides energy efficiency in two ways: aggregation reduces the total data transmitted, and the TDMA scheduling can eliminate collisions in addition to permitting nodes to go into sleep mode during inactive slots. Furthermore, for applications that require periodic data collection at a fixed rate, minimizing the schedule length allows for a longer sleep period in each data collection cycle.

fails to produce correct schedules mostly in sparse network deployments with higher path loss exponents, but even then only about 12 percent of nodes are scheduled incorrectly. This suggests that graph-based scheduling design followed by SINR-based validation and repair maybe an acceptable compromise in practice.

- Receiver-based frequency scheduling: In order to use multiple frequency channels, we define a receiver-based channel assignment problem as "the problem of assigning a minimum number of frequencies to the receivers such that all the interference links in an arbitrary network are removed". We show that the problem is NP-complete and introduce a greedy heuristic for channel assignment suitable for aggregation trees in WSNs. The basic idea of our scheme is to associate frequencies with receivers rather than transmitters, and to allocate frequencies greedily (with reuse) to minimize interference.

- Bounds on time and frequency requirements: We provide topology-specific bounds on the schedule length and frequency channel requirements. These bounds can be quite useful in characterizing fundamental performance since they can be determined readily from in-network interference measurements for a given routing topology.

- Impact of adjacent channel interference: One simplifying assumption often made about frequency channels is that the transmissions on different frequencies are orthogonal, or in other words interference-free. However, assumption of perfect orthogonal channels may fail in practice because of interference from adjacent channels as we have shown in Chapters 3 and 4. We find that the practical impact of this simplifying assumption depends upon the particular radio platform employed, as well as the density of deployment.

- Identification of connectivity bottleneck: On a tree topology whenever there are multiple senders (children) assigned to the same receiver (parent), each of these senders have to be allocated a different time slot since a single half-duplex transceiver can receive from only one node at a time. When the interference limitation can be eliminated or mitigated to a large extent using multiple channels and power control, we find that the maximum degree on the tree becomes the bottleneck for scheduling performance, especially in denser deployments.

- Routing enhancements: We investigate a degree-constrained routing tree construction mechanism, which turns out to be more useful. Simulation results show that combining a simple degree-constrained tree construction algorithm with frequency scheduling can reduce the schedule length up to 10 times than scheduling on simple minimum-hop routing trees on a single frequency channel.

The remainder of the chapter is organized as follows: in Section 6.2 we explain the mechanisms that we use to investigate the scheduling performance. Section 6.3 discusses different design possibilities on modeling co-channel and adjacent channel interference. Section 6.4 presents the possible upper and lower bounds on the time and frequency requirements. Section 6.5 gives the detailed simulation based evaluation of the discussed methods. Section 6.6 summarizes some of the related work. Finally, Section 6.7 provides the conclusions.

	Frame 1			Frame 2		
Receiver	slot 1	slot 2	slot 3	slot 1	slot 2	slot 3
Sink	3	1,4	2, 5, 6	3, 7	1, 4	2, 5, 6
Node 1	4			4		
Node 2	5	6		5	6	
Node 3		7			7	

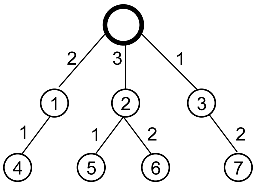

Figure 6.1: *Relationship between data collection rate and schedule length*

6.2 Mechanisms

6.2.1 Preliminaries

Before explaining the mechanisms studied, we first express the preliminary design details and assumptions:

- We consider a static WSN. The sensor nodes periodically sense the environment and send their readings over a multi-hop tree topology to a sink node.
- Time is divided into equal sized slots that are grouped into frames. We focus on minimizing the length of the frame such that each node is assigned one time slot.
- We consider minimum-hop routing trees where all the nodes select a parent node where they transmit their readings to be forwarded towards the sink node.
- We assume all the nodes in the network are sources and the data is aggregated such that the data coming from different sources are combined into a packet(s) before forwarding. If the incoming packets cannot be combined in a single packet and multiple packets have to be forwarded, we assume each time slot is long enough to transmit those packets. This is a reasonable assumption since the size of the sensor readings is usually very small.
- Time slot assignment is based on the following constraints: no node can transmit and receive at the same time slot, no node can receive from more than one transmitter at a time slot. If a receiver experiences excessive levels of interference due to simultaneous transmissions in a time slot, the transmitter should not be transmitting in that time slot.

Figure 6.1 shows the relationship between the schedule length and the aggregated data rate. The numbers on the links show the assigned time slots and the numbers inside the circles represent the node id's. On the left of the figure we see the schedule showing the received packets from the associated senders by each parent on each time slot. After frame 1, once the sink gets initial data from each source (a pipeline is established), the same schedule is repeated and the sink collects the aggregated data from the network at a rate of 3 time slots. Thus, the schedule length should be minimized to improve the data collection rate.

6.2.2 Joint Scheduling and Power Control

El Batt *et al.* [93] introduced a cross layer method for joint scheduling and power control in wireless multi-hop networks. They proposed an optimal distributed algorithm to improve the throughput capacity of wireless networks. The aim is to find a TDMA schedule which can support as many transmissions as possible in each time slot. We use their algorithm to investigate the impact of power control on the scheduling performance.

The solution is composed of 2 phases: scheduling and power control. The algorithm is to be executed at the beginning of each time slot in order to cope with excessive interference levels. The scheduling phase searches for a transmission schedule which is defined to be valid if no node is to transmit and receive simultaneously and no node is to receive from more than one neighbor at the same time. The power control phase iteratively searches for an admissible schedule which means that a set of transmission powers is available to satisfy the SINR constraints for all links in the given valid schedule. In each iteration the scheduler adjust the transmission powers of the nodes as follows:

$$P_{new} = \frac{\beta}{SINR} * P_{current} \tag{6.1}$$

where P_{new} is the new transmission power level in the next iteration, $P_{current}$ is the current transmission power level and β is the SINR threshold.

If the maximum number of iterations is reached and still there are nodes which cannot meet the SINR constraints, i.e., if the valid scenario is not admissible, the scheduling algorithm excludes the link with the minimum SINR. The power control algorithm is repeated until an admissible transmission scenario is found. Then, the nodes start transmission using the computed transmission powers in the current slot.

6.2.3 Frequency and Time Scheduling

The use of multiple frequency channels is an efficient way to improve the capacity of wireless networks. Simultaneous transmissions on different frequencies[‡] can take place without interference in the same spatial neighborhood.

In this section we introduce a simple scheduling method which separately assigns the time slots and frequencies on a tree topology. The motivation for this proposal is as follows:

- Intersecting links, which are defined as the links with a common destination (Figure 6.2), cannot transmit on the same time slot since they have to wait for each other's transmission. Assigning non-conflicting frequencies to these nodes does not improve the situation, either. Then the receiver should be assigned a frequency and the senders should use this frequency to transmit to the parent.

- Interfering or interference links are the links which cause/face excessive levels of interference if they are scheduled simultaneously. Figure 6.2 shows an example where the dotted line represents interference. Interfering links should not get the same time slot and frequency. Since our aim is to minimize the number of time slots, the best option then is to assign the same time slot on non-conflicting frequencies.

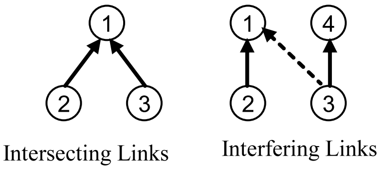

Figure 6.2: *Intersecting and Interfering Links*

Accordingly, we define the receiver-based channel assignment problem on a tree topology. First we explain the basics of the problem and next study the complexity of the problem.

Definition 1. *Interfering Parents: We define interfering parents as a pair of parent nodes p and p' such that a transmission by any child of p causes excessive levels of interference with a simultaneous transmission by any child of p' on a tree topology.*

As illustrated in Figure 6.2, nodes 1 and 4 are interfering parents when assigned the same frequency because simultaneous transmissions by their respective children 2 and 3 cause interference on parent 1.

Definition 2. *Receiver-based Channel Assignment Problem: Given f available channels, the problem is to assign the channels to the receivers (i.e. parents) such that all the interference links are removed.*

We model the sensor network as a graph $G = (V, E)$, where V is the set of nodes and E is the set of edges that represent communication links between nodes. We consider $s \in V$ as the sink node and $T = (V, E_T) \subset G$ be a spanning tree on the graph rooted at s that represents the routing tree. Given T, we create a graph $T' = (V, E_{T'})$ where $T \subset T'$ and a pair of nodes $v_i \in V$ and $v_j \in V$ on T form an interference link $(i, j) \in E_{T'}$ if a transmission from node v_i disturbs a reception at the node v_j or vice versa. In the following, we define the *Minimum Frequency Assignment Problem* and prove its hardness result.

Definition 3. *Minimum Frequency Assignment Problem (MFAP): Given a tree T on an arbitrary interference graph $T' = (V, E_{T'})$, and an integer f, is there a frequency assignment to the parents in T such that all the interference links are removed by using at most f frequencies on T'?*

Theorem 1. *The MFAP is NP-complete.*

Proof. It is easy to show that the problem is in NP. Given a particular assignment, one can verify using a non-deterministic algorithm in polynomial time if at most f frequencies are being used, and if the receivers of every interfering edge structure are assigned different frequencies. To show NP-hardness, we reduce an arbitrary instance G of the vertex color problem [139] to an instance G' of our problem. Our reduction is as follows, as illustrated

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[‡] If the frequencies are not orthogonal, transmissions on different overlapping frequencies may also be conflicting. We use non-conflicting frequencies and different frequencies interchangeably in the text.

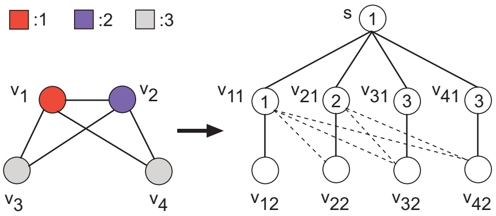

Figure 6.3: *Reduction from vertex color*

in Figure 6.3. For every vertex $v_i \in V$ construct two nodes v_{i1} and $v_{i2} \in G'$, and join them with an edge. For every edge $e_{ij} = (v_i, v_j) \in E_{T'}$, construct an interference link in G' either between v_{i1} and v_{j2}, or between v_{i2} and v_{j1}, if neither of them already exists. Finally, create a root node s and add edges from each v_{i1} to s. This new graph G' is an instance of the problem. Clearly, the reduction runs in polynomial time. Next, we show that there exists a solution to the vertex color problem using f colors if and only if there exists a solution to the original problem using f frequencies. Let G is vertex colorable using f colors, and let vertex v_i is assigned color j. Assign frequency j to node $v_{i1} \in G'$, and any of the j's to the root node s. Since no pair of adjacent vertices v_i and v_j in G are assigned the same color, no pair of vertices v_{i1} and v_{j1} in G' that have an interference link from either of them to the child of the other will have the same frequency. This is so, because by our construction an interference link is created either between the child of v_{i1} to v_{j1}, or between the child of v_{j1} and v_{i1} whenever v_i and v_j are adjacent in G. Finally, since the root does not have an interference link to any of the v_{i1}'s or their children, all the interference edges are removed.

Next, let there exists a frequency assignment in G' using f frequencies. If v_{i1} is assigned frequency j, assign color j to v_i in G. Since all the interference links are removed by such a frequency assignment, every pair of parents v_{i1} and v_{j1} that have an interference link from either of them to the child of the other are assigned different frequencies. And since their corresponding vertices v_i and v_j are adjacent in G, they will be assigned different colors. Therefore, the reduction is complete. □

Receiver-based Channel Assignment Algorithm

As we mentioned, the goal of the receiver-based channel assignment is to schedule the interference links on non-conflicting frequencies such that the receptions at the parents of the interfering senders are not disturbed. From Theorem 1, we know that the problem is NP-complete, in this section we introduce a greedy channel assignment algorithm. Initially, all the nodes operate on the same frequency. The method finds the interference links according to the SINR values. Accordingly, at each step the most interfered parent (the parent with the highest number of interference links) is assigned a frequency, if one is available. If not, the parent node and the associated children remain on the initial frequency and the interference conflicts have to be resolved in the time slot assignment phase.

The algorithm has a set of parents and a number of channels as an input and gives an output as the list of frequencies assigned to the parents, as illustrated in Algorithm 1. First, a list of interfering parents for each parent is created (we consider both graph-based and SINR-

Algorithm 1 *Receiver-Based Frequency Scheduling*

```
Input: $P$:set of parents, $f$:number of available channels
Output: $F$ be the frequencies assigned to the elements in $P$.
I. Create list of interfering parents
for all $p \in P$ do
    $C$: set of children of $p$
    $P'(p)$: set of interfering parents of $p$
    $AC(p)$: set of available channels for parent p
    $P'(p) \Leftarrow \phi, AC(p) \Leftarrow \{1, 2, ..., f\}$
    for all $c \in C$ and $c' \notin C$ do
        if $SINR(c, p) < \beta$ when $c'$ transmits then $P'(p) \Leftarrow$ parent of $c'$
    end for
end for
II. Channel Assignment
while $P \neq \phi$ do
    $p \leftarrow$ next most interfered parent from $P$
    $F(p) = i, i \in AC(p)$
    for all $p' \in P'(p)$ do
        $P'(p') = P'(p') \setminus p$
        $AC(p') = AC(p') \setminus i$
    end for
    $P'(p) = \phi$
    $P \leftarrow P \setminus p$
end while
```

based interference models and present the results in Section 6.5). After creating the list of interfering parents, the algorithm iteratively assigns the channels. At each step the most interfered parent (the parent with the highest number of interfering links) is assigned a frequency, if one is available. If not, the parent node and the associated children remain on the initial frequency and the interference conflicts have to be solved in the time slot assignment phase. During channel assignment, if the channels are considered to be orthogonal, the node can simply choose the next available channel. However, due to the channel overlaps, SINR value at the receiver may not be high enough to tolerate the interference. The algorithm considers the channel overlaps and assigns the channels according to the ability of the transceiver to reject the interference, i.e. adjacent channel rejection and blocking values.

The receiver-based frequency assignment makes the algorithm suitable for tree topologies and avoids frequent frequency switching for the transceiver since each node switches at most between 2 frequencies. In Section 6.5, we compare the performance of the receiver-based frequency assignment method with an alternative joint scheduling method where each sender is assigned a time slot together with a frequency.

It may be argued that the receiver-based frequency assignment uses a binary interference model since it uses a notion of interfering parents. For instance, nodes B, C, D may each individually not disturb a reception at node A, but, by transmitting together they might. Interference from multiple senders is captured during time slot assignment phase by using the additive physical interference model.

Assignment of Time slots

After the frequency scheduling, the algorithm continues with the time slot assignment to the senders. Similar to the power control approach, a node can be scheduled such that it cannot transmit and receive simultaneously and cannot receive from more than one neighbor at the same time, due to the transceiver limitations. If the parents of all interfering senders could be assigned different frequencies (this means the interference is totally eliminated), we can skip the interference check. If not, during the time slot assignment, the interference is checked among the interfering senders for successful transmissions.

If all the interfering link constraints are removed, the problem of minimizing the schedule length on a graph where interference links are also present reduces to one on a tree. The remaining constraint that still prevents simultaneous transmissions is the intersecting link constraint, which cannot be removed by using multiple frequencies. We propose an algorithm BFS-TIMESLOTASSIGNMENT in Algorithm 2. The algorithm gets as an input the tree $T = (V, E_T)$ where V is the set of edges that represent the nodes and E_T is the set of edges that represent the communication links between the nodes. The algorithm runs in $O(|E_T|^2)$ time and minimizes the schedule length on a tree. In each iteration (lines 2-6) of the BFS-TimeSlotAssignment, an edge e is chosen in the *Breadth-First-Search* [80] (BFS) order (starting from any node), and is assigned the minimum time slot that is different from all its adjacent edges.

Algorithm 2 *BFS-TimeSlotAssignment*

```
1. Input: $T = (V, E_T)$
2. while $E_T \neq \phi$ do
3.     $e \leftarrow$ next edge from $E_T$ in BFS order
4.     Assign minimum time slot to $e$ respecting adjacency constraint
5.     $E_T \leftarrow E_T \setminus \{e\}$
6. end while
```

As we mentioned, if the receiver-based channel assignment algorithm succeeds to remove all the interference, we do not need to check if the SINR condition is met at all the links that are assigned the same time slot. If not, during the time slot assignment, the SINR condition is checked according to the physical interference model. If the interference condition is not met for a link, it is deferred to be allocated a different time slot.

Figure 6.4 shows a scheduling example on a tree topology. In Figure 6.4(a), the solid lines between the nodes show the transmission links whereas the dotted lines show the interfering links[§]. The numbers inside the circles represent the node id's. Figure 6.4(b) shows the tree after time slot assignment with a single frequency channel. The numbers on the links show the assigned time slots. In this case, it takes 6 time slots to schedule the network. In Figure 6.4(c) we see how the scheduling is performed with 2 frequencies. First, the frequencies are assigned to the parents (represented inside the boxes next to each parent, $F1$ is the initial frequency). Then, the time slots are assigned to the senders. With 2 frequencies, the network is scheduled in 4 slots. Figure 6.4(d) shows the case with 3 frequencies. The network is then scheduled in 3 time slots. We achieve a %50 reduction on the schedule length thus the data collection rate at the sink node is doubled with the sufficient number of frequencies.

[§] Interference may not always be binary and concurrent transmissions from multiple senders may also disrupt the communication at a receiver. We use a graph-based, binary interference for the ease of illustration.

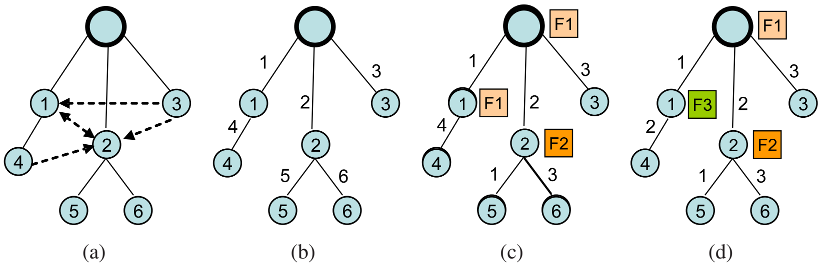

Figure 6.4: (a) *Communication links and interfering links*; (b) *Schedule with* 6 *time slots on a single channel*; (c) *Schedule with* 4 *time slots on* 2 *channels*;(d) *Schedule with* 3 *time slots on* 3 *channels*

6.2.4 Routing Strategies, Parent Selection

In the previous sections we have discussed the methods to cope with interference. Other than interference, connectivity may also limit the performance of scheduling. Consider the nodes that select the same parent. They have to wait for each others' transmission which simply increases the length of a schedule. In this section we investigate the methods that can adjust the degree of connectivity on a tree topology.

One option would be to construct balanced trees. We compare the scheduling performance on minimum-hop balanced and unbalanced trees. However, no improvement is observed with balanced trees since the sink node often remains the high-degree bottleneck. To avoid the bottlenecks, there should be a limitation on the number of children per parent. Thus, we explore scheduling on degree-constrained tree topologies.

Theorem 2. *The problem of degree-constrained spanning tree construction with the minimum hop constraint is NP-Complete.*

The proof is available in [154] which is shown by reducing the *set cover* problem [80] to this problem. Accordingly, we introduce a heuristic for constructing degree-constrained trees.

A degree-constrained minimum-hop tree is constructed using a modified version of Dijkstra's shortest path algorithm [80]. Consider a graph $G(V, E)$ and a given degree constraint *max_degree*. Each node n keeps a value for the number of its children $C(n)$ with an initial value = 0 and hop count to the sink $HC(n)$ with an initial value = ∞. The algorithm starts with a set T that contains the sink node s ($HC(s) = 0$), at each iteration we add a node $m \notin T$ to T with the following constraints:

- there is a node $m' \in T$ such that edge $(m, m') \in E$,
- $C(m') < max\_degree$ - 1,
- the hop count to the sink = $HC(m)$ is minimized.

The updates are made as $HC(m) = HC(m') + 1$ and $C(m') = C(m') + 1$. The algorithm stops when $|T| = |V|$ or when no more nodes can be added because the degree of the all nodes in T has reached the *max_degree*.

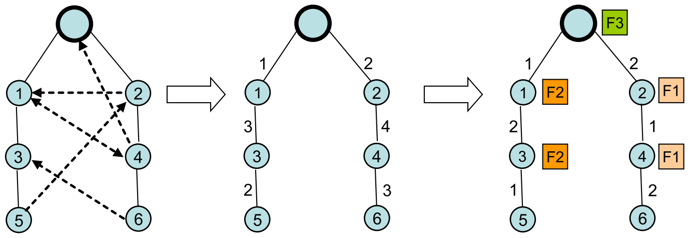

Figure 6.5: *Scheduling on a Degree-Constrained Tree*

To clarify the gains with this method, consider the case when all n nodes are in range of each other and the sink. If the nodes select their parents according the minimum hop criteria without a degree constraint, all the nodes will select the sink as a parent and this schedule will take n time slots. On the other hand, if we limit the number of connections per node as 2, this will result in 2 subtrees rooted at the sink. If there are enough frequencies to eliminate all the interference then the network can be scheduled in 2 time slots and we achieve a factor of $n/2$ reduction in the schedule length.

Figure 6.5 shows the same network as in Figure 6.4 with a different routing tree where the degree of a node is constrained to 2. The second part of the figure shows the time slot scheduling which takes 4 time slots on a single channel. The last part shows when time slots are scheduled over different frequency channels. This takes 2 time slots to schedule all the links which is ”3” times better than the baseline with a single frequency over a non-degree-constrained tree, given in Figure 6.4.

6.3 Models for Design

6.3.1 Interference Models

As we have discussed in Chapter 2, there are two different interference models that are commonly used in the literature: the protocol interference model, and the physical interference model. In Section 6.5.2, we investigate the correctness of the graph-based protocol model and the effects of the both models on scheduling performance.

6.3.2 Orthogonal Frequencies vs. Interfering Frequencies

As we have discussed in Chapter 4, the current literature on multi-channel protocols, mostly assumes that the channels are perfectly orthogonal (interference-free) or the use of overlapping channels is simply avoided. Assumption of perfect orthogonal channels fails in practice since radio signals are usually not limited to their allocated frequency band so that channel overlap/interference is observed between adjacent bands. On the other hand, the use of only orthogonal channels cannot utilize the spectrum efficiently. As we have shown in Chapter 4, interference between overlapping channels is influenced by the transmission power, distance between transmitters, channel spacing and transceiver characteristics.

In Section 6.5, we compare the impact of orthogonal frequencies and interfering frequencies on the scheduling performance for two different transceiver platforms. Moreover, we investigate the correctness of schedules generated with the orthogonal frequencies assumption.

6.4 Performance Bounds

In this section we present the theoretical upper and lower bounds on time slot and frequency requirements that are derived from graph coloring [113].

6.4.1 Bounds on the time slots

In this section, we present the bounds on the required number of time slots to schedule all the links in the network. We use the following formulation and notation:

> *Given a tree T, and the interference graph T' of T, schedule all links of T with minimum number of time slots.*

T includes the communication links (c, p) between the children and the associated parents. The interference graph T' is a graph which includes the links (i, p) that cause the SINR to be less than the threshold β for a link between parent p and any child of p.

After frequency assignment, if all the interference is eliminated such that each interfering parent has a disjoint frequency, then the the required number of time slots is lower bounded by,

$$\Delta(T) \tag{6.2}$$

where Δ is the maximum degree of T.

Theorem 3. *The algorithm BFS-TIMESLOTASSIGNMENT on a tree T gives a minimum schedule length equal to $\Delta(T)$.*

Proof. The proof is by induction on i. Let $T^i = (V^i, E^i_T)$ denote the subtree of T in the i^{th} iteration constructed in the BFS order, where E^i_T comprises all the edges that are assigned a slot, and V^i comprises the set of nodes on which the edges in E^i_T are incident. Note that, $|E^i_T| = i$, because at every iteration exactly one edge is assigned a slot. For $i = 1$, clearly the number of slots used is 1, equal to $\Delta(T^1)$.

Now, assume that the number of slots $N(i)$ needed to schedule the edges in T^i is $\Delta(T^i)$. In the $(i+1)^{th}$ iteration, after assigning a slot to the next edge in BFS order, the number of slots needed in T^{i+1} can either remain the same as before, or increase by one. Thus,

$$N(i+1) = \max\{N(i), N(i)+1\} \tag{6.3}$$

If it remains the same, $N(i+1)$ is still the maximum degree of T^{i+1} at end of $(i+1)^{th}$ iteration. Otherwise, if it increases by one, the new edge must be incident on a node v^*, common to both T^i and T^{i+1}, such that the number of incident edges on v^* that were already assigned a time slot at the end of i^{th} iteration was $\Delta(T^i)$. This is so because in the BFS traversal, *all* the edges incident on a node are assigned a slot first before moving on to the next node, and because the slot assigned to the new edge is the minimum possible that is different from all that already assigned to the edges incident on v^* until the i^{th} iteration. Thus, at the end of $(i+1)^{th}$ iteration, the number of slots used $N(i)+1$ is equal to the number of assigned edges incident on v^* which, in turn, equals $\Delta(T^{i+1})$. This proves the inductive step. Therefore, it holds at every iteration of the algorithm until the end when $i = |V| - 2$, yielding a schedule length equal to the maximum degree $\Delta(T) = \Delta(T^{|V|-1})$. Now, since assigning different time slots to the adjacent edges of T is equivalent to edge coloring T, which requires at least $\Delta(T)$ colors, the schedule length is minimum. □

We compare the performance of the algorithm with the calculated bound in Section 6.5.3.

6.4.2 Bounds on the frequencies

The aim of the receiver-based scheduling method is to schedule all the interfering parents on different frequencies to eliminate interference. In this section, we investigate and prove the bounds on the required number of frequencies. We construct a constraint graph $G' = (V', E')$ from the original interference graph $T' = (V, E_{T'})$ as follows: for each parent in the tree $v_i \in V$, construct a vertex $v_i^{'} \in V'$. Create a link $e'_{ij} = (v'_i, v'_j) \in E'$ if their corresponding vertices v_i and v_j in T' are interfering parents.

Theorem 4. *The number of frequencies needed that would be sufficient to remove all the interference links on T' is upper bounded by:*

$$f \leq \Delta(G') + 1, \tag{6.4}$$

where $\Delta(G')$ is the maximum degree of G'.

Proof. Since interfering parents are the ones for which simultaneous transmissions by their children on the same time slot and the same frequency cause interference, so long as we assign different frequencies to every pair of interfering parents v_i and v_j in the original graph T', we can remove all the interference links.

By our construction, we create a vertex in G' for each parent in T', and a link between two such vertices if they are interfering parents in T'. So assigning different frequencies to every pair of interfering parents in T' is equivalent to assigning different frequencies to every pair of adjacent vertices in G'. Therefore, the minimum number of frequencies required is equal to the minimum number of colors required to vertex color G', called the chromatic number $\chi(G')$, which is bounded by one more than the maximum graph degree. □

6.5 Evaluation

We use Matlab [21] to simulate the impact of different mechanisms on the scheduling performance. First, we explain the simulation settings. Then, in Section 6.5.1, we start the evaluations with the performance of the transmission power control method which was explained in Section 6.2.2. In Section 6.5.2, we evaluate the performance of the receiver-based scheduling method that was introduced in Section 6.2.3. In Section 6.5.3, we continue with the evaluation of the analytical bounds that were presented in Section 6.4. Finally in Section 6.5.4, we evaluate the impact of degree-constrained minimum-hop routing trees that we discussed in Section 6.2.4.

Nodes are randomly deployed over the area. Terrain dimensions are varied between 25×25 and 150×150 m^2 to simulate different levels of density whereas the number of nodes is

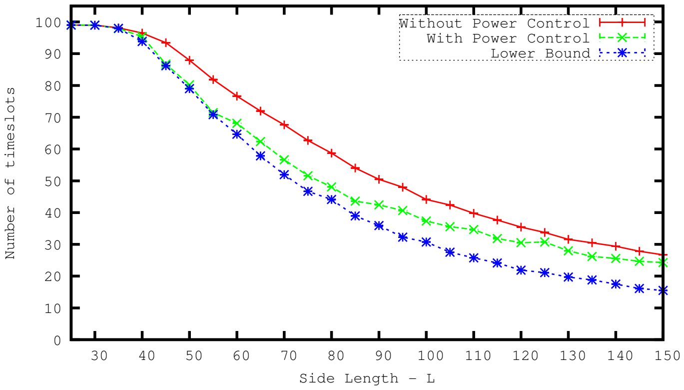

Figure 6.6: *Scheduling With and Without Transmission Power Control*

100 for all the simulations. During the topology construction phase, the node with id ”1” is always selected as the sink node. For different parameter settings, all the simulations are repeated for 1000 runs.

We use a log-distance path loss model [259] for signal propagation, with different path loss exponents, α, varying between 3 and 4 that are typical values for indoor environments. We simulate the behavior of the CC2420 radio [16] (unless otherwise specified) which is used on the Telosb [26] and MicaZ [22] sensor mote platforms. The transmission power can be adjusted between -24dBm and 0dBm over 8 different levels. SINR threshold is $\beta = 3dB$ and the transceiver is capable of operating on 16 different channels with a channel width of 5MHz within the 2.4GHz band.

6.5.1 Impact of Power Control

In this section we evaluate the impact of transmission power control on the scheduling performance. We investigate two cases: nodes transmit with the maximum transmission power and nodes adjust their transmission power according to the power control algorithm which was explained in Section 6.2.2. In both of the cases, the nodes communicate on the same channel and routing is performed on minimum-hop routing trees without the degree constraint. We use the physical interference model which was described in Section 6.3.

We investigate the required number of time slots to schedule the network according to different deployments with different densities. When transmission power control is not used, time slots are assigned to the nodes in a greedy manner. With the transmission power control, we follow the rules of the power control algorithm. The results are presented in Figure 6.6. The x-axis shows the side length L of the deployment area and the y-axis shows the number of time slots required to schedule all the nodes in the network.

We observe that the required number of time slots decreases as the deployments get sparser. As the network gets sparser, both the levels of interference and connectivity decrease and consequently the possibility of concurrent transmissions increases. In the worst case ($L = 25$), all the nodes are in the transmission range of each other. Since we employ a

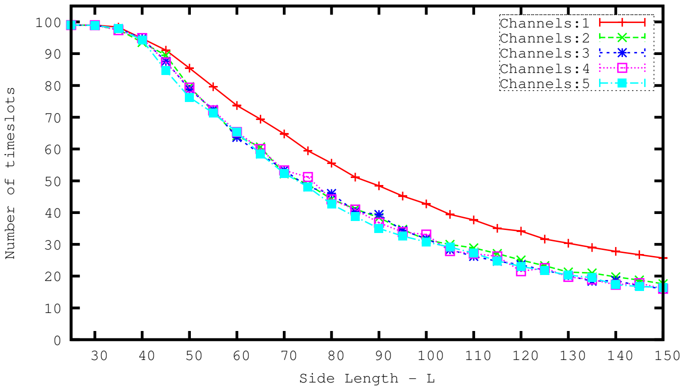

Figure 6.7: *Receiver Based Frequency and Time Scheduling with SINR based Interference Model*

minimum-hop routing scheme, all the nodes select the sink node as the destination. In this case the network can be scheduled with 99 time slots (since sink does not transmit), whether the nodes adjust their transmission power or not. In sparser scenarios, if the nodes employ a power control mechanism then the network can be scheduled in less time since the level of interference is reduced. We achieve a factor of $10-20\%$ reduction in the number of time slots in the best case.

As theoretically proved in [196], power control can help in reducing the effects of interference on scheduling. However, in practice we cannot achieve the lower bound, which is the maximum degree in the network, since the interference cannot be eliminated completely in some cases. This is due to the discrete power levels and the limited range of the transmission power. The CC2420 radio has 8 different power levels between 0 dBm and -24 dBm. Moreover, there is the sensitivity level of -95 dBm for the transceiver to be able to decode a signal successfully (sensitivity is the minimum received power that results in a satisfactory bit error rate). This also limits the sender to further reduce the transmission power.

6.5.2 Impact of Frequency Scheduling

In this section we analyze the performance of the receiver-based frequency scheduling which was introduced in Section 6.2.3. There are 16 channels on the radio in the 2.4GHz range and initially they are assumed to be orthogonal. Nodes transmit with the maximum transmission power and minimum-hop routing trees are used to collect data. We use the physical interference (SINR) model.

We investigate the required number of time slots to schedule the network according to different deployments with different densities. First the receivers are assigned frequencies according to the receiver-based channel assignment, then the time slots are assigned to the senders.

Figure 6.7 shows the results when the network is scheduled with the SINR interference model. The x-axis shows the density with respect to *L*, whereas the y-axis shows the required number of time slots. Different lines show the results for different numbers of channels.

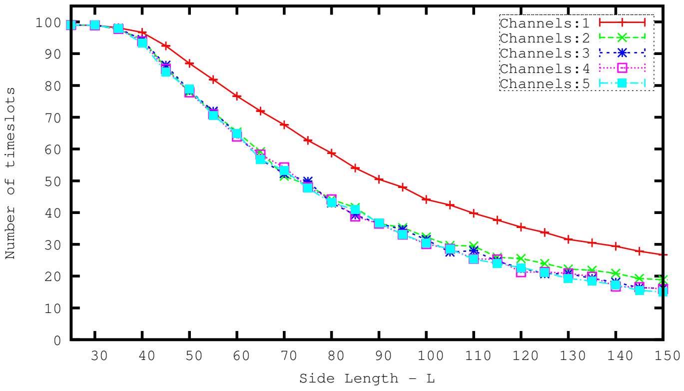

Figure 6.8: *Joint Scheduling with SINR based Interference Model*

The network can be scheduled in less time slots compared to the transmission power control mechanism. In sparser deployments ($L > 100$), we achieve a reduction of 40% on the schedule length. When the network is denser, having more frequencies does not help due to the increased connectivity in the network. In the worst case, the problem turns into a single-hop scheduling where the sink is the only destination for all nodes thus the degree of the sink is the dominant limiting factor. Another interesting observation is that when we have two or more different frequencies, the scheduling performance does not change since the interference limitation is already eliminated with two frequencies. Beyond this point, connectivity constraint limits the performance.

In order to discuss the efficiency of the receiver-based channel assignment method, we compare it with a joint time and frequency scheduling method. Joint time and frequency scheduling is a straight forward greedy approach. Time slots are assigned such that no node is to transmit and receive simultaneously and no node is to receive from more than one neighbor at the same time. If a node is eligible to get a time slot, we check the SINR constraints. The method searches for a free frequency channel on which the SINR constraints can be met. Figure 6.8 shows the results when the nodes are scheduled according to the joint time and frequency scheduling method. We observe very similar performance compared with the receiver-based scheduling. Both methods achieve to schedule the network with the minimum number of time slots which is the lower bound explained in Section 6.4. The advantage of the receiver based channel assignment method over the joint time slot and frequency scheduling is that it takes into account the topology characteristics. A parent node receives data on the same frequency from all its children such that it does not have to switch between different frequencies in each time slot.

Figure 6.9 shows the results for the same setting with the protocol interference model, which was described in Section 2.1.1, instead of the SINR model. The results are observed to be similar. However, when there is a single channel available, the number of required time slots is higher than that with the SINR model (Figure 6.7). As we discussed in Section 6.1, graph-based interference models may over/under estimate the level of interference.

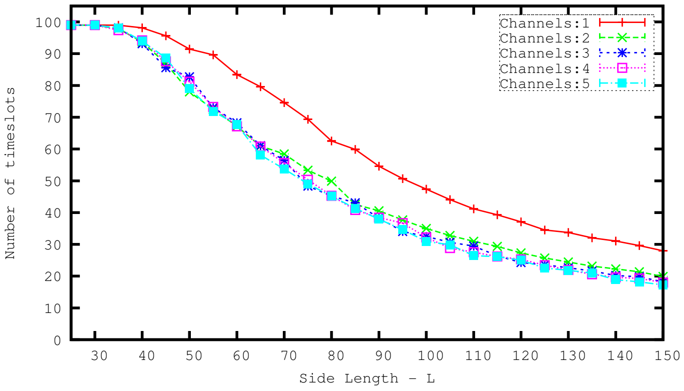

Figure 6.9: *Receiver Based Frequency and Time Scheduling with Graph-Based Interference Model*

Comparison of Graph-Based and SINR-Based Interference Models

In this section, we evaluate the impact of the interference model on the generated schedules. As we discussed, the graph-based interference models may not be realistic to capture interference with multiple senders or may overestimate the interference. In particular, we present the failure rate: a schedule generated with the protocol interference model is examined to be feasible or not according to the SINR constraints under additive interference.

Figure 6.10 shows the error rate in terms of the percentage of the nodes that are incorrectly scheduled versus the density. Different lines on the figure show the results for different number of frequencies and different values of path loss exponents (3, 3.5, 4). The value of the path loss exponent is investigated since it affects the value of the interference over the parallel transmissions.

The error rate is much higher in sparse deployments than in dense deployments. In sparse deployments, interference created by the individual transmitters is not high enough to jam the parallel transmissions. However, the cumulative interference from multiple senders can be detrimental which cannot be captured by a graph-based interference model. On the other hand, in dense deployments an individual transmitter can also jam a simultaneous transmission since the distances between the nodes are smaller and the level of interference is higher.

Path loss parameter is an important factor on the received signal strength and also on the level of interference. When the path loss exponent is set to a smaller value such as 3, received signal strength is high and also the level of interference by an individual jammer is high. That is why we do not observe a high error rate. If the path loss exponent is high, individual transmitters may not jam the desired transmission but multiple transmitters may. Having less channels also increases the error rate because more transmissions occur on the same channel.

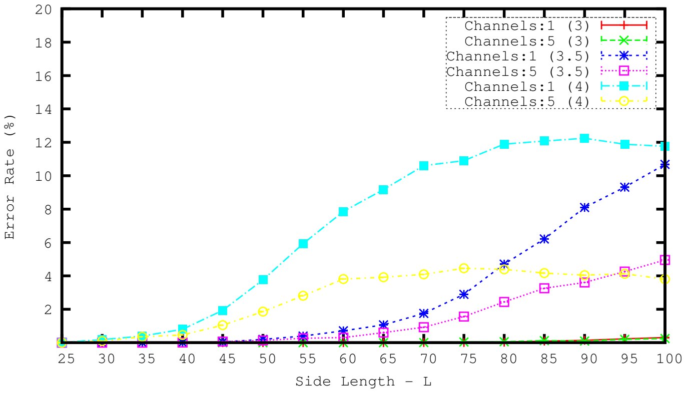

Figure 6.10: *Error Rate of Graph Based Interference Model*

Impact of Frequency Orthogonality

In this section, we evaluate the impact of the interference due to the overlaps between the channels. As we have discussed in Chapter 4, the assumption of perfect orthogonal channels may fail in practice. We present the failure rate of the orthogonality assumption: a schedule generated with orthogonal channels is examined to be feasible or not according to the adjacent/alternate channel rejection values of the transceiver. These values indicate how much power the receiver can tolerate on a nearby frequency/channel, and still can receive on a desired channel.

The error rate with the CC2420 radio is very low due to the high adjacent/alternate channel rejection values such that the channels behave like orthogonal[¶]. We repeat the simulations with the Nordic nRf905 radio [24]. The radio has smaller channel width (200 kHz) between the consecutive frequencies and smaller adjacent/alternate channel rejection values compared to the CC2420 radio.

Figure 6.11 presents the error rates. The x-axis shows the density with respect to L and the y-axis shows the error rate, i.e. the percentage of the nodes that are scheduled incorrectly. Initially the error rate is small. In dense deployments, the number of nodes that can be scheduled simultaneously is small and the connectivity constraint becomes the dominant factor instead of the interference constraint. Then the error rate starts increasing since the increase in the number of parallel transmissions increases the interference level. When the interference level is higher some nodes select the next available channel according to the orthogonal channel assumption. However, the level of interference experienced on the next channel can still be high to disturb the transmission. After the peak point, the network gets sparser and the effect of interference reduces.

[¶] In [291], it is shown that adjacent channel interferences may greatly impact radio reception on the CC2420 radio with a smaller network setting where the nodes are placed 2 feet apart from each other. However, in our simulation setting, the nodes were located with larger distances between each other. Thus, the error rate of the assumption of orthogonal channels with the CC2420 radio was observed to be very low.

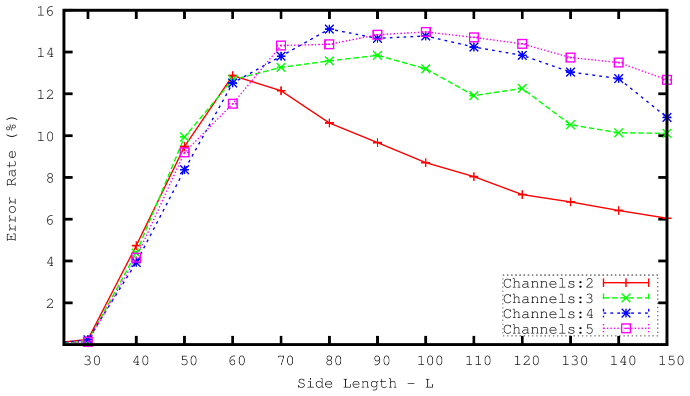

Figure 6.11: *Error Rate of Orthogonal Frequencies Assumption (nRf905 radio)*

6.5.3 Comparisons with the Analytical Bounds

Bounds on Time Slots

In this section we compare the simulation results with the analytical bounds that we presented in Section 6.4. The channels are assigned according to the receiver-based channel assignment on a minimum hop routing tree and the physical interference model is considered.

We show an example setting in Figure 6.12 where the number of nodes is 100 and the terrain dimensions are $100 \times 100\ m^2$. The x-axis shows the number of available frequencies, and the y-axis shows the number of required time slots to schedule the network. When all the nodes operate on the same channel, the required number of time slots is much higher than the optimal case, i.e. the lower bound. This is due to the interference. When the number of frequencies is increased to 2, the interference is eliminated and the dominating constraint is the connectivity. We also investigate the bottleneck in terms of the connectivity constraint. We simulated the scheduling behavior on unbalanced and balanced trees. However, no difference is observed because the sink node becomes the high-degree bottleneck on minimum-hop balanced trees. Since the maximum degree is similar in both cases, the bounds on time slots are observed to be the same.

Bounds on the number of frequencies

The receiver-based time slot and frequency scheduling aims to schedule the interfering parents on different frequencies. In this section, we investigate how the required number of frequencies to eliminate interference changes with the density.

Figure 6.13 shows the bounds that were analytically presented in Section 6.4 on the number of frequencies. The number of required frequencies is initially very low when the network is very dense $L < 40$. In this case, the transmissions cannot be scheduled in parallel since the number of receivers is low. When $L = 25$, all the nodes can directly reach the sink node, one frequency is sufficient. As the network gets sparser the number of receivers (i.e. parents) increases. Accordingly, the level of interference in the network increases and more frequencies are required to support parallel transmissions. However, when $L \geq 80$, the number of

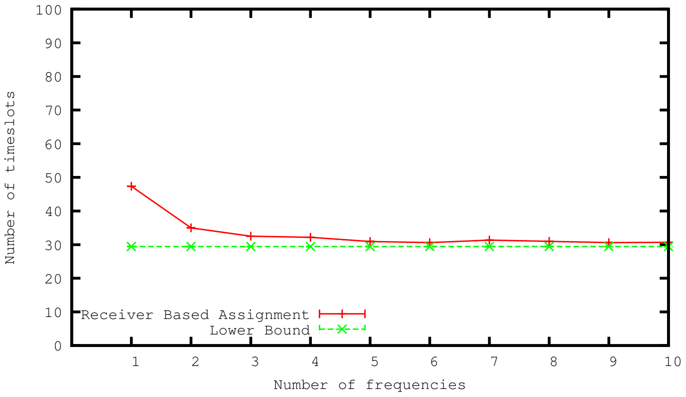

Figure 6.12: *Bounds on the number of time slots (100 nodes, 100*100 m^2)*

required channels decreases since the level of interference decreases. Trends of both lines are quite similar. Receiver-based channel assignment actually requires less time slots than the calculated upper bound and the required number of channels to eliminate interference is lower than or equal to the available number of 16 channels (in 2.4GHz) on CC2420 radios, with 100-node networks.

6.5.4 Impact of Routing Tree

In the preceding sections, we have discussed the performance of the methods to eliminate interference. We have assumed that the nodes select their parents according to the minimum hop criteria during tree construction. Accordingly, we observe that we can easily overcome interference limitation with multiple frequencies but connectivity still limits the performance.

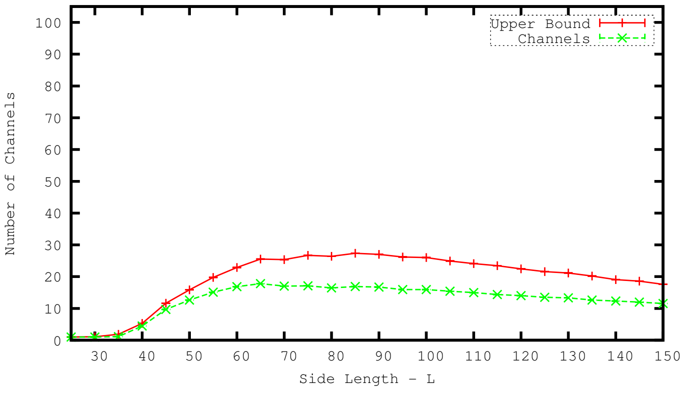

Figure 6.13: *Bounds on the number of frequencies*

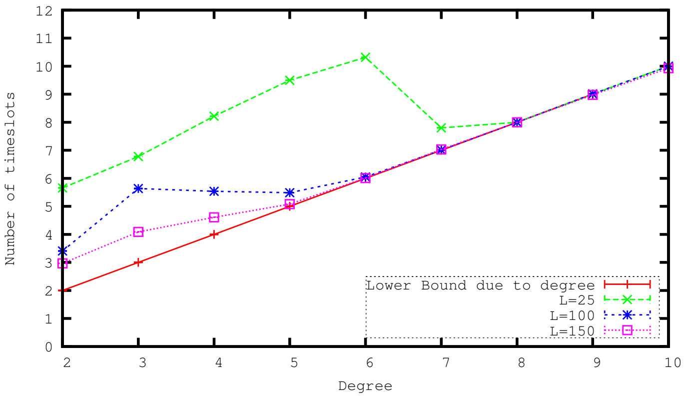

Figure 6.14: *Number of Time slots versus Maximum Routing Tree Degree*

In this section we investigate the scheduling performance on degree-constrained minimum hop routing trees.

Figure 6.14 shows the required number of time slots to schedule the network versus the degree of the tree topology. The nodes are assigned channels according to the receiver-based frequency assignment and 16 channels are available. Different lines in the figure show different density values. In the densest setting when $L = 25$, the required number of time slots hits the lower bound at degree 8. In smaller degrees, the number of frequencies is not sufficient to overcome interference but the required number of time slots at degree 2, for instance, is still smaller than the higher degrees. The same observations are valid for the sparser settings. However, we should note that in sparser scenarios with a degree 2, we have observed unconnected nodes since it was not possible for those nodes to find an available parent. For this scenarios, the minimum degree should be 3 since we aim to schedule connected topologies.

Figure 6.15 shows the scheduling performance when there is no degree constraint, when the degree is 3 with a single frequency and with multiple frequencies (16). On a single channel, we achieve some reduction in the number of time slots compared to the baseline with non-constrained minimum-hop routing. However, due to the interference effects the number of required time slots is still high. On the other hand, the minimum-hop routing on degree-constrained trees combined with multi-frequency communication achieves a greater reduction on the schedule length. In denser deployments, for instance when $L = 25$ the reduction is from 99 time slots to 7 time slots. In sparser deployments, for instance when $L = 150$, we achieve a reduction from 26 time slots to 4 time slots. In general, considering different densities, it can be concluded that an order of magnitude reduction in the number of time slots is achieved.

6.6 Related Work

Data aggregation is a commonly used technique in WSNs to eliminate redundancy, minimize the number of transmissions for saving energy and improving the network lifetime [158]. It is a form of in-network processing of data before relaying it towards the sink node. In-

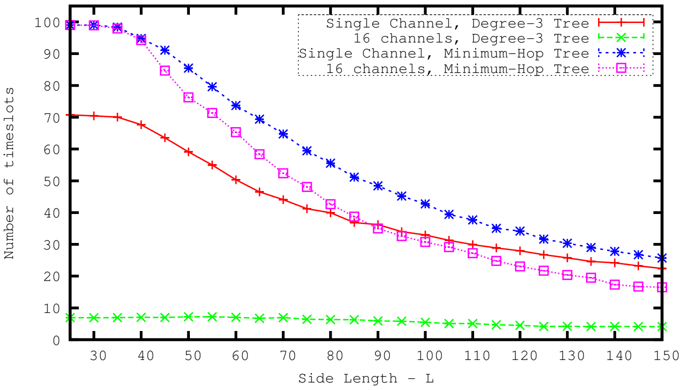

Figure 6.15: *Number of Time slots versus Density, Minimum-Hop Trees and Trees with Degree* = 3

network processing can be performed by a suppression of duplicate messages [135], using simple data reduction functions [182], such as calculating the minimum, maximum or average of the received data, using data compression techniques [150], using packet merging techniques [243], or taking advantage of correlations between sensor readings [63]. In this chapter, we assume perfect data aggregation such that all the received packets are combined and one packet is transmitted, for instance by using data reduction functions. Alternatively, packet merging or compression techniques can be used and if the data cannot be merged into a single packet, each time slot is assumed to be long enough to transmit multiple packets.

In [158], Krishnamachari *et al.* discuss the impact of data aggregation on the energy efficiency and delay issues in WSNs. The impact of different levels of data aggregation together with the impact of routing trees on convergecast operations are investigated in [271] where the objectives are the energy efficiency and low-latency. Different from these studies, we focus on methods to eliminate interference and finding suitable routing trees for enhancing the collection rate of aggregated data.

Joint scheduling and transmission power control is a well-studied method [53, 82, 93, 196] in wireless networks to increase the throughput by limiting the interference effects. In [196], Moscibroda theoretically proves that non-linear power control mechanisms (without discrete power levels) can significantly help to minimize the scheduling complexity and also improve the capacity of WSNs. However, we show that in a practical setting where the nodes have limited discrete transmission power levels, it may not be always possible to overcome excessive levels of interference.

As we have discussed in Chapter 2, the use of multiple channels is an efficient way to improve the capacity of wireless networks [49, 250, 307]. If the number of frequencies is sufficient and frequencies are assigned properly, the excessive interference can be eliminated. Following the classification presented in Chapter 2, we have presented a semi-dynamic channel assignment that uses realistic interference and channel models and requires only a single transceiver. The presented channel assignment is a centralized solution, but it can be modified to a distributed algorithm. The nodes may collect interference information in their neighborhood on the same channel, then migrate to new channels based on the levels of interference. The receiver-based channel assignment is well suited for data collection operations from sensors to the sink node. We compare the performance of the algorithm in Chapter 7 with the TMCP [291] protocol, which is a tree-based multi-channel protocol for data collection applications in WSNs. The receiver-based channel assignment outperforms TMCP for fast convergecast operations in WSNs.

TDMA or Spatial-TDMA (STDMA) is a common medium access technique with the advantage of reducing contention and collisions, thus minimizing energy consumption which is an important requirement in WSNs. TDMA-based MAC protocols for WSNs are presented in [46, 96, 179, 188, 224, 274]. Usually, time slots are assumed to be organized into frames and the problem is to determine the conflict-free assignment of slots in a shortest frame where each link or node is activated at least once [97]. This is related with the connectivity of the network and can be solved by graph coloring techniques [116]. Likewise, in this chapter, we show that once interference is eliminated, the schedule length is limited by the connectivity of the routing topology. Therefore, the maximum degree of the routing tree should be minimized. On the other hand, this approach may not lead to schedules with low latency since the number of hops increases with smaller degrees. We rely on the fact that convergecasts are periodic and once the pipelining of the packets is achieved, the sink receives the data with very short intervals. On the other hand, if the aggregation operations are performed once and minimizing latency is a requirement, then further optimization is needed, such as constructing trees with bounded degree and bounded diameter [222]. Minimizing the packet latency with TDMA scheduling is studied in [83, 96, 97, 179].

A similar problem has been addressed in [40] where interference is eliminated by using orthogonal codes. Nodes are assigned time slots from the bottom to the top of the routing tree, such that a parent node does not transmit before it receives all the messages from its children. This problem and the problem addressed in [68], are defined slightly different than our problem. In those studies, the shortest time for one single convergecast operation is investigated. Therefore, latency also becomes an important concern. In [208], aggregation of data is not considered but each node in a tree-formed Zigbee network is assigned one beacon period where the objective is to minimize the maximum latency. A receiver is assigned a beacon period during which it can receive data from all its children. Assignment of beacons is performed consecutively in each hop to minimize the delay. In [76, 105, 256] and in Chapter 7, the completion of convergecasts without data aggregation is discussed.

Data streaming in WSNs is addressed in [107] from a very different perspective. It is stated that link layer framing in WSNs faces a trade-off between large frame sizes and small frame sizes where in the former high bandwidth utilization can be achieved and in the latter effective error recovery is possible. The authors propose a streaming layer, *Seda*, that solves the problem by treating the packets as a continuous stream of bytes. In [148], reliable streaming of data is discussed and a transport protocol, *Flush*, is introduced. Flush finds the available bandwidth along a path using a combination of local measurements and a novel interference estimation algorithm. In [244], streaming of data in multimedia WSNs is discussed. Handling multimedia data has different requirements, such as handling large packet sizes or preventing holes in the sequence of transmitted data, which are out of the scope of this thesis.

There exist studies evaluating the performance of graph-based and SINR-based interference models [116, 136, 185]. Grönkvist *et al.* [116] report that the graph-based models may result in serious interference since the model does not consider the accumulated interference. Our observations confirm the already reported results and we further give implications on which type of deployments the graph-based models may not be accurate to predict interference. In [254, 283] the effects of interference on concurrent transmissions are experimented. However, unlike our focus in this chapter, those studies focus on scenarios where multiple senders transmit to a common receiver.

6.7 Conclusions

We have explored a number of techniques to enhance the aggregated data collection over a tree topology in WSNs. Our initial approach was to use interference-aware minimum frame-length TDMA-scheduling that enables spatial reuse. The second step was to combine the scheduling with transmission power control. Although the well-studied transmission power control method helped to overcome interference and reduce schedule length, it was found to be not always the best solution in a practical setting due to the limitations on the power settings of the nodes. The next step was to consider the use of multiple channels. With the extensive simulations we found that for networks of about a hundred nodes, the use of multi-frequency scheduling can suffice to eliminate most of the interference. Then, data collection rate was no longer interference-limited, but rather topology-limited. Thus, our final approach was to use an appropriate degree-constrained tree construction. Simulation results showed that, combining the last two techniques, that are the use of multi-channel communication and degree-constrained tree construction, can provide an order of magnitude improvement compared to the simple approach of scheduling on a single channel with minimum-hop routing trees.

We also evaluated the impact of different design choices to model interference. We concluded that graph-based interference models may result in serious interference especially in sparser deployments. Furthermore, adjacent channel interference cannot always be ignored since the orthogonality of frequencies is dependent on the transceiver characteristics.

The gains with the degree-constrained trees may be costly in terms of latency due to the increased number of hop distances to the sink node. As a future work, we are interested in addressing this open issue by using degree-constrained and diameter-bounded routing trees. Another issue to be considered is that some nodes may have a lot of data that require more than one time slot per frame while some others do not have any data to fill a time slot, hence the bandwidth may be wasted. It would be interesting to explore the scheduling performance in such scenarios with rate allocation algorithms.

CHAPTER VII [*]

Multi-Channel Scheduling for Fast Convergecast in Wireless Sensor Networks

Abstract We explore the following fundamental question - how fast can information be collected from a wireless sensor network? There are essentially two factors that hinder efficient data collection - interference and the half-duplex single-transceiver radios. We show that while power control helps in reducing the number of transmission slots to complete a convergecast under a single frequency channel, scheduling transmissions on different frequency channels is more efficient in mitigating the effects of interference (empirically, 6 channels suffice for most 100-node networks). We study a greedy channel assignment algorithm that efficiently eliminates interference, and compare its performance with other existing schemes via simulations. Once the interference is completely eliminated, we show that with half-duplex single-transceiver radios the achievable schedule length is lower-bounded by $\max(2n_k - 1, N)$, where n_k is the maximum number of nodes on any subtree and N is the number of nodes in the network organized as a tree. We present a distributed time slot assignment algorithm to achieve this bound and discuss the impact of suitable balanced routing schemes on the bound. Through extensive simulations, we demonstrate that convergecast can be completed within up to 50% less time slots, in 100-node networks, using multiple channels on balanced routing trees as compared to that with single-channel communication on unbalanced trees. Finally, we also demonstrate further improvements that are possible when the sink is equipped with multiple transceivers or when there are multiple sinks to collect data.

7.1 Introduction

Convergecast in wireless sensor networks (WSNs) refers to the typical many-to-one communication pattern, where data from a set of sources are collected at a common sink node. Convergecast is commonly used in periodic monitoring applications [187] and event-driven applications [126]. Often, it is important to deliver the data to the sink node in a bounded amount of time. For instance in Lites [44], which is a real time monitoring application, a typical event may generate up to 100 packets within a few seconds and the packets need to be transported from different network locations to a sink node.

Contention-free medium access control (MAC) protocols like TDMA (Time Division Multiple Access) can offer better solutions for fast data collection by eliminating collisions and retransmissions as opposed to contention-based protocols [105]. We consider a schedule of t time slots where the sink receives data from all nodes in the network. In such a context, our objective is to minimize the schedule length to increase the speed of data collection. Different from the problem that we have addressed in Chapter 6, we assumed the data is not

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[*] This chapter is a revision of the technical report with the same title presented in [9].

aggregated such that all the relayed packets towards the sink node have to be re-scheduled whereas in the former we assumed the nodes are scheduled only once.

We study different mechanisms in order to solve the fundamental problem: "How fast can data be convergecast to the sink over a tree topology?" The fundamental limiting factors are interference and the half-duplex nature of the transceivers on WSN nodes. To cope with interference we consider different techniques such as transmission power control and assigning different frequency channels on interfering links. We show that if multiple frequencies are properly used with TDMA, the convergecast schedule becomes limited by the number of nodes in the network once a suitable routing tree is used. For further improvements, we consider equipping a single sink with multiple transceivers, and also the deployment of multiple sinks to collect data. We evaluate the mentioned techniques using mathematical analysis and simulations based on realistic channel models and typical radio parameters. The following are some of the findings and key contributions of this work:

- Evaluation of transmission power control to eliminate interference: Power control mechanisms may provide unbounded improvements in the speed of data collection under idealized settings (unlimited power, continuous range). We evaluate the behavior with an optimal power control algorithm described in [93] in a practical setting considering the limited discrete power levels available in today's radios on WSN nodes.

- Receiver-based frequency assignment: We show that scheduling transmissions on different frequency channels is more efficient in mitigating the effects of interference compared to transmission power control. We use a simple heuristic algorithm to efficiently assign the channels[†] to the receivers to eliminate interference and increase the number of parallel transmissions. By simulations and analytical calculations, we evaluate the behavior of the heuristic algorithm and compare its performance with another channel assignment method which was recently proposed for WSNs with tree topologies [291].

- Bounds on convergecast scheduling: We show that, if the interference is eliminated, the achievable schedule length with half-duplex transceivers is bounded by $\max(2n_k - 1, N)$ slots where n_k is the maximum number of nodes on any branch of the tree and N is the number of nodes. We present a time slot assignment algorithm and show that the algorithm requires exactly $\max(2n_k - 1, N)$ slots to schedule a given network.

- Impact of Routing Trees: According to the bound on convergecast schedules, the branches of a routing tree should have a balanced number of nodes such that $2n_k - 1 < N$. Such a tree construction is defined as the "Capacitated Minimal Spanning Tree Problem" and was proven to be NP-complete in [209]. Given the hardness of the problem, we propose a heuristic algorithm and evaluate the impact of such routing trees on the schedule length by simulations.

- Multiple transceivers at the sink node: For further improvements we consider the sink having multiple transceivers and multiple sinks deployed in the network. We observe improved reductions on the schedule length that are proportional to the number of available transceivers and sink nodes.

[†] The terms "channel" and "frequency" are used interchangeably in the text.

The rest of the chapter is organized as follows: in Section 7.2, we introduce the problem in detail. In Section 7.3 we explain the techniques that we use to eliminate interference. In Section 7.4, we provide the bounds on the convergecast schedule when interference is eliminated and present a time slot assignment algorithm that achieves the lower bound. In Section 7.5, we discuss the impact of routing trees on the generated schedules. Section 7.6 gives the detailed evaluation of the discussed methods based on simulations. Section 7.7 summarizes some of the related work. Finally, Section 7.8 provides the conclusions.

7.2 Preliminaries and Problem Statement

Before explaining the studied techniques, we first describe our preliminary design and give the details of the problem formulation. We assume time is divided into equal sized slots and each node is assigned a time slot to transmit data. All the nodes in the network except the sink are sources and generate one packet for each convergecast operation.

We model the sensor network as a graph $G = (V, E)$, where V is the set of nodes and E is the set of edges that represent the existence of communication ability between two nodes. A pair of nodes $v_i \in V$ and $v_j \in V$ form a communication link (i, j) if the signal to noise ratio (SNR) is not less than a communication threshold γ. We assume G to be connected. Let $s \in V$ be the sink node and $T = (V, E_T) \subset G$ be a spanning tree on the graph G rooted at s that represents the routing tree. Given T, we create a graph $T' = (V, E_{T'})$ where $T \subset T'$ and a pair of nodes $v_i \in V$ and $v_j \in V$ on T form an interference link $(i, j) \in E_{T'}$ on T' if a transmission from node v_i disturbs a reception at the node v_j or vice versa, as illustrated in Figure 7.1.

The problem we address is the following. Given G and T, find an assignment of time slots to the transmitters on T such that the the number of time slots to complete a convergecast is minimized with subject to the following transmission constraints:

- Two adjacent edges on T (see Figure 7.1) cannot be scheduled at the same time slot. An edge (k, l) is adjacent to edge (i, j) if $\{i, j\} \bigcap \{k, l\} \neq \phi$.
- Two edges (i, j) and (k, l) cannot be scheduled simultaneously if (i, l) or (k, j) is an interference link on T' (we assume the level of interference between parallel transmissions is static and does not change over time).
- A node cannot be assigned a time slot to transmit a packet before it actually receives or generates that packet and a node cannot transmit more than one packet at a time slot.
- A node has a single half-duplex transceiver such that it cannot transmit and receive simultaneously and cannot receive from more than one transmitter at the same time.

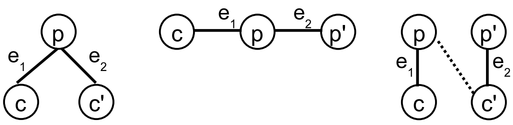


Figure 7.1: *Solid lines represent communication links whereas the dotted lines represent the interference links*

Previously, the problem was defined as the *Minimum Information Gathering Time Problem (MIGTP)* in [76] and is formulated as: "Given a tree T on an arbitrary graph $G = (V, E)$, and an integer t, is there an assignment of time slots to the edges in the tree using at most t slots?"

Theorem 5. *The MIGTP is NP-complete.*

This theorem has been proved in [76] by reducing the well known *Partition Problem* [108] to the MIGTP. If we can remove the interference links on T', then the second constraint is removed and T can be scheduled in polynomial time. Therefore, initially we focus on methods to eliminate interference.

7.3 Techniques to eliminate interference

We use the algorithm which was explained in Section 6.2.2 to investigate the impact of power control on the scheduling performance and we evaluate the improvements on the schedule length with the algorithm in Section 7.6.1. Moreover, we use the *Receiver-based Channel Assignment Algorithm* that was introduced in Section 6.2.3 to investigate the impact of frequency scheduling to eliminate the effects of interference on the schedule length of convergecast operations. We will evaluate the performance of the algorithm in Section 7.6.2.

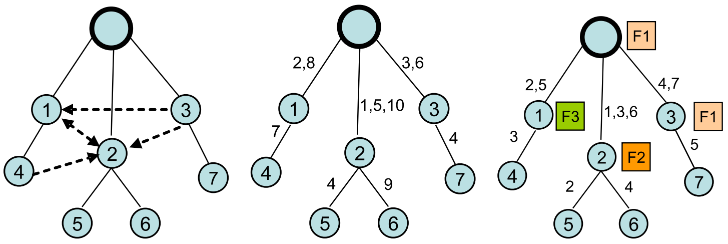
7.4 Time slot Scheduling for Tree Networks

In this section we explain how the transmissions are scheduled after the frequencies are assigned to the receivers. Transmissions take place on a TDMA schedule. At each time slot the nodes execute the algorithm shown in Algorithm 3.

The basic motivation is to schedule transmissions in parallel along multiple branches. A branch at the sink node is the subtree containing the sink as an endpoint [101], and we define a *"top subtree"* as the subtree that has a child of the sink node as a root. For example, in Figure 7.2 the branches can be listed as $\{sink, 1, 4\}$, $\{sink, 2, 5, 6\}$, $\{sink, 3, 7\}$ whereas the top subtrees are $\{1, 4\}$, $\{2, 5, 6\}$, $\{3, 7\}$.

We assume the sink has a single transceiver which implies that it can receive at most from one top subtree in a time slot. Therefore, the algorithm should decide which top subtree should be active in each time slot. The first block of the algorithm gives the scheduling rules for the sink node, between lines 3-11 of Algorithm 3. A top-subtree is eligible to transmit if the root of the subtree has a packet to transmit. Each (source) node keeps a buffer to store the packets to be transmitted. The buffers are initialized as full since all the nodes have packets to transmit at the beginning. The algorithm requires the nodes to hold no more than one packet in their buffers at any time slot.

In a given time slot, there may be more than one eligible top subtree. In that case, the sink receives from the top subtree with the highest number of remaining packets/nodes, since it takes longer to finish scheduling the transmissions over that subtree (line 5 of Algorithm 3). If the largest top subtree, which is the subtree with the highest number of packets left, is not eligible, then a random top subtree is selected to fill that time slot. With the alternation of the top subtrees, we aim to keep the sink node busy in receiving during all time slots.



(a) (b) (c)

Figure 7.2: (a) *Communication and interference links*; (b) *Schedule with a single channel*; (c) *Schedule with 3 channels*

Inside the subtrees, nodes are scheduled according to the rules given on the lines between 12 and 18 in Algorithm 3. After a node has transmitted a packet, the buffer of the node is empty. In the following slot, it receives from any child that has a packet to transmit. With this operation the buffers are emptied from bottom to top and packets are pipelined towards the sink node. The algorithm guarantees that, whenever a node empties its buffer, it will receive a packet in the next slot as long as there are packets to be relayed from the subtree rooted at this node.

We assume that the sink has the information about the number of nodes on each top subtree to keep a track of the largest subtree. The algorithm is locally executed by each node synchronously at every time slot.

Algorithm 3 *Scheduling Transmissions*

```
1: Input: s: sink node, $TS$: set of top subtrees, $n_i (i \in TS)$: the number of nodes in each top subtree, $C$: the set of
   children
2: self.buffer = full            // A source node starts with a full buffer
3: if self.id == s then
4:     if $\{\exists\, c \mid c \in C \bigwedge c$.buffer == full$\}$ then
5:         $c$ = the root of the largest top subtree, $n_c$=max($n_i$, $i \in TS$)      // Select the largest top subtree
6:         if $c$.buffer == empty then
7:             $c$ = the root of a random top subtree         // Select a random top subtree
8:         end if
9:         $c$.buffer = empty            // Receive from c
10:        $n_c - -$            // Decrement the number of packets left in the top subtree rooted at c
11:    end if
12: else
13:    if self.buffer == empty $\bigwedge \{\exists$ c | $c \in C \bigwedge$ c.buffer == full$\}$ then
14:        $c$ = a random child
15:        $c$.buffer = empty        // Receive from c
16:        self.buffer = full
17:    end if
18: end if
```

Figure 7.2 shows an example network and the generated schedule by the algorithm. Figure 7.2(a) shows the communication links and interference links. The numbers inside the circles represent the node id's. In Figure 7.2(b) nodes are scheduled on a single channel and it takes 10 time slots (the numbers on the links show the assigned time slots). In Figure 7.2(c), frequencies are assigned to the interfering parents (the numbers inside the boxes next to each parent represent the assigned frequencies and $F1$ is the initial frequency) and the time slot assignment takes only 7 time slots. If the interference cannot be eliminated as in the second part of the figure, we use a modified version of the presented algorithm such that among the nodes that are scheduled to transmit, the value of the signal strength is checked against the SINR thereshold. The algorithm schedules as many transmissions as possible and if the SINR value is below the threshold on a link, the transmission is deferred for that slot and the link is to be scheduled in one of the following slots.

7.4.1 Bounds on the Schedule Length

In this section we investigate the bounds on the schedule length to complete a convergecast on a tree network. We show that at least $max(2n_k - 1, N)$ time slots are required to convergecast all the packets from sources to a sink node. Next, we show that the presented scheduling algorithm requires exactly $max(2n_k - 1, N)$ slots to schedule the network. These bounds are obtained, considering that interference is eliminated by using multiple frequencies and the only limiting factor is the half-duplex nature of the radios on the sensor nodes.

Theorem 6. *The number of time slots to complete a convergecast is lower bounded by* $\max(2n_k - 1, N)$*, where* n_k *is the maximum number of nodes on any top subtree of the routing tree and* N *is the number of nodes in the network (both in* N *and* n_k*, the sink node is excluded).*

Proof. Let n_i represent the number of nodes in top subtree i. Order the top subtrees in non-increasing order of their sizes; let this order be $n_k \geq n_{k-1} \geq ... \geq n_1$. Consider the routing tree shown in Figure 7.3. Since no node can receive multiple packets in a single slot, N is a trivial lower bound to receive all the packets originated in the network. Next, consider top subtree k that has the highest number of nodes. The root of this top subtree has to transmit n_k packets, and the children of this root have to forward $n_k - 1$ packets in total. Due to the half-duplex nature, time slots assigned to the root of this top subtree must be distinct from those assigned to its children. Therefore, in total we need $n_k + (n_k - 1) = 2n_k - 1$ distinct time slots, and the theorem follows. □

We should note that this bound is smaller than the existing bound which was calculated as $3N$ for general networks and $\max(3n_k - 3, N)$ for tree networks, where the only limiting

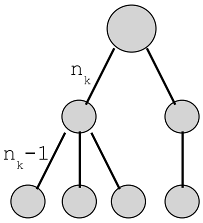


Figure 7.3: *Convergecast on a tree network*

factor is the half-duplex transceivers and the interference within the 2-hop neighborhood only over tree links. Gandham *et al.* [105] presented a time slot assignment algorithm and showed that the number of time slots required by the algorithm is $\max(3n_k - 1, N)$ which is 2 time slots more than the lower bound using a single channel. We show that our algorithm can compute schedules with a length of $\max(2n_k - 1, N)$, which is exactly the lower bound when interference is eliminated with multi-channel scheduling.

In the following, we investigate the performance of Algorithm 3 and prove that the algorithm requires exactly $\max(2n_k - 1, N)$ slots to schedule the network. Before giving the details of the proof, let us explain the insight how the algorithm achieves the lower bound. As we mentioned, the key idea of minimum-length scheduling is to keep the sink busy in receiving during all time slots due to the single-transceiver constraint. In the first block of the algorithm, the sink is scheduled to receive a packet as long as there is a packet to be received from a non-empty top subtree.

In the second block of the algorithm a node (which is not the sink) with an empty buffer, should always be scheduled to receive a packet from any of its children. Then, we need to prove that the node with an empty buffer always has a child with a full buffer as long as there are packets to be transmitted in the subtree rooted at the child node. This guarantees that a root of a top subtree is filled in the next slot after it transmits and becomes eligible again. Before we begin by this proof, we need to distinguish the parts of the network that have finished transmitting their packets and that are still active to transmit. We define an active subtree where all the nodes in the subtree still have packets to transmit. For instance when the leaves of a subtree have transmitted their packets they are excluded since they are not active anymore.

Lemma 1. *In an active subtree, a node with an empty buffer always has a parent with a full buffer or the parent is sink and the node always has a child with a full buffer.*

Proof. We prove by induction. At the beginning all the buffers are full so the theorem holds. We assume that at time slot t, the theorem is true. At time slot $t + 1$, let us assume that the theorem does not hold and we will prove by contradiction that this cannot be the case. If there exist a parent and a child that have both empty buffers at time slot $t + 1$, then at time slot t either,

- both the parent and the child had full buffers — if this was the case they cannot both empty their buffers at the same time slot, since the parent cannot transmit and receive at the same time,
- or, the parent had an empty buffer and the child had a full buffer — if this was the case then the parent's buffer is filled in this time slot,
- or, the parent had a full buffer and the child had an empty buffer — in this case the child had a child with a full buffer and its buffer is filled in.

Thus, the theorem holds for step $t + 1$. By induction, we conclude that the convergecast scheduling algorithm always empties the buffers from bottom to top and fills an empty buffer with a transmission from a child with a full buffer as long as the child has not finished the transmissions. □

Theorem 7. *The schedule length required by Algorithm 3 is exactly* $\max(2n_k - 1, N)$.

Proof. The first part of the proof is based on that given in [105]. Let n_i represent the number of nodes in top subtree i. Order the top subtrees in non-increasing order of their sizes; let this order be $n_k \geq n_{k-1} \geq ... \geq n_1$. Suppose $n_k > \sum_{i=1}^{k-1} n_i$. From Theorem 6, we know that it takes at least $2n_k - 1$ slots to schedule top subtree k, out of which the sink can use at most $n_k - 1$ slots to receive packets from other top subtrees. Since the total number of packets in the other top subtrees is at most $n_k - 1$, the schedule length is no more than $2n_k - 1$.

Now suppose $n_k \leq \sum_{i=1}^{k-1} n_i$. In this case, $\max(2n_k - 1, N) = N$. We need to show that there is always a top subtree to be selected when the largest top subtree is not eligible. In other words, there is always a subtree to complement the operation of the longest top subtree as long as the inequality $n_k \leq \sum_{i=1}^{k-1} n_i$ holds. In this case, the sink can be busy in receiving during all time slots. Otherwise, the first condition $n_k > \sum_{i=1}^{k-1} n_i$ holds and we know that the sink is idle during some of the time slots since the number of packets in the largest top subtree cannot be consumed in parallel with the other subtrees. Thus, we will prove that the algorithm keeps the inequality of $n_k \leq \sum_{i=1}^{k-1} n_i$ as invariant.

At every time slot the algorithm tries to schedule the largest top subtree (i.e. the top subtree with the maximum number of packets left) if the root of the subtree is eligible, i.e. has a packet to transmit. At the time slot after the longest top subtree has been scheduled, such that $n_k = n_k - 1$, there may occur 3 situations:

- The top subtree k is still the largest subtree such that $n_k \geq n_{k-1} \geq ... \geq n_1$. In this case, the root of a random full subtree is selected and again the inequality holds since $n_k - 1 \leq \sum_{i=1}^{k-1} n_i - 1$.
- The top subtree k has the same number of packets left with another top subtree j (note that there may be multiple top subtrees with the same number of packets left). In this case the subtree j is selected and still the inequality holds since $n_j - 1 \leq \sum_{i=1}^{k-1} n_i - 1$ (since $n_j = n_k - 1$).
- The top subtree k is not the longest top subtree anymore (which implies that there were other top subtrees with the same number of packets left with k in the previous step). In this case the new largest top subtree j is selected and the inequality holds since $n_j - 1 \leq \sum_{i=1}^{k-1} n_i - 1$ (since $n_j = n_k$).

Thus, the algorithm keeps the inequality as invariant. As long as the inequality holds this means that there is a top subtree that can alternately be scheduled with the largest top subtree. When $n_k = 1$ then $\sum_{i=1}^{k-1} n_i - 1 = 1$ which means that there are 2 packets left at 2 different top subtrees and these can be scheduled in alternating slots. Since this inequality holds for all the N steps, the sink always finds a subtree to receive from and the reception of the packets is completed in N slots. Moreover, from Lemma 1 we know that, a top subtree becomes eligible after a transmission, since the root of a subtree is filled in the next slot after it transmits.

□

7.5 Impact of Routing Tree

As emphasized in [76], routing trees that allow more parallel transmissions do not always result in a small schedule length. For instance, given a network, the schedule length would be N with a star topology whereas it would be $2N - 1$ with a line topology, assuming that the interference links are removed. Therefore, the structure of the routing tree also plays an important role on the schedule length. According to Theorem 6, the routing tree should be constructed with balanced number of nodes on branches, such that $2n_k - 1 < N$. In this section, we explore the possibilities of constructing such trees.

Theorem 8. *The following problem is NP-complete: Given an arbitrary graph G, can we construct a tree T on G, such that* $n_k \leq \frac{N+1}{2}$*?*

Such a tree construction is a variant of the "*Capacitated Minimal Spanning Tree (CMST) Problem*" where the problem is to determine a shortest spanning tree in a vertex weighted graph such that the weight of every subtree linked to the root by an edge does not exceed a prescribed capacity. In our case the weights of the links are 1, and the prescribed capacity is $(N + 1)/2$. The problem is proved to be NP-complete [209]. There exist approximation algorithms [142], linear integer programming formulations [111], tabu search algorithms [236], etc. to solve the problem.

Solving the problem in the most efficient way is out of the scope of this chapter. Instead, we rely on simple heuristics. Dai *et al.* [84] use a greedy heuristic in solving a variant of the problem where they search for routing trees with equal number of nodes on each branch. We present a simple algorithm, which is based on this heuristic, by adding a set of new rules:

- All the nodes know about their distance in terms of the minimum hop count to reach the sink node. The heuristic grows a tree hop by hop outwards the sink node.

- At each hop, first the nodes that have a single potential parent, i.e. a neighbor node that is connected to the tree and has a smaller hop count qualifies to be a potential parent for a node, are connected. Next, the node with the largest *growth set* should be added to the tree via the least loaded branch. A growth set of a node are the neighbors that are not yet connected to the tree and have a larger hop count, i.e. the potential children. This balances the number of nodes on different branches and prevents a branch to grow faster than the other branches.

- Selecting the least loaded branch may not always be the best option considering the nodes that are downwards on the tree. The nodes that are at higher levels on the tree limit the options for those nodes. We have a simple search strategy:
    - We create a *search set* for the node to be connected. The search set includes the nodes that are not yet connected to the tree and are the neighbors of the node at a higher hop count, i.e. the potential children. If the node joins this branch, and there is a node in the search set that will have access only to this branch, then this node should also be included in the decision. But if the node in the search set has other branches to connect to, it is not included. If it is the former, then the potential children of the new node are also added to the search set. Therefore,

this step guarantees that the options for the nodes below are not limited by the decision of the joining node.

For instance consider a situation in Figure 7.4. Dotted links show the potential connections and the solid lines represent the links between the nodes that have already joined the tree. Node 3 is processed (if the cardinality of the *growth set* of two nodes is the same, the node that has a smaller id is processed first) and is added to the branch 1 (B1). When node 4 is processed, again branch B1 should be selected considering only the weights of the branches. However, if node 4 also connects to the branch B1, the nodes 8,9 and 10 have only access to the branch B1 and branch B1 will be more crowded than branch B2. But if node 4 connects to branch B2, the nodes are balanced over the two branches and $n_k \leq \frac{N+1}{2}$.

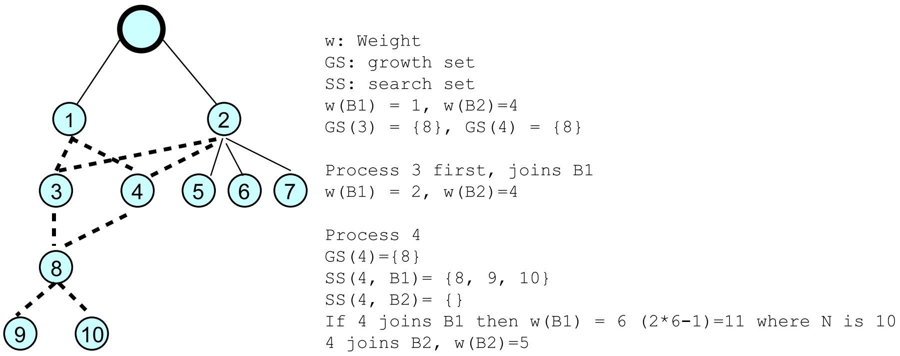
The pseudocode of the algorithm is presented in Algorithm 4. Although, this basic heuristic tries to keep the number of nodes on each branch as minimum, an additional balancing may still be needed. We use the adjustment algorithm used in [84] by moving the nodes on the most-loaded branch to the neighboring branches that can decrease the value of n_k.

Algorithm 4 Capacitated Minimal Spanning Tree

```
Input: $G(V, E)$ be the communication graph, $s$ be the sink, $BA$ is the set that includes potential branch access
  for each node
Output: $T$ represents the tree
$T \leftarrow s$+the roots of the top subtrees
$B \leftarrow$ id's of the roots of the top subtrees        //B is the branch set
$\forall n \in V, GS(n) \leftarrow n$, unconnected neighbors of $n$ with a higher hop_distance        //GS is the growth set
$\forall b \in B\ weight(b) \leftarrow 1$
$h = 2$
while $h \neq max(hop\_distance)$ do
    $N$: set of unconnected nodes at hop_distance $h$
    Connect the nodes that have a single potential parent first
    Sort N according to the $|GS|$ values in descending order
    for all $n \in N$ do
        for all $b \in B$ that $n$ can connect to do
            $SS \leftarrow GS(n)$        //Search set
            $PG(n, b) \leftarrow \phi$        //Potential growth set that n brings on b
            for all $i \in SS$ do
                if $BA(i, :) ==$ b then
                    $PG(n, b) \leftarrow i, SS \leftarrow GS(i)$
                end if
            end for
        end for
        Connect $n$ to the branch $b$ where $W(b) + |PG(n, b)|$ is the minimum
        Update the growth set's and weights of the related branches
        $T \leftarrow T + n + PG(n, b)$
        $h$++
    end for
end while
```

7.6 Evaluation

We simulate and evaluate the performance of the discussed mechanisms in Matlab [21]. We start by explaining the simulation settings. In Section 7.6.1, we evaluate the impact of the transmission power control on the schedule length to complete a convergecast operation with the method which was explained in Section 6.2.2. Then, in Section 7.6.2, we test the per-



```
w: Weight
GS: growth set
SS: search set
w(B1) = 1, w(B2)=4
GS(3) = {8}, GS(4) = {8}

Process 3 first, joins B1
w(B1) = 2, w(B2)=4

Process 4
GS(4)={8}
SS(4, B1)= {8, 9, 10}
SS(4, B2)= {}
If 4 joins B1 then w(B1) = 6 (2*6-1)=11 where N is 10
4 joins B2, w(B2)=5
```

Figure 7.4: *Balanced Tree Construction*

formance of the receiver-based scheduling method that we introduced in Section 6.2.3 and discuss the impact of the routing trees. We evaluate the bounds on the frequencies to eliminate interference in the network and compare the performance of the receiver-based channel assignment with another channel assignment strategy. Finally, we discuss the further improvements on the schedule length when the sink node is equipped with multiple radios or when there are multiple sinks to collect data.

Nodes are randomly distributed over the area. Terrain dimensions are varied between 20×20 and $300 \times 300\, m^2$ to simulate different levels of density whereas the number of nodes is kept as 100. All the results are averaged over 1000 runs.

We use a log-distance path loss model for signal propagation with a path loss exponent $\alpha = 3.5$ (unless otherwise specified) which is a typical value for indoor environments. We simulate the behavior of the CC2420 [16] radio which is used on the Telosb [26] and Tmote [27] sensor mote platforms. The transmission power can be adjusted between -24dBm and 0dBm over 8 different levels. SINR threshold is β=3dB. The transceiver is capable of operating on 16 different channels.

7.6.1 Impact of Power Control

In this section we evaluate the impact of transmission power control on the scheduling performance. In the initial set of simulations nodes transmit with the maximum transmission power and in the second set nodes adjust their transmission power according to the power control algorithm which was explained in Section 6.2.2. Nodes communicate on the same frequency. We use the physical interference model to exploit the effects of interference. Nodes transmit data over a minimum-hop routing tree.

We investigate the schedule length to complete a convergecast in the network according to different node deployments with different densities. We vary the density, by varying the side length L of the area, where the number of nodes is 100 in all deployments. The results are presented in Figure 7.5. The x-axis shows the length of a square area, L. The y-axis shows the number of time slots required to schedule all the transmissions to complete a convergecast in the network. Different lines display the results with different path loss exponents $\alpha =$

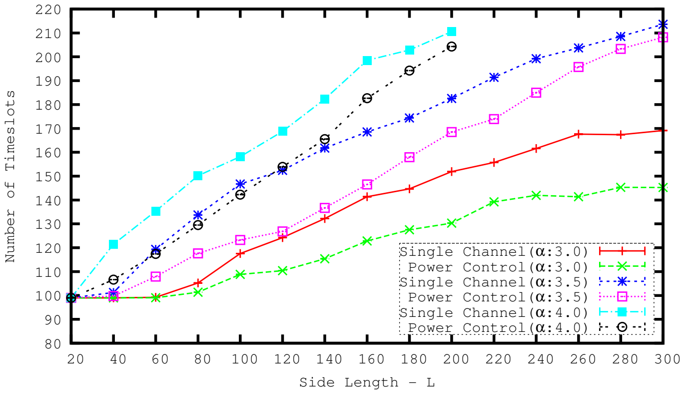


Figure 7.5: *Joint Scheduling and Transmission Power Control*

3.0, 3.5, 4.0 to discuss the impact of physical layer parameters. We cannot provide the results for $L > 200$, $\alpha = 4.0$ since it is hardly possible to generate connected trees.

The required number of time slots, i.e. the schedule length, increases as the network gets sparser. One would expect the other way around since in sparser deployments the reuse of the time slots should be higher which would result in a smaller schedule length. However, as the network gets sparser, the number of nodes that can directly reach the sink decreases such that the packets have to be relayed over multi-hops. In this case more packets have to be scheduled compared to scheduling packets in a single-hop setting. In the simulations we observe that the number of packets to be scheduled increases faster than the reuse ratio. In the densest setting ($L = 20$), where all the nodes can directly reach the sink, the schedule length is 99, equal to the number of source nodes in the network.

If the nodes adjust the level of transmission power, we observe that the schedule length is smaller since some interference is eliminated and the reuse of the time slots is increased. When $\alpha = 3.0$, most of the interference is eliminated with power control and the limiting factor is the routing tree structure. In this set of simulations the routing trees were constructed as shortest path (minimum-hop) spanning trees and the limiting factor is due to the maximum number of nodes on a branch such that $2n_k - 1 > N$. However, when $\alpha \geq 3.5$ the transmission power control approach cannot always eliminate the interference. In this case, the generated networks have less connectivity (transmission range is around 37.5m with $\alpha = 3.5$ and 23m with $\alpha = 4.0$ while it is around 68m with $\alpha = 3.0$). In sparse and less connected deployments, the nodes cannot decrease the transmission power further than the maximum level since the transceiver cannot decode the signals below the sensitivity level which is $-95dBm$. Especially in sparser deployments, $L \geq 200$, the results are similar either the nodes transmit with the maximum power or adjust the power level. Moreover, in mid-sparse deployments ($60 \leq L \leq 180$) the discrete power levels (8 levels) and the limited range of the transmission power limits the nodes to adjust their transmission power.

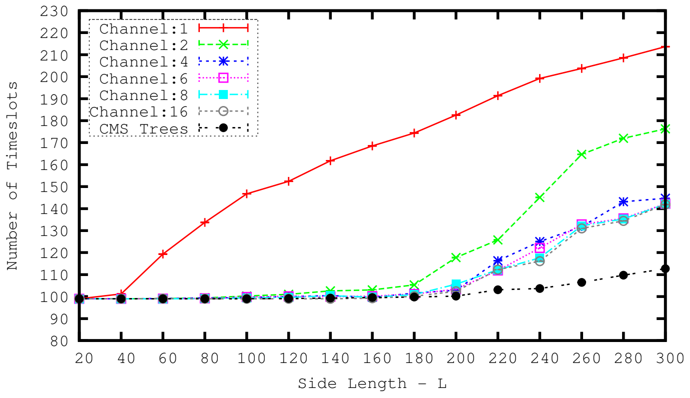


Figure 7.6: *Receiver-Based Frequency and Time Scheduling*

7.6.2 Impact of Receiver-based Scheduling and Routing Trees

In this section we analyze the scheduling performance when the transmissions are scheduled over different channels according to the receiver-based channel assignment which was introduced in Section 6.2.3. Nodes transmit with the maximum power. The radio can operate over 16 different channels and we take the channel overlaps into consideration. The physical interference model is used to capture the effects of conflicts on the parallel transmissions.

Figure 7.6 presents the results with the x-axis showing the length of a side of the square deployment area and the y-axis showing the schedule length. Different lines show the results for different number of channels. The first six lines present the results collected with shortest path, i.e., minimum-hop, spanning trees. The last line shows the schedule length when the routing tree is constructed with balanced number of nodes on each branch, such that $2n_k - 1 < N$, with the method explained in Section 7.5 (results are displayed only with 16 channels). We investigate the required number of time slots to schedule the network according to the different deployments with different densities. First the receivers are assigned frequencies according to the receiver-based channel assignment, then the time slots are assigned to the senders according to the Algorithm 3.

When the number of available channels increases, we observe a reduction on the schedule length. However, when the number of channels is 6 or higher, the schedule length cannot be reduced any more since the interference is eliminated and the limiting factor is due to the half-duplex operation of the sink node.

This set of simulations verifies that the receiver-based frequency assignment can achieve a schedule length which is bounded by $\max(2n_k - 1, N)$ as long as the number of available channels is sufficient to eliminate the interference. Compared with single-channel results in sparser scenarios, we achieve a reduction of up to 40% on the schedule length. In very dense scenarios (low L), reduction is small since most of the nodes can directly reach the sink node and the limiting factor is the half-duplex capability of the transceiver of the sink node.

In Figure 7.6, the last line presents the results according to the tree construction method explained in Section 7.5 (results are displayed only with 16 channels). The impact of such

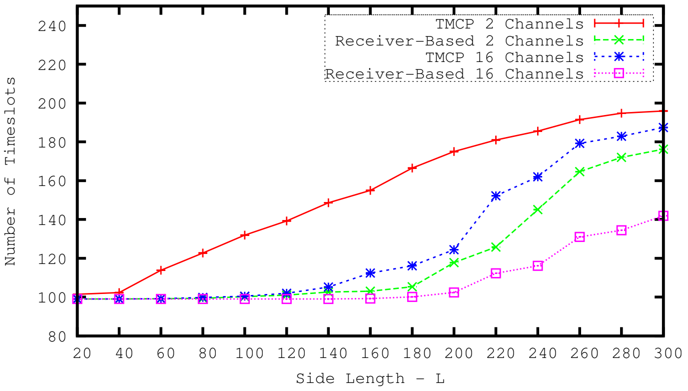


Figure 7.7: *Receiver-Based Channel Scheduling versus TMCP*

routing trees is more visible in sparser scenarios ($L \geq 200$) where a further reduction on the schedule length is observed. When $L \leq 200$, the schedule length is bounded by N. Beyond this point it is mostly not possible to construct trees where the $2n_k - 1 < N$ constraint can be met and the schedule length is limited by $2n_k - 1$ where n_k is minimized by the tree construction algorithm. As a result of this set of simulations, the receiver-based channel assignment combined with a suitable tree construction can achieve a reduction of up to 50% on the schedule length compared to single-channel communication on shortest path spanning trees.

In the following section, we compare the performance of the receiver-based channel assignment method with a cluster-based channel assignment method.

7.6.3 Comparisons of Receiver-based and Subtree-based Scheduling

In this section, we compare the performance of the receiver-based channel assignment with the *Tree-Based Multichannel Protocol (TMCP)* [291]. TMCP is a tree-based channel assignment method such that different channels are assigned to each top subtree of the tree. The goal is to partition the network into multiple subtrees with minimizing the intra-tree interference. It is a greedy algorithm and assigns the channels one by one to the nodes from top-to-bottom on a fat tree. When a node is to be added to a subtree, the subtree where the node brings the least interference is selected. After the channel assignment, time slots are assigned to the nodes with the same method as explained in Section 7.4. Figure 7.7 presents the comparisons between the receiver-based channel assignment and the TMCP protocol with 2 and 16 channels where the x-axis shows the side length of the deployment area and the y-axis shows the schedule length. We use shortest path routing trees (not the balanced trees) with the receiver-based channel assignment method for a fair comparison. Receiver-based channel assignment performs approximately the same only with 2 channels while TMCP uses 16 channels since the method allows more nodes to transmit in parallel. For instance, while a node is receiving from its children, the parent of this node can transmit simultaneously. This would not be possible if they communicate on the same channel, i.e. due to the intra-branch

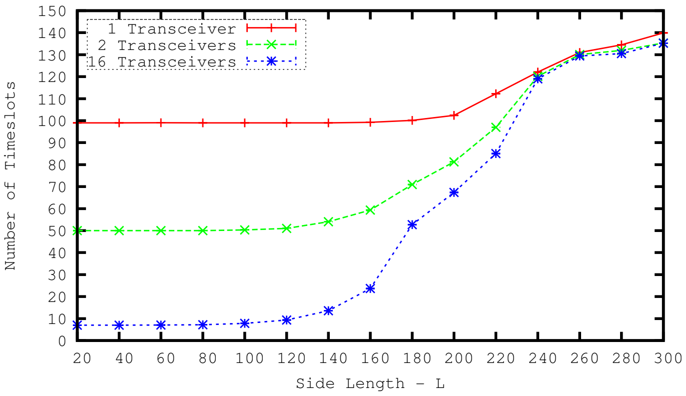


Figure 7.8: *Multiple Transceivers on the Sink Node*

interference in TMCP. The receiver-based channel assignment outperforms TMCP in fast data collection operations in WSNs.

7.6.4 Multiple Transceivers at the Sink Node, Multiple Sinks

In this section we analyze the schedule length when the sink is equipped with multiple half-duplex transceivers such that the transceivers can receive in parallel from different senders. We vary the number of transceivers, tx, from 1 to 16 and accordingly tx trees are created in parallel in the simulations. There are 16 channels available.

Figure 7.8 presents the results (shortest path spanning trees are used). In denser scenarios ($L < 140$), reduction on the schedule length is proportional to the number of available transceivers at the sink node. However, in sparser scenarios, especially when $L > 220$, there is almost no reduction on the achievable schedule length if the sink has a single transceiver or multiple transceivers. In sparser scenarios, the number of neighbors that a node can connect to is limited. Therefore, it is difficult to balance the number of nodes transmitting to a particular transceiver of the sink node. Additionally, since the number of nodes on the branches of minimum hop routing trees are not balanced, it becomes $2n_{kt} - 1 > N_t$, where n_{kt} is the maximum number of nodes on any branch of tree t and N_t is the number of nodes on tree t. In sparser scenarios n_{kt} with multiple transceivers and n_k with a single transceiver is mostly the same.

Next, we evaluate the schedule length if there are multiple sinks deployed within the network. We vary the number of sinks from 1 to 16. Sinks are randomly deployed as well as the nodes. Figure 7.9 shows the results. Compared to the results in Figure 7.8, we can achieve a reduction on the schedule length also in sparser scenarios since the number of transmitting nodes to different sink nodes can be balanced. In denser deployments ($L < 100$) the reduction is proportional to the number of available sinks. However, when $L \geq 200$, a factor of half of the available sinks is achieved due to the sparseness and less connectivity.

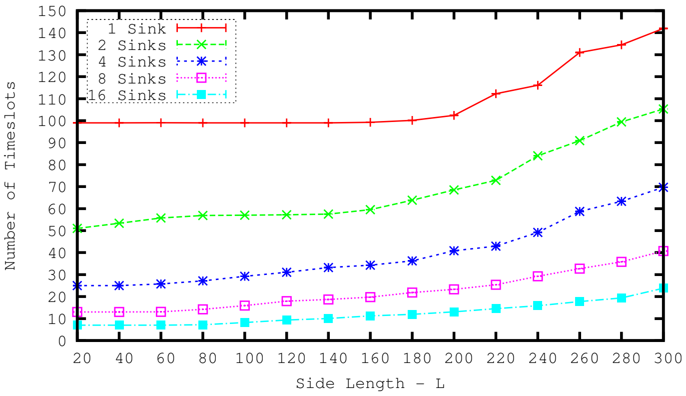


Figure 7.9: *Multiple Sinks*

7.7 Related Work

In this section we review the existing work on the topics studied in this chapter: TDMA scheduling in wireless multi-hop networks and in WSNs, convergecast operations in WSNs and fast data collection in WSNs. The reader can refer to Chapter 2 for the existing work on frequency assignment in wireless networks and the impact of topology on the capacity of WSNs.

7.7.1 TDMA Scheduling

Transmission scheduling describes the transmission rights where each possible transmission is assigned a time slot/channel in such a way that transmissions on the same time slot/channel do not conflict with each other [218]. By a conflict, we mean an unsuccessful transmission due to a collision, excessive interference, etc. Since the introduction of the Spatial-TDMA (STDMA) concept in [203], scheduling problems based on time slot or channel assignment have been extensively studied in the literature. There are two general methods: *broadcast scheduling*, also referred as node scheduling, and *link scheduling*, also named as link activation or point-to-point scheduling. In broadcast scheduling the time slots are assigned to the nodes, such that a transmission of a node in its assigned time slot is intended for, and must be received collision free by all of its neighbors [218]. In link scheduling, the links between the nodes are scheduled, such that a transmission from a node is intended for a particular neighbor, and should be received free of collisions by the intended destination. Examples of broadcast scheduling is presented in [73, 74, 95, 124, 131, 133, 176, 181, 219, 239] whereas link scheduling examples have been studied in [75, 88, 104, 121, 128, 212, 278].

Scheduling protocols differ according to the network and interference models they use, their objectives and the implementation methods such as centralized or distributed operation. In the following, we briefly survey the existing STDMA scheduling methods according to this classification.

Most of the scheduling algorithms assume that transmission ranges are limited (usually circular), and beyond this no interference is caused [115]. Accordingly, the scheduling problem can be transformed into a graph-theory problem where the network is represented as a graph with nodes as vertices and the communication links as the edges of the graph. If there is no edge between the nodes, this implies that the transmissions from those nodes cannot interfere with each other. This is the protocol interference model that we have explained in Chapter 2. Using this model, the problem can be solved by graph coloring algorithms. Although the model does not precisely capture the properties of the wireless medium, it is the most commonly used model in the literature [120]. A more detailed approach takes interference into account, and interference links are added between the vertices if the received signal strength is strong enough to interfere with receptions from other transmitters [120]. An advanced model is the physical interference model that we have described in Chapter 2. A node is assumed to successfully receive a packet if the received signal strength is sufficient compared to the noise and the signal level of all interfering simultaneous transmissions. Examples of scheduling studies that use the physical interference model can be found in [47, 58, 62, 115, 129, 131, 153, 198].

In terms of the objectives metric in our classification, there are many different scheduling methods. The most common objective is constructing a transmission schedule where all links are scheduled with the minimum number of time slots. It is usually assumed that time slots are organized into frames and a frame consists of a fixed number of time slots. The objective is to find a schedule with a minimum frame length [218] where each node or link gets activated at least once [97]. The problem of finding a minimum-length schedule has been proven to be NP-complete [42, 98]. Examples of minimum frame scheduling are presented in [52, 55, 102, 212, 218, 219]. Assigning a single time slot or the same number of time slots for each node/link per frame may degrade the performance since the traffic requirements over different links vary due to the relaying of packets in a multi-hop network and unused time slots may waste the bandwidth. Scheduling with considering the traffic demands on different links is addressed in several papers [233, 242, 285]. Maximizing throughput [57, 103, 265], minimizing latency [62, 130, 178], fairness [132, 234, 252, 267] and scheduling with deadlines [168] are the other most common objectives presented in scheduling wireless multi-hop networks.

Algorithms also differ according to the method of implementation. Centralized scheduling methods mostly benefit from graph theory or use SINR-based interference modeling [93, 121, 181, 203, 204, 218, 219]. Distributed scheduling approaches mostly use localized algorithms and the examples are presented in [51, 58, 72, 104, 225, 274, 292].

Following this classification, in this chapter we have proposed a link scheduling method where the objective is fast data collection by minimizing the completion time of convergecasts in WSNs. The proposed algorithm is distributed and the physical interference model is used to capture the conflicts among simultaneous transmissions. In Sections 7.7.2 and 7.7.3, we discuss the differences between the presented work and the existing studies on TDMA scheduling in WSNs.

7.7.2 TDMA Scheduling and Convergecasts in WSNs

STDMA scheduling has the advantage of collision-free medium access and preventing idle listening, which are the two main energy consuming operations in wireless communication and should be prevented in WSNs. Examples of schedule-based MAC protocols for WSNs are presented in [46, 96, 179, 188, 224, 251, 274]. Scheduling with minimizing packet delays [83, 96, 97, 179, 269], scheduling with max-min fairness [258], maximizing the parallel transmissions with TDMA scheduling [104] are the other topics related with TDMA scheduling in WSNs.

Other than the previous work, we focus on minimizing the time to complete the delivery of the messages in a convergecast operation (the related work is presented in Section 7.7.3). This is different from minimizing latency where the time for the delivery of a message from source to the destination is considered. We have shown that the minimum schedule length to complete a convergecast is bounded by $max(2n_k - 1, N)$ where N is the number of nodes on a tree topology and n_k is the maximum number of the nodes on any top subtree. If the schedule length is equal to N, then the average latency per packet will be $(N + 1)/2$ slots, which is also the average latency in a single-hop network with N nodes. Therefore, if the schedule length is N, by minimizing the schedule length we also minimize the latency. Combination of the two problems, minimizing both latency and the completion time of a convergecast, are addressed in [223] as optimization problems.

As we mentioned in Section 7.7.1, minimizing the frame length is a well-studied topic. For instance, in LMAC [274], which has been studied in Chapter 5, each node is scheduled once per frame and minimizing the frame size is one of the objectives. When the effect of interference is eliminated, the minimum frame size equals the maximum degree of the routing tree. However, in this chapter we do consider the nodes to be scheduled multiple times per frame since the traffic requirements of the nodes at different levels of the routing tree are different due to the relaying of the messages.

Convergecast communication has been addressed in the literature from many different aspects. Minimizing energy consumption [65, 125, 175], minimizing both latency and energy consumption [179, 229, 262, 271], increasing reliability [260, 301], increasing the network lifetime [1, 174], scalability [100], increasing security [231] are some of the discussed metrics on efficient data collection in WSNs.

7.7.3 Fast data collection in WSNs

Fast data collection for minimizing the time to complete a convergecast was previously studied in [76, 105, 164, 256] where the raw sensor readings are forwarded to the sink node and in [4, 40, 68, 196] where data is aggregated.

In [256], a time-optimum and energy-efficient packet scheduling algorithm with periodical traffic from all sensors to a sink node has been studied. The presented algorithm exactly achieves the bounds ($max(2n_k - 1, N)$) that we have presented for convergecast scheduling. Authors assume that interference is eliminated before scheduling. However, they only mention a 3-coloring channel assignment but it is not clear whether the channels are frequencies, codes or any other method of interference elimination is used. Different than this work, we propose a receiver-based frequency scheduling to eliminate interference, discuss the impact of routing topologies and compare our algorithms with alternative methods to eliminate interference and show further improvements with multiple sink nodes and sink nodes equipped with multiple transceivers.

In [105], a distributed time slot assignment mechanism is proposed to minimize the time to complete a convergecast in the presence of a single channel with TDMA protocols. Although the addressed problems are similar, we investigate/introduce mechanisms that can reduce the schedule length by eliminating the limitations due to interference and half-duplex transceivers. Furthermore, we improve the presented bounds on the length of convergecast schedules. In [76] the NP-completeness of the problem is proved with single-channel communication. Duarte-Melo *et al.* [91] discuss the convergecast operations in WSNs with flat and hierarchical topologies using probabilistic models. Their objective is not minimizing the schedule length but maximizing the transport capacity and they consider simpler graph-based interference models.

In [164], maximizing the throughput of convergecast operations by finding a shortest-length conflict-free schedule has been studied. A greedy graph coloring method is used to assign time slots to the senders and prevent interference. The impact of routing tree structures on the schedule length is discussed and a routing scheme called "disjoint strips" is proposed to transmit data over different shortest paths. However, since the sink remains as the bottleneck, sending data over different paths does not shorten the schedule length. As we have shown, the improvement in terms of the routing tree should be using capacitated minimal spanning trees where the number of nodes on a subtree should not be more than the half of the nodes on the remaining subtrees.

TDMA scheduling for fast broadcast (a converse problem of convergecast, one-to-many data delivery), where a source node sends a message to all the other nodes in the network, is a well-studied topic. In [74], the problem of finding an optimal slot allocation with minimal schedule length has been proven to be NP-hard for broadcasting in multi-hop wireless networks. In [172], data dissemination from sinks to the sensor nodes is studied by using multi-channel communication to reduce the completion time of the dissemination. Other example studies on fast broadcasting are presented in [71, 106, 219, 239].

7.8 Conclusions

We have explored fast convergecast scheduling in wireless sensor networks where the nodes communicate on a TDMA schedule and the objective is to minimize the schedule length to complete convergecast operations. By addressing the fundamental limitations due to interference and half duplex nature of the radios on the nodes, we explored techniques to eliminate those limitations. We found that while power control is helpful in reducing the schedule length, scheduling transmissions on different frequency channels is more efficient in mitigating the effects of interference. Once the interference is eliminated, we proved that with half-duplex radios the achievable schedule length is lower-bounded by $\max(2n_k - 1, N)$, where n_k is the maximum number of nodes on a subtree and N is the number of nodes in the network. Using an optimal convergecast scheduling algorithm, we showed that the lower bound is achievable once a suitable balanced routing scheme is used. Through extensive simulations, we demonstrated up to 50% reduction on the schedule length by using the mentioned improvements compared to single-channel communication on minimum spanning trees. For further improvements, we considered scenarios when the sink is equipped with multiple transceivers or when there are multiple sinks to collect data. In such scenarios we observed reductions proportional to the number of transceivers available.

Multi-Channel Scheduling for Fast Convergecast in Wireless Sensor Networks

CHAPTER VIII

Conclusions and Future Work

Since the introduction of the "wireless sensor networks (WSNs)" concept for military projects funded by DARPA in the late 1990's, WSN research still continues at full steam. WSNs have moved from the military to the civilian domain, attracting a significant amount of interest within the research community: a search for "wireless sensor networks" on Google Scholar has about 865.000 hits with about 190.000 of papers have been published after 2005, when the research reported in this thesis started. The number of annual workshops, conferences, symposia dedicated to WSN research is increasing every year. We still observe an increase in the number of research projects on WSNs funded by the European Union, NSF (National Science Foundation) and DARPA in USA, and local organizations in each country. On the other hand, commercial interest is lagging behind. However, given a typical 10 year time lag from research to commercial deployment, adoption of WSNs by commercial applications is prudent [189].

This thesis covers solutions to the communication problems that appear with the evolution of the WSNs from the low-rate, data-collection-based monitoring applications to more complex applications that require *timely* and *efficient* delivery of *large amounts* of data. We identify the barriers to achieve these in the wireless domain, namely interference and contention; and in the organization of the network, namely routing topologies. Accordingly, we provide solutions to overcome these barriers by using multi-channel communication and appropriate routing topologies. The contributions of the thesis are summarized in the following section.

8.1 Contributions Revisited

As we mentioned in Chapter 2, research on multi-channel WSNs is considerably recent compared to the research in other classes of wireless networks. There exist a few multi-channel MAC protocols and channel assignment strategies. This thesis makes one step forward by extensively studying the potential improvements that can be achieved with multi-channel communication in WSNs. The contributions of the thesis are revisited in the following:

- **Contribution 1: Characteristics, challenges and the use of multi-channel communication in wireless ad hoc networks and WSNs**
  We have reviewed the state of the art channel assignment protocols in wireless multi-hop networks, particularly in wireless ad hoc networks and WSNs. We classified the existing solutions according to the number of transceivers required per node and according to the dynamics of the channel assignment approaches. Since the channel assignment methods for other wireless ad hoc networks may not be directly applicable to WSNs, we gave brief comparisons between the two types of networks and discussed the additional challenges for using multi-channel communication in WSNs.

- **Contribution 2: Characterization of multi-channel interference**
  We have conducted an extensive set of experiments to investigate the characteristics of multi-channel communication in WSNs. The experiments show that when there are simultaneous transmissions operating on the adjacent spectrum in the same spatial domain, not only co-channel interference but also adjacent spectrum interference is observed. Based on the experiments, we have explored an analytical model on the interference characteristics and by using the analytical model we discussed the impact of channel orthogonality on the network performance with extensive simulations. The simulation results show that the overall network capacity significantly increases with the use of overlapping channels once they are assigned carefully by eliminating the effects of interference.

- **Contribution 3: Design and implementation of a multi-channel MAC protocol for WSNs**
  We have designed a multi-channel MAC protocol, MC-LMAC, which is a schedule-based multi-channel MAC protocol that takes advantage of interference and collision-free parallel transmissions on different channels. MC-LMAC provides high throughput and delivery ratio during high-rate traffic while it also meets the traditional requirements of WSNs such as energy efficiency and scalability. Extensive simulation results show that, MC-LMAC achieves a throughput very close to the maximum with the increased number of channels and outperforms the two other alternative protocols which also use multi-channel communication.

- **Contribution 4: Enhancing the rate of aggregated data collection**
  We have considered enhancing the data collection rate of *aggregated convergecast* operations in WSNs. We focused on finding the fastest rate of data collection with TDMA scheduling which is equal to minimizing the TDMA schedule length. We have explored a number of techniques to address this question, such as the use of transmission power control and the use of multiple frequency channels. We showed that, once multiple frequencies are employed along with spatial-reuse TDMA, the aggregated data collection rate often becomes no longer interference-limited, but rather topology-limited. Accordingly, we showed that the final step to enhancing the rate of periodic and aggregated data collection is to use an appropriate *degree-constrained tree* topology. Considering deployments at different densities, we showed that these enhancements can improve the streaming aggregated data collection by as much as 10 times compared to the baseline of single-channel data collection over non-degree-constrained routing trees.

- **Contribution 5: Fast convergecast scheduling in WSNs**
  We have studied finding the minimum time to complete the delivery of the messages in a convergecast operation, where data cannot be aggregated. Similar to the *aggregated convergecast* problem, we investigated the benefits of transmission power control and multiple channels to eliminate the effects of interference. Once interference is eliminated completely, we have shown that with half-duplex single-transceiver radios, the achievable schedule length is lower-bounded by $\max(2n_k - 1, N)$, where n_k is the maximum number of nodes on any subtree and N is the number of nodes on a tree

topology network. We studied a distributed time slot assignment algorithm to achieve this bound when a suitable routing scheme over a *capacitated minimal spanning tree* is employed. Through extensive simulations, we demonstrated that convergecasts can be completed within up to 50% less time slots using multiple channels on capacitated minimal spanning trees as compared to that with single-channel communication on unbalanced trees.

Having summarized the contributions, in the next section we provide a list of potential future research directions that are relevant to the topics covered in this thesis.

8.2 Future Research Directions

In this thesis, we have illustrated examples of communication techniques that can benefit from multi-channel communication and appropriate routing topologies to improve the performance of WSNs. There remain some issues such as testing the presented techniques on real, large scale WSN deployments. Moreover, further improvements can be incorporated to improve and extend the presented results. We believe that the use of multi-channel communication can enhance the operation of WSNs in different areas where interference or contention degrades the communication performance. In the following, we present a list of some possible future directions:

- *Effects of using multi-channel communication at upper layers:* In WSNs, the local channel contention and interference on the shared communication medium causes network congestion [118]. In [257], Rangwala *et al.* propose an interference-aware rate control for WSNs. If multi-channel communication is used to eliminate interference, effects of congestion can be alleviated and fair rate control could be possible for the nodes that suffer from interference. To the best of our knowledge, there is no congestion control or rate control algorithm that utilizes multi-channel communication in WSNs.

- *Compliance with real-time constraints:* In real-time applications, data is delay constrained and has a certain bandwidth requirement. For instance, scheduling messages with deadlines is an important issue in order to take appropriate actions in real time. However, due to the interference and contention on the wireless medium, this is a challenging task. Multi-channel communication can help to reduce the delay by increasing the number of parallel transmissions and help the network to achieve real-time guarantees.

- *Multiple applications running on the same network:* With the latest operating systems for WSNs, it is possible to have multiple applications running on the same network. This certainly leads to larger amounts of data to be transmitted in the network and handling the traffic, often with different priority levels, in an energy efficient way with avoiding collisions and interference becomes a major issue. Multi-channel communication can be a topic to be researched for solving the problems that arise with running multiple applications in the network.

- *Energy efficiency:* As we have emphasized throughout the thesis, one of the most important issues in WSNs is the energy efficiency. Although we have presented some basic results on the energy consumption of the multi-channel MAC protocol, MC-LMAC, in Chapter 5, it is not certain yet if multi-channel communication can help to reduce energy consumption in WSNs. Evaluating the energy consumption of the existing multi-channel protocols, together with the impact of channel switching, can be a major research topic, for instance together with the use of multiple transceivers on the sensor nodes.

- *Assignment of overlapping channels during run-time:* We have presented the advantages of using overlapping channels in Chapters 3 and 4, and have used overlapping channels for the receiver-based channel assignment in Chapter 6. However, this is based on a centralized assignment of the channels. Use of overlapping channels at run time during medium access is an interesting and challenging future research direction.

- *Experimentation of adjacent channel interference on other transceiver platforms with other parameters:* Filter characteristics, receiver selectivity, transmission power, distance between simultaneous transmissions, number of simultaneous transmissions are the major factors on the adjacent channel interference. In this thesis, we discussed the impact of those factors using an example radio platform. Exploring the impact of other factors such as error correction, modulation, adaptive coding, etc., can be considered as another future research topic to understand the characteristics of multi-channel communication.

The first three listed items and some of the topics addressed in this thesis, such as increasing throughput and enabling fast convergecast operations, can be associated with the quality-of-service (QoS) requirements in WSNs. Although there exist examples of previous studies that highlight the QoS issues in WSNs [36, 66, 137], not much attention has been paid to them so far. We believe that there exists a lot of potential to research the QoS requirements of WSNs according to different design issues, such as supporting mobility, co-existing networks, etc.

A final remark about the methods of research in WSNs may be the difficulty of comparing the performance of different protocols that we have faced during the course of this research. Even when testbeds are available, most of the WSN research is performed by simulations. The major problem is that it is not easy to compare the results of the simulations performed on different simulators due to the different models (e.g., the physical layer, traffic or mobility models) assumed. As emphasized in [284], it would be helpful to have a repository of the standard models not only for simulation codes but also the implementation details on the testbeds.

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