The Evolution of Ultra Wide Band Radio for Wireless Personal Area Networks

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Ultra wideband (UWB) wireless networks are in their infancy, but are poised to become a valuable component of consumer electronics and computer equipment. The IEEE 802.15.3a task group is currently developing a UWB standard that involves most of the major chip manufacturers, including Texas Instruments, Intel, Motorola, and Xtreme Spectrum.

This article provides a snapshot of the current state of the UWB standards process. According to the present timetable, drafts are now being completed and the standards should be determined by 2004. We also discuss the benefits of UWB radio, the regulatory environment of UWB, and the design issues that WPAN standards makers must consider.

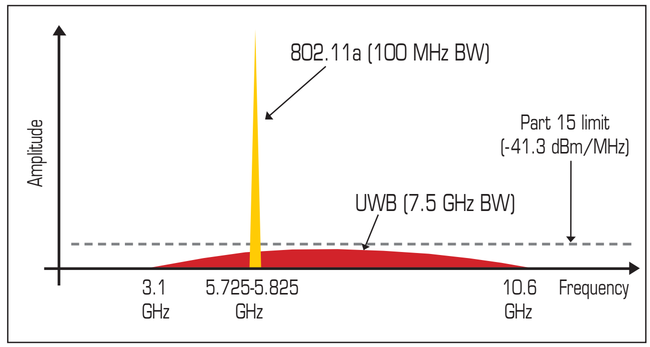

Figure 1 · Spectrum of UWB Signal Compared with Wi-Fi (802.11a) Signal (10).

Introduction

Many GHz of bandwidth has been authorized for license-free Wireless Personal Area Networks (WPANs) using UWB. This technology has the potential to provide unprecedented high-connectivity consumer products in the home, such as video conferencing, wireless video and audio distribution systems, new home entertainment appliances, diskless computers, and position location and navigation applications.

The concept of ultra wideband communication originated with Marconi, in the 1900s, when spark gap transmitters induced pulsed signals having very wide bandwidths. Spark transmissions created broadband interference and did not allow for coordinated spectrum sharing, and so the communications world abandoned wideband communication in favor of narrowband, or tuned, radio transmitters that were easy to regulate and coordinate.

in the mid-1980s, the FCC encouraged an entirely new type of wideband communications when it allocated the Industrial Scientific and Medical (ISM) bands for unlicensed spread spectrum and wideband communications use. This revolutionary spectrum allocation is most likely responsible for the tremendous growth in Wireless Local Area Networks (WLAN) and Wi-Fi today, as it led the communications industry to study the merits and implications of wider bandwidth communications than had previously been used for consumer applications. The Shannon-Hartley theorem states that channel capacity grows linearly with bandwidth and decreases logarithmically as the signal to noise ratio (SNR) decreases. This relationship suggests that radio capacity can be increased more rapidly by increasing the occupied bandwidth than the SNR. Thus, for WPANs that only transmit over small distances, where signal propagation loss is small and less variable, greater capacity can be achieved through greater bandwidth occupancy.

Many companies (such as Xtreme Spectrum and Time Domain) argued that they should be allowed to intentionally transmit at the incidental radiated power limits set by the FCC (where other narrowband users were already allowed to transmit accidentally), over an ultra-wide bandwidth, to take advantage of the capacity potential of UWB. This argument, that low power wireless services could operate below authorized out-of-band emissions limits to provide meaningful communications, was the key motivation for the FCC approval of UWB. This important concept is still being discussed by the FCC and its Technological Advisory Council (see minutes of FCC TAC, July 7, 2003, presentation by Michael Marcus).

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Operating frequency range	3.1 GHz to 10.6 GHz
Average radiated emissions limit	
Frequency range (MHz)	Mean EIRP in dBm/MHz (indoor / handheld)
960-1610	–75.3 / –75.3
1610-1900	–53.3 / –63.3
1900-3100	–51.3 / –61.3
3100-10600	–41.3 / –41.3
Above 10600	–51.3 / –61.3
Peak emission level in band	60 dB above average emission level
Max. unacknowledged transmission period	10 seconds

Table 1 · FCC requirements for indoor and handheld UWB systems (9).

On February 14, 2002, the FCC amended the Part 15 rules which govern unlicensed radio devices to include the operation of ultra wideband (UWB) devices. The use of UWB under the FCC guidelines [1] offers tremendous capacity potential (several Gbps) over short ranges (less than 10 meters) at low radiated power (mean EIRP of –41.3 dBm/MHz). The FCC defines UWB signals as having a fractional bandwidth (the ratio of baseband bandwidth to RF carrier frequency) of greater than 0.20, or a UWB bandwidth greater than 500 MHz. UWB bandwidth is defined as "the frequency band bounded by the points that are 10 dB below the highest radiated emission" [9].

The FCC ruling allows UWB devices to operate at low power (an EIRP of –41.3 dBm/MHz) in an unlicensed spectrum from 3.1 to 10.6 GHz (see Figure 1), with out-of-band emission masks that are at substantially lower power levels. The low in-band and out-of-band emission limits are meant to ensure that UWB devices do not cause harmful interference to (are able to coexist with) "licensed services and other important radio operations" [9], which includes cellular, PCS, GPS, 802.11a, satellite radio, and terrestrial radio. Table 1 summarizes a few of the guidelines most relevant to the use of UWB technology in WPAN devices. The fact that the FCC specified that UWB be a minimum bandwidth of 500 MHz is important—while UWB can occupy several GHz of bandwidth using small pulses (as pioneered by Xtreme Spectrum and Time Domain [23], [30]), the 500 MHz bandwidth rule has provided the impetus for chip makers to consider channelization, or a multiband approach, in the UWB standardization activity, mainly as a hedge against foreign governments who may not authorize the full U.S. 3.1 to 10.6 GHz allocation.

The key to UWB will be the development of low power CMOS chip technology up to the 10 GHz band, which many manufacturers are presently perfecting. Spectrum regulators in other countries have yet to authorize UWB, and are waiting to see how UWB performs in the U.S. In fact, the standards activity in the U.S. is being developed to anticipate varying spectral allocations in other countries.

Standards Activity of WPANs: IEEE 802.15

The standards activity of Wireless Personal Area Networks (WPANs) takes place in IEEE 802.15, an international standards working group which involves dozens of major companies. IEEE 802.15 (http://grouper.ieee.org/groups/802/15/) is responsible for cre-

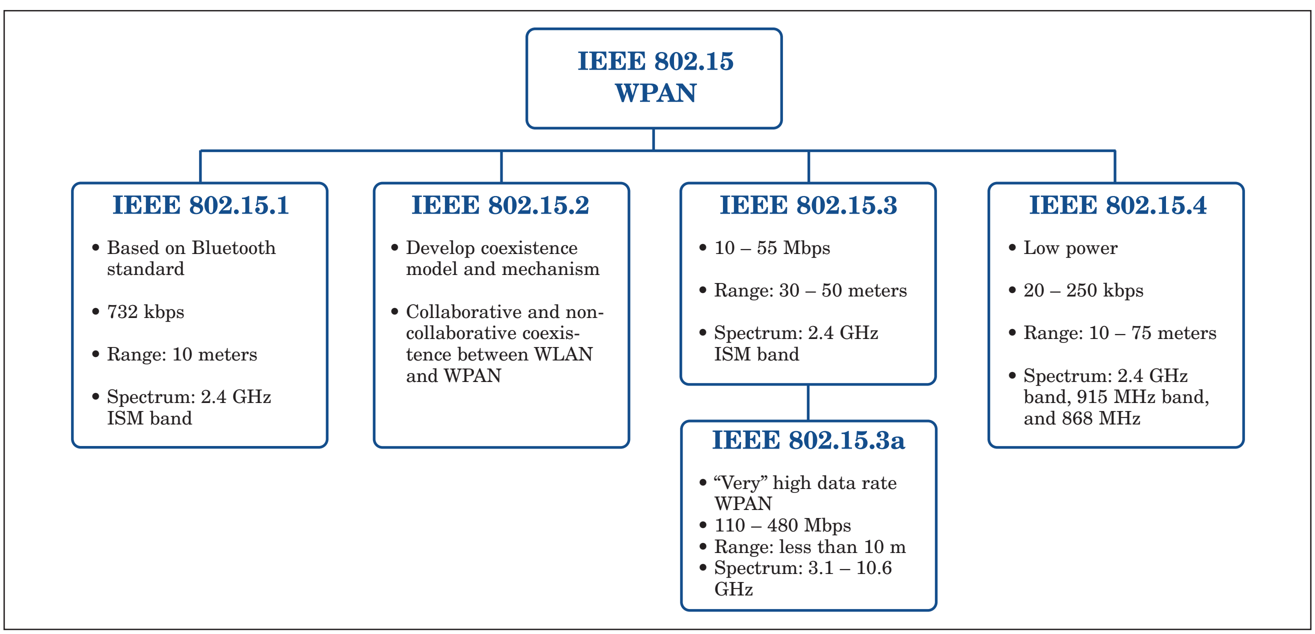

Figure 2 · Organization of IEEE 802.15.

ating a variety of WPAN standards, and is divided into four major task groups which are described in Figure 2. While this article focuses on the standardization efforts of UWB, which is the purview of IEEE 802.15.3a, an overview of all IEEE 802.15 efforts is useful to understand the WPAN landscape.

The *IEEE 802.15.1* task group was responsible for forging the standard based on Bluetooth v1.1 [2]. Bluetooth uses a short-range radio link (up to 10 m) to transmit data between personal devices, forming an ad-hoc network in the unlicensed 2.4 GHz band. The Bluetooth standard uses frequency hopping spread spectrum (FH-SS) with up to 1600 hops/s among 79 frequencies separated by 1 MHz intervals, and transmits 1 Msymbol/s using Gaussian shaped BFSK symbols (BT = 0.5). Data traffic can reach a maximum of 732 kbps (unidirectional) and 64 kbps (bi-directional). The 802.15.1 standard includes an adaptation of the Bluetooth Media Access Control (MAC) and physical (PHY) layers as well as a Logical Link Control/MAC (LLC/MAC) interface. In addition, it includes a high-level behavioral specification and description language (SDL) model for an integrated MAC sublayer. The 802.15.1 standard will eventually allow data transfers between a WPAN device and an 802.11 device. The IEEE Standards Association (IEEE-SA) approved this standard on April 15, 2002 and it was published on June 14, 2002.

IEEE 802.15.2 is concerned with coexistence issues that arise when two wireless systems share an environment of operation [3]. The IEEE 802.15.2 task group has two goals: 1) to quantify the effects of mutual interference between WPAN and WLAN devices, and 2) to establish mechanisms for coexistence of WPAN and WLAN (e.g. IEEE 802.15.1 and IEEE 802.11b) at both the MAC and PHY layer. These mechanisms can be broadly categorized as collaborative or non-collaborative. Some of the metrics for evaluating the performance of a coexistence method include the receiver sensitivity degradation (in dB) and the reduction of throughput in the presence of an interferer. A collaborative mechanism that facilitates coexistence needs to have coordinated scheduling efforts, such as TDMA or CSMA. Adaptive frequency hopping, MAC scheduling, and transmit power control schemes are non-collaborative mechanisms for coexistence [4]. The task group is establishing recommended practices for coexistence between WLAN and WPAN

The *IEEE 802.15.3* task group is developing WPANs up to 55 Mbps. The draft standard operates on five 15 MHz channels in the 2.4 GHz ISM band, two of which interfere with IEEE 802.11b traffic. Modulation (QPSK, DQPSK, 16/32/64-QAM) and coding (trellis-coded modulation) are varied to provide five data rates (11 Mbps, 22 Mbps, 33 Mbps, 44 Mbps, and 55 Mbps) [5]. The MAC layer described by this standard allows for the coordination of WPAN devices to form piconets. The MAC layer also allows for multimedia quality of service (QoS), power management, and ad-hoc networking support. IEEE 802.15.3 gained sponsor ballot approval in May 2003. The focus of UWB occurs in a separate task group, *IEEE 802.15.3.a*, which is discussed below.

The *IEEE 802.15.4* task group is focused on low data rate, low power WPAN (LP-WPAN). IEEE 802.15.4 investigates low data rate WPAN solutions with a battery life ranging from months to several years and a very low complexity. The IEEE 802.15.4 standard is intended to operate in unlicensed and international frequency bands. The spectrum allocation for this standard is as follows: 1 channel at 868 MHz, 10 channels in the 915 MHz band, and 16 channels in the 2.4 GHz band [6]. Using either MSK or BPSK (depending on the data rate), this standard transmits a spread spectrum signal. The range is 10 to 75 meters nominally, depending on the consumption for a given application. The MAC layer included in this standard supports various ad-hoc topologies and guaranteed packet delivery. IEEE-SA approved the draft proposed by IEEE 802.15.4 on May 12, 2003.

The remainder of this article focuses on the up-to-the minute standardization activities of IEEE 802.15.3a, concerned with very high data rate WPAN, where UWB is employed. IEEE 802.15 Task Group 3a was formed in late 2001 to identify a higher speed physical layer alternative to 802.15.3. The IEEE 802.15.3a task group is aimed at developing physical layer standards to support data rates between 110 Mbps and 480 Mbps over short ranges of less than 10 meters (i.e. alternatives to the original IEEE 802.15.3 physical layer). It should be noted that 802.15.3.a is only concerned with physical layer alternatives and uses the same MAC layer as IEEE 802.15.3, which is described in [8].

IEEE 802.15.3a: Current Status

The IEEE 802.15.3a task group (also called “TG3a”), established technical requirements and selection criteria for a WPAN physical layer in December 2002 (see Table 2), and is currently debating proposals submitted by various companies, including Intel, Texas Instruments, Motorola and Xtreme Spectrum. The IEEE 802.15.3a task group set forth goals for low power consumption and low cost to ensure that the WPAN standard is amenable to implementation in CMOS technology. These requirements will ensure that the high data rate physical layer drafted by 802.15.3a can be easily integrated into WPAN devices which have MAC and network layers already implemented in CMOS technology [8].

The flexible standard to be developed by TG3a will enable data rates of 110 - 480 Mbps (data rates necessary for wireless USB), WPAN over a cost effective architecture, and will operate on the IEEE 802.15.3 MAC layer which is already well defined [8]. The new TG3a standard will enable a broad range of applications, including multimedia requiring in excess of 100 Mbps, such as wireless video conferencing.

Since IEEE 802.15.3a began hearing proposals in March 2003, many companies have merged their ideas and collaborated to form coalitions to support a single proposal. Before TG3a's May 2003 meeting, the UWB Multiband-Coalition (www.uwbmultiband.org) was led by Intel and includes several other major companies [33-38] that support a multiband approach which employs pulsed modulation. On July 14, 2003, industry titans Intel and Texas Instruments merged their proposals to form a united approach that employs multiple bands and uses OFDM modulation. The newly formed Multiband-OFDM Coalition (www.multiband-ofdm.org), whose membership includes TI and the UWB Multiband-Coalition, endorses a proposal which is essentially the same as the original TI proposal, with an optional operating mode which uses seven bands (as opposed to three) [43]. TG3a heard its final round of proposals at their July 21-25, 2003 meeting and now faces the task of selecting one or more approaches from which to draft a standard.

Parameter	Value
Data rates (measured at PHY-SAP)	110, 220, and (optional 480 Mbps
Range	10 m, 4 m and below
Power consumption	100 mW and 250 mW
Power management modes	Capabiliites such as power save, wake up etc.
Co-located piconets	4
Interference susceptibility	Robust to IEEE systems, PER <8% for a 1024 byte packet
Co-existence capability	Reduced interference to IEEE systems, interfering average power at least 6 dB below the minimum sensitivity level of non-802.15.3a device
Cost	Similar to Bluetooth
Location awareness	Location information to be propagated to a suitable management entity
Scalability	Backwards compatibility with 802.15, adaptable to various regulatory regions (such as the US, European countries or Japan)
Signal Acquisition	<20 µs for acquisition from the beginning of the preamble to the beginning of the header
Antenna practicality	Size and form factor consistent with original device

Table 2 · Summary of Technical Requirements and Selection Criteria for 802.15.3a. (19, 20).

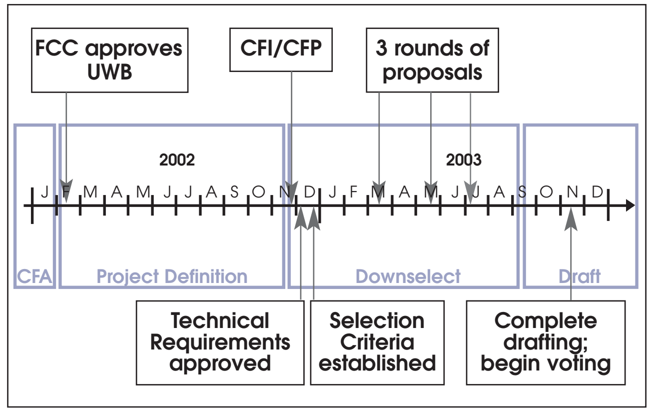

Figure 3 · IEEE 802.15.3a timeline (7).

After its July 2003 meeting, TG3a is now left with two primary contenders: (1) The Texas Instruments OFDM-based multiband approach which uses 528 MHz channels (three mandatory lower band channels and four optional upper band channels) supported by the Multiband-OFDM Coalition, and (2) the Xtreme Spectrum-Motorola dual-band Impulse Radio spread spectrum approach, where there is a high band (above the 5.2 - 5.8 GHz unlicensed band) and a low band (from 3.1 GHz to just below the 5.2 - 5.8 GHz unlicensed band), and which exploits all of the UWB spectrum allocation.

Spectrum Allocation	
No. of bands	3 (1st generation bands), 10 optional bands
Bandwidths	528 MHz
Frequency ranges	Group A: 3.168-4.752 GHz Group B: 4.752-6.072 GHz Group C: 6.072-8.184 GHz Group D: 8.184-10.296 GHz
Modulation scheme	TFI-OFDM (with 128-point FFT), QPSK
Coexistence method	Null band for WLAN (~5 GHz)
Multiple access method	Time-frequency interleaving
No. of simultaneous piconets	4
Error correction codes	Convolutional code
Code rates	11/32 @ 110 Mbps, 5/8 @ 200 Mbps 3/4 @ 480 Mbps
Link margin	5.3 dB @ 10 m @ 110 Mbps 10.0 dB @ 4 m @ 200 Mbps 11.5 dB @ 2 m @ 480 Mbps
Symbol period	312.5 ns OFDM symbol
Multipath mitigation method	1-tap (robust to 60.6 ns delay spread)

Table 3 · Overview of the TI Multiband-OFDM Physical Layer proposal supported by the newly-formed Multiband-OFDM Coalition (28, 43).

Spectrum Allocation	
No. of bands	2
Bandwidths	1.368 GHz, 2.736 GHz
Frequency ranges	3.2 – 5.15 GHz 5.825 – 10.6 GHz
Modulation scheme	BPSK, QPSK, DS-SS
Coexistence method	Null band for WLAN (~5 GHz)
Multiple access method	Ternary CDMA
No. of simultaneous piconets	8
Error correction codes	Convolutional code, Reed-Solomon code
Code rates	1/2 @ 110 Mbps RS(255,223) @ 200 Mbps RS(255,223) @ 480 Mbps
Link margin	6.7 dB @ 10 m @ 114 Mbps 11.9 dB @ 4 m @ 200 Mbps 1.7 dB @ 2 m @ 600 Mbps
Chip time	731 ps (Low band), 365.5 ps (High band)
Multipath mitigation method	Decision feedback equalizer and RAKE

Table 4 · Overview of the Xtreme Spectrum CFP Document (30).

If the standardization process finishes according to the TG3a timeline (Figure 3), high data rate WPAN devices with IEEE 802.15.3a will be available well before 2005.

As shown in Table 3, Texas Instruments prefers a channelized UWB system. There are three Group A bands which are used for standard operation. The four Group C bands are allocated for optional use in areas where simultaneous operating piconets are in close proximity (this is only used at close proximity since propagation loss severely limits signals at these higher frequencies). Group B and D bands are reserved for future expansion. Each band uses frequency hopping orthogonal frequency division multiplexing (TFI-OFDM), which allows for each UWB band to be divided into a set of orthogonal narrowband channels (with much larger symbol period duration). Because of the increased length of the OFDM symbol period, this modulation method can successfully reduce the effects of ISI. However, this robust multipath tolerance comes at the price of increased transceiver complexity, the need to combat inter-carrier interference (ICI), and tighter linear constraint on amplifying circuit elements. The University of Minnesota also proposed a similar OFDM approach [29].

The Xtreme Spectrum-Motorola proposal uses a dual band approach, as shown in Table 4, which employs short duration pulses to transmit over each band, having bandwidth in excess of 1 GHz (this is often referred to as impulse radio). Xtreme Spectrum's design benefits from a coding-gain achieved through the use of direct sequence spread spectrum (DS-SS) with 24 chips/symbol, and exploits the Hartley Shannon principals to a greater degree than the Multiband-OFDM approach, has greater precision for position location, and realizes better spectrum efficiency. However, it has less flexibility with regard to foreign spectral regulation and may be too broadband if foreign governments choose to limit their UWB spectral allocations to smaller ranges than authorized by the FCC. Sony [31] and Parthus Ceva [32] also have offered similar proposals which employ DS-SS over very wide bandwidths. A comparison of the trade-offs between impulse radio and multibanded UWB is presented next to emphasize the primary differences between the Xtreme Spectrum-Motorola and the Multiband-OFDM Coalition proposals.

Impulse Radio (IR) vs. Multibanded UWB

The two major approaches being considered by IEEE 802.15.3a differ primarily with regard to their allocation of UWB spectrum. Impulse Radio (IR), the traditional approach to UWB communication, involves the use of very short-duration pulses that occupy a single band of several GHz. Data is commonly modulated using pulse-position modulation (PPM); and multiple users could be supported using a time-hopping scheme [21]. Xtreme Spectrum's proposals, similar to two independent IR bands, uses a high chip rate direct sequence spread spectrum (DS-SS) signal to occupy its bandwidth.

The other approach to UWB spectrum allocation is

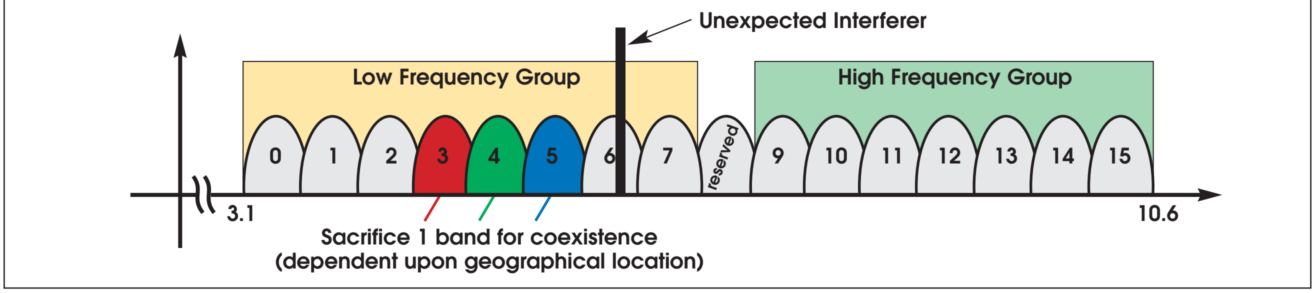

Figure 4 · Time Domain Corp.'s multiband spectrum allocation (23).

a multibanded system where the UWB frequency band from 3.1 - 10.6 GHz is divided into several smaller bands. Each of these bands must have a bandwidth greater than 500 MHz to comply with the FCC definition of UWB. Frequency hopping between these bands can be used to facilitate multiples access. Companies in the newly formed Multiband-OFDM coalition support this approach primarily because it has greater flexibility in adapting to the spectral regulation of different countries and avoids transmitting in already occupied bands. Figure 4 illustrates the division of the UWB spectrum into sub-bands.

Performance Comparison of Multiband OFDM vs. DS-SS IR

In the presence of a severe Narrow Band Interferer (NBI), as described in [25], a multiband system would drop the band under attack, thereby reducing its bandwidth efficiency and overall capacity. An impulse radio system (as employed by Xtreme Spectrum, also known as DS-CDMA) could mitigate these effects through the processing gain inherent in a DS-SS system with a RAKE receiver [24].

OFDM can be thought of as several, parallel, narrowband channels, or subbands, and thus each subband undergoes parallel flat fading in the indoor channel. This means that OFDM does not require a digital equalizer in its receiver structure, whereas a CDMA IR receiver needs a RAKE equalizer to exploit multipath. The longer symbol period used in OFDM makes it less sensitive to timing jitter in the receiver as opposed to Impulse Radio, which has much shorter time pulses. OFDM's resistance to frequency selective fading comes at the price of greater inter-carrier interference (ICI) from its own subband transmissions, and greater sensitivity to dynamic range (thus requiring a higher peak to average power ratio, and thus more battery drain). IR proponents argue that because of the long pulses used in the Multiband-OFDM approach, such a method cannot capture the benefits of signal processing techniques used to mitigate multipath and improve signal detection and ranging accuracy. These techniques require the high multipath resolution provided by wide signal bandwidth [44].

In the presence of multipath, the wider bandwidth of impulse radio leads to more resolvable multipath components. The RMS delay spread of an indoor environment (~25 ns or less [27]) is larger than an IR pulse, but is much less than the OFDM multiband approach. Thus, the channel looks like a flat fading channel for the OFDM subband approach, which could cause fading and difficult propagation situations when multipath combines to provide a deep fade at a particular location; whereas the IR approach exploits multipath by its fine timing resolution, but requires signal processing to equalize or gate-time multipath to improve reception. In addition, the greater number of resolvable multipath components increases the number of rake fingers needed for the impulse-based approach for a given signal to interference ratio (SIR), leading to a more complex receiver.

Multibanded UWB, as proposed by the TI/Intel Multiband-OFDM coalition, has greater flexibility in coexisting with other international wireless systems and future government regulators, who may choose to limit UWB spectrum allocations to smaller contiguous bandwidths than the US allocation. OFDM is a new and complex multiple access method, but is gaining popularity in WLAN and IEEE 802.11a and 802.16 standards activities. DS-CDMA has better multipath resolution and bandwidth efficiency, and seems more in the spirit of the FCC's original UWB concept, but will likely need a RAKE receiver with considerably more fingers than today's popular CDMA cellphone RAKE which has only a few fingers. DS-CDMA Impulse Radio has already been implemented in working silicon, whereas OFDM has been proven in IEEE 802.11a. Both approaches represent and exciting modern approach to wireless high speed data. While the jury has not yet cast its ballot, it is possible that both standards may survive.

Conclusion

The FCC approval of UWB for commercial use has prompted the IEEE 802.15.3a standards committee to explore a new physical layer standard for consumer electronics applications. Two leading standards proposals have emerged, and the commercialization of UWB is just around the corner. Based on the selection criteria and technical requirements set forth by the task group, it is likely that a proposed method and drafting of the standard should be completed by November 2003.

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NOTE: Some references are not called out in the text, but are useful for additional background on this topic.

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