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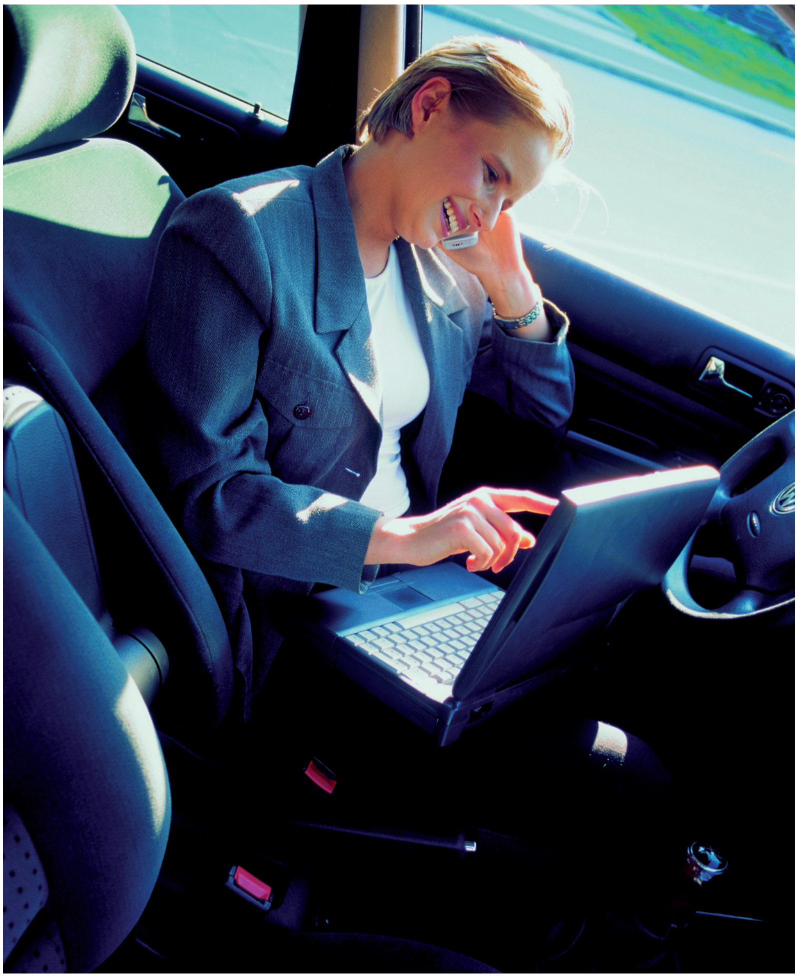
White Paper

From UMTS to LTE and beyond: Outlook on the fourth generation of mobile communications



boosting wireless efficiency

We do not find ourselves within the epic story of "The Lord of The Rings", however there is a minor parallel. Tolkien's book ends with the final retreat of the Elves from Middle Earth in the direction of the Grey Havens, at the same time ending the Third Age; and the Fourth begins. A rough comparison can also be drawn in the field of cellular wireless. Along this vein, HSDPA and HSUPA are even speaking of the 3.5th generation of cellular wireless under the general acronym of HSPA (High Speed Packet Access) and already many minds are buzzing with the details of the fourth generation of cellular wireless. The magic word here is OFDM – not new technology, but one where its application can only be fully exploited now.

It is not easy to say which of the many existing technologies and acronyms can already be attributed to the fourth generation (4G) of cellular wireless. The only thing that is certain is that HSPA (High Speed Packet Access) with the relevant sub-standards for downlink and uplink (HSDPA/HSUPA) can be called the "third and a half" generation (3.5G). This is an extension of the existing UMTS standard (3G); HSPA uses the basic functions of UMTS. The UMTS standard was specified by the responsible standards committee 3GPP (3rd Generation Partnership Project) in the specification known as 3GPP Releases 99 and 4. HSDPA was added to the downlink in Release 5, whereas the uplink saw its revaluation with Release 6. Several new developments and optimisations were introduced in Release 7 (HSPA+), such as MIMO, which refers to transmitting and receiving using multiple aerials. In addition, initial preparations were integrated into the forthcoming changes. These changes will be finally integrated with Release 8, which currently is still in the definition phase; in other words, it has not yet been officially approved. Generally speaking, Release 8 already describes the "final" successor to UMTS, known under the acronym of 3GPP LTE (Long Term Evolution). Currently, though, the network operators in many places are still working on integrating or perfecting HSDPA and only a few have already implemented Release 6 locally and to a limited extent, and have therefore also integrated HSUPA into their networks. The situation is the same when it comes to terminals. Due to restrictions relating to the receiver hardware, terminals are not able to use the full capacities of HSDPA at present. And for HSUPA as well there are only a few terminals, primarily data cards; however these have not yet moved beyond prototype status and are not yet being mass produced. This also means that it is not even remotely possible to consider exploiting the advantages of Release 7 or the final innovations in Release 8. This situation was also reflected at the world's two largest mobile wireless trade fairs, the 3GSM World Congress in Barcelona (Spain) and the CTIA Show in Orlando (USA) in spring 2007. It goes without saying that HSPA was on everyone's lips, with HSUPA receiving the most attention from a metrology point of view, whereas HSDPA had certainly already made great strides in the previous year to become the latest hot topic. Just a few of the exhibitors in the mobile wireless sector, primarily the manufacturers of base stations and network elements, as well as the market leader in the field of metrology for R&D demonstrated their proposals and solutions for HSPA+ and 3GPP LTE. However, due to the fact that the status of Release 8 was still open, it came as no great surprise that this attracted less interest.

So why all this then? Why this advance in the theory and specifications if the practical side of things is "dragging its heels" by years? The answer to both of these questions demands a slightly deeper analysis of the technical situation and parameters making up the individual standards and supplements defined in the releases.

HSDPA today offers data rates up to 3.6 Mbit/s, and in time up to 7.2 Mbit/s should be possible in practise. This is solely dependent on the type of terminal used, as the receiver architecture used today (rake receiver) offers very little scope for fully exploiting the advantages of HSDPA. With HSUPA for the uplink, theoretical data rates of 5.76 Mbit/s are already specified, although the first terminals are currently capable of delivering no more than 1.4 Mbit/s. Nevertheless, the data rate offered by HSPA for both directions is higher by a factor of 10 than for today's most widely established UMTS/WCDMA. Among engineers a leap forward in technology is deemed to have taken place when a significant technical parameter of a system improves by a factor of 10.

It is now over six years ago since WCDMA first went "live" in the commercial sense in Japan. Despite this, in spring 2007 there were only around 105 million subscribers worldwide using a 3G-compatible terminal. Actually quite a sobering end result for the sometimes horrendous investment levels the network operators were required to make, not least in licence fees. The business models at the time (which are still valid today) were targeting the provision of many different types of streaming services – from a technical point of view it matters relatively little whether these are audio or video services. These types of services have a significant challenge to overcome: namely that of a continuous data stream. A well-known example is the Voice over IP (VoIP) service and the various implementation options, including "VoIP over cellular". An extreme application is to want to use VoIP via UMTS and in addition at a relatively high speed, for example in a car or in a train. In this case, unacceptably long delays occur, and clear communication is no longer possible. Here, WCDMA would be more than adequate for the 100 kbit/s required for VoIP. No, in this case it's another parameter that is the critical one; the latency time, also known as round trip time. This parameter specifies the time that elapses before the receiver station acknowledges the successful receipt of the data packet and the transmitter, whether terminal or base station, is able to reject this packet and view the transmission process as complete. Table 1 provides information on the latency times for the mobile wireless systems available today and their future enhancements. With the introduction of HSPA, the network operators promise a considerable reduction in latency by up to 60 ms. This is achieved on the one hand by reducing the frame length considerably. With HSDPA it is just 2 ms, as opposed to the 10 ms with UMTS, and for HSUPA either 10 ms as standard or even 2 ms. In addition, various processes are being introduced and supported, brought together as Hybrid Automatic Request (HARQ), and this can be used to acquire a data packet from multiple, unsuccessful transmissions. In addition, the execution of these functions by the Radio Network Controller (RNC) is shifted to the base station (Node B) to support the shorter frame length and these processes. UMTS is therefore optimised using HSPA for the transmission of data packets with regard to providing a continuous data flow. This all favours the real-time applications that have been discussed recently, such as online gaming (GoIP, Gaming over IP), as part of the IP Multimedia Subsystem (IMS). IMS is used in 3GPP to specify the ultimate merging of the internet and the cellular worlds. It will only be possible to offer such services as online gaming, however, when they can be implemented with the required quality levels from a technical point of view. What is required here are short latency times and no loss of information, and the standards implemented today are not capable of this.

System	Latency
GSM, (E)GRPS	up to 1000 ms
UMTS (Release 99/4)	~180 to 200 ms
HSDPA (Release 5)	~ 80 to 90 ms
HSUPA (Release 6)	~ 60 to 70 ms (anticipated)
HSPA+ (Release 7)	~ 40 ms (anticipated)
3GPP Long Term Evolution (LTE) (Release 8)	~ 20 ms (anticipated)

Table 1: Latency times in today's mobile wireless systems

However these already impressive values, achieved using HSPA for the latency, are to be reduced by some considerable measure once again with the help of HSPA+, also known as "Super3G". The use of Multiple Input Multiple Output (MIMO) should make this possible. Multiple transmitter and/or receiver aerials are used in this case (generally an aerial field). The stepped up frequency, time and code levels (FDMA/TDMA/CDMA) have another level added to them, the spatial level. The receiver signal can be improved using multiple receiver aerials, the channel capacity increases depending on the number of aerials used, and this means that the transmission rate can be increased significantly (spatial multiplexing). Naturally this also involves a reduction in the bit error rate. In the transmission direction, a beam forming characteristic can be generated, which improves the reception accordingly or which can be used to hide interference signals (spatial diversity). In general, MIMO can be used to greatly increase the spectral efficiency, in other words how many bits per second per Hz can be transferred, or depending on the bandwidth available. For further clarification, Table 2 shows the development of the systems, starting with the second generation of mobile wireless (GSM) to the current Release 8 (3GPP LTE) which is just about to be published.

System (DL only)	Access technology	Peak data rate (theoretical value) [Mbit/s]	Bandwidth used [MHz]	Spectral efficiency [bit/s/Hz]
GSM	FDMA/TDMA	0.0144 max.	0.2	0.17
EDGE	FDMA/TDMA	0.384 max.	0.2	0.33
UMTS	WCDMA	0.384 max.	5	0.077
HSDPA	WCDMA	14.4	5	2.88
HSPA+	WCDMA (MIMO)	~28	5	5.6
3GPP LTE	OFDMA	~100	20	10.0

Table 2: Spectral efficiency of different systems

New and old technologies for downlink and uplink

Table 2 illustrates an important point: the access technology changes with Release 8 and the introduction of 3GPP LTE! OFDMA is the magic word here. OFDMA stands for Orthogonal Frequency Division Multiple Access and is based on OFDM. This access process is used to counteract one of the most restrictive factors, which counteracts all wireless technologies, not just mobile wireless: the characteristic of the transmission channel. Generally speaking this is subject to the multipath propagation, this means it is not possible to predict at what frequency on the radio channel larger, linear distortions occur. In addition, the properties of this channel change in terms of time. Due to reflexion, absorption and diffraction, caused among other things by buildings, the symbols transmitted reach the receiver at different times. This results in interference known as intersymbol interference (ISI) in the receiver, among other things. This occurs when the runtime of the echoes exceeds the time interval between two transmitted symbols. With WCDMA this effect occurs in the context of the chip duration (260 ns) already. Highly susceptible to intersymbol interference are all input processes used in all modern mobile communication procedures. As early as the beginning of the 1950s, a process that counteracts this interference was developed and tested using OFDM. With OFDM – unlike with today's mobile communication system – the data is distributed onto multiple narrow-band carriers which are then modulated, combined and transmitted individually. These carriers are orthogonal to one another, in other words: independent from one another. At the maximum for a subcarrier (subchannel) all other subcarriers have a zero crossing.

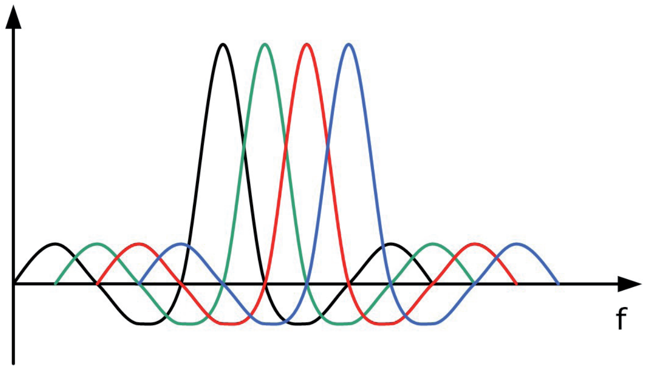


Figure 1: OFDM spectrum

OFDM can be used to reduce ISI to a minimum and at the same time achieve a high data throughput. With Release 8, OFDM will also be introduced into mobile wireless, and here it is already being used for WLAN and for the mobile TV standards T-DMB and DVB-H . The advantages and disadvantages of OFDM for applications in wireless systems are summarised in Table 3.

Advantages	Disadvantages
• High spectral efficiency • With sufficient dimensioning: no occurrence of ISI (simple channel equaliser in the receiver) • Significant degree of robustness in comparison to the Doppler effect	• Precise time and frequency synchronisation essential for correct operation • High crest factor (highest possible requirements for performance amplifier)

Table 3: Advantages and disadvantages of OFDM

What are the special features of OFDMA? OFDMA offers, like traditional OFDM, a scalable number of subcarriers ranging from 128, 512, 1024 to 2048 but can be assigned to not one, but to multiple subscribers. Here the subcarriers assigned to a user have no fixed position in the frequency band (bandwidth), but the position changes with each symbol. This "Frequency Hopping" makes the entire transmission stable in relation to multipath propagation and other interference. In the literature, HSOPA is also often referred to in the context of 3GPP LTE, where the O stands for OFDMA as the access technology used. Why this distinction? With 3GPP LTE a different access technology is used in the uplink. Even if the specification is on the verge of being completed, analysts estimate that it will only be feasible to use the technology in the year 2011 at the earliest. With the uplink for LTE, single carrier FDMA (SC-FDMA) are to be used, which is comparable to OFDMA in terms of the technology. However, whereas there is only one signal in the downlink, which is used to supply all subscribers, there are many individual signals in the uplink. This results in an increase in the noise in the receiver. As shown in Table 3, a disadvantage in the use of OFDM(A) is the high crest factor, in other words the peak-to-average ratio (PAR, see Figure 2).

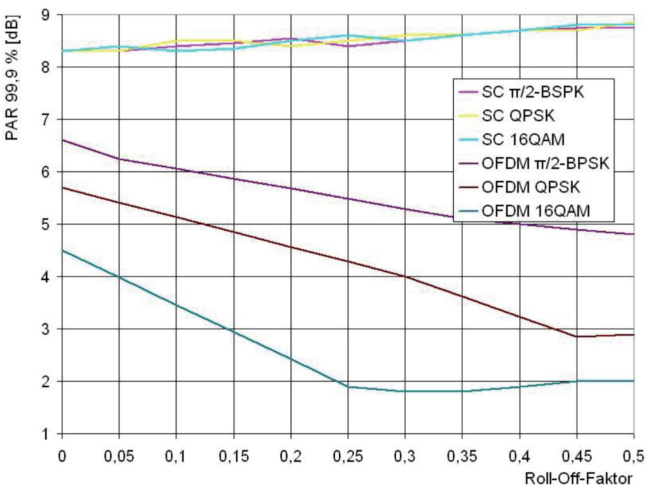


Figure 2: Peak-to-average ratio (crest factor) for OFDM and SC-FDMA using different roll-off factors (filters)

As shown in the graphic, OFDM has a high, really constant crest factor of more than 8 dB (upper line field) for every modulation type and regardless of the filter used. With SC-FDMA this is dependent on the modulation form and reduces with increasing steepness of the filter. With WCDMA or HSDPA, a root-raised cosine filter (RRC filter) with a roll-off factor of 0.22 is used. The use of OFDM(A) would also mean that the noise in the uplink increases again, which is of course not something to be desired. To minimise this effect, very linear output amplifiers would be required, which would however have a negative effect on the battery performance. SC-FDMA also offers the advantage that less output is required (saves the battery). The use of SC-FDMA in the uplink and the use of MIMO (two aerials) permit a theoretical data rate of 50 Mbit/s. The modulation types QPSK and 16QAM are used to achieve this.

Still no 4G?

Back to those names we mentioned at the start. We have noticed that HSPA is known as 3.5G of mobile wireless, for HSPA+ the designation "Super3G" is used, and which in many places is still expanded to 3GPP LTE. It is then possible to refer to 3.75G for HSPA+, the "EDGE of the UMTS" so to speak. To use a rule of thumb that technological advances are based on improving a significant system parameter by a factor of 10, this evaluation does not apply to 3GPP LTE as neither the bandwidth used changes by a factor of 10, nor does the data rate increase by this factor. With many experts, 3GPP LTE is therefore classified as 3.9G, also in regard to the considerations below. This is because what the conceptualists and developers promise with the fourth generation of mobile wireless puts even the values already determined for 3GPP LTE very much in the shade: The data rates in the downlink are increased to up to 1 Gbit/s; in the uplink the talk is of up to 60 Mbit/s.

In overall charge of the development of 4G is NTT DoCoMo once again, the leading Japanese network operator. This company was the world's first operator to put a commercially available WCDMA network (FOMA) into commercial operation. Based on 3GPP LTE, 4G will also use two different technologies for the downlink and uplink. The DoCoMo development labs favour technologies based on 3GPP LTE here. Nevertheless, even higher bandwidths are required for this than are currently available today. This unavoidably results in the call for a new frequency range to be introduced. Even the bandwidth of 20 MHz required for LTE requires a re-distribution of the frequency spectrum, as has already taken place in Europe with the allocation of the additional frequency blocks between 2.5 and 2.7 GHz for mobile wireless. For 4G, carrier frequencies of between 3 and 6 GHz are being favoured; and not just by NTT DoCoMo.

The technology in the uplink this is a known technology, but one which is more developed. Instead of a single carrier, NTT DoCoMo is backing MC/DS-CDMA (Multicarrier Direct Sequence CDMA). Here the uplink signal is distributed across two carriers with a bandwidth of 20 MHz each. The chip rate intended for this purpose is 16.384 Mcps per carrier. With UMTS and the follow-on technologies, this is still 3.84 Mcps. This corresponds to not only a quadrupling of the chip rate per carrier, but also an eight-fold increase in the current bandwidth used with UMTS or with HSPA. Similarly the length of a time frame has been reduced. Whereas with WCDMA this is 10 ms for uplink and downlink, the frame length with the NTT DoCoMo proposal for 4G is just 500 µs. As a comparison: an individual GSM time slot occupies 577 µs. As the modulation process there are three alternatives to choose from, as for LTE: QPSK already used for WCDMA, 16QAM introduced with HSDPA and the entirely new 64QAM. With 64QAM, 6 bits are transmitted per symbol. This of course narrows down the choices, and requires more sensitive receivers and optimum conditions on the radio channel. With a bit error rate (BER) of 10^{-3} required, for example, the use of 64QAM already demands a signal-to-noise ratio (SNR) of more than 22 dB.

According to initial observations, QPSK (2 bits per symbol), two carriers, a chip rate of 16.384 Mcps, the 0.5 ms frame length and a coding rate of 3:4 can achieve a maximum data rate of 24.576 Mbps for the uplink. To do this, both carriers are spread by a factor of 4. Table 4 offers a summary of the parameters for the uplink.

Parameter	Description
Access technology	MC/DS-CDMA
Carrier frequency	4.900 GHz
Bandwidth	40 MHz
Subcarriers	2 (2 x 20 MHz, roll-off factor = 0.22)
Chip rate per carrier	16.384 Mcps
Frame length	0.5 ms, 8192 chips per carrier
Modulation	QPSK, 16QAM, 64QAM
Code rate	1:3 – 5:6, 1:16
Spreading factor	4 – 16

Table 4: Uplink parameters for 4G (NTT-DoCoMo proposal)

For the downlink these figures are topped once more – in this case the bandwidth demanded is 101.5 MHz. As with the 3GPP LTE, too, OFDM is to be used here, albeit in a slightly modified form. All of this is known under the acronym VSF-OFCDM – Variable Spreading Factor Orthogonal Frequency and Code Division Multiplexing.

Parameter	Description
Access technology	VSF-OFCDM
Carrier frequency	4.635 GHz
Bandwidth	101.5 MHz
Subcarriers	768 (131.836 kHz carrier spacing)
OFDCM symbol duration	9.259 µs (incl. 1.674 µs safety spacing)
Frame length	54 OFCDM symbols (= 0.5 ms)
Modulation	QPSK, 16QAM, 64QAM
Code rate	1:3 – 5:6
Spreading factor	Max. 128 (time domain: max. 16)

Table 5: Downlink parameters for 4G (NTT-DoCoMo proposal)

The "place of use" determines the combination of parameters summarised in Table 5 here. In what are known as "hotspot areas“ (isolated-cell environment), no spreading is required at all (SF = 1) and only OFDM is used, as well as all subcarriers being assigned to one user. A mobile wireless system is designed as a cellular system, however, and depending on the system these cells are also organised in clusters, as with GSM, for example. In this case the carrier frequencies are only permitted to be re-used at specific intervals. This is necessary to avoid interference between the individual carrier signals. As the 4G proposal is an OFDM system with TDMA/CDMA features, however, the same frequency can be re-used in each cell. How does the data preparation work for the downlink in what is known as the "multi-cell environment" though, and in general applications?

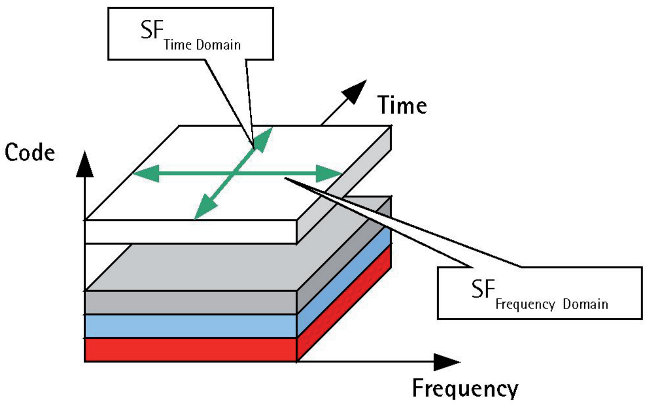


Figure 3: VSF-OFCDM principle

VSF-OFCDM relies on two-dimensional spreading, in other words in the frequency and time domains. The digitised data organised into packets is channel-coded using coding rate R, which means it is modified to the current dominant propagation conditions of the transmission channel. These symbols are then spread and scrambled. Walsh-Hadamard codes are used as spreading codes, as with known mobile wireless systems (e.g. CDMA2000, WCDMA), and the scrambling codes are also PN sequences which, however, are matched specifically to the number of subcarriers (768). The inverse fourier transformation (IFFT) is used to generate the OFCDM symbols, according to which the OFDM frame then consists of 48 data symbols and 2+4 pilot symbols. With a symbol duration of 9.259 µs, the timeframe then reaches the length mentioned earlier of 0.5 ms (see Figure 4). This means that as before there will be dedicated code channels once again in the downlink, which are assigned to a terminal in the cell.

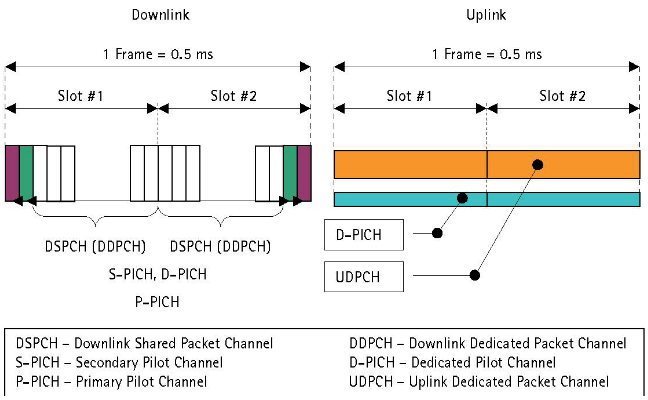


Figure 4: Frame structure for the uplink and downlink

On the receiver side, the autocorrelation function is used to determine the symbol duration and the duration of the guard interval for each individual OFCDM symbol and averaged via 54 OFCDM symbols. Synchronisation is reached at the maximum of the correlation and the guard interval can be eliminated. The symbols are then converted back using fast fourier transformation (FFT), descrambled and despread. The symbols are then converted in parallel-serial and decoded. Using lab simulations and tests in practise (pilot network in Yokosuka south of Tokyo), a peak data rate of 2 Gbit/s was realised in December 2005, with the receiver moving at around 20 km/h. To do this, the engineers used an aerial range of a size of 6x6 and used 64QAM to transmit the data. This meant that the spectral efficiency rose to 25 bit/s/Hz, which with a bandwidth of around 100 MHz makes 2.5 Gbit/s. In practise, the goal is to achieve average data rates of over 300 Mbit/s for the downlink, independently of the existing signal-to-noise ratio and the resultant system parameters determined.

Effects on metrology

What is required initially is to attend to the relevant frequency range, whether for the base station test or for the terminals. In the NTT-DoCoMo proposal, frequencies between 4 and 5 GHz are cited; and in a very general sense, the assumption is for carrier frequencies between 3 and 6 GHz. A significant role will be played by the bandwidth of more than 100 MHz for the downlink and still 2x20 MHz for the uplink. Performance measurements on such wide-band signals can currently only be created with exceptional difficulty and at high cost. In addition, it remains to be seen whether this will operate as a standalone technology or standard, or whether a fallback standard is used, such as GSM with WCDMA. At present it is assumed that this will most likely be used in hotspot areas. What happens to an existing connection when the user leaves this area? All these questions remain open, of course, and still require clarification. With today's third generation mobile terminals as well as with HSDPA, measurements are conducted under special conditions. The designations Reference Measurement Channel or Fixed Reference Channel are familiar terms for the experts. These channels simulate different scenarios (e.g. data rates) and/or at the same time characterise different terminal categories. In addition, they restrict the variable and flexible system parameters and deliver a defined measurement signal, such as that required to assess a terminal. The uplink is gauged when testing the terminal. The measurement device transmits these defined measurement channels on the downlink, the test sample must respond with the relevant uplink complement and the difference between the ideal and recorded signal analysed. As the uplink signal is a similar CDMA signal to today's 3G systems, the assumption that fixed measurement channels will be utilised to analyse the behaviour of the mobile terminal is entirely feasible. Similarly, the terminal category will also play a role. For testing on the base stations, the familiar measurement methods for OFDM signals (output measurement, EVM measurements, etc.) are safely used in modified form.

Summary

4G is already having far-reaching implications, even though the expectations are that the technology will not be introduced onto the networks before 2011. To do this, the exact definition and specification is required, as is currently being completed for 3GPP LTE. The latest opinions are that integration into terminals will be reserved for those terminals which have a sufficiently high battery life, such as notebooks. If battery technology should continue to make the same progress as in the last few years, this technology could also make an appearance in mobile terminals such as telephones and PDAs. Nevertheless, according to insights from NTT DoCoMo, the system will be market-ready in 2010/2011 – an ambitious plan. If you look at history and use 3G as an example, it is entirely realistic to tack on another one or two years to those dates. In addition to the Japanese network operator, other companies are also researching the basic principles for 4G. For example, Motorola in Chicago has constructed a test network and used it to carry out testing. Significant system parameters such as bandwidth or carrier frequency were at 20 MHz and 3.6 GHz in this case. The decisive trend in the direction of higher frequencies and more bandwidth is confirmed for 4G. In addition to these heavyweights, other companies have also joined forces in industrial alliances and forums, to follow their interests in relation to 4G together.

However, it remains to be seen whether the advantages and enormous data rates will make it worthwhile for the network operators to integrate and convert their existing networks. For HSDPA, "all" that would be required is a change in the Radio Access Network. Similarly the fourth generation will not stop at the core network, either: 4G will be based on the IPv6 protocol!

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