LTE

Project

EE-424

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Table of Contents

1 Introduction

In a world of fast changing technology, there is a rising requirement for people to communicate and get connected with each other and have appropriate and timely access to information regardless of the location of the each individuals or the information. The increasing demands and requirements for wireless communication systems ubiquity have led to the need for a better understanding of fundamental issues in communication theory and electromagnetic and their implications for the design of highly-capable wireless systems.

1.1 First Generation

With the invention of microprocessors and the cellular communications concept in the 1970s and 1980s, the first generation (1G) mobile communication systems were born. First generation systems use semi cellular coverage, where the coverage area is divided into small cell areas. The 1G systems were essentially analog systems using Frequency Division Multiple Access (FDMA) to communicate and were designed for voice transmission only (no data). NMT (Nordic Mobile Telephone), AMPS (Advanced Mobile Phone Service), TACS (Total Access Communication System), ETACS (Extended Total Access Communication System), JDC (Japan Digital Cellular) etc., were among first generation systems [1]. NMT was the first analogue cellular phone system that started operating in Scandinavia in 1979. In the beginning, it used the 450MHz band and therefore was named NMT 450. Later it used the 900MHz band because of the need for more capacity and was called NMT 900. An AMP was introduced in 1978 by the Bell telephone company in the USA and started operation in 1983 in Chicago. TACS was introduced in UK in 1982. ETACS was the extended version of TACS and was deployed in 1985. The cellular systems called C-450 (operated in the 450 MHz band) and Radicom 2000 (operated in the 200 MHz band) were also introduced in Germany and in France respectively in 1985. These systems had numerous problems such as capacity limitations regarding number of subscribers, big size and heavy mobile stations, incompatibilities across geographies (USA, Japan and Europe), only nationwide coverage, no open interfaces except the radio interface, low speech quality and no security in speech transmission. The major first generation analogue cellular radio system standards are compared in Table 1-1.

Table 1-1 Major analogue cellular system standards.

specification	AMPS	TACS	NMT450	NMT900
Channels	823	1320	180	1000/2000
TX frequency	824-849	872-905	453-457.5	872-905
Channel separation	30KHz	25KHz	25/30KHz	25kHz
Tx power	3 watts	2.8watts	15watts	3watts
Data deviation	5kHz	6.4kHz	3.5kHz	3.5kHz
Receiver sensitivity	-116dBm	-113dBm	-113dBm	-113dBm
Adjacent channel selectivity	60dB	55dB	70dB	70dB
Signaling method	Manchester	Manchester	FFSK	FFSK
Speed	10kbps	8kbps	1.2kbps	1.2kbps
Duplexing method	FDD	FDD	FDD	FDD

1.2 Second Generation

Second generation systems started to appear across the world in the early 1990s. Advances in integrated circuit technology brought digital transmission to mobile communications. Second generation systems are based on digital technology and offer data speed up to 9.6kb/s and use TDMA or CDMA access methods in combination with FDMA. Second generation systems are capable of providing voice, data, fax transfer as well as other services. 2G systems can be categorized as 2G cellular mobile systems and 2G Personal Communication Systems (PCSs). GSM, US-TDMA (IS-136), CDMAOne (IS-95) and PDC are included in second generation cellular systems. The four most popular 2G cellular radio standards are listed in Table 1-2. D-AMPS (Digital-Advanced Mobile Phone Services) is a digital version of AMPS. D-AMPS is also known as US-TDMA/IS-136. IS-54 (US Digital Cellular) service is an old version of the IS-136. GSM was originally designed to operate in the 900MHz band but was later adapted to operate in 1800MHz and 1900MHz bands. The GSM 450 (operate at 450MHz band) may start to operate in some countries to replace old analogue networks. Currently the maximum data rate for GSM is 14.4kbps. IS-95 is based on narrowband spread spectrum technology and uses 1.25MHz channel bandwidth. Therefore it offers increased capacity, wider bandwidth and is very flexible because it uses CDMA access method. IS-95 and IS-136 are capable of operating in the same band as AMPS and specified to be dual-mode systems. 2G systems compared with 1G systems allow more efficient use of the radio spectrum since they can handle more calls than analogue FDMA technology [2] and [3].

Table 2-2 Second generation digital cellular standards summary.

specification	GSM	IS-54	PDC	IS-95
Year of introduction	1990	1991	1993	1993
Frequency MHz	890-915 (R) 935-960 (F)	824-849 (R) 869-894 (F)	810-830 (R) 940-960 (F)	829-849 (R) 940-960 (F)
Multiple Access	TDMA/FDMA/FDD	TDMA/FDMA/FDD	TDMA/FDMA/FDD	CDMA
Modulation	GMSK (TB=0.3)	π/4 DQPSK	π/4 DQPSK	QPSK OQPSK
Carrier separation	200kHz	30kHz	25kHz	1.25MHz
Channel Data Rate	1270.833kbps	48.6kbps	42kbps	19.2kbps
Number of voice channels	1000	2500	3000	4000
Spectrum efficiency	1.35kbps/Hz	1.62kbps/Hz	1.68kbps/Hz	2.58kbps/Hz
Channel coding	CRC with R=1/2; L=5 Conv.	7 bit CRC with r=112: L=6 Conv.	CRC with Cony	NA
Equalizers	Adaptive	Adaptive	Adaptive	Adaptive
Portable Tx. Power max./avg.	1W/125mW	600mW/200mW	125mW	200mW
Duplexing method	FDD	FDD	FDD	FDD

1.3 2.5Generation

2.5 generation systems address the data capacity limitations associated with the 2nd generation systems. Even though the boundary between 2G systems and 2.5G systems is somewhat unclear, 2.5G systems provide clear upgrades to the 2G systems that almost make it possible to provide similar capabilities as 3G systems. A number of technologies are commonly used to provide these capabilities such as High Speed Circuit Switched Data (HSCSD), Enhanced Data rates for Global Evolution (EDGE) and General Purpose Radio Services (GPRS). Using GPRS, data rates up to 115kbps with error correction are possible using approximately eight time slots. This technology is based on packet switching and thus makes efficient use of the available bandwidth using variable bit rates. It is also suitable for services that use bursty data due to its ability to dynamically allocate resources.

EDGE is an improvement over GSM which increases the traditional GSM data rates over 300%. It uses eight phase shift keying (8 PSK) method for modulation. This is an attractive solution for existing GSM networks as the change required is only a software upgrade. Due to its ability to co-exist with the Gaussian minimum shift keying modulation, it allows users to continue using their current handsets. IS-136 also can be upgraded using EDGE [4].

1.4 Third Generation

Third generation systems opened the way for a completely new era of wireless services that enabled access across multiple geographies. 3G systems provide a platform that is common for multiple wireless standards and technologies. They are aimed to carry data up to 2Mb/s, about 200 times faster than the 2G systems in indoor environment and a minimum of 144kbits/s in other environments. Because of the high-speed data rate, 3G systems will be able to support services such as audio, video, multimedia, internet, data and speech [4].

The goal of 3G technologies is to create a single global standard that allows for global roaming. The International Telecommunication Union (ITU) and the United Nations organization responsible for global telecommunications began its studies on global personal telecommunications in 1986. The ITU World Administrative Radio Conference in 1992

(WARC-92) identified 230MHz, in the 2GHz band, on a world wide basis for the satellite and terrestrial components of Future Public Land Mobile Telecommunication Systems (FPLMTS). Later it was renamed as IMT-2000. WRC-2000 (World Radio Conference in 2000) identified three additional bands i.e. 806-960MHz, 1710-1885MHz and 2500-2690MHz for terrestrial IMT-2000.

The European Telecommunications Standards Institute (ETSI) regards 3G systems as UMTS. In 1998 the first decision in the standardization process of UMTS was made by ETSI [4]. ETSI chose the W-CDMA concept to be adopted in the spectrum (for uplink one band of spectrum and for down link another band of spectrum, - FDD duplex mode) of UMTS. The Telecommunications Industry Association (TIA) in United States proposed CDMA2000 [5]. The major difference between W-CDMA and CDMA2000 is that W-CDMA is backward compatible with GSM networks and CDMA2000 is backward compatible with IS-95 networks. Due to the different technologies used in different regions in the world, a family of compatible standards was adopted under IMT-2000 umbrella. WCDMA (UTRA FDD) technical summary is shown in Table 1-3 and CDMA2000 technical summary is shown in Table 1-4.

Table 1-3 W-CDMA (UMTS) technical summary [4].

Frequency band	1920MHz-1980MHz and 2110MHz-2170MHz (FDD) UL & DL
Min. frequency band required	2*5MHz
Frequency reuse	1
Carrier spacing	(4.4-5.2) MHz
Max. number of channels (voice) on 2*5MHz	≈196(spreading factor 256 UL , AMR 7.95kbps)/ ≈98(spreading factor 128 UL,AMR 12.2kbps)
Voice coding	AMR codecs (4.75kHz – 12.2kHz , GSM EFR =12.2kHz)& SID(1.8kHz)
Channel Coding	Convolutional coding, Turbo code for high rate data Dublexer needed (190kHzseparation), Asymmetric connection supported
Receiver	Rake
Receiver sensitivity	Node-B: -121dBm, Mobile -117dBm at BER of 10e -3
Data type	Packet and circuit switch
Modulation	QPSK
Pulse shaping	Root raised cosine ,roll-off=0.22
Chip rate	3.84Mcps
Channel raster	200kHz
Max. user data rate (physical channel)	≈2.3Mbps (spreading factor 4,parallel codes (3 DL/ 6UL), 1/2 rate coding) but interference limited
Max. user data rate	384 kbps , higher rates ≈2Mbps , HSPDA offer data speeds up to 8-10Mbps and 20Mbps using MIMO systems
Channel bit rate	5.76Mbps
Frame length	10ms (38400 chips)
Number of slots / frame	15
Number of chip / slot	2560 chips
Power control range	UL 80dB, DL 30dB
Mobile peak power	Power class 1: +33dBm (+1dB/-3dB) class2: +27dBm, class3 : +24dBm , class4: +21dBm
Number of unique base station identification	512/frequency

Table 1-4 CDMA2000 technical summary [5].

Min. frequency band required	1x: 2x1.25MHz, 3x: 2x3.75
Chip rate	1x: 1.2288, 3x: 3.6864Mcps
Max. user data rate	1x: 144kbps now, 307kbps in the future 1xEV-DO: max 384kbps -2.4Mbps, 1xEV-DV: 4.8Mbps.
Frame length	5ms, 10ms or 20ms
Power control rate	800Hz
Spreading Factor	4 … 256 UL

1.5 Beyond 3G

In continuous development of mobile environments, the major service providers in the wireless market kept on monitoring the growths of 4th generation (4G) mobile technology. 2G and 3G are well-established as the mainstream mobile technology around the world. 3G is stumbling to obtain market share for a different reasons and 4G is achieving some confidence.

The first step in the evolution of UMTS radio access is the introduction of High Speed Downlink Packet Access (HSDPA) in Release 5 of the UMTS specifications. Although packet-data communication is supported already in the first release of the UMTS standard, HSDPA brings further enhancements to the provisioning of packet-data services in UMTS, both in terms of system and end-user performance. The downlink packet-data enhancements of HSDPA are complemented by Enhanced Uplink, introduced in Release 6 of the 3GPP UMTS specifications. HSDPA and Enhanced Uplink are often jointly referred to as High-Speed Packet Access (HSPA).

The important requirements for cellular systems providing packet-data services are high data rates and low delays while, as at the same time, maintaining good coverage and providing high capacity. To achieve this, HSPA introduces several of the basic techniques, such as higher order modulation, fast (channel-dependent) scheduling and rate control, and fast hybrid ARQ with soft combining. Altogether, HSPA provides downlink and uplink data rates up to approximately 14 and 5.7 Mbps, respectively, and significantly reduced round trip times and improved capacity, compared to Release 99 [4]. The evolution of the UMTS radio access continues and will continue also in the future. For example, 3GPP Release 7 introduces several new features. MIMO is a tool to further improve capacity and especially the HSPA peak data rates. Continuous Packet Connectivity aims at providing an ‘always-on’ service perception terminals.

1.6 LTE

Although HSPA is good system and 3GPP will continue developing it, 3GPP will not stick with it alone. HSPA is based on CDMA which has limitation in some requirements. Most notable are the requirements on high data rate at the cell edge and spectrum flexibility. The most disadvantage of CDMA is the Cell Berthing where the coverage of the cell shrink when it become loaded as shown in figure 1.1 where the signal level > -10 dB decrease strongly when the number of users increased from 10 to 20 [6]. This figure is form planning tool used in CDMA networks design. The second problem of CDMA is the spectrum requirements. For example UMTS needs 5 MHz bandwidth and the not easy to allocate usually.

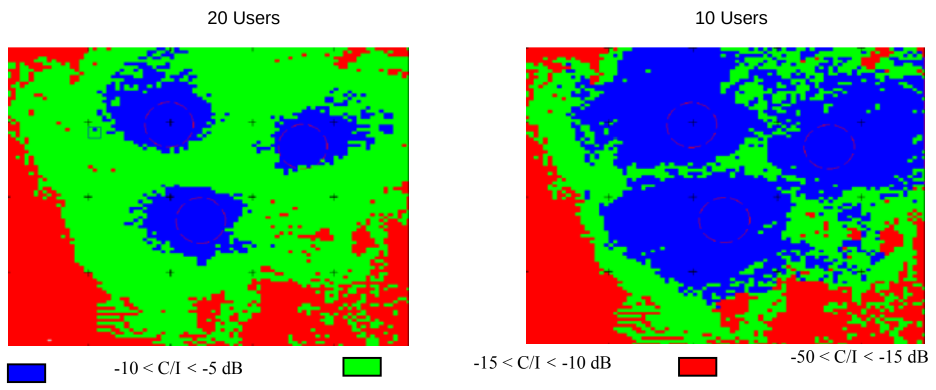

Figure 1.1. Cell Birthing of CDMA.

During the fall 2005, 3GPP made extensive studies of different basic physical layer technologies and in December the 3GPP plenary decided that the Long Term Evolution (LTE) radio access should be based on OFDM in the downlink and single carrier FDMA in the uplink.

Recently, a worldwide convergence has occurred for the use of Orthogonal Division Frequency Multiplexing (OFDM) as an emerging technology for high data rates. The wireless local network systems such as WiMAX, WiBro, WiFi etc., and the emerging 3.9G mobile systems are all OFDM based systems. OFDM is a digital multi-carrier modulation scheme, which uses a large number of closely-spaced orthogonal sub-carriers that is particularly suitable for multipath fading channels and high data rates. This technique transforms a frequency selective wide-band channel into a group of non-selective narrow-band channels, which makes its robust against large delay spreads by preserving orthogonality in the frequency domain. Moreover, the introduction of a so-called cyclic prefix at the transmitter reduces the complexity at receiver to FFT processing and overcome the fading.

2. OFDM

Orthogonal Frequency Division Multiplexing (OFDM) has become an attractive technique and gained more popularity recently. Many new communication systems have selected OFDM because its good properties, e.g. tolerance to inter-symbol interference (ISI) and good spectral efficiency. Although the idea of OFDM was developed in the 60's, the major boost for OFDM was the lowered prices for integrated circuits and the possibility to use fast Fourier transform. At the moment OFDM is used in wireline and wireless communications. Systems such as ADSL, Power Line Communications, WiMAX, wireless LANs, digital radio and digital television are using OFDM. In this chapter some insight is given to the basic operation and to the theory of OFDM [7].

2.1 OFDM Features

Orthogonal Frequency Division Multiplexing (OFDM) is technique based on multi carrier modulation (MCM) and frequency division multiplexing (FDM). OFDM can be considered as a modulation or multiplexing method. The basic idea behind multi carrier modulation is to divide the signal bandwidth into parallel subcarriers or narrow strips of bandwidth. Unlike traditional MCM system, where subcarriers are non-overlapping, OFDM uses subcarriers that are mathematically orthogonal; information can be sent on parallel overlapping subcarriers, from which information can be extracted individually. These properties help to reduce interference caused by neighboring carriers and makes OFDM based systems more spectrally efficient as shown in Figure 2.1.

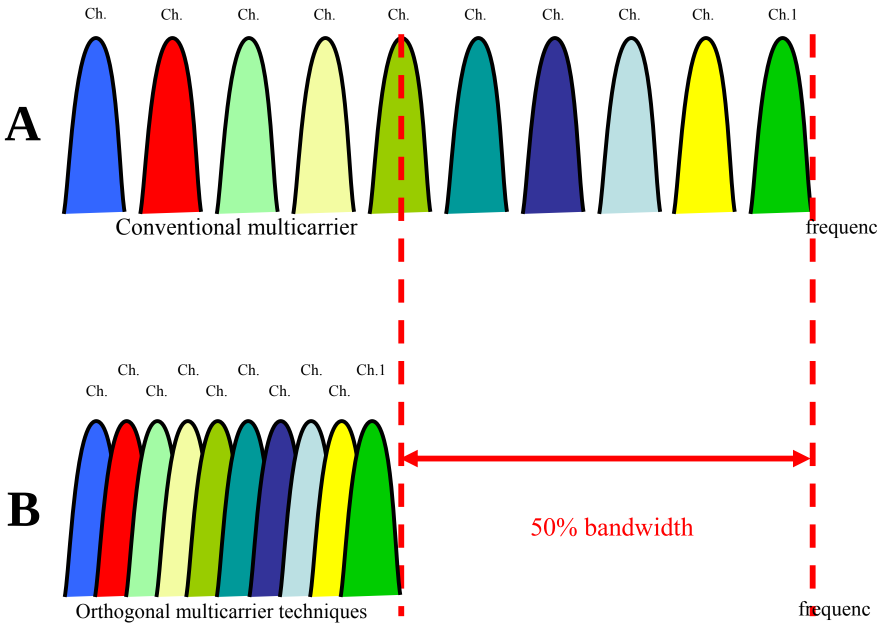

Figure 2.1. The spectrum of traditional FDM and OFDM

Dividing channel into smaller subchannels helps OFDM to combat against frequency selective fading. Narrow subchannel bandwidths leads to each subchannel to experience flat fading channel in the transmission medium. Other advantages of OFDM based systems are the simplicity of implementation, robustness to channel impairments and narrowband interference. It allows the use of advanced antenna techniques.

2.2 OFDM Implementation

Figure 2.2 shows the OFDM system where the OFDM symbol is created in the digital domain before transmission. Serial data is first mapped using common methods e.g. BPSK or 16-QAM. This data stream is converted into N parallel streams, which are to be converted into an OFDM symbol. An OFDM symbol generated by an N subcarrier OFDM system, or the discrete-time representation of the signal after IFFT is:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k).e^{j2\pi k \frac{n}{N}}, \qquad n = 0..N-1 \tag{1}$$

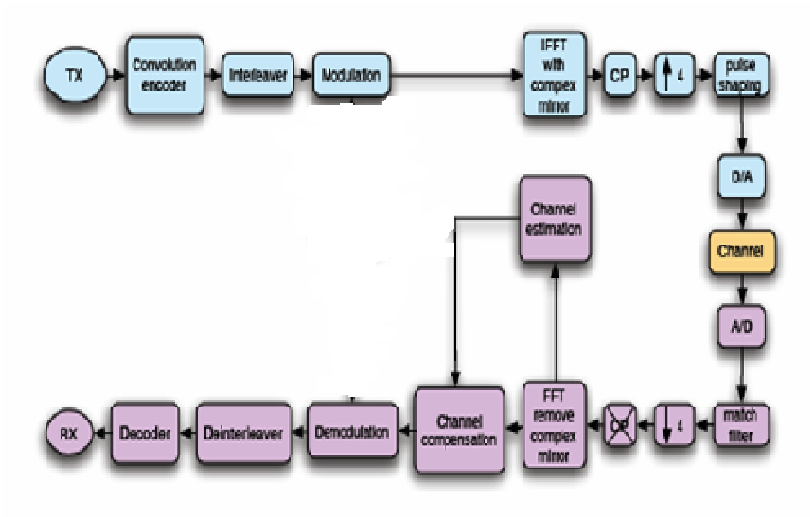

Figure 2.2. OFDM System.

Spacing of subcarriers and frequencies are carefully selected to achieve subcarrier orthogonality. Orthogonality by definition means, that the average value over time T of multiplication of two signals is zero.

$$\frac{1}{T}\int_{T} x(t)\,y(t)\,dt = 0 \qquad (2)$$

Equation (2) means that the signals are uncorrelated i.e. they are two different and independent signals. In OFDM, Sinc -shaped pulses are used as subcarrier spectra. According the properties of sinc-pulses, zero crossings are located at the multiples of 1/T as shown in figure 2.3. The use of sinc-pulses and subcarrier center frequency f_i selection with equation (3), subcarrier orthogonality is maintained.

$$f_i = f_c + \frac{i}{T} \quad i = \frac{-N}{2} \ldots \frac{N}{2} \qquad (3)$$

Where f_c is the channel center frequency and N is the number of subchannels. This way each subcarrier has the maximum at its own center frequency and zero at the center frequency of the other subcarrier as shown in 2.3.

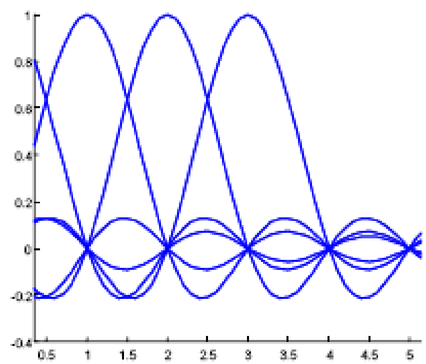

Figure 2.3. Basis functions in OFDM system

After serial-to-parallel conversion, inverse discrete Fourier Transform (IDFT) is applied to each stream. In practice, this transform can be implemented very efficiently by the inverse fast Fourier Transform (IFFT). This equals transition from frequency-domain to time-domain. After IFFT, all parallel data is summed and transmitted.

2.3 OFDM and Frequency Selective Fading Channel

One of the most important features in OFDM system is the division of the frequency selective channel into smaller subchannels. These subchannels can be considered to be equal to coherence bandwidth, in which the channel is behaving like flat fading channel, if the system has been correctly designed. Whole OFDM symbol experiences frequency selective fading channel and the subcarrier signals flat fading channel as shown in Figure 2.4.

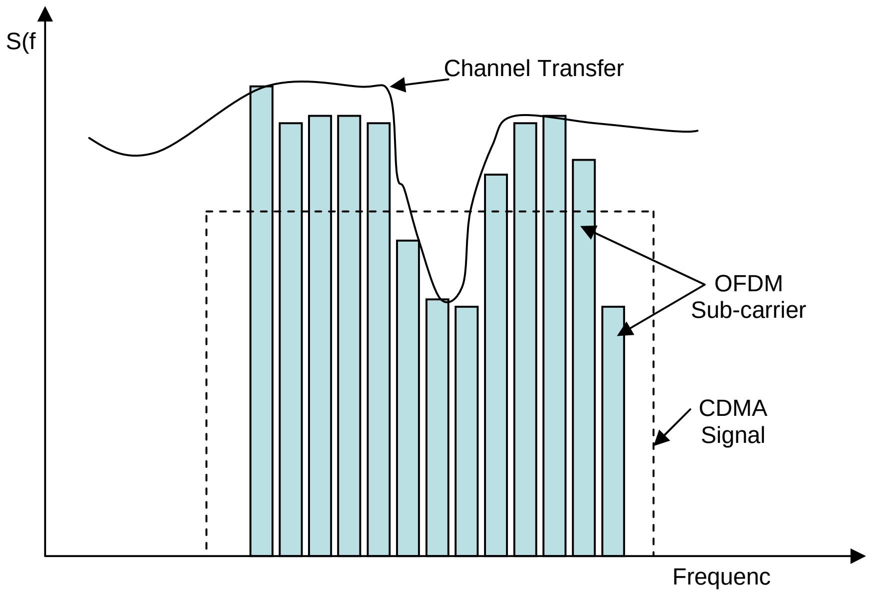

Figure 2.4. Flat fading

The channel impulse response or the coherence bandwidth of the channel is proportional to the inverse of the delay spread, Bm = 1/Tm, and is a measure of frequency selectivity of the channel as shown in figure 2.5. When the coherence bandwidth is larger than the symbol bandwidth, channel is flat fading. Frequency selective fading occurs when the symbol bandwidth is larger than coherence bandwidth.

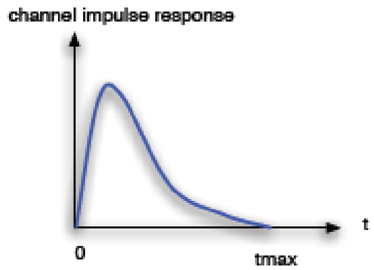

Figure 2.5. Channel impulse response

Delayed copies of the symbol cause intersymbol interference (ISI). ISI causes errors to the received symbol sequence and requires some form of error detection or correction. With out possibility to correct the received symbol, re-transmission is required to achieve reliable transmission. Moving scatterers, transmitter or receiver cause Doppler shift. In OFDM, Doppler shift causes subcarriers to shift on adjacent subcarrier. This phenomenon is called intercarrier interference (ICI). ICI is ‘crosstalk’ between different subcarriers, which means that they are no longer orthogonal. E.g. scatterers moving 120 km/h causes 250 Hz Doppler shift. As subchannel bandwidths are 312,5 kHz, Doppler-shift has no significant meaning.

Conversion from fast serial data stream into N slower parallel data streams enables possibility to use longer symbol periods. Longer transmission times allow more delay spread than shorter symbol durations. This property makes OFDM suitable for difficult multipath environments, because longer symbol times make OFDM robust against ISI. Even though OFDM is very resilient to ISI, it is very susceptible to frequency offsets and phase noise. Minor variations in frequencies yield directly to loss of orthogonality.

2.4 Cyclic Prefix in OFDM

To combat intersymbol interference a guard time is inserted between consecutive OFDM symbols. The guard time allows multipath components to fade away before the information is extracted from the next symbol. Guard time is set to be larger than the delay spread. This way ISI caused by multipath propagation is almost completely removed. As long as the delay spread is smaller than the guard time, there is no limitation in multipath component signal levels. This still leaves interference introduced by copies of the same signal.

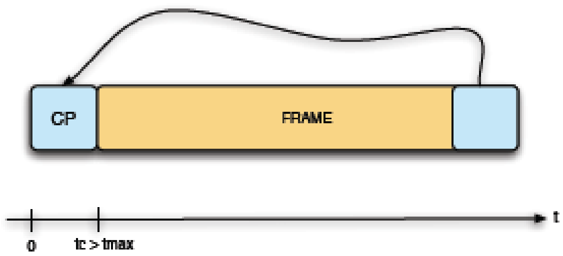

Figure 2.6. Cyclic Prefix implementation.

The guard time is usually implemented with a Cyclic Prefix (CP) of the symbol. Part of the signal end is copied and placed in the front of the signal as shown in figure 2.6. This effectively extends signal period and still maintains orthogonality of the waveform. Because signal waveform in CP is a cyclic extension of the signal, every multipath component has an integer number of cycles in fast Fourier Transform (FFT) integration time. FFT integration time is the same as symbol time. This yields to same phase sine waves to sum up to a sine wave. If delay spread exceeds CP, orthogonality is lost and phase transitions cause interference.

In an OFDM system, the channel has a finite impulse response. We note t_{max} the maximum delay of all reflected paths of the OFDM transmitted signal, see Figure 2.5. Cyclic prefix is a crucial feature of OFDM to combat the effect of multipath as shown in figure 2.7. Inter symbol interference (ISI) and inter channel interference (ICI) are avoided by introducing a CP at the front, which, specifically, is chosen to be a replica of the back of OFDM time domain waveform.

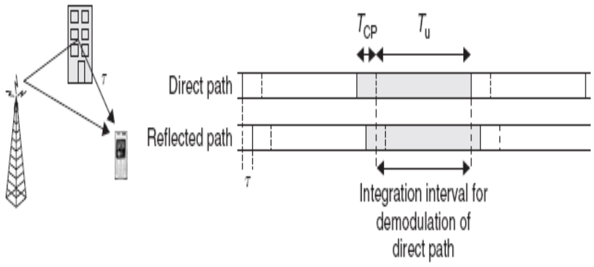

Figure 2.7. Using CP to overcome multipath.

3 LTE

LTE's study phase began in late 2004. The overall goal was to select technology that would keep 3GPP's (UMTS) at the forefront of mobile wireless well into the next decade. Key project objectives were set in the following areas: peak data throughput, spectral efficiency, flexible channel bandwidths, latency, device complexity, and overall system cost. The main decision was whether to pursue the objectives by continuing to evolve the existing W-CDMA air interface (which incorporates HSPA) or adopt a new air interface based on OFDM. At the conclusion of the study phase, 3GPP decided that the project objectives could not be entirely met by evolving HSPA. As a result, the LTE evolved radio access network (RAN) is based on a completely new OFDM air interface.

This does not mean the end of 3GPP's interest in GSM and W-CDMA. Rather, the investment in these technologies means that LTE is not the only format being developed in 3GPP Release 8. For example, the EDGE Evolution project will be pushing GSM to newer levels and the HSPA+ project will continue to evolve the underlying W-CDMA, HSDPA and HSUPA technologies. By using OFDM, LTE is aligning with similar decisions made by 3GPP2 for Ultra-Mobile Broadband (UMB) and by IEEE 802.16 for WiMAX.

3.1 When LTE

Figure 3.1 shows an overall timeline for the LTE project. Compared to UMTS, the overall timescale is shorter, due largely to a much smoother standardization process. The instability and subsequent delays in the UMTS standard led to commercial deployment of a proprietary system in Japan before the worldwide standard was available. It is expected that the surprises and delays of UMTS will be averted with LTE, meaning its introduction should be more predictable and better able to avoid a proprietary launch. The dates in Figure 3.1 are acknowledged as aggressive and may slip; however, progress is solid and, as UMTS proved, trying to rush the process can be counterproductive [ ].

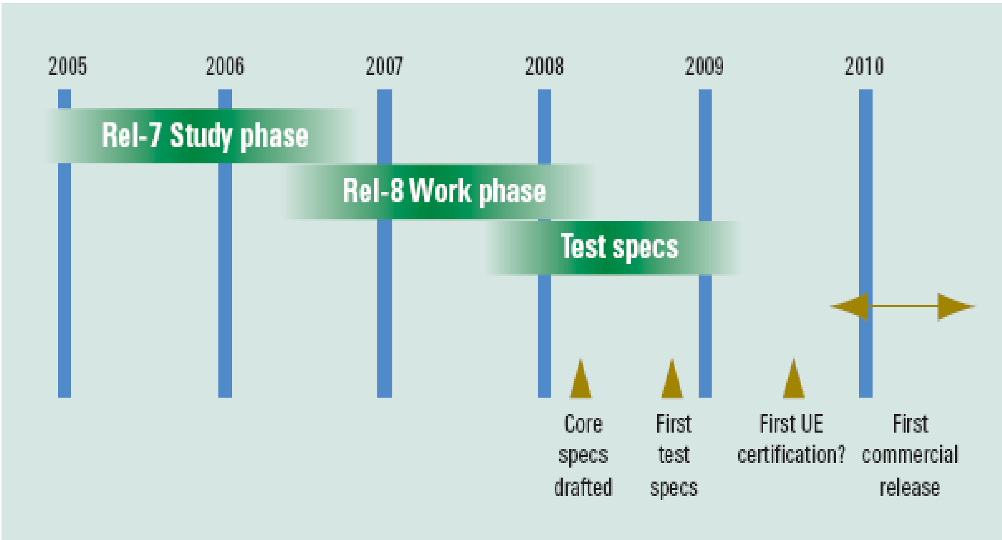

Figure 3.1. LTE Timing.

The capabilities of the eNodeB and UE are obviously quite different. Not surprisingly, the LTE PHY DL and UL are quite different. The LTE modulation in DL is OFDM and in the UL SC-FDMA were used. In this report only UL will be covered. The DL supports physical channels, which convey information from higher layers in the LTE stack, and physical signals which are for the exclusive use of the PHY layer. Physical channels map to transport channels, which are service access points (SAPs) for the L2/L3 layers. Depending on the assigned task, physical channels and signals use different modulation and coding parameters.

3.2 LTE Modulation

OFDM is the modulation scheme for the DL. The basic subcarrier spacing is 15 kHz, with a reduced subcarrier spacing of 7.5 kHz available for some scenarios. Table 3.1 summarizes OFDM modulation parameters. LTE support most of the old systems bandwidth so it works on 1.25, 2.5, 5, 10, 15, and 20 MHz.

Table 3.1. Downlink modulation parameters for LTE.

Transmission BW		1.25 MHz	2.5 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Sub-frame duration		0.5 ms					
Sub-carrier spacing		15 kHz					
Sampling frequency		1.92 MHz $1/2 \times 3.84$ MHz	3.84 MHz	7.68 MHz 2×3.84 MHz	15.36 MHz 4×3.84 MHz	23.04 MHz 6×3.84 MHz	30.72 MHz 8×3.84 MHz
FFT size		128	256	512	1024	1536	2048
CP Length (μs)	Short	4.69	4.69	4.69	4.69	4.69	4.69
	Long	16.67	16.67	16.67	16.67	16.67	16.67

The CP is chosen to be slightly longer than the longest expected delay spread in the radio channel. For the cellular LTE system, the standard CP length has been set at 4.69 μs, enabling the system to cope with path delay variations up to about 1.4 km. Note that this figure represents the difference in path length due to reflections, not the size of the cell. Inserting a CP between every symbol reduces the data handling capacity of the system by the ratio of the CP to the symbol length. For LTE, the symbol length is 66.7 μs, which gives a small but significant 7% loss of capacity when using the standard CP [8].

The ideal symbol length in OFDM systems is defined by the reciprocal of the subcarrier spacing and is chosen to be long compared to the expected delay spread. LTE has chosen 15 kHz subcarrier spacing, giving 66.7 μs for the symbol length. In a single-carrier system, the symbol length is closely related to the occupied bandwidth. For example, GSM has 200 kHz channel spacing and a 270.833 ksps symbol rate, giving a 3.69 µs symbol length that is 18 times shorter than that of LTE. In contrast, W-CDMA has 5 MHz channel spacing and a 3.84 Msps symbol rate, producing a 0.26 µs symbol length that is 256 times shorter than LTE. It would be impractical to insert a 4.69 µs CP between such short symbols because capacity would drop by more than half with GSM and by a factor of 20 with W-CDMA. Systems that use short symbol lengths compared to the delay spread must rely on receiver-side channel equalizers to recover the original signal.

Each 15 kHz subcarrier in LTE is capable of transmitting 15 ksps, giving LTE a raw symbol rate of 18 Msps at its 20 MHz system bandwidth (1200 subcarriers, 18 MHz). Using 64QAM which is the most complex of the LTE modulation formats, in which one symbol represents six bits, the raw capacity is 108 Mbps. Note that actual peak rates as described in the LTE sidebar are derived by subtracting coding and control overheads and adding gains from features such as spatial multiplexing [7] [8].

References

[1] N. J. Boucher, *Cellular Radio Handbook – A Reference for Cellular System Operation*, Quantum Publishing Inc., California, 1992.

[2] T. S. Rappaport, *Wireless Communications Principles and Practice*, Prentice Hall PTR, New Jersey, 1996.

[3] V. Grag, and J. E. Wilkes, *Wireless and Personal Communications Systems*, Prentice Hall, Upper Saddle River, 1996, p 445.

[4] *UMTS World WCDMA Specification and Information Page*, *http://www.umtsworld.com/technology/wcdma.htm*

[5] *cdma2000 Specification and Information Page*, *http://www.umtsworld.com/technology/cdma2000.htm*

[6] Lee Huang, CDMA *FR planning*, Huawei

[7] Erik Dahlman, Stefan Parkvall, Johan Sköld and Per Beming, *3G Evolution HSPA and LTE for Mobile Broadband,* Elsevier Ltd.2007

[8] Moray Rumney, *3GPP LTE: Introducing Single-Carrier FDMA*, Agilent Measurement Journal.2008