Basics about Multi-carrier Based Multiple Access Techniques

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Abstract

In this report, we are going to outline several choices of Multiple Access (MA) techniques for Uplink (UL) and Downlink (DL) for the 4^{th} Generation (4G) systems. The basic characteristics of the schemes are described. Possible scenarios and system parameters for 4G systems is also presented. The goal is to discuss the basic principles of the available MA techniques. In no way, this report is intended to become a complete guide for studying the techniques. Interested authors are requested to refer to the relevant references in the bibliography.

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List of Abbreviations

2G	2^{nd} Generation
3G	3^{rd} Generation
4G	4^{th} Generation
AMC	Adaptive Modulation and Coding
AP	Access-Point
AoA	Angle of Arrival
AoD	Angle of Departure
BER	Bit Error Rate
BS	Base Station
CE	Controlled Equalization
CDMA	Code Division Multiple Access
CE	Controlled Equalization
CSI	Channel State Information
DL	Downlink
DLC	Data Link Control
DMT	Discrete Multi-Tone
DS-CDMA	Direct Sequence Code Division Multiple Access
DSA	Dynamic Sub-Carrier Allocation
DSL	Digital Subcriber Line
EGC	Equal Gain Combining
FLASH-OFDM	Fast Low-Latency Access with Seamless Handoff Orthogonal Frequency Division Multiplexing
FSCH-OFDMA	Fast Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access

ICI	Inter-Carrier Interference
ISI	Inter-Symbol Interference
LAN	Local Area Network
LOS	Line of Sight
MA	Multiple Access
MAI	Multiple Access Interference
MC-CDMA	Multi-Carrier Code Division Multiple Access
MC-DS-CDMA	Multi-Carrier Direct Sequence Code Division Multiple Access
MLSSE	Maximum Likelihood Symbol-by-Symbol Estimation
MRC	Maximal Ratio Combining
MS	Mobile Station
MT-CDMA	Multi-Tone Code Division Multiple Access
MuD	Multi-user Diversity
MUI	Multiuser Interference
NBI	NarrowBand Interference
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA-CDM	Orthogonal Frequency Division Multiplexing with Code Division Multiplexing
OFDM-CDMA	Orthogonal Frequency Division Multiplexing - Code Division Multiple Access
OFDM-CDMA-SFH	Orthogonal Frequency Division Multiplexing - Code Division Multiple Access - Slow Frequency Hopping
OFDM-TDMA	Orthogonal Frequency Division Multiplexing - Time Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio
QoS	Quality of Service
RF	Radio Frequency
RMS	Root Mean Square
RSCH-OFDMA	Random Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access
SCH	Subcarrier hopping
SCH-OFDMA	Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access

SCH-OFDMA-CDM	Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access with Code Division Multiplexing
SINR	Signal to Interference+Noise Ratio
SNR	Signal to Noise Ratio
SSCH-OFDMA	Slow Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access
TDD	Time Division Duplex
UL	Uplink
VSF-OFCDM	Variable Spreading Factor - Orthogonal Frequency and Code Division Multiplexing
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

Chapter 1

Introduction

The history of wireless networking stretches farther back several decades. It was over fifty years ago, during World War II, when the United States Army first used radio signals for data transmission. This inspired researchers in 1971 at the University of Hawaii to create the first packet based radio communications network. ALOHANET, as it was named, was essentially the very first Wireless Local Area Network (WLAN). This was the beginning of WLAN era.

With the advent of 3^{rd} Generation (3G) wireless systems, it is expected that higher mobility with reasonable data rate (up to 2Mbps) can be provided to meet the current user needs. 3G promises a wire line quality of services via a wireless channel. Naturally 3G is not the end of the tunnel; ever increasing user demands have drawn the industry to search for better solutions to support data rates of the range of tens of Mbps. For wide area coverage, further expansions of 3G systems are already a question of research in all over the world. Certainly the bit rate will be much higher than 2Mbps for such a system, up to tens of Mbps [1]. For local area coverage, WLANs, such as IEEE 802.11a, HiperLAN/2 or MMAC[1] standards are capable of providing data rates up to 54 Mbps. Along with these three, there are few other emerging short-range wireless applications available, such as Bluetooth, HomeRF, etc.

WLANs can potentially be a promising tool in different user environments, namely home, corporate and public environment etc. WLANs are used to connect wireless users to a fixed Local Area Network (LAN) in corporate environments. A major WLAN application will be in public sectors, where WLAN can be used to connect a user to the backbone network. Airports, hotels, high-rising offices, city centers will be target area for such public WLAN usage.

A person-centered network can also be established, which is often termed as Wireless Personal Area Network (WPAN). WPAN can be able to connect TV, refrigerator, home security appliances, and sensors etc. WPAN, such as Bluetooth PAN, can facilitate a comfortable office by connecting the computer, printer, fax and other office appliances without any wire. Wireless Personal Area Networks refer to the short-range personal network concepts, which spread the networking area towards the personal space surrounding a person. A person can communicate with the devices attached to his body or within his personal space, and can seamlessly move within the existing networks environment [2]. Due to WPANs functional behavior, they are very closely associated with WLANs, and will be treated as such in future.

Like any other wireless system, there was a need for an industry standard devised to ensure the compatibility and reliability among all manufacturers of the devices, so that the WLANs are widely accepted. There are quite a few standards for wired and wireless communication networks that use the principles of Discrete Multi-Tone (DMT) modulation and Orthogonal Frequency Division Multiplexing

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[1] IEEE802.11a is an USA-standard, HiperLAN/2 is a European standard and MMAC is developed in Japan. All three of the standards are almost similar in their PHY layer.

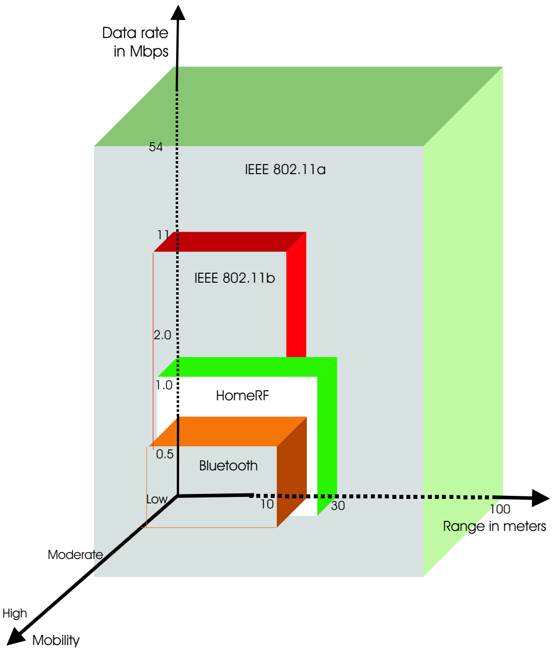

Figure 1.1: Graphical Look at the Data Rate, Mobility and Coverage Range of Existing WLANs, HomeRF and Bluetooth

(OFDM). Starting from fixed Digital Subcriber Lines (DSLs), there are broadcasting systems such as DAB and DVB-T and WLANs such as IEEE 802.11a, MMAC and HiperLAN/2 use OFDM as the core PHY technology. The latest wireless standard based on OFDM is the IEEE 802.16a for *Fixed Broadband Wireless Acess* (FBWA) system. Recently a new standard group IEEE 802.20 was formed to devise a new standard for future *Mobile Broadband Wireless Access* (MBWA) system. The workgroup is considering OFDM as the possible PHY solution. IEEE 802.20 promises very high mobility while providing data rates to support multimedia applications.

1.1 OFDM for Future Wireless Systems

The nature of WLAN and WPAN applications demands high data rates. Multimedia communications, such as video transmission, can require high user data rate for good quality of viewing. Naturally dealing with ever-unpredictable wireless channel at high data rate communications is not an easy task. The idea of multi-carrier transmission has surfaced recently to be used for combating the hostility of wireless channel. OFDM is a special form of multi-carrier transmission where all the sub-carriers are orthogonal to each other. OFDM promises a higher user data rate transmission capability at a reasonable complexity and precision.

At high data rates, the channel distortion to the data is very significant, and it is somewhat impossible to recover the transmitted data with a simple receiver. A very complex receiver structure is needed which makes use of computationally extensive equalization and channel estimation algorithms to correctly estimate the channel, so that the estimations can be used with the received data to recover the originally transmitted data. OFDM can drastically simplify the equalization problem by turning the frequency selective channel to a flat channel. A simple one-tap equalizer is needed to estimate the channel and recover the data.

Future telecommunication systems must be very efficient spectrally to support number of users with high data rate. OFDM uses the available spectrum very efficiently. This is very useful for multimedia communications. Thus, OFDM stands a good chance to become the prime technology for 4G. Pure OFDM or hybrid OFDM will be most likely the choice for physical layer multiple access technique in the future generation of telecommunications systems [3].

1.2 Motivation

One of the main issues involved in the development of the 4G wireless systems is the choice of MA technique. Unlike the existing 2^{nd} Generation (2G) and 3G systems which are low speed and mainly aimed at voice communications, the 4G systems are designed to provide much higher data rate and to support IP-based data services. The 4G systems is expected to be packet-based networks with data rate on order of several 10Mbps, and its services range from VoIP, high-quality video conference and network games to email, web surfing and file transferring. The 4G terminals can be heterogeneous, with various processing and computation capabilities. Short-range communications might also be employed to support peer-to-peer communications and to enhance the communication between Base Station (BS) and terminals. Such vision requires the 4G systems to have a scheme that:

- Supports high data rate with high spectrum efficiency.
- Provides a fine level of granularity for accessing the medium, which facilitates efficient usage of available network resources.
- Offers scalable bandwidths to users, which allows bursty and scheduled traffic, and small and large bandwidth-requirement applications to coexist in the 4G system.
- Supports tunable features in order to adapt to different scenarios (indoor and outdoor, micro and macro cell) and to allow heterogeneous terminals to operate.
- Support short-range wireless links that are controlled by BS.

In addition to these key requirements, MA scheme for 4G must also be low complexity, robust against severe wireless channel, and resilient to interference.

1.3 Scope and Goals of the Report

In this report, we are going to outline several choices of MA techniques, and to put forward an initial proposal MA schemes for UL and DL for the 4G systems. The scope is to discuss the basic principles of the available MA techniques. In no way, this report is intended to become a complete guide for studying the techniques. Interested authors are requested to refer to the relevant references in the bibliography.

1.4 Organization of the Report

This report will be organized as following: Chapter describes the system scenarios and possible set of parameters for 4G system. Important characteristics of three basic multi-carrier based multiple access scheme is placed in Chapter . For a better understanding of the system, we have presented some wireless standards which employ multi-carrier based systems in Chapter .

Chapter 2

System Scenarios and Parameters

This chapter presents scenarios and system parameters of the 4G systems, which are necessary for our discussion of MA scheme later on.

2.1 Outdoor Scenario

2.1.1 Physical Description of Outdoor Channel

- Large cell radius, in the order of 3-4km for urban and more than 4km for rural scenario
- At the cell area, the cells are overlapping to each other
- Large number of users, as higher cell area will naturally be occupied by higher number of users.
- User mobility will be higher (i.e. higher than pedestrian mobility of 3kmph). Similarly, the scatterers around the users may also have higher mobility. Thus, a very dynamic environment can be easily assumed.
- Large Root Mean Square (RMS) Delay spread will be experienced
- Usually the BS antennas are mounted much higher than Mobile Station (MS) antennas. This is because BSs are located on building roof top level or on top of a high place.

2.1.2 Impact of Outdoor Characteristics on the system

- High Doppler shift will be experienced on user-by-user basis due to high mobility
- As the users will be situated at irregular and sufficiently varying distances, wide distribution of user transmit power is expected, which will create the near-far scenario in cellular system.
- As large number of users are present in the system, the Multiuser Interference (MUI) can be very high.
- Larger cell area means that the BSs need to transmit at higher power to reach out the users at the cell-edge, this in turns means that larger inter-cell interference is present in the system.
- For highly mobile users, frequent handovers are necessary. This increases the need for re-synchronization of transceivers and increases signaling overhead.

- Due to long distance between the BS and MS, and due to the height of BS antennas, it may be possible to have Line of Sight (LOS) conditions. Also the Angle of Arrival (AoA) (or Angle of Departure (AoD)) can be quite small in outdoor scenario.
- Users at the cell edge will experience low Signal to Noise Ratio (SNR) conditions, whereas users close to BS will have high SNR.
- Large timing offset among users in terms of transmission window (i.e. receiver DFT window for multi-carrier systems) can be expected.

2.2 Indoor Scenario

2.2.1 Physical Description of Indoor Channel

- Smaller cell area, typically few 10s of meters to few 100 meters
- Relatively small number of users
- Low mobility is a special feature of indoor environment, a large portion of users are almost stationary and the highest user mobility is at the pedestrian mobility level. The surrounding environment is also very static.
- The BS and MS antennas are almost of similar height, as the BS are usually mounted on wall or ceiling.
- Low delay spread is experienced, that means a large coherence bandwidth can be assumed.
- Cells are located with some spatial separation.
- Rich scattering is experienced in the environment due to the presence of close scatterers.

2.2.2 Impact of Indoor Characteristics on the system

- The interference in indoor scenario are mainly from Bluetooth networks, home networks, ISM band devices etc.
- Neighbor cell interference is usually comparatively smaller (or almost zero).
- As the cell are sparsely located and as the user mobility is comparatively little, frequent handover is not required.
- The coherence time is much higher because of low user mobility (and almost static environment), thus channel remains static for a long period, so algorithms can be implemented for large frames.
- Algorithms that require Channel State Information (CSI) at the transmitter can be implemented with relatively lower spectral wastage. These include, Adaptive Modulation and Coding (AMC), CSI assisted resource scheduling, etc.
- User timing offset will not vary too much, as is the case in outdoor situation.
- User transmit powers are usually uniformly distributed, so little problem in power management is expected.

2.3 System parameters

In this section, we explain a set of multi-carrier (i.e. OFDM) related parameters for 4G systems. These parameters are designed based on various requirement for PHY layer activities.

In Section 2.3.1, we describe related wireless channel parameters. Appendix A.1 and A.2 contain useful information to understand these parameters. In section 2.3.2, basic OFDM system related parameters are explained. A number of these parameters are design and implementation related, thus, these parameters always require to be tuned for specific implementation and design environment.

2.3.1 Channel Parameters

Wireless channel parameters are chosen to support highly mobile (i.e highly time-variant) and severely frequency selective environment. This is exactly the scenario for outdoor wide area cellular system with high user data rate requirement.

Parameters	Units	Value	Comments
Maximum MS velocity, v	kmph	100	
Maximum RMS delay spread, τ_{rms}	μs	1	[4]
Coherence bandwidth, B_c	kHz	200	Appendix A.1
Maximum delay spread, τ_{max}	μs	5	$\tau_{max} \approx 5\tau_{rms}$
Maximum Doppler shift, f_d	Hz	463	Appendix A.2
Coherence time, T_c	ms	0.914	Appendix A.2

2.3.2 Multi-Carrier System Parameters

In this section, we explain the OFDM system related parameters. The number of required pilots and zero sub-carriers are very much of implementation related issue. We assigned some estimated numbers for those parameters for this moment, but it should be noted that as we will be designing pilot and pre-amble sequences, the number of frequency domain pilots and time-domain pre-ambles will vary. In that case, a little tuning of the parameters will do.

Parameters	Units	Set-1	Set-2	Comments
System Bandwidth, B	MHz	40	20	
Carrier frequency, f_c	GHz	5	5	
FFT size, N		2048	1024	
Number of non-zero subcarriers, N_{nz}		1440	720	$\approx 0.7 * N = N_d + N_p$
Number of zero subcarriers, N_z		608	304	$= N - N_{nz} = N - (N_d + N_p) =$
Number of data sub-carriers, N_d		1299	650	$= N_{nz} - N_p$
Number of pilot sub-carrier, N_p		141	70	Once every coherence bandwidth for data sub-channels

Number of sub-band		16	8	180(90) non-zero sub-carriers per sub-band
Number of sub-channels		180	90	
Number of sub-carriers per sub-channel, N_{sch}		8	8	$180(90) * N_{sch} = N_d + N_p$
Sub-carrier spacing, $\Delta f = \frac{B}{N}$	kHz	19.53	19.53	Must be $f_d << \Delta f << B_c$
Sampling time, $T = \frac{1}{B}$	ns	25	50	$T * N = T_u$
DFT window time, T_d	μs	51.2	51.2	$= T * (N_d + N_z)$
Cyclic prefix samples, N_g		200	100	
Cyclic prefix duration, T_g	μs	5	5	$= N_g * T$
Total OFDM symbol duration, T_s	μs	56.2	56.2	$= T_d + T_g$
Number of OFDM symbols per basic time-frequency frame cell, S		16	16	
Basic frame duration, T_f	ms	0.899	0.899	$= S * T_s$

Chapter 3

Basic Multi-Carrier Multiple Access Schemes

Before deciding on the probable access technique for 4G wireless communication systems, we here briefly summarize the basic properties of three fundamental multi-carrier based multiple access techniques, namely Orthogonal Frequency Division Multiple Access (OFDMA), Orthogonal Frequency Division Multiplexing - Time Division Multiple Access (OFDM-TDMA) and Orthogonal Frequency Division Multiplexing - Code Division Multiple Access (OFDM-CDMA).

3.1 Definition of Basic Schemes

OFDM-TDMA

In OFDM-TDMA, a particular user is given all the sub-carriers of the system for any specific OFDM symbol duration. Thus, the users are separated via time slots. All symbols allocated to all users are combined to form a OFDM-TDMA frame. The number of OFDM symbols per frame can be varied based on each users requirement. Frequently, an error correcting code is applied to the data to compensate for the channel nulls experienced by several random bits. This scheme allows MS to reduce its power consumption, as the MS shall process only OFDM symbols which are dedicated to it. On the other hand, the data is sent to each user in bursts, thus degrading performance for delay constrained systems delay constrained systems [5].

OFDMA

In OFDMA, available sub-carriers are distributed among all the users for transmission at any time instant. The subcarrier assignment is made for the user lifetime, or at least for a considerable time frame. The scheme was first proposed for CATV systems [6], and later adopted for wireless communication systems.

OFDMA can support a number of identical downstreams, or different user data rates, [e.g. assigning a different number of sub-carriers to each user]. Based on the sub-channel condition, different baseband modulation schemes can be used for the individual sub-channels, e.g. QPSK, 16-QAM and 64-QAM etc. This is investigated in numerous papers and referred to as adaptive subcarrier, bit, and power allocation or Quality of Service (QoS) allocation [7, 8, 9, 10].

In OFDMA, frequency hopping, one form of spread spectrum, can be employed to provide security and resilence to inter-cell interference.

OFDM-CDMA

In OFDM-CDMA, user data is spread over several subcarriers and/or OFDM symbols using spreading codes, and combined with signal from other users [11]. The idea of OFDM-CDMA can be attributed to several researchers working independently at almost the same time on hybrid access schemes combining the benefits of OFDM and Code Division Multiple Access (CDMA). OFDM provides a simple method to overcome the Inter-Symbol Interference (ISI) effect of the multi-path frequency selective wireless channel, while CDMA provides the frequency diversity and the multi-user access scheme. Different types of spreading codes have been investigated. Orthogonal codes are preferred in case of DL, since loss of orthogonality is not as severe in DL as it is in UL.

Several users transmit over the same sub-carrier. In essence this implies frequency domain spreading, rather than time domain spreading, as it is conceived in a Direct Sequence Code Division Multiple Access (DS-CDMA) system. The channel equalization can be highly simplified in DL, because of the one tap channel equalization benefit offered by OFDM.

3.2 Characteristics of Basic Schemes

3.2.1 Flexibility

OFDM-TDMA

Different OFDM symbols can be allocated to different users based on certain allocation conditions. Since the OFDM-TDMA concept allocates the whole bandwidth to a single user, a reaction to different subcarrier attenuations could consist of leaving out highly distorted sub-carriers [12]. The number of OFDM symbols per user in each frame can be adapted accordingly to support heterogeneous data rate requirements. An efficient multiple access scheme should grant a high flexibility when it comes to the allocation of time-bandwidth resources. On the one hand, the behavior of the frequency- selective radio channel should be taken into account, while on the other hand the user requirements for different and/or changing data rates have to be met [13]. For example, both for OFDMA and OFDM-TDMA, the usage of AMC on different sub-carriers, as proposed in [7], may increase overall system throughput and help in further exploiting CSI.

OFDMA

In OFDMA, the granularity of resource allocation is higher than that of OFDM-TDMA, i.e. the flexibility can be accomplished by suitably choosing the sub-carriers associated with each user. Here, the fact that each user experiences a different radio channel can be exploited by allocating only “good” sub-carriers with high SNR to each user. Furthermore, the number of sub-channels for a specific user can be varied, according to the required data rate. Thus, multi-rate system can be achieved without increasing systme complexity very much.

OFDM-CDMA

In OFDM-CDMA, the flexibility lies in the allocation of all available codes to the users, depending on the required data rates. As OFDM-CDMA is applied using coherent modulation, the necessary channel estimation provides information about the subcarrier attenuations; this information can be used when performing an equalization in the receiver [14].

3.2.2 Time-Frequency Resource Allocations

OFDM-TDMA

Unit resource is one OFDM symbol. Thus, in a frame unit (consists of a number of basic OFDM symbols), the symbols can be wholly assigned to any particular user. Thus, similar to OFDMA, static and dynamic allocation can be implemented. In largely static environment, such as indoor scenario, Dynamic Sub-Carrier Allocation (DSA) based on CSI may not give much improvement in OFDM-TDMA compared to static allocation scheme. For very dynamic environment, DSA can be very beneficial for this scheme. But, from another point of view, channel changes very frequently for a very dynamic wireless channel, and so, static allocation may be enough to avoid fading.

It can be safely assumed that resource allocation is much simpler in this scheme than OFDMA.

OFDMA

Different methods of allocating and re-allocating different sub-carriers to different users may be used:

Static: Sub-carriers are allocated to a user for the entire duration of the connection time without considering CSI. If the user is allocated some sub-carriers that are in fade, the signal will remain faded until the user moves out of the fade or the sub-carriers are re-allocated after some number of frames. So, when a user is in fade in allocated sub-carriers, it remains there for long time, which is not desirable.

Dynamic: Sub-carriers are allocated dynamically, assuming that the base station has instantaneous (or near-instantaneous) knowledge of the CSI for each user. This is called DSA. In this case, the sub-carriers are allocated in real-time based on the knowledge of channel strength at all sub-carriers for all users.

The sub-carriers are assigned into sub-channels in a contiguous or interleaved manner [15]. For contiguous assignment, the sub-carriers are divided into contiguous sub-channels, where one benefit is the simplicity, but a disadvantage is the possible throughput degradation due to channel fading. In the interleaved case, the sub-carriers are successively assigned to the different users and then interleaved over the total number of sub-carriers. One important advantage is that it has potential to reap more channel diversity gain. The disadvantage is that issues like synchronization for the entire OFDM symbol become crucial, as the user sub-channel is scattered over the OFDM symbol.

In the dynamic sub-carrier assignment case, CSI is used to assign the sub-carriers best suited for each user. This is advantageous in the sense that users at different locations have different channel conditions, and most likely different optimal sub-carriers. The benefit is that high throughput rate can be obtained, the disadvantages are that; channel information is needed, sub-carriers must be reassigned whenever conditions change, leading to additional signalling overhead whenever sub-carriers are reassigned [7].

OFDM-CDMA

All sub-carriers are shared by all the users. Thus, resource allocation does not include sub-carrier allocation. In this scheme, user code allocation is the resource allocation. Practically, any well-known code allocation scheme used in Wideband Code Division Multiple Access (WCDMA) system can be adopted for OFDM-CDMA scheme. The resource allocation scheme is much simpler in OFDM-CDMA compared to other two schemes.

3.2.3 Variants of the Basic Schemes

OFDM-TDMA

Besides static and dynamic allocation of OFDM symbols for different users, symbol hopping can also be implemented in OFDM-TDMA system. As it is mentioned earlier, this can bring some benefits for severely time and frequency selective outdoor scenario.

OFDMA

When it is not possible to be obtained CSI at the transmitter, an alternative to DSA can be Subcarrier hopping (SCH) schemes. Frequency hopping in OFDMA systems can be obtained in two ways: contiguous sub-band hopping as it is seen in [16] and sub-carrier hopping as shown in [17]. Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access (SCH-OFDMA) system combines all the capabilities of an OFDMA system with sub-carrier hopping spread-spectrum techniques. When users hop randomly on the available sub-carriers, then we can call the system as Random Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access (RSCH-OFDMA). This is very similar to Fast Low-Latency Access with Seamless Handoff Orthogonal Frequency Division Multiplexing (FLASH-OFDM) system.

Depending on the frequency of the hopping schemes, SCH-OFDMA can be divided into two kinds of systems, namely Fast Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access (FSCH-OFDMA) and Slow Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access (SSCH-OFDMA). In an FSCH-OFDMA system, once sub-carriers are allocated to users, the index of the assigned subcarrier is changed, i.e. hopped at every OFDMA symbol. Users are separated by non-overlapping subcarrier hopping patterns [18]. These patterns constitute the hop-set available at the BS. The arrangement of the hop-set available at neighboring cells depends on the cellular structure of the system. SSCH-OFDMA system is very similar to FSCH-OFDMA system, except that the hopping duration is at least a number of OFDM symbols.

OFDM-CDMA

The OFDM-CDMA scheme that we are referring here was actually proposed in [11] in the name of Multi-Carrier Code Division Multiple Access (MC-CDMA). One variation of this scheme is Orthogonal Frequency Division Multiplexing with Code Division Multiplexing (OFDMA-CDM), where one user is given a set of sub-carriers and all the data symbols it has to transmit, are spread on those sub-carriers only and transmitted in OFDM fashion. There is a need of such variation of the original OFDM-CDMA scheme to make it even more usable. The afore-mentioned scheme has the advantage that it does not introduce Multiple Access Interference (MAI) as MC-CDMA does. A variation of OFDMA-CDM is DoCoMo's well published Variable Spreading Factor - Orthogonal Frequency and Code Division Multiplexing (VSF-OFCDM), where variable spreading factors for users are used in different environment [19]. SCH can be incorporated along with OFDMA-CDM to create a scheme called, Sub-Carrier Hopped Orthogonal Frequency Division Multiple Access with Code Division Multiplexing (SCH-OFDMA-CDM), which can also give substantially good scheme for indoor environment [20].

By changing the spreading procedure, several other variant of OFDM-CDMA schemes are studied and analyzed, such as Orthogonal Frequency Division Multiplexing - Code Division Multiple Access - Slow Frequency Hopping (OFDM-CDMA-SFH) [16], Multi-Carrier Direct Sequence Code Division Multiple Access (MC-DS-CDMA), Multi-Tone Code Division Multiple Access (MT-CDMA) etc. A review of some of those schemes can be found in [21].

3.2.4 Processing Requirements

OFDM-TDMA

Users need to process the data symbols that are intended for them only. This is a feature that gives OFDM-TDMA a little advantage over other two schemes.

OFDMA

As all the active users are present at every OFDM symbol in OFDMA, it is a requirement that all active users need to receive, detect and decode every OFDM symbol. This is expensive, in terms of power requirement etc.

OFDM-CDMA

Similar to OFDMA, all the users need to receive and decode all the symbols in OFDM-CDMA system.

3.2.5 Synchronization

In the DL, synchronization requirements for OFDM-TDMA, OFDMA and OFDM-CDMA are similar and they are not different from the basic OFDM technique. Once the timing- and frequency-offset are estimated and corrected, the OFDM symbol can be decoded without MUI penalty.

In the UL, OFDMA and OFDM-CDMA require that active users be synchronized in time and frequence to maintain orthogonality among themselves. Otherwise, MUI will occur.

3.2.6 Peak to Average Power Ratio

A multi-carrier signal consists of a number of independently modulated sub-carriers, which can give a large Peak to Average Power Ratio (PAPR) when added up coherently. Thus, all access techniques discussed here suffer from PAPR problem. A large PAPR brings disadvantages like an increased complexity of the analog-to-digital (A/D) and digital-to-analog (D/A) converters and a reduced efficiency of the Radio Frequency (RF) power amplifier [3].

Complex solutions to solve this problem are devised in the literature. In the DL, BS transmitter can perform the complex calculations to solve the PAPR problem. It can be a severe problem in UL, where only a small number of sub-carriers are used, thus, PAPR can be very high. This is the case for all the schemes being discussed in the document.

3.2.7 BER Performance

OFDM-TDMA

The Bit Error Rate (BER) performance in this scheme is not different from basic OFDM scheme, unless a form of AMC is used.

OFDMA

The BER of an OFDMA system is given by the modulation scheme used and averaged over the channel distribution. For the same channel conditions, the overall BER of an OFDMA system does not differ from the one found for OFDM systems [22]. When CSI-based resource allocation is used to exploit Multi-user

Diversity (MuD), then the BER performance of OFDMA gets much better compared to single-user basic OFDM system.

OFDM-CDMA

The amount of MAI depends on particular combining scheme. This dominates the BER performance. In general, BER degrades with increasing number of users [23]. Using schemes such as soft interference cancellation or Maximum Likelihood Symbol-by-Symbol Estimation (MLSSE) can improve the performance. Otherwise the performance depends a lot on the channel estimation and equalization.

3.2.8 Spectral Efficiency

OFDM-TDMA

The spectral efficiency is equals to that of OFDM for a single user case. The spectral efficiency depends on the baseband modulation scheme, and the code rate used.

OFDMA

OFDMA might have lower spectral efficiency than OFDM-TDMA when it is used in the uplink. Due to Inter-Carrier Interference (ICI), a guard band must be introduced between different users, leading to a loss in spectral efficiency.

OFDM-CDMA

OFDM-CDMA is a highly spectral efficient in the DL, as long as orthogonality of the codes can be preserved. In non-ideal conditions, it is not possible to operate under full load because of the MAI produced by the orthogonality loss. High throughput under ideal conditions can be achieved.

Due to the available frequency diversity via spreading across all the sub-carriers, BER performance improves, which in turn also improves the throughput.

3.2.9 Delay Spread Tolerance

In the DL, delay spread tolearance of all basic schemes does not differ from the basic OFDM scheme: Delay spread can be tolerated, provided that the guard interval is larger than maximum delay spread.

In the uplink, due to different timing-offset between users, the delay spread tolerance of OFDMA and OFDM-CDMA might be affected [24].

3.2.10 Mobility

OFDM-TDMA

Mobility gives Doppler spread, and this causes ICI. In OFDM-TDMA, a single user is allocated all the sub-carriers of any particular symbol, thus, MAI due to ICI does not happen in this scheme, while this happens in other two schemes. Because of this, the error floor due to Doppler spread in OFDM-TDMA happens at a much lower BER and higher SNR than in other schemes [12].

OFDMA

Mobility can simply be evaluated on the ratio between OFDM symbol duration and channel coherence time, where $T_s < T_c$. In Appendix A.2, coherence time for different user speeds is shown. If compared to the IEEE 802.14.4c downstream mode from Table 4.1, it is obvious that for the 2k mode, extreme mobility cannot be handled, whereas low mobility is not a problem.

OFDM-CDMA

Maximum doppler spread tolerance is dependent on the sub-carrier spacing. As such there is MAI due to non-ideal channel compensation under synchronous environment as well. Doppler spread leading to frequency spread will add to it since inter sub-carrier interference will come into play, further worsening the situation. But if the sub-carrier spacing is large enough, which is again a system design issue as in an OFDM system, such that the doppler frequency is very small compared to the sub-carrier spacing, i.e. normalized doppler frequency is small and the ICI will be less. Otherwise the system will become interference limited.

3.2.11 Latency

OFDM-TDMA

Processing is done on every OFDM symbol, but a user gets service once in every $U * T_s$, given that there are U number of users in the system and everyone is given one OFDM symbol per frame.

OFDMA

In OFDMA the processing is made on one OFDM symbol, giving that the latency is equal to T_s.

OFDM-CDMA

Latency is similar to OFDMA system.

3.2.12 Intra-cell Interference

OFDM-TDMA

No intra-cell interference is present also as only one user is transmitting at any certain OFDM symbol duration.

OFDMA

For OFDMA, there will be no Intra-Cell interference, since all users are using a unique sub-set of the available sub-carriers. Depending on ICI and Doppler spread, the users who occupy neighboring sub-carriers, may interfere each other.

OFDM-CDMA

In DL, the effect of MAI is already mentioned before. It occurs due to orthogonality loss among spreading codes because of channel fading. It has also been noted that channel estimation error introduces intra-cell interference and highly influences the performance of the system.

3.2.13 Inter-cell Interference

OFDM-TDMA

Inter-cell interference happens only if other cells are using the same time-slot and carrier frequency as the current cell.

OFDMA

In a multi-cell environment there will be interference, assuming that the same carrier frequency is used. The reason is that sub-carriers are assigned to sub-channels, and when a neighbor cell uses the same sub-carriers there will be interference.

OFDM-CDMA

With proper choice and allocation of codes to users based on location and co-ordination between BS, inter-cell interference can be kept to a quite low value, but in general, the system is susceptible to inter-cell interference.

3.2.14 Narrowband Interference Rejection

One of the major problems associated with transmitting information from subscriber premises is so called NarrowBand Interference (NBI). In OFDM-based systems, the effect can be loss of sub-carriers and degraded BER performances.

OFDM-TDMA

[25] reported that NBI affects OFDM-TDMA much more severely than OFDMA systems. As only one user occupies the whole bandwidth, if the particular user is subdued with high Signal to Interference+Noise Ratio (SINR), then the whole system collapses. This is evident in the results mentioned in the above mentioned paper, where it is shown that OFDM-TDMA collapses at around 2dB of SINR, which is a staggering 30dB higher than OFDMA systems.

In summary, a low interference level jams a few carriers in OFDMA and slightly reduces the system capacity, whereas an OFDM-TDMA system can still operate at its full capacity. However, as the interference level exceeds a certain threshold OFDM-TDMA entirely breaks down, whereas OFDMA only loses a small percentage of its total capacity [25].

OFDMA

[25] also reported that OFDMA performs better when NBI is present in the system. NBI affects certain sub-carriers, thus, only the users who are allocated those sub-carriers are affected by increasing NBI. Thus, number of users operating at a certain BER when NBI increases is reduced gradually, and only at very low SINR, i.e. at -30dB level, all users are out of service due to NBI.

OFDM-CDMA

Users spread their signals over whole of the bandwidth, thus, NBI does not affect the system as it does in OFDM-TDMA. This is one of the benefits that is brought by incorporation of CDMA with OFDM.

3.2.15 Frequency Reuse Factor

OFDM-TDMA

The same result mentioned below in case of OFDMA should be valid for OFDM-TDMA system also.

OFDMA

In [19], it was shown that the reuse factor for OFDMA in multi-cell environments is at least 3. This is shown by simulation.

OFDM-CDMA

This does not have unity frequency re-use factor, but using a PN-sequence might provide this benefit [22].

3.2.16 Signalling Overhead

Usual network control related signalling overhead is almost similar to all of the systems. The main difference appears when the amount of signalling is compared for resource allocation purpose.

OFDM-TDMA

Signalling overhead in OFDM-TDMA is much smaller compared to DSA-based OFDMA system. When dynamic allocation is used, then only an average value of channel strength for all users are required in OFDM-TDMA scheme. This means that MSs need to send much less information to BS for allocation purposes. Similarly, the BS needs to send only the information of OFDM symbol by symbol allocation. This is much smaller compared subcarrier by subcarrier allocation information in OFDMA systems, especially for large bandwidth with large number of subcarriers in the system.

With different number of users in the system, OFDM-TDMA requires the least amount of signalling compared to OFDMA and OFDM-CDMA schemes [13].

OFDMA

For static allocation, once the allocation information is comveyed to the user, the BS does not need any other resource allocation based signalling. For DSA, CSI is required continuously, thus significant signalling is needed for transmitting both channel information and subcarrier allocation. In case of SCH systems, conveying the hopping seed at the beginning of communication is enough for the system to perform perfectly.

OFDM-CDMA

The signalling overhead is very limited compared to above two schemes. Some information about spreading code is enough for MS to start transmitting.

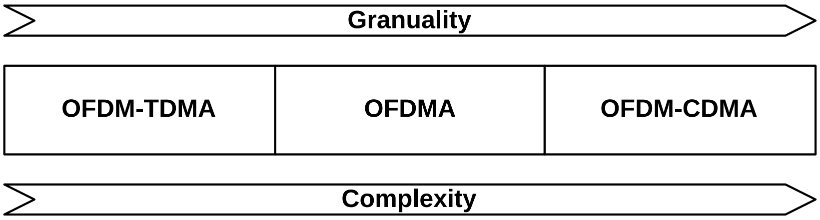

Figure 3.1: Relative comparison of basic multi-carrier multiple-access techniques

3.2.17 Implementation Complexity

OFDM-TDMA

Implementation complexity is very much similar to basic OFDM system. Even when dynamic allocation is used, the decision about resource allocation needs to be taken once per symbol, which requires much smaller effort than deciding on every sub-carrier.

OFDMA

In the case of static subcarrier assignment, the complexity of OFDMA is identical to a traditional OFDM system, only adding the mapping and de-mapping of subchannels. For the dynamic subcarrier assignment, CSI is required and huge computational effort is expected to compute the best subcarrier assignment policy. Thus, continuous channel estimation for all the users on whole band and computationally extensive resource assignment policy increases the system complexity very much.

OFDM-CDMA

OFDM-CDMA is simpler compared to DS-CDMA rake receiver because of frequency domain combining. The complexity depends upon the detection strategy used. Equal Gain Combining (EGC), Maximal Ratio Combining (MRC) and Controlled Equalization (CE) are some of the simple methods of detection. Several other complex detection schemes exist such as Soft Interference Cancellation and MLSSE. The performance of the scheme increases with the complexity of the detection scheme. It is a purely implementation tradeoff that needs to be decided for a particular situation.

3.3 Summary

As showing in the previous section, we can consider OFDM-TDMA as the most basic multiple-access scheme, while OFDMA scheme is an extension of OFDM-TDMA, and in turn, OFDM-CDMA scheme as an extension of OFDMA (see Figure 3.1). Going from OFDM-TDMA to OFDM-CDMA, we have increased the level of flexibility in multiple-access of the system, but at the same time, increased the complexity. The OFDM-CDMA shall observe all requirements from OFDMA, plus its owned requirements. And similarly, OFDMA must fulfil all requirements of OFDM-TDMA.

Table 3.3 summarizes advantages and disadvantages of three basic multi-carrier multiple-access schemes:

Table 3.1: A summary of multiple access scheme

	Advantages	**Disadvantages**
OFDM-TDMA	Power savings (only receives own symbols) Simple resource allocation Easiest to implement	Relatively high latency Frequency-reuse factor ≥ 3 Lowest flexibility
OFDMA	Simple implementation Flexibility	Frequency-reuse factor ≥ 3
OFDM-CDMA	Spectral efficiency Frequency diversity MAI and inter-cell interference resistance Frequency-reuse factor = 1 Soft handover capability Highest flexibility	Requirement of power control Implementation complexity

OFDM-TDMA

OFDM-TDMA is simple to implement, but it may lack in highly delay constraint system. For DL, basic OFDM-TDMA may not perform very well compared to other two schemes, but in UL, it may be very worthy. In UL, user time and frequency offset can cause real havoc in the system, and both OFDMA and OFDM-CDMA have to implement substantial procedure to combat the offsets, while OFDM-TDMA may be able to handle them quite easily. This is based on the fact that the entire bandwidth is allocated to a single user for several OFDM symbols, thus practically avoiding MAI.

OFDMA

The OFDMA scheme is distinguished by its simplicity, where the multi-access is obtained by allocating a fraction of sub-carriers to different users. The benefit is that the receiver can be implemented in a relatively simple manner.

OFDMA is already in use in some standards, e.g. IEEE 802.16a, and can be used for both DL and UL. For the UL case, issues like synchronization are a big issue, and are studied in several papers. Regarding the assignment of sub-carriers, the literature provides no definitive answer whether it should be static/dynamic or contiguous/interleaved.

OFDM-CDMA

This scheme is potentially a very good scheme in DL due to its ability to exploit available frequency diversity, even coded-OFDMA can only make use of limited frequency diversity. It has been pointed that this scheme is vulnerable to near–far effect as a normal CDMA system is. Hence this scheme suits best mainly in an indoor DL scenario [22]. Now one is easily led to argue that in an indoor situation the coherence bandwidth is very large. In 5 GHz band, it ranges from 6MHz to 20 MHz. Thus to make use of its special advantage of providing frequency diversity, the system has to use a very wide band. Otherwise, even with a 20 MHz channel it will get as much frequency diversity as a coded interleaved OFDM system. In outdoor scenario, the loss of orthogonality due to severe channel coding may diminish the frequency diversity effect and introduce MAI to reduce the BER performance.

Chapter 4

Multi-carrier Based Standards

In this chapter, we briefly explain the existing multi-carrier based based standards. Out of the three basic access techniques, only OFDM and OFDM-TDMA has been found to be accepted in wireless standards. variants of OFDMA is included in IEEE 802.16a and OFDM-TDMA is taken in HiperLAN/2 WLAN systems. So far, there is no system which adopted OFDM-CDMA or any of its variants as the standard for PHY layer.

The goal is to understand the scenario, motivation and design criterion of OFDMA and OFDM-TDMA based systems.

4.1 OFDMA Based-Standards

In 1998 the IEEE 802.16 Working Group started the preparation of various proposals for Wireless Metropolitan Area Networks (WirelessMAN), also known as the "last mile" networks. The initial interest was the 10-66 GHz band, desired for LOS communication. Later extended to the 2-11 GHz band, as it was realised that NLOS communication schemes are preferable. In 2003 IEEE published the 802.16a standard consisting of a common MAC layer and four different PHY layers. One of these is the WirelessMAN-OFDMA PHY layer, obviously using the OFDMA access technology.

Parameters	Down-link	Up-link
Number of FFT points	2048	2048
Usable carriers	1702	1696
Number of subchannels	32	32
Number carriers per subchannel	48	53 (5 pilots)
Data carriers	1536	1536
Number of Pilots	166	160
Guard carriers	173, 172	176, 175

Table 4.1: The IEEE 802.16a subcarrier specification. (For the Guard carriers, representing respectively the left and right number of subcarriers.)

The OFDMA symbol contain of 2048 subcarriers, containing data and pilot carriers. In DL the pilots are first allocated, which contain fixed and variable pilots. The carrier indices for the fixed pilots never change, whereas the variable pilots are rotated with a four OFDM symbol duration. To allocation the data subchannels, the remaining carriers are partitioned into groups of contiguous carriers, where the individual data subchannels are assigned one carrier in each group. Meaning that data subchannel is interleaved over the remaining usable carriers. In UL the procedure is different, first the carriers are partitioned into subchannels (interleaved over the carriers, as described for the DL), containing 53 carriers with 48 data carriers, one fixed pilot carrier and 4 variable pilot carriers.

In Table 4.1 a summery of the carrier specification can be seen.

Parameters	Mode 2k	Mode 1k	Mode 256	Mode 64
Number of FFT points	2048	1024	256	64
Usable carriers	1696	848	212	53
Number of subchannels	32	16	4	1
Number carriers per subchannel	53	53	53	53
Guard band	176, 175	88, 87	22, 21	6, 5
Symbol duration	102.4 μs	51.2 μs	12.8 μs	3.2 μs

Table 4.2: The IEEE 802.16.4c four downstream modes. (For the Guard band, the two numbers are the guard interval (number of subcarries) to the left and the right of the OFDM symbol, respectively.)

As mentioned previously, OFDMA is used in the IEEE 802.16 standards, Under the same umbrella the IEEE 802.16.4c proposal, is another example of a OFDMA standard [26]. For the downstream, the standard has the configuration listed in Table 4.2. The standard has four modes (defined by the FFT length). For subcarrier assignment, the standard uses a permutation code that is defined for all four modes. The standard supports data rates of up to 65.4 Mbps, depending on the modulation and code rate used.

4.2 OFDMA-FSCH Based Standards

An OFDMA-FSCH based standard is called "Fast Low-Latency Access with Seamless Handoff (flash) OFDM" [17]. flash- OFDM operates below the 3.5 GHz range and designed for Frequency Division Duplex (FDD) operation. It has a bandwidth of 1.25 or 5 MHz. Subcarriers are separated by 12.5 kHz. This corresponds to a total of 400 subcarriers for 5 MHz bandwidth and 100 for 1.25 MHz bandwidth. The subcarriers are assigned to individual users when they have data to send. Each subcarrier is adaptively modulated [17].

OFDMA-FSCH scheme has been proposed to IEEE 802.20 working group [27]. This scheme is still under development by IEEE 802.20 working group. Similar to flash-OFDM, channel bandwidth is 1.25 MHz. The system parameters are listed in Table 4.2 as follows [27]:

The access intervals are separated from data intervals in the UL. Access intervals have a duration of 0.8 ms, i.e. 8 symbols [27]. Like in flash-OFDM, FDD is used. Adaptive coding and modulation is supported by allowing users to report their channel conditions to the BS. For more details on the frame structures, the reader can refer to [27].

One disadvantage of OFDMA based access schemes is their susceptibility to frequency offset errors. As given in Appendix A, the maximum doppler frequency shift is less than 162 Hz for a vehicle speed of 50 km/h and for a carrier frequency below 3.5 GHz. At the maximum doppler frequency shift, the subcarrier separation of 12.5 kHz as standardized in flash-OFDM corresponds to a relative frequency offset error which is less than 1.3 % for a carrier frequency less than 3.5 GHz. This corresponds to an SNR degradation less than 0.2 dB for QPSK modulation scheme and approximately 1 dB for 64-QAM modulation scheme [28]. The largest constellation in IEEE.802.11, i.e. 64-QAM, can not tolerate beyond

Basic System Description Parameter	Value
Carrier frequency	$\leqslant 3.5$ GHz
Channel bandwidth	1.25 MHz
Subcarrier separation	11.25 kHz
Available subcarriers	113
Symbol duration	0.1 ms
Cyclic prefix Duration	11.1 μs (16 symbols)
Modulation	QPSK or 16 QAM
Peak rates	DL > 4 Mbps, UL > 800 Kbps
Slow subcarrier hopping in UL	tones hop every 7 OFDM symbols
Coding (Low-Density Parity-Check Codes) rates	$1/6$ to $5/6$

Table 4.3: System parameters for OFDMA-FSCH scheme under development by IEEE 802.20 working group

2 % of frequency error [28]. The problem of frequency offset errors can be solved by inserting pilot symbols. However, as the subcarrier separation bandwidth decreases, more pilot symbols are needed to cope up with doppler frequency shift effects.

4.3 OFDMA-SSCH Based-Standards

For the OFDMA-SSCH standard, it refers to *flash* technology [17] (see Table 4.2). In fact, considering the UL for that technology, subcarriers hop once every 7 OFDM symbols, so this kind of subcarrier hopping can be classified as *slow*. The 7 symbols mentioned before are named *dwell time* (among them, one is a reference symbol and the other 6 are data symbols). Since there are no shared UL pilots, data is modulated in each dwell time with the reference symbol.

About UL access, in each *superslot* (11.3 ms long) there is an *access interval* of 8 symbols (that is 0.8 ms). The access intervals are separated from *data intervals* and they are used by access mobiles (which are not yet UL-synchronized) and by existing mobiles (for periodic timing tracking). Concerning signaling (a very important issue whenever it refers about subcarrier hopping), an access signal is a multi-tone signal which provides diversity and timing resolution. The access signals can be detected with low processing complexity. Only this kind of signals are contention-based, after access all signaling is contention-free.

4.4 OFDM-TDMA Based-Standards

The HiperLAN2 standard specifies a radio access network that can be used with a variety of core networks. This is possible due to a flexible architecture based on core-network-independent physical (PHY) and Data Link Control (DLC) layers as well as a set of core-network-specific convergence layers that enable access to different core networks. The standard supports MS mobility of at least 10 m/s. In addition, it includes a means to handle different interference and propagation environments with the aim to provide efficient communication at low signal-to interference power ratios, maintain QoS, and trade off between range and data rate.

The carrier frequency spacing has been selected as 20 MHz to provide a reasonable number of channels in 100 MHz bandwidth [29], which may be the narrowest continuous system bandwidth available,

Data rate (Mbps)	Modulation scheme	Coding rate	Coded bits per subcarrier	Code bits per OFDM symbol	Data bits per OFDM symbol
6	BPSK	$\frac{1}{2}$	1	48	24
9	BPSK	$\frac{3}{4}$	1	48	36
12	QPSK	$\frac{1}{2}$	2	96	48
18	QPSK	$\frac{3}{4}$	2	96	72
24	16-QAM	$\frac{1}{2}$	4	192	96
36	16-QAM	$\frac{3}{4}$	4	192	144
48	64-QAM	$\frac{2}{3}$	6	288	192
54	64-QAM	$\frac{3}{4}$	6	288	216

Table 4.4: HiperLAN2 OFDM PHY Modulation Techniques

for instance, in Japan. In order to avoid unwanted frequency products in implementations the sampling frequency is also chosen equal to 20 MHz at the output of a typically used 64-point inverse fast Fourier transform. The obtained subcarrier spacing is 312.5 kHz. In order to facilitate implementation of filters and to achieve sufficient adjacent channel suppression, 52 sub-carriers are used per channel. 48 sub-carriers carry actual data and 4 sub-carriers are pilots, which facilitate coherent demodulation. The duration of the cyclic prefix is equal to 800 ns, which is sufficient to enable good performance on channels with (r.m.s.) delay spread up to at least 250 ns. An optional short cyclic prefix with 400 ns may be used for short-range indoor applications. These parameters are also shown in Table 4.5.

HiperLAN2 WLAN standard implements a form of OFDM-TDMA in their PHY resource allocation procedure. Along with OFDM-TDMA like reservation based MAC channel, it also has a random access based (i.e. CSMA/CA based) access system. When a user enters into the coverage area of any access point, then the Access-Point (AP) assigns a TDMA/TDD slot to the particular user [29].

The main characteristics of the OFDM-TDMA/Time Division Duplex (TDD) scheme can be summarized as follows [30]:

1. OFDM-TDMA/TDD is realized with a frame duration of 2ms. The OFDM related system parameters are listed in Table 4.5.
2. Several choices of modulation and channel coding is proposed, thus a flexibility in link adaptation is available 4.4.
3. Three possible transmission links are scheduled on TDMA/TDD slots,
   (a) DL: AP to MS
   (b) UL: MS to AP
   (c) Peer-to-peer: MS to MS
4. Centralized scheduling is proposed in the standard,
   (a) AP creates the air interface frame
   (b) MSs requests for resource to be allocated to them.

(c) AP allocates the available resource slots to all the users (and to different transmission links), here the slots of OFDM symbol slots

(d) In both DL and UL, the OFDM-TDMA slots can be allocated dynamically based on CSI knowledge at the transmitter, or via random allocation. Fixed TDMA structure is not mandatory, though it can be implemented for CBR type traffics.

(e) The access technique could consider QoS and link adaptation modes as explained in Table 4.4.

(f) As the resource allocation is done via centralized allocation procedure (i.e. by AP), transmission of data PDU and ARQ PDU happens without any collision.

(g) Because of MS to MS link, peer-to-peer communication and multi-cast communication can be supported.

Each physical layer burst includes a preamble, of which three different types are used for:

1. The broadcast control channel
2. Other DL channels
3. The UL and random access channel

There are a short and a long preamble for the UL channel. The preamble of the optional direct link bursts is identical to the long UL preamble. The preamble in the broadcast control channel enables frame synchronization, automatic gain control, and frequency synchronization as well as channel estimation. In contrast, the preamble in the DL traffic bursts is designed for channel estimation only. The UL traffic bursts and random access bursts enable channel estimation and frequency estimation. Consequently, there are several preambles with different structures and lengths. A detailed description can be found in [31].

Table 4.5: OFDM System Parameters in HiperLAN2 standard

OFDM subcarriers, N	64
Data subcarriers, N_{data}	48
Pilot subcarriers, N_{pilot}	4
Null subcarriers, N_{null}	12
CP length, N_{CP}	16
OFDM Symbol Duration, T_s	4μs
Useful data period, T_{data}	3.2μs
CP period, T_{CP}	0.8μs
Data Symbol mapping	QAM
Pilot Symbol mapping	BPSK
Channel coding scheme	$\frac{1}{2}$-rate Convolutional coding
System bandwidth	20MHz
Carrier frequency	5.4GHz

Chapter 5

Conclusion

In this report, we have presented the basics about multi-carrier based multiple access techniques. Three basic schemes are considered for the description. Indeed, several variants of the basic schemes can be derived. Also, hybrid schemes based on amalgamation of the basic schemes can be found in literature. For more interested readers, we suggest to look into the appropriate references.

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Appendix A

Time and Frequency Selectivity of Wireless Channel

A.1 Coherence Bandwidth

If the coherence bandwidth is defined as the bandwidth over which the frequency correlation function is above 0.9, then the coherence bandwidth is approximately, $B_c^{0.9} = \frac{1}{50\tau_{rms}}$, where τ_{rms} is RMS delay spread [32, Section 4.4.2]. If the definition is relaxed so that the frequency correlation function is above 0.5, then the coherence bandwidth is approximately $B_c^{0.5} = \frac{1}{5\tau_{rms}}$ [33]. Based on this two, we can define the values for coherence bandwidth as shown in Table A.1.

RMS delay spread	50% Coherence bandwidth	90% Coherence bandwidth
τ_{rms}	$B_c^{0.5}$	$B_c^{0.9}$
50 ns	4 MHz	400 kHz
100 ns	2 MHz	200 kHz
200 ns	1 MHz	100 kHz
0.5 μs	400 kHz	40 kHz
1.0 μs	200 kHz	20 kHz
3.0 μs	66.67 kHz	6.67 kHz
5.0 μs	40 kHz	4 kHz

Table A.1: Channel coherence bandwidth with respect to different RMS delay spread

A.2 Coherence Time

Coherence Time (T_c) is a measure of the time-variance of a channel. If the coherence time is defined as the time over which the time correlation function is above 0.5, then the coherence time is approximately $T_c^{>0.5} = \frac{9}{16\pi f_m}$, where f_m is the maximum Doppler shift given by $f_m = \frac{v}{c} f_c$ [32, Section 4.4.3]. Here v, c and f_c are user velocity in kmph, speed of light in m/s and carrier frequency respectively.

A less strict definition of the coherence time is to define it as the time over which the time correlation function is 0.5, that can be obtained by the geometric mean of $T_c^{>0.5}$ and $T_c = \frac{1}{f_m}$, giving $T_c^{0.5} = \sqrt{\frac{9}{16\pi f_m^2}} = \frac{0.423}{f_m}$.

	2.4GHz			5GHz		
υ, kmph	f_d, Hz	$T_c^{0.5}$, ms	$T_c^{>0.5}$, ms	f_d, Hz	$T_c^{0.5}$, ms	$T_c^{>0.5}$, ms
3	6.6672	63.466	26.855	13.9	30.442	12.881
10	22.224	19.040	8.057	46.3	9.139	3.867
20	44.448	9.520	4.028	92.6	4.570	1.934
50	111.12	3.810	1.611	231.5	1.828	0.773
100	222.24	1.904	0.806	463.0	0.914	0.387
150	333.36	1.269	0.537	694.5	0.609	0.258
200	444.48	0.952	0.403	926.0	0.457	0.193
250	555.6	0.762	0.322	1157.5	0.366	0.155

Table A.2: Channel coherence time at 2.4 GHz and 5 GHz with respect to receiver mobility