OFDMA for the 4th Generation Cellular Networks

Gholamreza Parsaei, Iran Telecommunication Research Center, Tehran, Iran
Abdulrahman Yar-ali, Murray State University, KY, USA

Abstract—an extended overview on the Orthogonal Frequency Division Multiple Access (OFDMA) technique and its applications in the 4th generation cellular mobile networks is presented in this paper. After introducing the main idea, a comparison between the performance of OFDMA and other multiple access systems is carried out. Moreover, some practical notes for the system deployment are discussed. Finally, two standardized telecommunication systems—that use OFDMA as air interface—are introduced and their basic parameters are compared.

I. INTRODUCTION

It can be claimed that telecommunications science and its related industry were the most-evolving area of technology in the last decade. The Internet has been growing exponentially, from both the number of users and the amount of information content points of view during these years. Moreover, 2.5G mobile communication systems have been rolled-out in many countries and 3G systems are in the last steps of implementation. At the same time, a new field called Fourth Generation (4G) is going to raise on top of the most important research issues. These developments, together with an increasing growth in scientific, military and entertainment applications have been resulted in a huge need for high-speed and reliable wireless systems, such that almost none of the today’s technologies would be able to fulfill these demands in near future.

As mentioned above, many of standardization organizations and research institutes have concentrated their efforts on 4G wireless systems since a few years ago. The most important goal in development of 4G systems is to integrate all existing wireless technologies, including cellular networks, WLANs, WPANs, even broadcasting systems like DVB and DAB, and build up a new seamless IP-based infrastructure to control and manage all of them. However, 4G cellular systems would have to be able to offer new exciting multimedia services with superb quality, which means with highest bit-rate and lowest bit error rate. For instance, the system must provide a bit-rate near 20Mbps with less than 10^-6 BER for the transmission of high quality audio-visual signals.

Today it is proved in practice that traditional radio interface systems, like TD/FDMA or even CDMA are not capable to provide required criteria because of their inherent limitations. That is why a large amount of research efforts in the field of radio communications is focused on multicarrier transmission methods and these techniques are now considered as the only way to support future demands.

Amongst various multicarrier radio transmission systems, Multi-Carrier CDMA (MC-CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) are the two most important methods for cellular wireless telecommunication industry, due to their ability to support multiple users in a cellular mobile network. Both MC-CDMA and OFDMA are combinations of well-known CDMA and OFDM systems; and both of them are taken into account as parts of UMTS standard. Moreover, these multiple access techniques are being studied as the most likely options for the radio interface of future 4G cellular systems.

In this paper, we present an overview on OFDMA principles and its implementation challenges. In short, OFDMA is the multi-user scheme of OFDM modulation method, in which a certain number of total system subcarriers is assigned to each user, based on their requirements.

Although the primary introduction of OFDM goes back to more than 30 years ago, OFDMA is actually a new idea. It was first presented in a paper by M. Wahlqvist et al. In 1996 [3]. After introducing the main idea and discussing some details, the authors proposed an interesting implementation of a typical OFDMA system, adapted to UMTS system requirements. This proposal was later accepted in standardization forum without any considerable changes and is now a part of 3G standard.

The rest of this paper is organized as follows:

In section II we will introduce principles of OFDM briefly and study the basic approach for converting it to a multi-user system. Some additional techniques for improving the performance of this system are also presented. In section III, OFDMA system performance is compared to other multiple access schemes, like TDMA, FDMA, single carrier CDMA and MC-CDMA. Section IV discusses some major problems, which one may face during the deployment of an OFDMA-based radio interface, such as synchronization, power amplifier design, cyclic prefix and last but not least, subcarrier allocation to meet BER and capacity demands. In section V the reader will become familiar with some standardized systems that are currently using OFDMA as the radio interface and their basic parameters. Finally, section VI concludes the paper.

II. OFDM AND OFDMA BASICS

A. OFDM

OFDM is one of multicarrier transmission methods and perhaps, the most important between them. In OFDM, every portion of input data is transmitted on one of available subcarriers. In this view, OFDM seems very similar to traditional FDM systems. However, contrary to FDM, the spectrum of OFDM subcarriers can interfere to each other. Therefore, there is no need for wide guard bands to provide reliability, as was in FDM. However, in order to be able to restore the transmitted symbols in the receiver, subcarriers should be located in frequency domain such that the energy of the interference caused from each subcarrier becomes exactly zero at the central frequency of the others (See figure 1). Therefore, the signal modulated on each subcarrier is “orthogonal” to others and the data can be restored successfully at the receiver.

Although primary OFDM systems needed a large number of very accurate oscillators (and that is why they could not come in use rapidly), but the development of digital signal processing techniques made it possible to implement OFDM transmitters and receivers using IFFT and FFT algorithms, respectively, and considerably reduce the hardware complexity.

A simplified block diagram of an OFDM system is shown in Figure 2. The transmitter first divides the high-rate input data stream into a number of low-rate streams using a serial
to parallel converter (S/P), each of which will be transmitted on one subcarrier. Individual bits are then grouped properly and mapped into QAM symbols. An IFFT block transfers the frequency domain symbol set (i.e. QAM symbols) into a set of time domain samples, called an OFDM symbol. Finally, a cyclic prefix (CP) is added by repeating a portion of the symbol’s tail at its head, in order to prevent symbol. Finally, a cyclic prefix (CP) is added by repeating a portion of the symbol’s tail at its head, in order to prevent it against inter-symbol interference (ISI) and inter-channel interference (ICI). At the receiver, first, the CP is eliminated since it carries corrupted data, then the time-domain symbol is converted to a set of noisy QAM symbols in frequency domain, using FFT algorithm. QAM symbols are passed through a detector (e.g. a hard limiter) and mapped to the binary space to obtain data bits. Finally, a parallel to serial converter (P/S) combines the resulted bit streams and restores the original sequence.

The OFDM mathematical background is widely available in literature. See, for example, [1-3] for studying basic formulation and properties of the system, [4-7] for some details such as channel estimation and synchronization, and [8-10] to know more about the mechanism of interference rejection by cyclic prefix.

B. OFDMA

OFDM can be easily utilized as a multiple access technique, namely OFDMA. This is done by dividing the total FFT space into a number of subchannels. A subchannel (SC) is a subset of available subcarriers that are assigned to a user for data exchange. Users may also occupy more than one subchannel, upon their Quality of Service (QoS) profiles and system loading characteristics.

Figure 3 depicts two possible scenarios for establishing subcarrier groups. The first scenario groups subcarriers in the same frequency range in each subchannel, whereas in the second, subchannels are spread over the total bandwidth. It is clear that the second scenario is more advantageous, especially in frequency selective fading channels, since a deep narrow-band fade can affect only a little fraction of subcarriers in each subchannel.

Although the principle idea of OFDM seems very simple, it is not usable in many applications because of its serious disadvantages. For example, it is likely in practice that a number of subcarriers, which are allocated to a user, have a very low signal to interference plus noise ratio (SINR) and cause the system performance to drop dramatically from this user’s point of view. Moreover, traditional OFDMA system uses the same modulation scheme on every subcarrier for simplicity. The overall system throughput can be improved significantly by selecting the signal constellation size for each subcarrier based on its SINR value.

Here we will introduce three approaches to enhance the performance of an OFDMA system, namely random frequency hopping (FH), adaptive FH, and adaptive modulation.

Random Frequency Hopping
An OFDMA system, in simplest form, assigns each user a predetermined subset of available subcarriers. However, as stated before, the received signal power on some subcarriers may drop down randomly due to interference or channel fading. Thus the users, to whom these low-SINR subcarriers are assigned, would experience a very low signal quality or even may lose the connection to the network. In such situation, a few number of users observe a poor transmission reliability (e.g. BER>10^{-2}), even though the overall system performance is too high (e.g. BER<10^{-6}). Therefore, the operator cannot guarantee a higher quality of service for the users. In other words, the performance of a simple OFDMA system is restricted to the worse case of signal quality, not to its average.

This problem can be overcome by hopping in-use subcarriers in certain time intervals. This, in fact, converts OFDMA to a FH-CDMA system. [] suggests to transmit the subcarrier groups in short time slots and frequency-hop them randomly to ensure that it is very unlikely to assign a low-SINR subcarrier to a particular user during a long period of time.

This also improves frequency diversity, because each user utilizes the whole system bandwidth. Moreover, since none of the users suffers from very low-SINR subcarriers for a long time, all users would have the same share of strong and weak subcarriers. Therefore, the FH-OFDMA system performance depends on the average received signal power, not on the worst case []. This advantage is common in all CDMA systems and is usually called “interference averaging.” Note that the user might be unable to recover the data sent on low-SINR subcarriers. However, since it is too easier to recover short-time outages rather than long-time ones by error control coding, a combination of coding and frequency hopping is usually used in practice to
minimize the BER and restore the data that is lost due to fading.

Another important benefit of FH-CDMA compared to DS- or MC-CDMA is its ability to remove intracell interference completely. This can be done by using orthogonal hopping sequences. In general, when the system has N subcarriers, it is possible to construct N orthogonal hopping patterns. Some rules for generation of such hopping patterns are introduced and discussed in [1].

**Adaptive Frequency Hopping**

A new FH technique is proposed in [1], in which remote stations help the system in FH-management process, by providing a feedback from channel condition. After the radio channel has been characterized based on the received information, each user is assigned a group of subcarriers that have the highest SINR for him. Because different users are located in different positions, they are likely to observe different channel responses at the same time. Therefore, it is usually possible to determine the best subcarriers for nearly all users without any considerable conflict.

Simulation and experimental studies have shown that adaptive FH (AFH) increases the received signal power significantly ($5^{th}$ to $20^{th}$) and is able to fill almost all deep valleys in channel frequency response. Figure 4 shows the result obtained from a practical implementation of a single-user adaptive FH-OFDM system that has been performed in James Cock university in 1993 [1]. In figure 4(a), light areas show those points in time- (or distance-) frequency plane that have relatively high SINR, whereas dark areas show deep notches in frequency domain, when the mobile station is moved through a certain path. Circles are used here to show which subcarriers are assigned to the user in each point of the path. It can be easily seen that system has selected the strongest subcarriers at any moment and assigned them to the user. Figure 4(b) shows the average received power as a function of distance from the starting point of movement. Clearly, AFH system is able to protect the signal against frequency selective fading, by not contributing faded subcarriers in the data transfer process. (See more detail about this experiment in [1]).

Using AFH, however, causes some extra costs for the system. For example, computational complexity for both mobile and base stations will be increased, since the MS must analyze channel frequency response rapidly and the BS has to execute a more complex algorithm for channel allocation. In addition, the MS should send channel condition reports to the BS and this, in turn, will increase control data exchanges in the network.

**Adaptive Modulation**

Ordinary OFDM systems use the same modulation scheme on all subcarriers for simplicity. However, there is no theoretical limit if one designs the system such that it uses different signal constellation sizes on different subcarriers. This type of OFDM systems are said to have adaptive modulation, because the system usually selects the modulation method based on the channel characteristics. Therefore, adaptive modulation can be used in any OFDM(A) system to increase the system reliability and spectral efficiency. There is always a tradeoff between the spectral efficiency and error probability when choosing a higher or lower modulation size. Higher order modulations, such as 64-QAM, map a larger number of data bits onto a single QAM symbol, thus provide a high spectral efficiency. However, given a constant average signal power, using a higher order modulation increases the error probability, because the distance between adjacent QAM symbols decreases. Optimization is achieved by choosing highest order modulation scheme that fulfills a criterion, e.g. maximizing channel capacity or minimizing the BER.

Several methods with different criteria are proposed for such optimization. These methods are also referred to as “bit allocation” or “system loading” algorithms in the literature. [1] outlines three possible approaches for adaptive modulation.

The first approach selects the modulation scheme for each subcarrier (or a group of them) by thresholding the SNR value of that. For example, subcarriers with $\text{SNR} < T_1$ are left unused, those with $T_0 < \text{SNR} < T_1$ are assigned 1 bit (BPSK modulation), and so on. The $T_i$ values can be computed based on channel condition and other system parameters, such that the target criterion is fulfilled. The second approach considers the BER of each subcarrier as the optimization criterion. In this approach, the highest modulation order, whose BER is lower than a predetermined threshold, is assigned to each subcarrier. Finally, the third approach defines a state model to select a

![Figure 4. Adaptive Frequency Hopping (a) Subcarriers of highest signal power are allocated for data transfer, (b) Frequency selective fading is virtually eliminated using AFH.](image-url)
modulation scheme that provides the lowest possible BER, when the system throughput is fixed.

As stated, the constant throughput algorithm (the 3rd one) shows a significant superiority over the two others. Some other bit allocation algorithms can be found in [1].

Besides its extensive advantages, adaptive modulation has some costs. This technique is applicable only in duplex transceivers, since the transmitter must have accurate information about the channel condition. In addition, channel estimation has to be performed by the receiver and a larger amount of overhead signals must be sent in the reverse link, in order to provide the transmitter with necessary knowledge about the channel. Furthermore, systems using adaptive modulation are more sensitive to distortion, frequency errors, and some other parameters. See [1] for more detail about this matter.

III. OFDMA SYSTEM PERFORMANCE

As any other multiple access technique, OFDMA has some advantages as well as some weak points. A number of beneficial properties of OFDMA that leads to the recent interest in this technique are listed below:

- OFDM(A) transceivers are easily implemented using FFT and IFFT algorithms.
- Combines nearly all multipath elements without need for sophisticated RAKE structures at the receiver.
- Transforms the frequency selective fading channel to a large number of flat fading subchannels, which are much easier to equalize. Usually 1-tap equalizers are used.
- The division of the signal to a large number of more or less independent channels will provide the flexibility needed for all foreseen future multimedia services (variable bit rate with different quality of services).
- OFDM(A) signals have sharp edges in the frequency domain, i.e. have a near-rectangular shape, especially when a large number of subcarriers is used.

On the other hand, OFDM(A) has some Achilles' heels that must be considered very carefully during the system designing procedure, because even an imperceptible error in these points may cause a large negative impact on the system performance. Synchronization and power amplifier design are two such sensitive points.

Although it is difficult to find the proper criteria and perform a fair comparison between different radio access systems, we want to compare OFDMA with other single- and multicarrier multiple access techniques. This comparison will be carried out from different points of view, like robustness against radio channel conditions and interference, channel capacity, peak to average power ratio (PAR), multiple access interference generation and so on.

In figure 5 (adapted from [1]) the bit error rate (BER) of a single carrier system like TDMA is compared to that of a fixed and adaptive modulated OFDMA, assuming a non-line-of-sight (NLOS) radio channel between the MS and the BS. As seen in this figure, uncoded OFDMA system with fixed modulation has a larger BER than TDMA in frequency selective channels, since the data is not spread over the whole bandwidth. However, adaptive modulation improves the system performance due to the choice of signal constellation size according to channel frequency response.

Figures 6(a) and 6(b) show the impact of user mobility on the performance of single carrier and OFDMA systems respectively. The BER is sketched in these figures, respect to the user's velocity in an NLOS environment. Clearly, adaptive OFDMA outperforms the single carrier system. For instance, the BER value of $10^{-6}$ at $v=0\text{m/s}$ is obtained in $31.7\text{dB}$ by OFDMA, while the single carrier system in similar conditions must have a much larger C/I value, i.e. nearly $41\text{dB}$ to get the same BER. In addition, at $v=2\text{m/s}$ the steady state BER values become $10^{-5}$ and $1.6\times10^{-4}$ respectively in single carrier and OFDMA systems.
Therefore, there is almost one-decade gap between the BER of adaptive OFDMA and a single carrier system. Figure 7 compares OFDM and CDMA in terms of system performance, assuming two different values of user velocity, i.e., 50 and 350 km/h. Here, we assume that the CDMA system uses a RAKE receiver that combines all multipath elements. It is also assumed that the spreading factor is 16 and all spare spreading codes are in use by other users. The main factor that leads the CDMA system to be outperformed by OFDM is multiple access interference (MAI), which is caused because the spreading codes are not exactly orthogonal and have non-zero cross correlation values. Figure 8 demonstrates the impact of MAI by comparing the system performance of a CDMA system with MAI (3 active users) and without MAI (only 1 active user). The BER values of coherent and differential OFDM systems are also included in figure 8. In the absence of MAI, the CDMA system shows a better performance than OFDM. However, since the RAKE receiver is unable to eliminate MAI although its complexity, this type of interference has a large negative impact on the CDMA system.

Large values of peak to average power ratio (PAR) is another problem with OFDM(A) signals. This constrains us to use power amplifiers that are linear in a wide range of input values. Such amplifiers are very difficult to design and very expensive, as well. This problem can be solved using some channel coding methods and/or clipping the signal peaks, but these solutions will increase the complexity or decrease system performance in turn. Figure 9 shows the PAR values for an OFDM system with 256 subcarriers and three CDMA systems with SF=16, 64 and 256. It can be seen that CDMA does also suffer from high PAR. Note that large PAR values are the case in both up- and downlink in OFDM systems. By contrast, in CDMA, this is true only for the downlink, because in the uplink, each user transmits only his own signal.

Channel capacity for TDMA, CDMA, and OFDMA radio interfaces are compared in figure 10. TDMA and CDMA systems can hold the channel capacity constant at 100% until the C/I ratio is above a certain threshold, but the capacity drops rapidly when the C/I comes down the threshold. Conversely, OFDMA benefits from “soft capacity” property, which implies that the channel capacity declines slowly when C/I is lowered, and finally becomes zero at very low C/I values. This advantage can make OFDMA system very flexible and robust against different channel conditions.

[] has performed a conceptual comparison between OFDMA and MC-CDMA, briefly mentioning some of the basic similarities and differences between this two techniques. The most important difference between OFDMA and MC-CDMA is that in an OFDMA system, users, who are located within the same cell area, use a certain subset of available subcarriers, while in MC-CDMA, all subcarriers are simultaneously assigned to all users. MC-CDMA systems use orthogonal or near-orthogonal spreading codes to distinguish each user’s signal from that of the others. [...] “... Because of code distortion by multipath fading channels, however, MC-CDMA loses its orthogonality in the uplink even for a single cell. This makes rather complicated equalization.
techniques necessary, which introduce a loss in SNR performance and diminish the complexity advantage of OFDM over single-carrier techniques”. In contrast, by using OFDMA as the air interface, one can completely prevent intracell interference, which is the source of a considerable fraction of the total interference in a typical cellular system. Since the capacity of a CDMA system is inversely proportional to the total amount of interference power, OFDMA can provide a maximum capacity gain of 2.8 when compared to a DS- or MC-CDMA system.

In addition to its simplicity and inherent capabilities, OFDMA inherits many advantages from CDMA when these two systems are combined. For example, FH-OFDMA benefits from “interference averaging” property, which helps to decrease unnecessary fade margins. Moreover, OFDMA is capable of doing soft-handoff, which makes the radio links more stable, improves the system capacity, and offers the operator a bigger degree of freedom in sharing available resources between cells. This phenomenon, along with some other issues about OFDMA system implementation is discussed in the following section.

IV. IMPLEMENTATION ISSUES

In this section, we are going to discuss some important notes that should be considered when one is designing an OFDMA based air interface. Some of these points, such as CP length reduction, are optional and the designer may use them to improve the system performance or throughput, whereas the others, like power control and synchronization, are necessary for the system to work properly.

A. Cyclic Prefix

As mentioned in section II, in order to mitigate the harmful impacts of the multipath channel, a fraction of the OFDM symbol should be copied from its tail to its head. This part of the OFDM symbol is usually called “cyclic prefix” (CP) or “guard interval” (GI). CP also simplifies the synchronization process for the receiver. To completely prevent ISI and ICI, the CP has not to be shorter than the channel delay spread. On the other hand, the CP does not contain usable information, since it is subject to the interference caused by multipath channel. Therefore, it is a redundant part of the transmitted signal and reduces the data throughput.

Recently, in many high performance data transmission systems, such as 4G cellular networks, the system uses a CP shorter than the delay spread, and tries to minimize the resulted interference power by means of a time domain equalizer (TEQ). This technique is considered especially when the delay spread is so large that using a standard CP would cause a dramatical drop in the system throughput. Both linear- and decision feedback equalizer (DEF) can be used for this purpose.

[] studies the impact of inserting non-sufficient CP on OFDM signals and developed them mathematical formulation for ISI and ICI.

A number of proposed methods for designing linear and decision feedback equalizers can be found in [] and [] respectively.

B. Peak to Average Power (PAP)

An OFDM signal is the sum of a number of independently modulated subcarriers. Such signals, naturally, have a large PAP ratio. In general, when N sinusoidal waves with the same phases are summed, the resulted peak power will be N times larger than the average power.

The larger PAP values for a signal are, the more complex D/A and A/D converters, as well as power amplifiers, will be needed. Therefore, the transmitter must use some special techniques to reduce the PAP ratio. These techniques are essentially divided into three categories: 1) Signal distortion methods, like clipping, windowing, and peak removal; 2) Using some channel coding algorithms that reduce the probability of generating high PAP symbols, along with error control; and 3) Scrambling methods, that are basically similar to the second category, except that scrambling codes do not have the error detection or correction capability. The scrambler combines the OFDM symbol with a number of scrambling codes, one by one, and selects the output sequence with the lowest PAP ratio for transmission.

Each of these methods has its advantages and disadvantages. For more detail, see related papers, such as [].

C. Soft Handoff (SHO)

SHO is one of the most important capabilities, which are common between OFDMA and CDMA systems. To perform a SHO procedure between two neighbor cells in an OFDMA system, identical sets of subcarriers should be simultaneously used in both involving base stations. Thus, in the downlink, the mobile set will receive the sum of two signals with the same data content. More technically speaking, due to multipath, the MS will observe time-shifted copies of the signal, that are originated from both BS’s. However, the MS is not able to distinguish the two different base stations. In fact, SHO appears just as adding extra multipath components to the received signal, hence improves diversity.

Similar to DS-CDMA, there is no need for additional hardware, nor extra signal processing at the receiver, for SHO in OFDMA systems. However, this type of handoff makes the system limited in some areas. For example, exactly the same set of subcarriers must be used in both BSs during the SHO process, and the two BSs have to be precisely synchronous, such that the delay differences of two BSs are well within the guard time of the OFDM symbols [].

D. Synchronization

Synchronization in OFDM(A) systems includes three consecutive processes: Symbol timing acquisition, frequency offset estimation, and phase tracking. Figure 11 shows the block diagram of an OFDM synchronizer.

Let us begin with the first step, i.e. synchronization in time domain. Since the guard interval of each OFDM symbol is repeated at its both head and tail, the autocorrelation function of the symbol has a sharp peak at its starting time sample. So an autocorrelator can be easily used to perform acquire symbol start time. This step also can be done by inserting PN sequences in the symbol preamble, as stated in [].

Figure 11. Simplified structure of an OFDM receiver. Shaded blocks are involved in synchronization process (Adapted form []).
When the first step is passed, the frequency offset (FO) of every subcarrier should be estimated and then, compensated for. Note that the frequency offset has much more damaging effect in multicarrier compared to single-carrier systems, because in multicarrier transmission, the channels are narrow-band and overlap with each other. Thus a bit error in frequency-domain synchronization may result in completely loss of orthogonality. To obtain a reasonable BER, the maximum frequency offset on each subcarrier should not exceed 1% of the frequency spacing between two adjacent subcarriers.

Several algorithms for FO estimation are presented in the literature (See [ ] for example). However, a straightforward way for estimating FO is to use two pilot symbols equal to each other, but shifted by \( \Delta \pi t \) (the length of the guard interval) samples. Such pilot signals will appear very similar in time domain, except for a factor of \( e^{j2\pi f_g t} \), which is, in fact, a phase difference proportional to the FO \( \Delta \pi \). So a rough estimate for FO can be simply computed, giving this value.

Once the FO is estimated and compensated for, the synchronizer should start the phase tracking process, to track the FO changes caused by the time varying channel, also minimize the residual error of the primary estimation. Digital phase locked loops (DPDLL) are extensively used to track the FO variations, and phase noise as well. Using pilot symbols is another popular method for post-initial synchronization in frequency domain. See [ ] for more detail on this topic.

### E. Subcarrier and power allocation

The media access control (MAC) layer in cellular structures is in charge of arranging a suitable regime for allocating available radio resources to the users, such that their requirements are fulfilled and at the same time, the time and frequency resources are used with the maximum possible efficiency.

Radio resources of an OFDMA system include time (timeslots), bandwidth (subcarriers), signal space size (number of bits carried by each subcarrier) and transmission power. A wide variety of resource allocation algorithms for OFDMA are proposed by now, taking into account different criteria and approaches. [ ], as a good example, expresses a straightforward formulation for the resource management in a fixed modulation cellular OFDMA system. It also presents a straightforward scenario for the MS and BS negotiation on quality of service (QoS) before the service being offered to the user.

According to this scenario, each user first submits his requested QoS profile to the network. Requested QoS profile for the \( i \)th user is defined as \( rQoS_i=rRbu_i-rBER_i \), where \( rRbu_i \) is the requested bit rate and \( rBER_i \) shows the maximum acceptable bit error rate. In other words, a QoS profile describes the data throughput and the reliability requirements for the specified user. The network will then reviews all submitted profiles, considering the amount of existing resources, and returns an offered QoS profile, \( oQoS_i \), together with a cost of service, CoS, to each user. If user accepts one of these \( oQoS_i \) profiles, a contract will be signed between him and the network, and the communication begins.

Knowing the radio channel frequency response and signal to noise ratio (SNR) separately for each user, subcarriers can be allocated such that the cost of service, i.e. the total transmit power is minimized. This kind of formulation is, however, too simple. Many more parameters - such as bit allocation to subcarriers, the probability of arriving new users to the cell and so on – have to be added to this scenario to make it a practical one.

After all, it should be mentioned that power control process in OFDMA is not as critical as is in CDMA, because OFDMA provides orthogonality by frequency division, not by code division. Therefore, imperfect power control could not destroy the multiple access basis in OFDMA. In any case, a precise and robust power control system would not only optimizes the energy consumption, but also minimizes the inter-cell interference, hence improves the overall system capacity.

### V. OFDMA IN THE REAL WORLD

UMTS, the European standard for the 3G cellular mobile communications, and IEEE 802.16, a broadband wireless access standard for metropolitan area networks (MAN), are two live examples for industrial support of OFDMA. Table 1 shows the basic parameters of these two systems.

UMTS divides the total spectrum, which can be between 100kHz to 1.6MHz wide, into 100kHz bandslots. Each bandslot is then divides into 24 subcarriers with 4.16kHz spacing. Differential and coherent QPSK and 8-PSK modulation schemes are supported by the UMTS standard. Frequency hopping is performed on a bandslot basis every 1.14msec.

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<th>Table 1. OFDMA system parameters in the UMTS and IEEE 802.16 standards</th>
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<tr>
<td><strong>UMTS (Cellular)</strong></td>
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<tr>
<td>System bandwidth</td>
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<tr>
<td>Number of subcarriers</td>
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<tr>
<td>Subcarrier spacing</td>
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<tr>
<td>Number of Subcarriers / Band-unit</td>
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<td>Modulation time</td>
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<td>Guard time</td>
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<td>Frequency hopping</td>
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<td>Max. Data throughput</td>
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No frequency planning is required for this system, so an effective reuse factor of 1 can be considered for cell designation. GSM Backward compatibility is provided, since the GSM time and frequency units are integer factors of OFDMA units. Another advantage is that this system requires only 100kHz of bandwidth to be deployable, so the operator can use it in the areas with sparse spectrum. Considering all these advantages, OFDMA seems to be a powerful and flexible choice for the air interface of high-speed cellular mobile networks.

IEEE 802.16 does also divide its total 6MHz bandwidth into 32 subchannels. Each subchannel includes 32 subcarriers and is spread over the whole bandwidth, as is shown in figure 3(b). Three modulation schemes, QPSK, 16-QAM and 64-QAM, are supported by the standard. Space-Time processing, turbo coding, adaptive modulation, random frequency hopping and other techniques for performance improvement are applicable in this system. See [] for more detail.

VI. CONCLUSION

In this paper, we presented an overview on orthogonal frequency division multiple access and the way it can be used in cellular telecommunication networks. OFDM principles were first introduced, then we study the basic concept of OFDMA, as a multi-user version of OFDM. As we stated in section II, OFDMA in its simplest form is not an efficient technique, mainly because of its low frequency diversity. Therefore, it must be equipped with other techniques, like random- or adaptive frequency hopping, adaptive modulation, channel coding, etc., to become usable in practical systems.

In the third section, we compare OFDMA and other multiple access systems, such as TDMA, single- and multi-carrier CDMA. This comparison shows that OFDMA outperforms other multiple access methods from several aspects, but also have some sensitive points that must be considered very carefully in the system design process.

Section IV presented some other feature, which can help the system designer build up a much more efficient and robust radio interface. synchronzation, peak to average power reduction, CP shortening and soft handoff in OFDMA are discussed in this section.

Finally, we introduce two standardized telecommunication systems, namely UMTS (a European standard for the 3G cellular mobile communications) and IEEE 802.16 (a broadband wireless access technology for WMAN networks), both supporting OFDMA in the air interface, and briefly compared the most important parameters of these systems.

REFERENCES