OFDMA in the Field: Current and Future Challenges

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ABSTRACT

OFDMA will be the predominant technology for the air interface of broadband mobile wireless systems for the next decades. In recent years, OFDMA-based networks based on IEEE 802.16, and increasingly also on 3GPP LTE are rolled out for commercial use. This article gives an overview of the main challenges for the deployment and operation of state-of-the-art OFDMA networks, along with an outlook into future developments for 4G and beyond 4G networks.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Wireless Communications; C.2.3 [Computer Communication Networks]: Network Operations

General Terms

Design, Standardization, Algorithms, Management

Keywords

OFDMA, WiMAX, LTE, Radio Resource Management, Deployment, Network Operation, Survey

1. INTRODUCTION

Orthogonal Frequency Multiplex Division (OFDM) and the corresponding multiple access scheme OFDM-Access (OFDMA) is the result of an evolution spanning decades of digital transmission techniques and advances in the digital signal processing methods and technologies [1]. Initial applications of OFDM were used for broadcast systems. First, it was adopted for digital radio and video broadcasting standards in Europe for the Digital Audio Broadcasting (DAB) system in 1995 and the Digital Video Broadcasting-Terrestrial system (DVB-T) in 1997. Soon after, OFDM technology found its way into wireless standards such as IEEE 802.11a for wireless LAN and the European HiperLAN project in 1999, IEEE 802.16 in 2001 and Mobile WiMAX in 2005. Today OFDMA is selected for all future broadband wireless systems in recognition of its proven advantages for broadband wireless transport.

In this article we focus on one of the main applications of OFDMA technology as air interface technology for current and future mobile wireless broadband access systems. The next section provides a brief overview of the evolution of mobile communication systems towards OFDMA and an introduction of the basic principles. In the remaining part of the article, we present challenges faced in the deployment of such systems in the field and we look at some of the solutions used to defuse these challenges. Furthermore, we will give a glimpse at the candidates for 4th generation (4G) mobile communication systems and look into future developments beyond 4G.

2. OFDMA-BASED BROADBAND WIRELESS ACCESS SYSTEMS

Historical sketch

Mobile communication is constantly evolving to meet the increasing demand for access capacity. Figure 1 gives an overview of some of the access technologies and standards implemented in the evolution from the first digital mobile communication systems GSM (Global System for Mobile Communications) and IS-95 (Interim Standard 95) to the true broadband wireless access systems 3GPP LTE (Long Term Evolution) and WiMAX. (Worldwide Interoperability for Microwave Access) The figure also illustrates that the initial diversity of access schemes (TDMA, FDMA and CDMA in different variations) converges towards OFDMA as the only relevant multiple access technology.

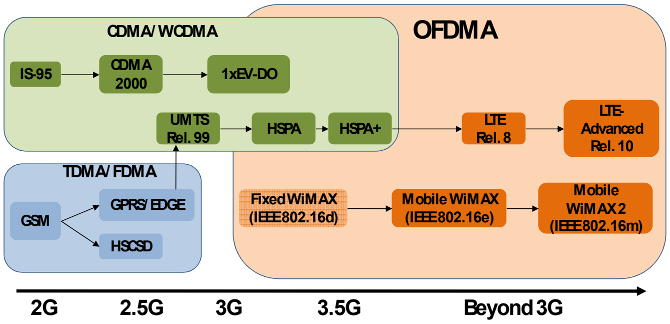

Figure 1: Evolution of mobile cellular systems towards OFDMA

OFDMA was first introduced as an air interface technology for broadband wireless systems with the WirelessMAN-OFDMA air interface of IEEE 802.16d in 2004 [2]. Although initially designed for fixed wireless applications, enhancements for mobility support in IEEE 802.16e [3] transformed WiMAX in 2005 into Mobile WiMAX, and therefore into an alternative for established mobile cellular technologies like UMTS and 1xEV-DO. Consequently, 3GPP started in 2005 to develop an evolution of the Wideband CDMA based UMTS standard, called the “Long Term Evolution”. 3GPP LTE Rel. 8 [4] was completed in 2008, and is the foundation for the current development efforts for LTE networks.

OFDM and OFDMA principles for wireless broadband access networks

The basic OFDM principle is to utilize orthogonal subcarriers in frequency for data transmission. The wideband wireless radio channel with frequency-selective fading is thus turned into a set of narrow-band channels (the subcarriers) with flat fading. Each data symbol is then transmitted on one subcarrier, making it resilient against multipath propagation. Further advantages of OFDM are the very efficient spectrum usage and, with digital signal processing being cost-effective and flexible, also low-complexity application of the MIMO principle. The interested reader is pointed to a wide body of literature in these areas [5].

OFDMA as implemented by WiMAX and LTE allocates a number of time/frequency resources to specific users. In order to keep the overhead at a reasonable level, the time/frequency resource grid is subdivided into logical basic resource units which consist of subbands in frequency and one or more OFDM symbols in time domain. A subband comprises several subcarriers. The basic resource units are then mapped to the physical OFDMA frame as illustrated in Figure 1. If the subcarriers and symbols are permuted in frequency and optionally additionally in time (distributed scheme), the data is spread over the carrier frequency, such that frequency diversity is exploited. This reduces the probability that a whole data block is dropped due to frequency selective fading or interference in a subband.

In contrast, in the contiguous permutation scheme the logical resource units are mapped one to one to the corresponding physical subcarriers. This allows for exploitation of multi-user diversity by frequency-selective scheduling. However, inter-cell interference must then be avoided by frequency partitioning or by coordination schemes. Both WiMAX and LTE specify these permutation schemes. However, currently only the distributed permutation scheme (called PUSC in WIMAX) is deployed in commercial networks due to its lower requirements on channel feedback and lower scheduling complexity.

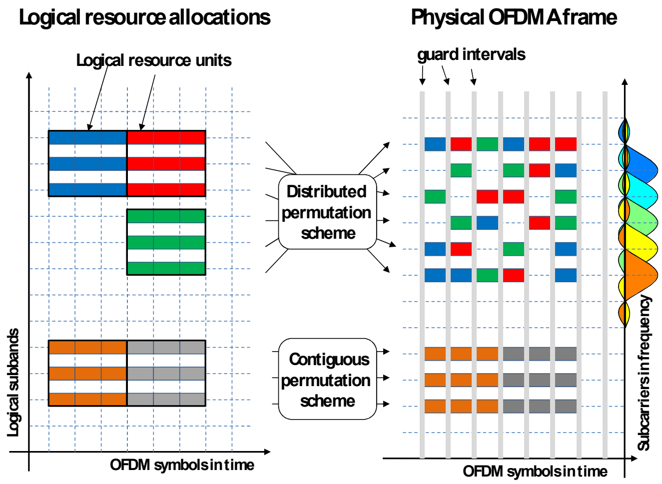

Figure 2: OFDMA resource allocation and frame permutation schemes

Wireless broadband access networks based on WiMAX are now in commercial use and a new generation of WiMAX and LTE will be deployed in the next few years. In the following, we present some of the main challenges for operators and vendors using OFDMA-based technology for mobile wireless access systems.

3. CHALLENGES

OFDMA for broadband wireless access is a relatively new technology as it is less than a decade old for this application. In spite of the potential and the flexibility of OFDMA, experience in network and hardware design as well as in deployment and operation of OFDMA networks is not yet as rich as for competing multiple access technologies like CDMA.

3.1 Design Concepts

Physical layer design challenges

On physical layer there are some technical challenges which mainly affect mobile communication devices. One is the peak-to-average power ratio (PAPR) which is generally high in OFDM/OFDMA systems, since the OFDM waveform in time domain is a superposition of sinusoids with frequencies which are n-times the frequency of the “lowest” subcarrier. A high PAPR requires power amplifiers in the transmitter chain to provide linear output over a large range. This decreases the power efficiency, and hence increases the energy consumption of an OFDMA terminal if no PAPR reduction schemes are implemented. For this reason, 3GPP LTE uses SC-FDMA (Single-Carrier Frequency Division Multiple Access) [6] in the uplink, which has still most of the benefits of OFDMA but with a reduced PAPR. In SC-FDMA, data symbols are precoded with a discrete fourier transformation, such that each data symbol is transmitted in parallel over a group of subcarriers. The resulting time-domain waveform resembles single-carrier waveforms with lower PAPR.

IEEE 802.16e utilizes OFDMA in the uplink, but supports specific PAPR reduction zones in the OFDMA frame. Furthermore, proprietary techniques can be applied independently from the implemented standard [7].

PAPR is closely related to the battery life of OFDMA mobile devices. However, also the increased chipset complexity due to the implementation of advanced receiver designs like MMSE and MIMO techniques lead to higher energy consumption if compared to 3G or 2G systems. Efficient power-saving modes for mobile devices are therefore essential for the everyday use. Both LTE and WiMAX support adaptive power saving techniques optimized for different traffic profiles like voice over IP or web-browsing.

Furthermore, MIMO techniques require accurate channel estimation techniques. Here, a trade-off in the design between complexity at receiver side and overhead for pilot symbols must be found to keep cost and energy consumption at an acceptable level, while maintaining a good estimation accuracy.

Interference mitigation schemes

In OFDMA networks, cell edge users are constrained by interference. In contrast to CDMA systems, macro-diversity schemes like soft-combining are not used in LTE and WiMAX. Instead, interference mitigation or avoidance schemes are employed. The most basic schemes are simple frequency reuse (FR) schemes in conjunction with frequency diversity permutations. In frequency reuse, the available spectrum is subdivided into fractions which are then assigned to cells/sectors such that the distances between cells with the same spectrum partition are maximized. In conventional FR schemes, the frequency reuse factor corresponds to the number of partitions (e.g. FR3).

However, conventional frequency reuse schemes divide the available spectrum in fixed parts which are independent of the actual received interference at the mobile stations. This leads to lower peak capacities for users at the cell center. Fractional frequency reuse (FFR) or soft frequency reuse schemes are addressing this problem by assigning the whole frequency spectrum to user at the cell center, while maintain a higher-order frequency reuse scheme for cell-edge users. In LTE, this is achieved by different power allocations across the frequency dimension, while IEEE 802.16e uses a time-division approach with a FR3 and a FR1 time zone within a radio frame. One of the main challenges here is to decide which mobile devices are assigned to which frequency bands or time zones [8, 9].

Another, complementary interference mitigation technique is beamforming by means of antenna arrays. In its most basic form, beamforming means to focus the antenna lobe on the mobile device by phase delaying at the antenna elements ("beamsteering"). In the downlink, this leads to a narrower antenna pattern (the "beam") towards the mobile station, such that interference in other directions is reduced. In the uplink, the array gain from the summation of the signals at the antenna elements additionally increases performance. Furthermore, uplink interference from adjacent sites can be cancelled by placing nulls into the direction of the main interferers.

Basic transmit and receive beamforming is well suited for FR3 or FFR scenarios. The main challenge with this technique is that preamble signals required for synchronization cannot be beamformed, since they must be received by potentially connecting mobile devices. Therefore, a gap between the coverage of the beamformed signal and the preamble signal exists, although cyclic delay diversity [10] can help to mitigate this problem. This effect must also be considered in the network planning phase.

Operators and vendors

WiMAX as the currently only OFDMA broadband wireless access system which is commercially deployed in large scale is going through its 3rd generation of maturity as it has started as a fixed access technology, then evolved to Mobile WiMAX, and currently equipment and systems with additional enhancements are being deployed for the market as WiMAX Release 1+. This evolution phase and enhancements in system features present challenges for vendors and operators alike.

For vendors, these challenges start during the development phase of the technology platform. They have to choose between platform flexibility with enough power to support future enhancements while maintaining low cost in order to meet the market requirements. The operators on the other hand need to decide on the best choice of features which meets their business model as their customers base grow and services evolve. They also need to ensure the availability of a diversity of devices without any interoperability problems.

The choices which operators are facing includes the decision on the right size of spectrum for their license acquisition, deployment scenarios, frequency reuse patterns, the list of features supported for roll-out, and their evolution roadmap in order to get the most out of their network in terms of spectral efficiency and coverage as their network grows and mature. At this stage they are then faced with the challenge of continuously going through the cycle of optimizing their network and maintaining co-existence between their BS and devices used in their networks.

Operators design and build their networks based on business models with a planned return on investment over a period from 3 to 5 years. For wireless broadband service, the business plan would include specific requirements such as minimum user throughput, coverage area, traffic information such as number of subscribers, type of traffic either voice and/or data and their corresponding parameters. For example for voice services the design requirement would include the average calls per hour per subscriber, the average call duration per call per subscriber and the ratio between the uplink and downlink activities. For data traffic, models for the downlink and uplink volume are defined. The business model would also include information such as the available spectrum. The available spectrum dictates the choices for the channel bandwidth and the possible frequency reuse patterns. These must be selected carefully in order to meet the requirements for business plan.

3.2 Deployment and Operation

Radio network planning

The first step before network deployment and operation is radio network planning to find the number of base station and sites required in the network and to determine their configuration in the network. Network planning is based on the business model and target services planned by the operators as described in Section 3.1. WiMAX and LTE follow a similar approach for their network design and optimization as they are both based on OFDMA technology and target similar services, such as high-quality video streaming, high-volume web-browsing, etc.

Cellular networks are designed based on criteria derived from the operator's business plan and the available spectrum. The design criteria include parameters such as cell edge throughput, which is defined as the 5th percentile of the cell throughput distribution, offered cell load, minimum received signal strength indicator (RSSI) determining the maximum cell size, expected cell throughput per active user and total expected cell throughput.

One of the key challenges for the operators is the trade-off between cell edge throughput and cell load. The reason is that as the load in the network increases, interference will also increase resulting in a lower signal-to-noise-and-interference-ratio. This in turns leads to lower modulation and coding schemes at the cell edge resulting in lower cell edge throughput.

Frequency reuse plan

An important step in the network design is the frequency planning. The frequency plan determines the capacity of the network in terms of cell loading and the target cell edge received signal strength. The outcome of the planning is a frequency reuse pattern and the cell configuration. The planning is performed based on the available spectrum and the channel bandwidth of the equipment. For example the most common channel bandwidths for Mobile WiMAX are 5, 7 and 10 MHz. One of the key challenges for the operators is thus to find the optimum frequency plan which maximizes the use of their most valuable resource: the licensed spectrum. Since the network load varies it is a challenging task to find one frequency plan which is optimal at all time during the network operation. Therefore, the operators choose the frequency plan which satisfies their target throughput during the initial phase of deployment, and confirm its performance by simulation.

The next step is to select all possible frequency plans which meet the target load. For each of these, the interference level and throughput is then obtained by simulation. After determining the target cell edge modulation and coding and the frequency plan which meets the requirements, the target RSSI is calculated from the link budget for each of the candidate frequency plan for both downlink and uplink. The highest RSSI requirement is then selected as the one that determines the cell size. In WiMAX this is likely to be the uplink.

Network dimensioning

The final step is to estimate the number of base stations required for the coverage area based on the input from the business plan. This step is known as the dimensioning of the network. The dimensioning of the network depends on the propagation model, the network parameters, equipment capabilities such as maximum transmission power, receiver sensitivity, supported features, e.g. MIMO or beamforming etc. and the type of traffic.

Following the dimensioning of the network, the basic network design can then be evaluated by verifying the parameters obtained from the dimensioning and the simulation, the coverage and the traffic requirements. A simulation is then executed after positioning of the sites accordingly. In the final stage the site locations are verified by simulation and by drive tests.

Many of the more advanced features (MIMO, beamforming, FFR) are not yet supported in detail in commercial planning tools, such that the configuration and parameter tuning of the system currently rely mainly on the experience gained from field trials and operations.

Indoor coverage

Indoor coverage is a major challenge for all mobile cellular systems. The wall material of buildings usually leads to high penetration losses of the radio signal. For OFDMA systems, this problem is even more challenging due to the typical deployment frequencies in the range of 2.3GHz to 3.6GHz, and the use of high-order modulations to achieve high bandwidths.

Vendors and some mobile operators see femtocells as a cost-effective solution for this problem. Femtocell base stations are low-cost, low-power base stations which are self-deployed by the customers in their premises. The femtocell base station is connected via a fixed broadband connection to the operator's radio access network. So, in contrast to a WiFi access point, the femtocell base station operates in a licensed frequency and is managed by the operator. This enables the mobile operator to employ interference mitigation techniques for good signal qualities and quality of service (QoS). The femtocell concept is supported in LTE, as well as in WiMAX in the WiMAX Forum specifications [11, 12].

Backhaul capacity

The increased capacity on the air interface leads to increased requirements on the mobile operator's backhaul network. This is especially the case for 2G/3G operators which often built network topologies resembling the hierarchical architecture of their systems currently in operation. The most challenging part here is at the edge of the operator's network, i.e. between base station and core network entities. Although the statistical multiplexing gain on aggregate links means that a linear increase of the capacity is not necessary, the connection between base station and the first aggregation point (such as an IP router) should support the expected BS air interface capacity to avoid bottlenecks. An additional challenge is the direct connection between base stations, such as the X2 and R8 interface in LTE and WiMAX, respectively. These logical links have stringent requirements on delay since they are used for hand-over and interference management.

3.3 A First Conclusion

Although OFDMA offers high flexibility and performance suited for a wide range of services, the relative immaturity of the technology constitutes a challenge for vendors and operators alike. Especially the various design options which are now available in current OFDMA specifications constitute one of the main problems due to the increasing complexity both in terms of technical and network design. In the next section we will illustrate how next generation systems aggravate this tendency by introducing novel features to meet 4G requirements.

4. WHAT IS COMING NEXT?

4.1 The Future: IMT-Advanced

The International Mobile Telecommunications-Advanced (IMT-Advanced) programme of the Radio Communication Sector of the International Telecommunication Union (ITU-R) defines requirements for the 4th generation radio interface technologies, like very high peak and cell edge spectral efficiencies which translate into 1 Gbps downlink capacity with 100MHz bandwidth [13]. Currently, two candidate technology standards are developed for submission to the ITU-R: IEEE 802.16m [14] which defines the WirelessMAN-Advanced Air Interface as an amendment to the existing IEEE 802.16-2009 standard, and 3GPP LTE Rel. 10 (LTE-Advanced). IEEE 802.16m is expected to be ratified in the first quarter of 2011, LTE-Advanced will follow in 2012.

Both proposals use advanced MIMO and multi-carrier aggregation schemes to reach the IMT-Advanced requirements. Performance evaluation studies of the proposals showed that especially Multi-User MIMO (MU-MIMO) [15] is a key technology for cell performance.

With MU-MIMO the same time/frequency resources can be assigned to different users, thus the spectral efficiency increases significantly. MU-MIMO can be seen as a generalization of space division multiple access (SDMA) with the possibility to choose the number of data streams to each terminal according to the condition of its channel transfer matrix. MU-MIMO requires accurate channel feedback at the transmitter, or alternatively for reduced feedback, selection of precoding matrix indices (PMI) in a predefined precoding codebook at the receiver side. The latter option requires less feedback, but for the price of lower performance and higher complexity at the terminal.

Multi-carrier aggregation, on the other hand, is essential to reach peak throughput values in large, not necessarily adjacent, frequency bands. Different frequency carriers are managed and utilized by the same user terminal according to the current bandwidth requirements [16].

Some further features are support for more antennas (up to 8) and reduced overhead due to group resource allocations and persistent scheduling schemes.

In order to meet the high requirements for cell-edge user throughput, interference management is evolving from static methods like interference averaging or frequency reuse to coordination schemes. This means that base stations have to exchange information about radio resource allocation and scheduling decisions, such that the available spectrum can be exploited as much as possible. The next logical step, cooperation between base station, will be realized in the beyond 4G generation.

4.2 Beyond IMT-Advanced

As today's standardization efforts are focusing on 1Gbps as per the IMT-A requirements, in 2015 we will start looking at systems providing 10 Gbps peak capacity and above. Study groups in IEEE and 3GPP, but even more the research community, are actively investigating the enabling technologies for such systems.

It is somewhat delicate to make statements on future developments; however, it is clear that for interference mitigation the tendency is to move from coordination to cooperation, by means of cooperative multipoint transmission (CoMP) or network MIMO [17]. In this technology, the network cooperates to transmit simultaneously for coherent reception, thus theoretically drastically increasing cell-edge user performance. As trade-off, requirements on inter-site links will increase at the same rate.

In order to reduce the costs for the operators for operation and management due to the increasing system complexity, self-organizing networks are seen as an integral part of future generation networks. Here, the cycle of measurement, decision, optimization and reconfiguration is performed autonomously by the network itself or only with minimized human input.

Furthermore, cognitive radio is under investigation to exploit spectra which are not available exclusively for mobile communications. An example is the so-called TV whitespaces, which are blocked for TV broadcasting but only regionally in use [18].

Finally, radio access will diversify again – not necessarily for the basic modulation and access techniques, but for the cell types and medium access layer (MAC). Heterogeneous networks will choose the best access for the requested service. For example, best-effort services can be transported via Wireless LAN, while QoS traffic like video telephony is transported via LTE access. Optimizations for special devices and applications like machine-to-machine communications are under development.

4.3 The Main Challenge: System Complexity

The complexity of the system considering different MIMO modes, multiple carrier frequencies, channel states, user QoS and power allocation, as well as constraints by inter-cell coordination, will be one of the main challenges. Let us consider the scheduling problem as an example. In 2G and also 3G systems, radio bearers are specifically designed and optimized for a certain service such as voice. Transportation followed the circuit-switched paradigm, meaning that a certain amount of radio resources is exclusively allocated to a user, regardless whether the resources are currently required or not. In 3.5G and beyond systems, the packet-switched paradigm was introduced for all types of services. This means that a scheduler in the base station has to ensure that resources are allocated to packets of different users and services while ensuring that QoS metrics are met. The advantage is that the available resources can be better utilized, however, for the price of a higher complexity of the scheduler.

In 4G and beyond systems, MU-MIMO and inter-site coordination and cooperation will add additional complexity to the system. Figure 3 illustrates this development exemplarily on the degrees of freedom for scheduling decisions: With the number of features, the decision space increases exponentially.

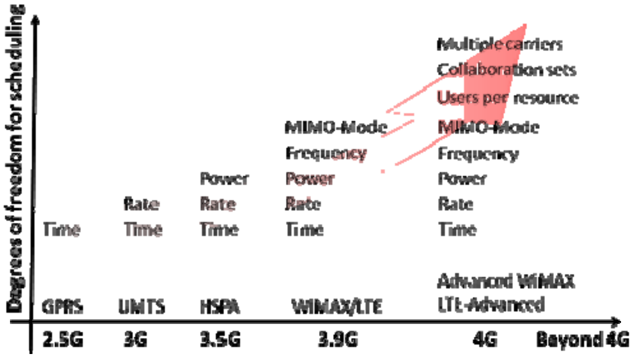

Figure 3: Increasing complexity for evolved access technologies

5. CONCLUSION

OFDMA made an interesting development as access technology for broadband wireless access systems. Within 10 years, it became the predominant technology for next generation networks in near and mid-term. We pointed out some of the reasons for this success, and illustrated the challenges that come along. Especially the high flexibility of OFDMA is also one of the biggest challenges due to the increasing system complexity.

In the near term, technology-related immaturities like high power consumption and indoor coverage problems will be solved, helping the operators to introduce OFDMA-based networks in large scale. The experienced gained in the operation and deployment will help for the development of 4G IMT-Advanced networks. However, the system complexity and the introduction of novel, not yet field-proven technologies like MU-MIMO will become one of the major challenges for operators and vendors alike.

The research community has a key position in enabling the success of OFDMA broadband wireless communication systems, by investigating practical solutions in real-world problems faced by operators and vendors, and by pushing the edge of the technological frontier towards very high capacity wireless networks.

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