WIRELESSCOMMUNICATIONSUSINGOFDMFORNEXTGENERATION

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Abstract— OFDM (Orthogonal frequency division multiplexing) efficient technique used as a digital multi- carrier modulation method, but it is one of the most popular and effective technologies used in nowadays communication systems. In this work we present a brief summary of the history of OFDM, a description of the key features of this technology is delivered, and with it we argue why OFDM has been the fundamental scheme of many communication systems for the past and current years. At the same time, we verify the continuity of OFDM in future applications, and how it clearly outperforms other similar technologies.

Keywords—Cellular technology, Code division multiple access (CDMA), filter bank multicarrier (FBMC), Orthogonal frequency division multiplexing (OFDM), fourth generation (4G), fifth gen- eration (5G).

I. INTRODUCTION

The incredible stories of carrier pigeons, smoke signals or perhaps the telegraph, are clear examples of the need for humans to communicate. In modern times the ways in which we communicate have changed dramatically, and this is because the invention of cellular technology gave us the ability to call people instead of places, generating a huge paradigm shift in society. On the other hand, the increasingly faster technological progress has meant that the change of a technological generation to another is approximately every 10 years, in which the way of sharing data changes abruptly be- tween each technological shift, and transmission rates continue to rise seemingly without limits.

It all started in the 80s, where first generation (1G) analog cellular systems allowed users only to make simple phone calls, but at the same time gave them the mobility that society previously could not find in the existing public switched telephone network (PSTN). In the 90s, telecommunication systems were digitized and second generation (2G) networks allowed people to start sharing binary data from their mobile phones. So at this point, users were able to send text messages using the Global System for Mobile communications (GSM) technology, and in later versions of this technology (2.5G) they were able to establish Internet connections [1], but at rates that could not compare to those obtained in present times.

Then, in 2000 with the birth of third generation (3G) networks, transmission rates and processing capabilities of data increased significantly, allowing the creation of new mobile ap- plications that facilitated users to access multimedia services, such as downloading music or videos. This last fact led to the use of Internet as a daily practice within the services offered by mobile devices, changing the way of using cellular phones and turning them into the well known “smart phones”, capable of being connected to the network anytime and anywhere.

Currently, fourth generation (4G) networks offer users browsing speeds that are comparable, or superior, to those provided by Wi-Fi services at home. On the other hand, mobile devices are no longer simple “smart phones”, but somehow are becoming into something similar to portable computers due to its extraordinary data processing ability. It is for these previous reasons that today users can make video calls or watch streaming media from their devices without experiencing significant delays. This is why current networks and mobile devices available in the market are not simply used to talk between people because browsing through them has turned into a new way of communication.

Second and third generation technologies were based on code division multiple access (CDMA) schemes. The use of orthogonal signals and signal-spreading techniques allowed these kind of systems to almost perfectly address the prob- lem of multiple access, providing a comparative advantage over other technologies. But the lack of scalability to higher transmission rates that CDMA-based systems were starting to experience was a big problem in a world that increasingly demands higher processing and transmission rates. This last fact led the standardization groups to juggle the idea of using some new techniques for future technological generations, and finally upon the candidates, the winner was not the well- known CDMA, but orthogonal frequency division multiplex- ing (OFDM). One of the main reasons for this decision, was because between 2000 and 2004, OFDM-based systems showed excellent performance in terms of transmission rates and quality of wireless links.

This latest technology was proposed as a mathematical model in the 60s, but taken into reality in the 90s thanks to technological progress that allowed to generate the Discrete Fourier Transform (DFT) in digital circuits. So, even though OFDM's story might seem long, apparently it is far from being obsolete, by contrast, we can find it in many daily application technologies. Along with mm-wave technology, OFDM-based systems combined with multiple-input multiple- output (MIMO) techniques are being studied and proposed as one of the technologies to be implemented at the physical layer of 5G cellular networks [2]–[6].

The big question now is whether OFDM will be able to keep the pace with the growing needs of the world by increas- ing its transmission rates and outperforming new competitors such as filter bank multicarrier (FBMC) schemes [7], [8], or some already well-known techniques such as CDMA, partial block multi carrier CDMA (PB/MC-CDMA) [9], time-division multiple access (TDMA), frequency division multiple access (FDMA), among others.

This paper has the following organization. Section II provides the main features of OFDM-based systems. In Section III we talk about the relationship between OFDM and 4G technologies. In Section IV we argue why OFDM is planed to be used in the upcoming communication generations. Finally, conclusions are presented in Section V.

II. CHARACTERISTICS OF OFDM-BASED SYSTEMS

As previously indicated, OFDM is a concept that has been built for several years, but it became a practical reality when the birth of applications coincided with developments in electronics, and new efficient softwares [10]. One of its main features is the high reliability provided to its users, because it deals almost perfectly with common wireless transmission scenarios, such as multipath fading channels, where we con- sider that the signal sent by the transmitter may take different paths before reaching the receiver. Therefore, the transmitted signal could suffer phase rotation, attenuation, frequency and time offsets, delay spread, among other effects [11]–[13].

In OFDM, the inverse discrete Fourier transform (IDFT) and Discrete Fourier Transform (DFT) are used for modulating and demodulating each low-rate data symbol on a different orthogonal subcarrier, respectively. In simple words, an OFDM symbol (IDFT output samples) is formed by the sum of N data constellation points{an }traveling on a subcarrier, where
phase-shift keying (PSK), quadrature amplitude modulation
(QAM), or other type of digital modulation schemes may be used for the symbol mapping. Further, N is also the number of IDFT/DFT points.

A simple representation of the time-domain complex en- velope of an OFDM symbol can be written as [14]

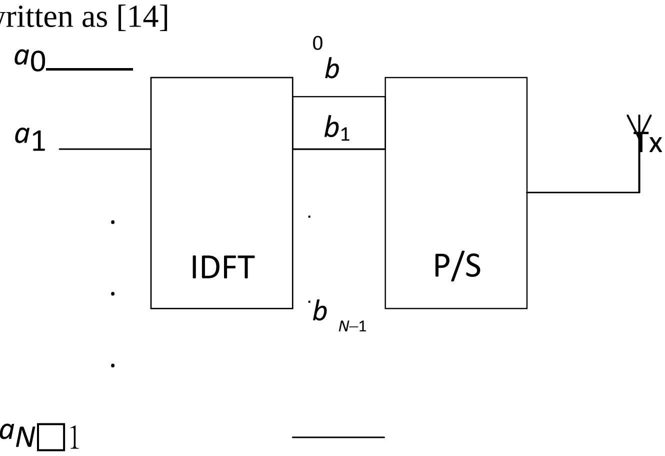

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Fig. 1.Simplified scheme of the IDFT operation in an OFDM-based system.

block, as depicted in Fig. 1. After this transformation, the N parallel output samples are converted into a serial form. Then, the CP is added, the signal is lowpass filtered, passed to a quadrature modulator which shifts the signal spectrum to center it on the center carrier frequency f0 = ω0/2π, and finally passed through a high-power amplifier (HPA) to be transmitted towards the receiver. On the receiver side, the received signal is coherently demodulated, sampled at the symbol rate 1/T , and passed to a DFT operator which converts the signal back to the frequency domain. The demodulator comprises a lowpass filter which limits noise and interference from adjacent channels, without distorting the received signal. A simplified scheme of an OFDM-based transceiver is shown in Fig. 2.

By analyzing (1), one may say that OFDM-based systems divide the original message into smaller fragments, which finally travel on different orthogonal subcarriers. This last fact is the one that makes the signal even more robust tomulti- path fading because it converts a frequency selective fading channel, into several nearly flat fading channels, de- creasing the losses and error rate at the receiver side. Further, orthogonal subcarriers allow these kind of systems to have better spectral containment and efficiency, because the Fourier transform of the various data overlaps by using the principle of orthogonality, as seen in Fig. 3. This last fact increases the available bandwidth, enabling OFDM-based systems to reach transmission rates much higher than those offered by CDMA [15] and other technologies.

s(t) = Re

(Σ+∞)

bng(t − nT)e jω0 t+φ

, (1)

On the other hand, OFDM-based systems use guard in- tervals or a cyclic prefix (CP), whose lengths exceed the maximum excess delay of the multipath propagation channel.

n=−∞

√

where j is the imaginary unit (

—1), Re( )•

denotes the real

Due to this, systems are able to cancel almost completely the delay spread phenomena at the receiver side. The delay

part of the transmitted signal, g(t) designates the transmitter filter impulse response, T is the symbol period, ω0 is the carrier frequency given in radians, φ is the carrier phase, and the transmitted sequence{bn}is obtained from the input information sequence {an }through an N -point IDFT. In order to distinguish successive DFT blocks, we write the index n in

spread effect arises when the receiver gets the same message

repeated over time since the signal takes different paths when irradiated in all directions by the antennas of the transmitter. This latter issue may generate interference or degradation of

(1) as n = m • M + k with k = 0, 1, . . . , N − 1 and m integer.

The {bn} sequence in (1) is then given by

Data in

1 N−1

k

N l=0

al(m)e

j2πlk/N

, (2)
Data out

where k ∈ 0{, 1 . . . N − }1 . In this 2-index representation,
al(m) represents the l-th input symbol of the m-th IDFT
block, and bk(m) is the k-th output sample of the same Fig. 2. General and simplified scheme of an OFDM transceiver.
the signal, and it is a common problem observed in cellular communication systems.
The above and other features that OFDM offer makes it one of the most, if not the most, used digital transmission scheme at the moment. OFDM-based systems are found in technologies such as DSL modems [16], digital television [17], Wi-Fi [18], 4G [19], WiMAX [20], broadband power-line communication systems (BPLC) [21], [22], and even in some rather complex military applications [23], among others.

III. OFDM AND 4G

Being more specific on issues related to 4G networks, lets try to deliver the major facts that explain the choice of OFDM as the base technology of the current cellular communication systems. Between 2002 and 2004 the International Telecom- munication Union (ITU), and the 3rd Generation Partnership Project (3GPP) began studying which would be the technology used in the upcoming networks. This latter discussion arose because at that moment 3G CDMA-based systems were start- ing to experience problems on allowing further technological progress towards the predicted transmission rates for the com- ing years (red trend curve in Fig 4). In fact, in 2010 (year in which 4G was launched) CDMA2000 (3G) obtained by intensive manipulations, and probably by stressing the limits of this technology, downlink data transmission rates of 14.7 Mbit/s using EV-DO Rev. B techniques [3], [24].
As previously mentioned, even when CDMA exhibited “acceptable” speeds, and supports almost perfectly multi-user and simultaneous communications, several drawbacks exist [25]. Moreover, by then, OFDM systems showed a better response compared to typical broadcast cellular technologies, and its transmission rates were significantly higher than those obtained with CDMA [26]. But unfortunately this technology did not have the valuable multiple access feature. Therefore, while this latter problem was not solved, the consolidation of

OFDM as the preferred technology for 4G networks would remain doubtful.
The great solution to the above issue arrived around the year 2005 with the birth of orthogonal frequency division multiple access (OFDMA). This technology; based on OFDM, allows to have multiple access networks because it uses a digital block able to map and assign different subcarriers for each user [27]. As shown in [28], this technology presents a performance that surpasses CDMA and other traditional multi- ple access technologies, such as TDMA) or FDMA, not only in terms of browsing speeds, but also by maintaining the ability of almost perfectly dealing with multipath fading channels. Further, OFDMA-based systems are easily expandable to be combined with MIMO techniques, therefore they are able to increase transmission rates much faster than other multiple access technologies.
So, based on these latter reasons, OFDMA was considered as the technology to be used in the downlink of 4G networks, whereas single-carrier frequency-division multiple access(SC-FDMA) in the uplink. Thus, for the first time in history, different technologies are used in the upstream and downstream data link with the base station. SC-FDMA also bases its operation on OFDM [29], but unlike OFDMA, it uses an extra DFT digital block, which enables each of the subcarriers to be modulated by the same data point in a short duration of time. This last feature allows the generated signal to have a smaller peak-to-average power ratio (PAPR) in comparison with the one obtained by OFDMA. This favors the battery life of mobile phones without sacrificing the transmission rates or the advantages that OFDM-based systems offer [30]–[32]. A simple block diagram of these two technologies is shown in Fig. 5.

IV. OFDM AND THE FUTURE

It can be argued that the choice of the radio waveform to be implemented in the future 5G networks will have a high impact on the conception of this new technology. This is because the

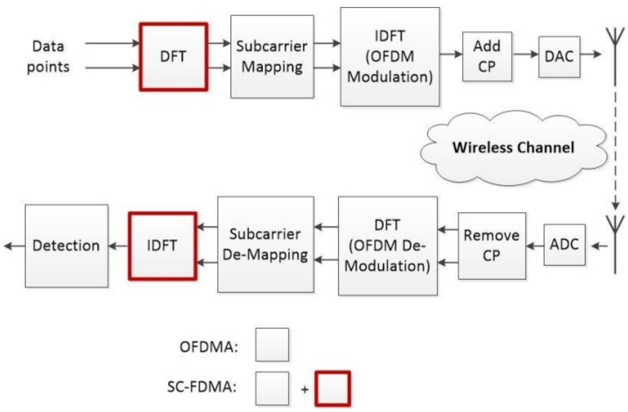

Fig. 5.Simplified scheme of SC-FDMA and OFDMA systems.

choice of the selected technology affects not only the design of transmitters and receivers, but also the complexity of the system as a whole, since each technology has different ways on addressing problems in wireless communication models. Therefore, it is essential to determine how to generate signals, determine the duration of the symbols, the structure of the data packets, and so on.

Given the fact that there is still no proposed standard by either the IEEE or 3GPP specifying the technical capabilities that a next generation networks shall present, one can only speculate on the scopes that 5G systems will reach. Projections and stipulations of the transmission rates to be achieved in 2020 (possible release date of 5G [2]) can be seen in [33]. Now, since this type of network plans to support data transmission rates of the order of Giga-bits per second (Gbps), the waveform to be used must meet the following minimum requirements [34]:

1) Limited computational complexity for both the gen- eration and detection.
2) Good spectrum containment [35].
3) Well-limited spectrum that enables to have small separation between the different channels assigned to each user; allowing better utilization of the total bandwidth.
4) Easily expandable to be combined with MIMO sys- tems.
5) Deal almost perfectly with multipath transmissions.
6) Cope well with frequency selective channels.

Based on [8] and [36], it is shown that both OFDM and FBMC meet the above specifications better than other tech- niques, so they are considered the most attractive candidates for being used in 5G networks. Going further in the results, one may notice that the spectrum containment of FBMC responds better than OFDM, but the first one is extremely much more complex than the second one. On the other hand, FBMC-MIMO current models are not easy to conceive, and its applicability is still not feasible for industrial levels, whereas OFDM-MIMO systems already proved to be effective, and enforceable in the IEEE 802.11ac protocol [37], and 4G. These facts makes FBMC not to respect the low complexity and easy extension to MIMO techniques that 5G networks require (items
1 and 4 of the above list). Therefore, OFDM-based systems are becoming a strong candidate for being the key scheme in next generation wireless communication systems.

Even though OFDM-based systems have gained consid- erable attention over the last few years, it has been noted that OFDM has to face many challenges when considered for adoption in more complex networks. Carrier and timing syn- chronization represent the most challenging tasks in these kind of systems [38]. Another limitation of OFDM-based systems is transmitting digital data over a set of non contiguous frequency bands; also known as carrier aggregation [38]. Further, these type of systems introduce significant out of band noise to other users, as well as pick-up radiation from adjacent channels. On the other hand, FBMC is an alternative transmission method that resolves the above problems by using high quality filters that diminish out-of-band and in-band radiation [8], [38]. Moreover, FBMC systems do not need synchronization signals from the mobile nodes attached to the network [38]. Despite the benefits of FBMC systems, many attempts have been made to adopt the technology in various standards [38], but past and current trends seem to point to the continuity of OFDM-based systems in 5G cellular networks.

Already at this point, we have successfully demonstrated the true potential of OFDM and how it outperforms its closest competitors. It is the technology that deals better with the channels (multipath fading channels) of typical wireless com- munication systems, while it has the highest data transmission rates. These latter facts, and its perfect adaptability to a wide range of functions have allowed OFDM to be used in many past and contemporary applications. Added to this, its easy extension to MIMO systems, currently allows 4G networks to considerably increase their transmission capacity and further, in a not too distant future by using massive MIMO, we will probably be able to reach transmission rates almost unthink- able for nowadays technologies [39]. Therefore, its favorable time and frequency domain characteristics make it a strong candidate for becoming the technology to be implemented in 5G cellular networks, which would allow it to expand into the likely future heterogeneous networks (HetNets) [40] composed of macrocells, microcells, and femtocells. Meaning a significant increase in its total applications. Further, it could be the basis for Device-to-Device (D2D) [3], [41], Machine-to-Machine (M2M) [41], and Vehicle-to-Vehicle communication protocols (IEEE 802.11p) [42].

The proposed ideas in this work are supported by LauriOksanen, Head of Research and Technology at Nokia Siemens Networks, where in [43] he states:

“There are some proposals for new coding meth- ods’ but when we look at whether we can do better than OFDM, there doesn’t seem to be any significant improvement with these new methods. You find you can improve power efficiency, for example, but the spectrum efficiency goes down. We believe that OFDM is the best way to go forward - and it looks to be the most promising way for local-area 5G radio.”

V. CONCLUSION

In this work it has been shown that OFDM is clearly superior to its competitors in terms of technology and perfor-mance, meaning that in the present and in the upcoming years it will be the base technology for most telecommunication applications. It is the technology that deals better with typical wireless communication channels, while it has the highest data transmission rates. Added to this, its easy extension to MIMO systems currently allows 4G networks to considerably increase their transmission capacity and, in a not too distant future, by using massive MIMO and mm-wave technology, OFDM-based systems will probably reach transmission rates many orders of magnitude greater than the ones obtained in nowadays technologies.

As a final thought, FBMC promising theoretical and ex- perimental results are, in most aspects, better than the ones obtained by OFDM, so one may ensure that it is the its clear successor in future applications. But, for this to happen, FBMC will have to wait for a breakthrough in the development of technology, as well as OFDM had to wait for several events to happen before strongly entering the telecommunications mar- ket, because as stated above, the implementation complexity that FBMC-systems exhibit are beyond our actual reach.

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