A Review of OFDMA and Single-Carrier FDMA and Some Recent Results

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***Abstract*—The controversial debate on OFDM vs. single-carrier (SC) transmission started back in the 1980s at the time of the European Digital Audio Broadcasting (DAB) and Digital Video Broadcasting (DVB) projects. The same debate took place in wireless communications a decade later, and OFDM transmission with TDMA was adopted in the IEEE 802.11a specifications for wireless local area networks (WiFi) and by the WiMAX Forum for fixed WiMAX systems. Later, orthogonal frequency-division multiple access (OFDMA) was adopted by the WiMAX Forum for mobile WiMAX systems and more recently by the 3GPP for the downlink of Long Term Evolution (LTE) systems. In contrast, single-carrier FDMA was adopted for the uplink of LTE. In this overview paper, we will review these historic developments and give some recent results on OFDMA and Single-Carrier FDMA.**

***Index Terms*—OFDM, OFDMA, SC-FDMA.**

I. Introduction

ORTHOGONAL frequency-division multiplexing (OFDM) which was known since the 1950s, was revived in the 1980s with the European Digital Audio Broadcasting (DAB) [1] and Digital Video Broadcasting (DVB) projects. This technique was standardized for both DAB and digital terrestrial TV broadcasting (DVB-T). The technical literature at that time, mostly by authors involved in the DAB and the DVB projects, did not leave much alternative to using OFDM for digital terrestrial TV, particularly for mobile reception.

In 1993, Sari et al. presented a conference paper [2], which reviewed the potential advantages and drawbacks of OFDM and introduced single-carrier transmission with frequency-domain equalization (SCT-FDE) as an alternative technique. The paper suggested that an SCT-FDE system could achieve the performance of OFDM on frequency-selective multipath radio channels while alleviating its peak-to-average power ratio (PAPR) and synchronization problems. This paper, which was contradicting the claims of many authors, started a long debate, which is still not closed. In the 1994-1995 time period, the same authors published several other papers on the same topic, the most well-known of which being [3].

The OFDM vs. SCT-FDE issue in the 1990s was focused on a pure transmission problem in the context of broadcasting (the wireless communications community was not yet a part of this discussion). In parallel with digital terrestrial television broadcasting, the DVB project was also addressing digital video broadcasting by satellites (DVB-S) and by hybrid fiber/coax (HFC) cable networks (DVB-C). After defining the technical specifications for the broadcast part, the group in charge of the specifications of digital cable TV systems started discussing the return channel for interactive services. One of the proposals was based on a simple orthogonal frequency-division multiple access (OFDMA) system, which assigned one carrier to each subscriber. The carriers were locked to a common source such that the frequency spacing was the inverse of the symbol period used in the transmission. The signals transmitted by the cable modems were therefore single-carrier signals, but the received signal was an OFDM signal. This proposal was rejected by the DVB cable group, but the concept was published in 1996 in [4], which laid the foundation of OFDMA. The word OFDMA itself was coined in this pioneering paper. Several other papers by the same authors followed in 1996-1998, see e.g. [5] and [6].

The motivation for OFDMA in cable TV networks was related to the presence of narrowband interference which affects the uplink. Indeed, TDMA- and CDMA-based systems are very sensitive to this interference and they cannot operate when the interference level exceeds some threshold. In contrast, in an OFDMA system, the cable head-end which assigns resources to cable modems can discard the carriers that are subject to interference and assign only those which have a good signal-to-interference-plus-noise ratio (SINR). The resulting performance improvement over TDMA and CDMA was shown to be substantial [7].

Multicarrier techniques appeared in communications networks with the IEEE 802.11a standard for wireless local area networks and IEEE 802.16-2004 standard for wireless metropolitan area networks. The first of those adopted OFDM for transmission, but multiple access was based on pure TDMA. This kind of OFDM/TDMA was also included in IEEE 802.16-2004, but the standard also featured two other physical (PHY) layers, namely SCT-FDE and OFDMA, and intended to let the market decide. However, the WiMAX Forum, which defines mandatory profiles for fixed WiMAX systems, decided to include the OFDM/TDMA mode only. The IEEE 802.16 group continued its work and released its IEEE 802.16e-2005 specifications for portable and mobile services in 2005. This set of specifications too included 3 PHY layers, but for these applications, the WiMAX Forum selected the OFDMA mode, leading to incompatibility between fixed WiMAX and mobile WiMAX standards.

Another major development in communications networks was born when the Third-Generation Partnership Project (3GPP) started its work to define a technical standard for the so-called Beyond 3G (B3G) systems. Release 8 of the 3GPP standard, which was finalized at the end of 2008, made a large technological gap with respect to previous releases and adopted OFDMA for the downlink and single-carrier FDMA (SC-FDMA) for the uplink. The choice of SC-FDMA for the uplink was motivated by the limited PAPR of this technique

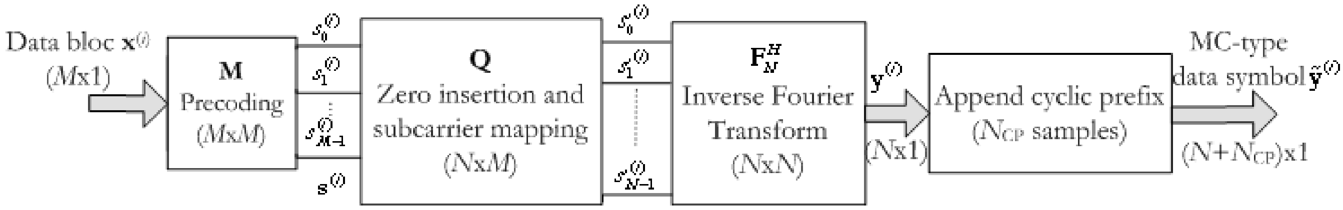

Fig. 1. Generalized MC transmitter for SISO transmission.

compared to OFDMA.

After this historical review, this paper will give a brief overview of OFDMA in the next section and of SC-FDMA in Section III. Next, in Section IV, we will give some recent performance results comparing the two schemes in a real environment. Finally, we give some conclusions in Section V.

II. Brief Review of OFDMA

Figure 1 presents the baseband structure of a generalized multicarrier (MC) transmitter, which applies to all types of single-carrier (SC) or MC modulation signals transmitted in blocks. Let us denote by $x_k^{(i)}$ the information symbols (e.g., QAM symbols) which are parsed into data blocks $\mathbf{x}^{(i)}$ of size M. Data blocks belonging to a certain user are precoded with an $M \cdot M$ matrix M. The user-specific M-sized output $\mathbf{s}^{(i)}$ is then mapped onto a set of M out of N inputs of the inverse discrete Fourier transform (IDFT) conveniently chosen by the user-specific subcarrier mapping $N \cdot M$ matrix $\mathbf{Q}$. $\mathbf{F}_N$ and $\mathbf{F}_N^H$ stand for the N-point direct and inverse normalized DFT matrices, respectively. A cyclic prefix which needs to be longer than the largest multipath delay is usually inserted before transmission to eliminate the intersymbol interference arising from multipath propagation. In this general representation, OFDMA corresponds to the case without precoding, i.e., the precoding matrix corresponding to OFDMA is the identity matrix ($\mathbf{M} = \mathbf{I}_M$). The IDFT operation is equivalent to splitting the information into M parallel data streams that are transmitted by modulating M out of the N distinct subcarriers equally spaced in the channel bandwidth. Thus, OFDMA consists of assigning different subcarrier groups of an OFDM symbol to different users. Compared to an OFDM/TDMA system, which assigns the entire OFDM symbol to one user ($M = N$), an OFDMA system reduces the granularity in the radio resource allocation mechanism, and this improves the efficiency of the medium access control (MAC) protocol. In addition, an OFDMA system can use the available power more efficiently than a TDMA system. Indeed, focusing on the uplink, an OFDMA system concentrates the power that is available in the user terminal on the carrier group assigned to this terminal, whereas a TDMA system distributes it over the entire channel bandwidth. In an OFDMA systems with N carriers which allocates M carriers to each user, the SNR gain with respect to OFDM/TDMA on the uplink is $10 \log_{10}(N/M)$ dB, which leads to a significant extension of the cell range. Similar gains can also be achieved on the downlink by allocating more power to subcarriers assigned to distant users. But like all other MC schemes, OFDMA suffers

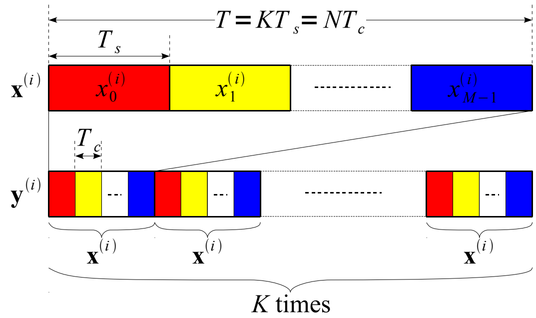

Fig. 2. IFDMA signal generation.

from the PAPR problem. Each sample at the IDTF output being the sum of M independent variables, it is asymptotically Gaussian, and this leads to high envelope variations.

III. Single-Carrier FDMA

SC-FDMA combines the properties of SC transmission with an OFDMA-like multiple access and attempts to take advantage of the strengths of both techniques: Low PAPR and flexible dynamic frequency allocation.

Depending on the way the subcarriers are allocated to each user or on the way the signal is generated, SC-FDMA can be found in the literature under different names. SC-FDMA was first conceived in a time-domain implementation [8] called IFDMA (Interleaved Frequency Division Multiple Access). At instant (i), blocks of M data symbols are parsed into data blocks $\mathbf{x}^{(i)}$ of duration $T = MT_s$, where T_s is the QAM symbol duration. These blocks are K-time compressed and K-time replicated to form the IFDMA signal $\mathbf{y}^{(i)}$ with the same duration $T = NT_c$ as depicted in Figure 2. Here, $N = KM$ and $T_s = NT_c$, T_c being the chip duration.

As theoretically proven in [9], this manipulation has a direct interpretation in the frequency domain: The spectrum of the compressed and K-times replicated signal $(\mathbf{F}_N \mathbf{y}^{(i)})$ has the same shape as the spectrum of the original signal $(\mathbf{F}_N \mathbf{x}^{(i)})$, with the difference that it includes exactly $K-1$ zeros between two data subcarriers, as it can be seen in the example of Figure 3.

This feature enables us to easily interleave a maximum of K different users in the frequency domain by simply applying to each user a specific frequency shift, or equivalently, by multiplying the time-domain sequence by a user-specific phase ramp. Obviously, this structurally imposes a distributed subcarrier allocation. The spectral considerations above open the way to a frequency-domain implementation of SC-FDMA [10], sometimes called DFT-spread OFDM, and which is in

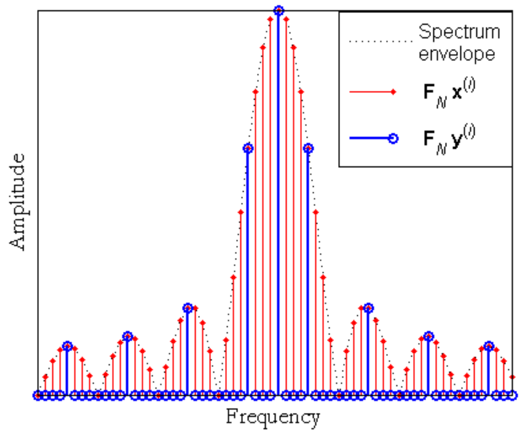

Fig. 3. Spectral illustration of IFDMA (N=64, K=4).

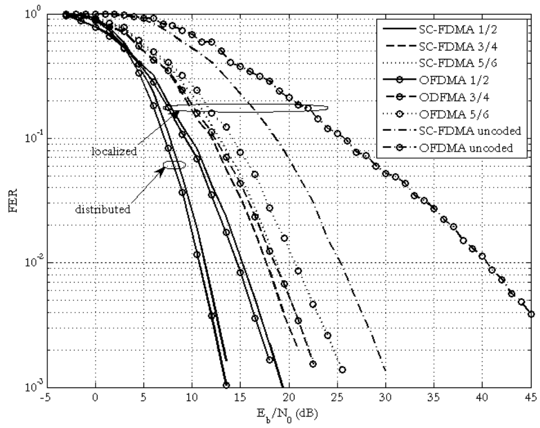

Fig. 4. SC-FDMA vs. OFDMA performance with QPSK and 5 RBs.

TABLE I
GAIN OF OFDMA OVER SC-FDMA (dB)

FER=1%		QPSK (dB)		16-QAM (dB)		64-QAM (dB)	
		1 RB	5 RB	1 RB	5RB	1RB	5RB
localized	1/2	0.4	0.5	1.8	2.6	2.5	4.4
	3/4	-0.8	-0.8	1.1	2.0	1.9	4.8
	5/6	-1.7	-1.8	0.3	1.0	1.2	3.9
	uncoded	-4.2	-13.6	-3.8	-13.2	-3.5	-12.8
distributed	1/2	0.6	0.6	2.9	2.2	6.7	3.9
	3/4	-1.4	-0.5	3.8	2.3	7.9	5.2
	5/6	-2.0	-1.6	3.1	1.4	6.7	4.9
	uncoded	-13.4	-19.3	-10.3	-17.5	-8.6	-14.9

fact a classical precoded OFDMA scheme, where precoding is done by means of a DFT. This corresponds to using $\mathbf{M} = \mathbf{F}_M$ as precoder in Figure 1. Frequency-domain SC-FDMA has a more flexible choice in resource allocation, since matrix $\mathbf{Q}$ can be chosen so as to correspond to contiguous, distributed, mixed or even channel-dependent subcarrier allocation.

The role of the DFT precoder is two-fold: On one hand, this precoding restores the SC-like properties of the signal envelope, alleviating the PAPR problem that is inherent to OFDMA signals. Indeed, we have seen that in the distributed case $\mathbf{y}^{(i)}$ is simply the condensed repeated version of $\mathbf{x}^{(i)}$, and thus an SC signal. In a localized subcarrier mapping scenario, the spectrum of the SC signal $\mathbf{x}^{(i)}$ is simply mapped into a portion of the spectrum of $\mathbf{y}^{(i)}$ as in a conventional FDMA system, which does not substantially change the PAPR.

On the other hand, like all precoders, the DFT performs a spreading operation. As a consequence, each modulation symbol $x^{(i)}$ is spread over M subcarriers. This introduces some built-in frequency diversity, and losing the information on one subcarrier because of a fading dip does not lead to losing all the information in a modulation symbol as in OFDMA. But spreading does not only have beneficial consequences. It also causes intercode interference on frequency selective channels. Indeed, frequency selective fading causes a loss of orthogonality between the M-sized spreading codes. This affects all the modulation symbols composing $\mathbf{x}^{(i)}$, and the effect is especially disturbing with high-order modulations, as it will be shown in the simulations section.

IV. PERFORMANCE RESULTS

In this section, we report some simulation results obtained for the uplink of the LTE systems. Among N = 512 subcarriers which compose the transmitted signal, 300 are modulated data carriers, the remaining 212 being reserved as guard bands. The 300 data carriers are split into 25 resource blocks (RBs) of $M = 12$ subcarriers. After data scrambling, we use a turbo code (TC) with different rates prior to QAM signal mapping. A cyclic prefix with a length of 31 samples is employed. Groups of 12 SC-FDMA symbols are encoded together and sent through a vehicular A channel profile with 6 taps and a maximum delay spread of 2.51 μs. Perfect channel state information (CSI) was assumed in a first step. The channel bandwidth was 5 MHz and the sampling frequency was 7.68 MHz. The results are reported in Figures 4, 5, and 6, for QPSK, 16-QAM, and 64-QAM, respectively. In the simulations, 5 localized RBs (60 localized subcarriers) are allocated to each user.

Figure 4 shows the results for QPSK. Since OFDMA has no built-in diversity, its performance is very dependent on the coding rate. When a high coding rate is employed or the system is uncoded, OFDMA performs poorly because coding does not manage to compensate the influence of subcarriers with a low SNR. When stronger coding is present (e.g., rate 1/2), OFDMA benefits from the coding diversity and recovers its performance loss and even outperforms SC-FDMA by 0.5 dB at the frame error rate (FER) of 1%.

With higher-level modulations, there is a tradeoff between the frequency diversity gain (due to the spreading performed in SC-FDMA) and the intercode interference caused by the frequency selectivity of the channel. This tradeoff is also driven by the coding rate. Let us examine the FER results in Figures 5 and 6, centered on a target FER of 1%. We notice that SC-FDMA is more sensitive to intercode interference when the modulation order increases (16-QAM, 64-QAM). In this case, coded OFDMA has better performance. The higher the modulation order, the stronger this effect is: OFDMA with code rate 1/2, for example, outperforms SC-FDMA by 0.6 dB, 2.6 dB and 4.4 dB when employing QPSK, 16-QAM and 64-QAM respectively. SC-FDMA outperforms OFDMA when low modulation order (QPSK) or uncoded modulation is employed. The results are summarized in Table I.

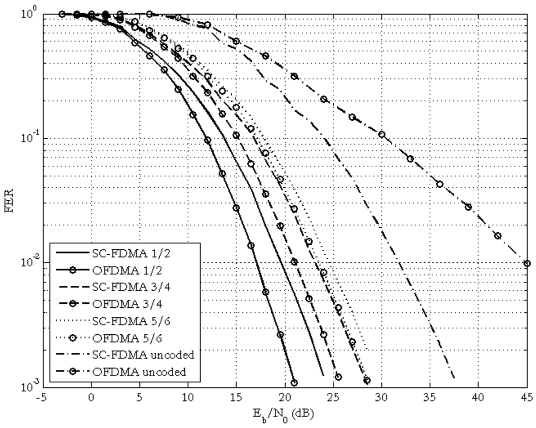

Fig. 5. SC-FDMA vs. OFDMA, 16-QAM and 5 localized RBs.

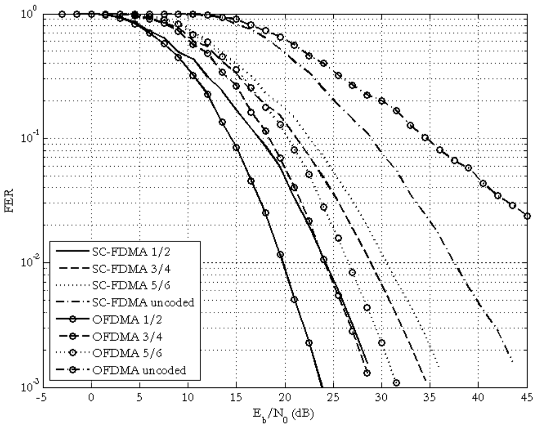

Fig. 6. SC-FDMA vs. OFDMA, 64-QAM, 5 localized RBs.

In Figure 4, distributed vs. localized subcarrier allocations are also investigated. Localized subcarrier mapping has poorer performance as it provides less frequency diversity than distributed mapping. Nevertheless, in practice, the channel estimation errors are more important in the distributed subcarrier mapping: Here, Wiener filtering was used to estimate the channel. In a localized subcarrier mapping scenario, we can take advantage of the channel's correlation profile in the frequency domain in order to maximize the SNR of the estimation, while in distributed subcarrier mapping this is not possible since the pilots experience uncorrelated channel realizations. This problem becomes even more critical in the case of multiple transmit antennas. The FER performance advantage due to higher frequency diversity in the distributed case is lost because of channel estimation difficulties, and localized scenarios are preferred in LTE uplink. To gain some frequency diversity, localized subcarrier mapping with frequency hopping (FH) is an interesting option, especially in the case of small spectral allocations.

Next, we investigated the impact of high-power amplifier (HPA) nonlinearities on the performance of these techniques using the requirements of the LTE system. Three main requirements need to be fulfilled here.

These are: (1) the spectrum emission mask (SEM), (2) the in-band distortion (which is measured in percentage by the error vector magnitude, EVM), and (3) the out-of-band emissions (limited by the adjacent channel leakage ratio, ACLR). Numerical bounds for these constraints are given in [11]. ACLR and EVM are respectively bounded by a minimum attenuation of 30 dB for the out-of-band emissions and maximum in-band signal distortion of 17.5% in the case of QPSK.

To make good use of the available power, it is necessary to operate the HPA near saturation. But this results in nonlinear signal distortion, which is higher in the case of signals of high dynamic range. To reduce signal distortion, the HPA output power needs to be backed-off with respect to its saturation level. High output back-off (OBO) values reduce distortion, but they also reduce the power efficiency. To optimize the operating point of the HPA in terms of output power and signal distortion, we need to minimize the total SNR degradation which is defined as the sum of the OBO and of the resulting SNR degradation caused by nonlinear signal distortion. The impact of the nonlinearities and the different components of the nonlinear degradation suffered by a system are summarized in Figure 7.

As illustrated in Figure 7, there exists an optimum operating point $\mathbf{I}_{opt}$ (and thus an optimum value of the OBO) which minimizes the total degradation. Unfortunately, $\mathbf{I}_{opt}$ is not always possible to achieve in practical systems due to spectral mask requirements. The optimum operating point $\mathbf{I}_{opt}$ in this figure corresponds to an OBO of 4 dB and leads to a total in-band degradation of approximately 5.4 dB. But, $\mathbf{I}_{opt}$ lies in a region which corresponds to high levels of out-of-band emissions, and might also cause high EVM. Therefore, the HPA in this figure must operate at a point $\mathbf{I}$ which is the closest point to $\mathbf{I}_{opt}$ which satisfies all system requirements (ACLR, SEM, EVM). The gap between the operating point $\mathbf{I}$ and the optimum point $\mathbf{I}_{opt}$ may attain several dB in real systems.

With a precoded-OFDMA system as described at the beginning of this section, we used the Rapp model with knee factor 2 [12] as well as the Saleh model with $\alpha = 1$, $\beta = 1/4$, $\alpha_p = \beta_p = 1$ [13] for the HPA nonlinearity and evaluated the optimum back-off for the amplifier under system constraints. The simulations were carried out for localized subcarrier allocations and for different numbers of RB allocations to users, with QPSK signal mapping, as shown in Table II. Detailed results including distributed carrier mapping are given in [14] and [15]. The Rapp amplifier model exhibits amplitude distortion, but no phase distortion. The in-band distortion (measured by EVM levels) is less significant than in the case of Saleh model, also introducing phase distortions.

With the Rapp model, the SEM is the strongest constraint, while with the Saleh model EVM is the strongest constraint and operating points lie at much higher values of the back-off due to the more pronounced nonlinear HPA characteristics.

Due to its PAPR advantage, SC-FDMA systematically gains 1.5 - 2 dB in terms of OBO, thus offsetting its performance loss on wireless channels. This is confirmed in Figure 8, where comparative total degradation results adding up the effects of both nonlinearities and behavior in frequency selective channels are presented. SC-FDMA, which was outperformed

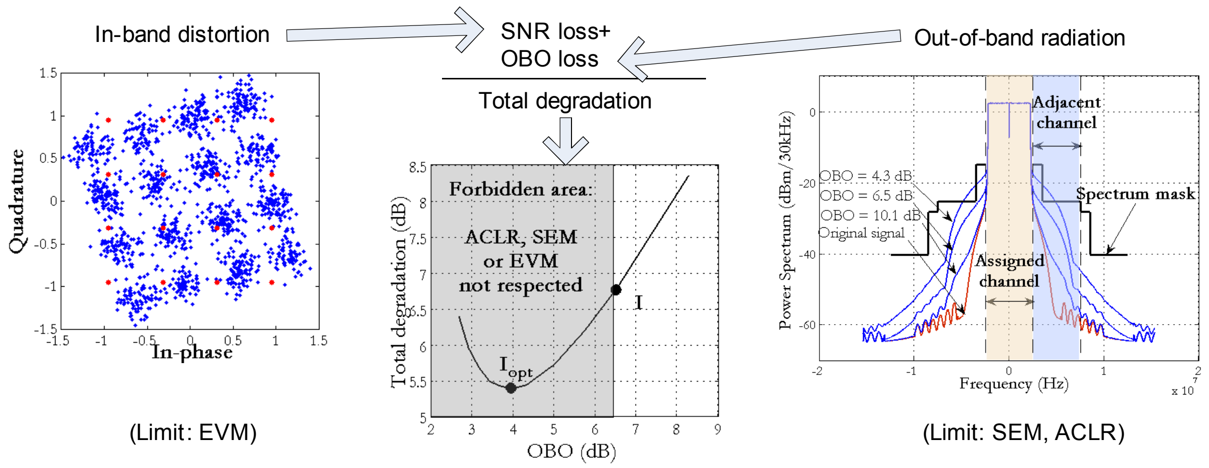

Fig. 7. Illustration of nonlinear distortion in an uncoded OFDMA system with 16-QAM signal mapping.

TABLE II
COMPARATIVE PERFORMANCE OF OFDMA AND SC-FDMA UNDER SYSTEM CONSTRAINTS

Under SEM constraints		SC-FDMA		OFDMA	
		1 RB	5 RB	1 RB	5RB
Rapp HPA	OBO (dB)	3.1	3.6	4.5	5.6
	EVM (%)	14.6	11.6	17.1	12.2
	ACLR (dB)	30.9	31.7	31.8	32.7
Saleh HPA	OBO (dB)	8.9	8.9	10.6	10.7
	EVM (%B)	17.4	17.3	17.4	17.4
	ACLR (dB)	31.6	31.9	31.9	32.8

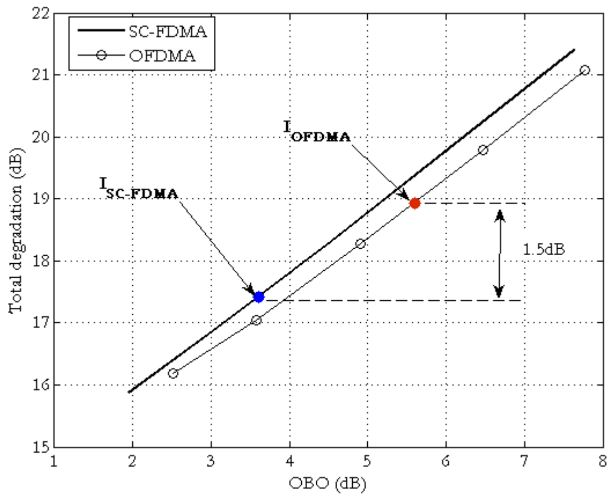

Fig. 8. Total system degradation of OFDMA and SC-FDMA, QPSK 1/2, 5 localized RBs, target FER 1%, Rapp HPA.

by OFDMA by 0.5 dB on the wireless channel, turns out to have an OBO advantage of 2 dB due to its better PAPR performance. Overall, the gain of SC-FDMA over OFDMA in this case amounts to 1.5 dB. Note that the part of the SNR loss in the total degradation balance (visible from the convex shape of the total degradation curve corresponding to low OBO in Figure 7) is highly reduced in coded systems. Indeed, the in-band distortion is mostly eliminated by the error correcting code when operating in the range of reasonable OBO values. The operating point is pushed into the linear part of the total degradation curve in Figure 8, because the SNR degradation due to in-band distortion (on the order of 0.2 dB) is completely negligible with respect to OBO values, which are on the order of several dB.

On the other hand, when the modulation order increases in the presence of strong coding, OFDMA becomes more and more attractive, since two effects combine: The potential OBO gain decreases (less PAPR difference), and the performance gain of OFDMA over SC-FDMA strongly increases, as it has been shown in Figures 4 and 5.

V. CONCLUSIONS

In this paper, we have given a historical review of two popular multiple access techniques, which are OFDMA and SC-FDMA. The controversial SCT-FDE vs. OFDM issue, which started in the early 1990s at the time of the European DVB project, continues today as an SC-FDMA vs. OFDMA debate in wireless communications. Whereas OFDMA was selected by the WiMAX Forum for mobile WiMAX systems for both downlink and uplink, the 3GPP project preferred to use OFDMA for the downlink only and favored SC-FDMA for the uplink.

We have also reported the results of some recent work on performance evaluation of these two multiple access techniques, which indicate that both techniques have some virtues and neither of them is better than the other in all conditions. In summary, OFDMA turns out to have better performance with high-order modulations which are used in favorable propagation conditions (typically for users near the base station). Stated differently, OFDMA lowers the SNR threshold above which high-level modulations and high code rates can be used. In contrast, SC-OFDMA is superior with QPSK and low code rates used typically near the cell edge and for users with bad propagation conditions. As a result, OFDMA can be expected to offer a higher cell capacity, while SC-FDMA can lead to cell range extension.

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