

# An Analysis of Three Multiple Access Techniques for the Uplink of Future Cellular Mobile Systems

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## SUMMARY

Orthogonal Frequency Division Multiple Access (OFDMA) is today a part of many standard specifications. Despite its attractive features, it has two main drawbacks when employed in the uplink: The high peak-to-average power ratio inherited from Orthogonal Frequency Division Multiplexing (OFDM) and the inherent frequency diversity loss. The loss of frequency diversity can be alleviated by precoding. Variants of Precoded OFDMA include Spread Spectrum Multi-Carrier Multiple Access (SS-MC-MA) and the frequency-domain implementation of single-carrier (SC) FDMA. The latter transforms OFDMA into a SC transmission system, avoiding the PAPR problem. This paper analyzes OFDMA, several variants of Precoded OFDMA and SC-FDMA in its frequency-domain implementations and compares them for uplink transmission.

## 1. INTRODUCTION

Future broadband cellular systems should meet stringent requirements such as high data rates over dispersive channels, coexistence of different services, good coverage, robustness to interference or high performance. These requirements turn the design of such a system into a real challenge, especially for the uplink with low-cost and low-complexity mobile terminals.

Although the principle of multi-carrier (MC) systems is not new, it is only in the past decade that this technique gained recognition and became a key component of many standards. Coded OFDM schemes are today used for terrestrial digital video broadcasting (DVB-T), wireless local area networks (IEEE 802.11a, ETSI Hiperlan2) and wireless metropolitan area networks (IEEE 802.16). Almost all current proposals for the air interface of Beyond Third Generation (B3G) and Fourth Generation (4G) cellular systems involve OFDM, OFDMA or one of its derivatives, e.g., multicarrier code division multiple access (MC-CDMA) and SS-MC-MA. Nevertheless, MC systems suffer from one major problem: The high peak-to-average power ratio (PAPR). This counterbalances the advantages of MC techniques, particularly on the uplink of cellular systems, since the output power of user terminals is limited and must be efficiently utilized in order to increase coverage. The debate on the choice

between SC and MC systems is still not closed. SC transmission alleviates the PAPR problem, but MC transmission opens the way to OFDMA [1], which significantly increases the cell range compared to a SC system or an OFDM system with time division multiple access: FDMA concentrates the available transmit power in a fraction of the channel bandwidth, improving the signal-to-noise ratio (SNR).

These considerations lead to the conclusion that SC-FDMA is best suited for the uplink, as it combines the low-PAPR characteristics of SC transmission with the advantages of OFDMA. The first SC-FDMA system description emerged under the form of a time domain implementation called IFDMA [2-4]. Its basic principle is the following: The input data stream is split into symbol blocks, each block is repeated a predetermined number of times and multiplied with a user-specific phase ramp. This results in interleaving different users' signals in the frequency domain without having to make any transformations between the frequency and the time domains. The 3GPP (Third Generation Partnership Project), which focuses on the Long Term Evolution (LTE) of UMTS (Universal Mobile Terrestrial Systems) radio access, has favored a frequency-domain implementation of SC-FDMA, which is actually a Precoded OFDMA scheme, where precoding is carried out by means of a DFT matrix. The major argument in

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favor of this scheme (called DFT-Spread OFDM by 3GPP) is

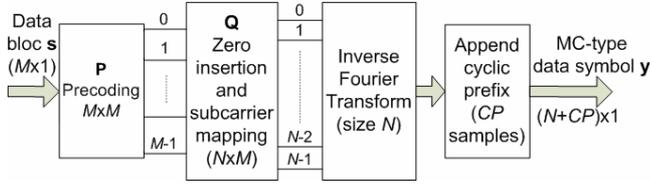


Figure 1. General MC transmitter.

its flexibility in terms of sharing the spectrum between different users. In downlink, OFDMA is preferred.

This paper provides an analysis of these different multiple access schemes. The paper is organized as follows: Section 2 gives the fundamentals of the multiple access techniques reviewed above. Section 3 presents the system model used in our simulations. Performance is evaluated and the results are discussed in Sections 4 and 5. Finally, the conclusions are given in Section 6.

## 2. MULTIPLE ACCESS TECHNIQUES FOR THE UPLINK

Fig. 1 presents the baseband structure of a general MC transmitter, suitable for all types of SC or MC modulation signals transmitted in blocks [5]. Data blocks of size  $M$  are precoded with the  $[M \times M]$  matrix  $\mathbf{P}$ . The  $M$ -sized output vector is then mapped on  $M$  out of  $N$  inputs of the inverse DFT according to the subcarrier mapping  $[N \times M]$  matrix  $\mathbf{Q}$ . A cyclic prefix of length  $CP$  is inserted in front of each  $N$ -sized block delivered by the inverse DFT. A different number of subcarriers and a different modulation and coding scheme can be assigned to each user. Let us denote by  $\otimes$  the Kronecker product, by  $\mathbf{0}_{M \times N}$  the all-zero matrix of size  $[M \times N]$  and by  $\mathbf{I}_M$  the  $[M \times M]$  identity matrix. For clarity, we assume that the size  $N$  of the inverse DFT is a multiple of the block size, i.e.,  $N = MK$ . Let us also denote by  $s(n)$  the information symbols which are parsed into data blocks of size  $M$ . The  $i$ -th data block  $s^i$  can thus be written as:

$$s^i = [s(iM), \dots, s(iM + M - 1)]^T. \quad (1)$$

The index  $i$  will be omitted in the sequel.

### 2.1. OFDMA

The trivial case when  $\mathbf{P}$  is the identity matrix,  $\mathbf{P} = \mathbf{I}_M$ , leads to OFDMA. The user-specific data block  $\mathbf{s}$  is directly mapped onto a subset of  $M$  subcarriers,

conveniently chosen by the user-specific subcarrier mapping matrix  $\mathbf{Q}$ . The vector  $\mathbf{Q}\mathbf{s}$  is fed to the entries of the inverse DFT. The form of the matrix  $\mathbf{Q}$  might lead to either a *localized* (2) or a *distributed* (3) mapping:

$$\mathbf{Q}_{N \times M} = \begin{pmatrix} \mathbf{0}_{q \times M} \\ \mathbf{I}_M \\ \mathbf{0}_{(N-q-M) \times M} \end{pmatrix}, \quad (2)$$

$$\mathbf{Q}_{N \times M} = \mathbf{I}_M \otimes \begin{pmatrix} \mathbf{0}_{n \times 1} \\ 1 \\ \mathbf{0}_{(K-n-1) \times 1} \end{pmatrix}. \quad (3)$$

By assigning different groups of subcarriers to different users, each user's transmit power can be concentrated in a restricted part of the channel bandwidth, resulting in significant coverage increase. Different user signals remain orthogonal only if carrier synchronization is maintained and an appropriate cyclic prefix is appended to compensate for timing misalignment at the receiver. In order to keep good performance on frequency-selective channels, efficient forward error correction must be employed.

### 2.2. Precoded OFDMA

Precoded OFDMA consists of using a precoding matrix  $\mathbf{P}$  that spreads the energy of symbols over the subcarriers allocated to the user. Uniform energy distribution is favored in practice. One of the most well known precoding matrices is the Walsh-Hadamard (WH) matrix:

$$\mathbf{P} = [\mathbf{p}_0, \mathbf{p}_1, \dots, \mathbf{p}_{M-1}]^T, \quad (4)$$

where the row vectors  $\mathbf{p}_i$ ,  $i = 0 \dots M - 1$ , are orthogonal WH sequences of length  $M$ . This type of Precoded OFDMA was coined SS-MC-MA [6,7]. The precoding operation  $\mathbf{P}\mathbf{s}$  consists in spreading the data symbols by multiplication with orthogonal WH sequences and superimposing them on the same set of subcarriers according to matrix  $\mathbf{Q}$ . Another precoding matrix that spreads the symbol energy uniformly is the DFT matrix. We will discuss this precoding in the following section. Precoded OFDMA conserves the advantages of OFDMA in terms of cell range extension and spectrum spreading, which is expected to provide some robustness against cellular interference. With respect to MC-CDMA, it loses some frequency diversity, but this loss can be compensated by frequency interleaving or frequency

hopping techniques [8]. The well-known advantages of MC systems are sometimes counter-balanced by their high PAPR. If we want to avoid nonlinear effects, the input signal must lie in the linear region of the HPA. In order to avoid the use of extremely high back-offs and costly amplifiers, occasional clipping and/or soft thresholding must be allowed. This leads to in-band distortion (which degrades the bit error rate) and to spectral widening that increases adjacent channel interference. Many PAPR reduction algorithms have been developed in order to alleviate this problem. Unfortunately, they do not always yield significant performance gains in practical applications [9].

### 2.3. SC-FDMA

As an alternative to MC-FDMA, SC-FDMA schemes have been envisioned, since a single-carrier system with an OFDMA-like multiple access would combine the advantages of the two techniques, which are low PAPR and high coverage. The first SC-FDMA concept [2] was IFDMA, which is based on compression and block repetition in the time domain of the modulated signal. As theoretically proven [4], this manipulation has a direct interpretation in the frequency domain. The spectrum of the compressed and  $K$ -times repeated signal has the same shape as the original signal, with the difference that it presents exactly  $K-1$  zeros between two data subcarriers. This feature enables us to easily interleave 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 specific phase ramp. Besides, as for OFDMA, robustness to cellular interference can be achieved by coordinating resource allocation between adjacent cells.

The same waveform can be obtained in the frequency domain: by using in Fig. 1 the discrete Fourier matrix:

$$\mathbf{P} = [p_{k,n}], \quad p_{k,n} = e^{j2\pi \frac{kn}{M}} \quad (5)$$

as precoding matrix, we obtain DFT-Precoded OFDMA, which is mathematically identical to IFDMA in a distributed carrier scenario. The precoding operation  $\mathbf{P}$  is equivalent to an  $M$ -point DFT transform. With a mapping matrix  $\mathbf{Q}$  as given in (3), the spectra of distributed DFT-Precoded OFDMA and IFDMA are identical, and thus they correspond to the same waveform. The two techniques are just different implementations of SC-FDMA. The advantage of DFT-Precoded OFDMA is its more flexible structure: While IFDMA imposes a

distributed signal structure, DFT-Precoded OFDMA allows us to choose the mapping matrix  $\mathbf{Q}$  as desired. Localized carrier versions or channel-dependent mappings are possible. Also, pulse shape filtering can be performed in the frequency-domain, with a lower complexity than time-domain filtering. Note that in case of a frequency selective channel, interference may occur within the  $M$  elements of each data block. This degradation, which is more important in a distributed subcarrier mapping, impacts WH-Precoded OFDMA as well.

### 3. SYSTEM MODEL

In what follows, WH-Precoded OFDMA will simply be referred to as Precoded OFDMA. The simulated system model employs OFDMA, Precoded OFDMA and SC-FDMA transmission. We use a signal with  $N = 512$  subcarriers, among which 300 are data carriers, split into 25 resource blocks (RB) of 12 subcarriers. A DC subcarrier is added in the case of OFDMA, and the remaining 211 (OFDMA) or 212 (Precoded OFDMA, SC-FDMA) are guard carriers. With these parameters, the sampling frequency corresponding to a 5 MHz channel is 7.68 MHz. The signal constellation is QPSK, 16QAM or 64QAM with Gray mapping. We employ a  $(753,531)_8$  convolutional code with rate 1/2, 3/4 or 5/6. The codes of rate 3/4 and 5/6 are obtained by puncturing the 1/2 code. The data is scrambled before coding and interleaved prior to QAM mapping. Groups of 7 OFDMA-type symbols are encoded together in order to take advantage of the channel diversity. We used soft Viterbi decoding. Minimum mean square error (MMSE) Frequency-domain equalization is assumed if the channel is frequency selective (section 5).

The HPA is Rapp's solid state model [10]:

$$v_{OUT} = \frac{v_{IN}}{\left(1 + (|v_{IN}|/v_{SAT})^{2p}\right)^{\frac{1}{2p}}}, \quad (6)$$

where  $v_{IN}$ ,  $v_{OUT}$  are respectively the complex input and complex output signals (baseband equivalent, normalized) and  $v_{SAT}$  corresponds to the output saturation level normalized to unity,  $P_{SAT} = |v_{SAT}|^2$ . We consider a Rapp model HPA with knee factor  $p = 2$ , since it is reported in [11] to be a good representation of typical HPAs in the sub-10GHz frequency range, as is the case of our system. We also define the input back-off (IBO) and output back-off (OBO) with respect to the saturation values:

$$IBO|_{dB} = -10 \log_{10} \frac{E \left\{ |v_{IN}(t)|^2 \right\}}{P_{SAT,IN}}, \quad (7)$$

$$OBO|_{dB} = -10 \log_{10} \frac{E \left\{ |v_{OUT}(t)|^2 \right\}}{P_{SAT,OUT}}. \quad (8)$$

#### 4. IMPACT OF NONLINEARITIES

We would like to evaluate the impact of nonlinearities on OFDMA, Precoded OFDMA and SC-FDMA. All the Bit Error Rate (BER) results in this section suppose an AWGN (additive white Gaussian noise) channel in order to evaluate only the effects due to the presence of the HPA. The behavior of these systems on fading channels will be separately treated in the next section.

##### 4.1. Signal Envelope Variations

Let us first analyze the signal envelope variations of these types of signals. To do so, we define the Complementary Cumulative Distribution Function (CCDF) of the instantaneous normalized power (INP) as being:

$$CCDF(INP(v_{IN})) = \Pr \left( \frac{|y_i|^2}{P_{avg,IN}} > \gamma^2 \right), \quad (9)$$

where  $v_{IN}$  is the signal present at the input of the HPA,  $y_i$  denotes its samples and  $P_{ave\_IN} = E\{|v_{IN}|^2\}$  is its average power. CCDF of INP [9] is a more relevant performance criterion than the widely used CCDF of PAPR: It takes into account all signal samples that are susceptible of causing degradation when passing through the HPA, and not only the highest peak of each OFDM symbol.

Let us consider that 24 distributed subcarriers (2 RBs) are allocated to each user. Fig. 2 presents the CCDF of INP with QPSK, 16QAM and 64QAM signal mappings. The SC properties of SC-FDMA result in low envelope variations for all signal mappings: At a clipping probability per sample of  $10^{-4}$ , SC-FDMA outperforms OFDMA by 2.7 dB, 1.9 dB and 1.8 dB when QPSK, 16QAM and 64QAM are employed, respectively. OFDMA exhibits high envelope variations for all signal mappings. Precoded OFDMA has somewhat lower PAPR than OFDMA, but still largely superior to SC-FDMA. Distributed and localized SC-FDMA exhibit the same

good performance for all signal mappings (results for 16QAM and 64QAM are not plotted here for better figure

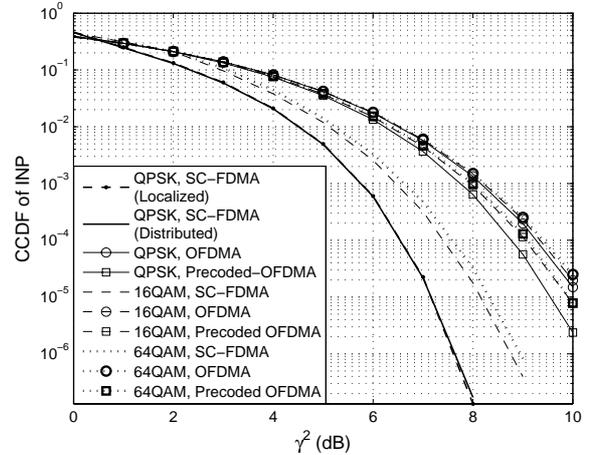


Figure 2. CCDF of INP for SC-FDMA, OFDMA and Precoded OFDMA with QPSK/16QAM/64QAM, oversampled 4 times.

readability). This result can be confirmed for all spectral allocations (1 to 25 RBs allocated to the same user). Note that this evaluation compares localized and distributed frequency-domain implementations of SC-FDMA, generated by the structure described in section 3. No pulse shape filtering or time windowing were performed. Ideal IFDMA (with no guard intervals) is reported to have a somewhat lower PAPR than SC-FDMA [12].

##### 4.2. Spectral Analysis

The main drawback of high-PAPR signals is the necessity of backing-off the operating point of the nonlinear HPA in order to avoid excessive spectrum widening and out-of-band radiation. For practical system design, the relevant evaluation criterion is the necessary amount of OBO that would be needed in order to satisfy three main constraints: Comply with the spectrum mask requirements, comply with the out-of-band radiation limits, and preserve good system performance. Spectrum masks are defined by regulatory standards bodies, based on system-dependent prerequisites. Here, we will take into account the general E-UTRA (Evolved Universal Terrestrial Radio Access) spectrum emission mask (SEM) defined by the 3GPP-LTE for the user equipment (UE) [13] OOB radiation represents the unwanted emissions immediately outside the nominal channel, resulting from the modulation process and from the non-linearity of the transmitter. One way of measuring the OOB is to evaluate the Adjacent

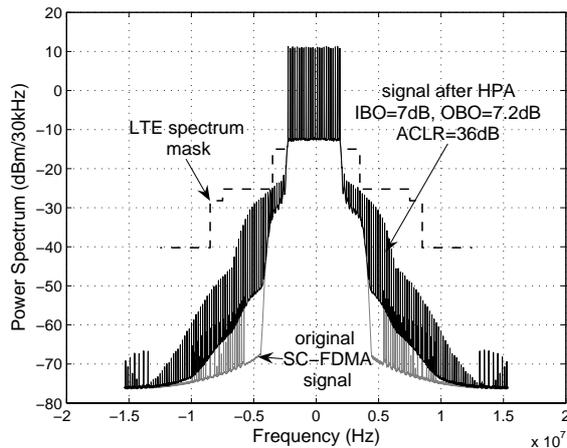


Figure 3. SC-FDMA spectrum, 16QAM, 2 distributed RBs, complying with LTE mask.

Channel Leakage Ratio (ACLR). ACLR is defined as the ratio of the RRC (Root Raised Cosine)-filtered mean power centered on the assigned channel frequency to the RRC-filtered mean power centered on the adjacent channel frequency. For an assigned channel bandwidth of 5 MHz, actual regulations [13] impose an indicative limit of 33 dB of ACLR (still subject to further modification). ACLR is to be measured with a 3.84 MHz bandwidth RRC filter with roll-off factor  $\alpha = 0.22$  centered on the adjacent channel. Here, we concentrate on these first two spectral requirements. The system performance, evaluated with respect to some BER target (e.g., tolerable  $E_b/N_0$  loss at  $\text{BER} = 10^{-4}$ ), will be addressed in the following subsection.

Fig. 3 shows the spectrum of a SC-FDMA signal with 2 distributed RBs allocated to one user, with 16QAM signal mapping. Since less than 8 RBs are allocated, [13] imposes that measurements be conducted for a maximum radiated power of 22 dBm. An OBO of 7.2 dB (corresponding to an IBO of 7 dB) is needed in order to comply with the spectrum mask requirements. The mask constraint is in this case stronger than the ACLR constraint. Similar considerations show that OFDMA / Precoded OFDMA would require an OBO of 8.4 dB (which corresponds to  $\text{IBO} = 8.2$  dB) in order to comply with the SEM, for an ACLR of 35.4 dB and 35.8 dB, respectively. Employing SC-FDMA brings a gain of 1.2 dB in terms of OBO.

Let us now consider the case of 2 localized RBs, depicted in Fig. 4. The worst-case scenario of spectral allocation is when the RBs are allocated at the edge of the channel, causing a maximum of OOB radiation. A UE

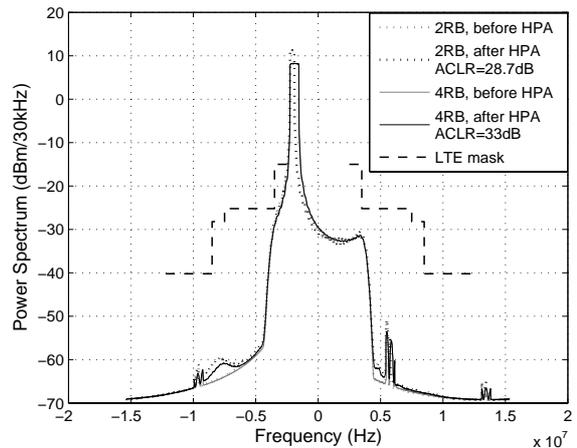


Figure 4. SC-FDMA spectrum, 16QAM @  $P_{\text{out}} = 22$  dBm, 2 or 4 localized RBs, OBO=7.2 dB.

radiating an emission power of 22 dBm cannot comply with the actual ACLR requirements: Even in the absence of the HPA, its OOB emission corresponds to an ACLR of 28.7 dB. Let us now consider that 4 localized RBs are allocated to the user. We notice that the signal easily complies with the SEM, but an OBO of 7.2 dB is necessary to ensure the required ACLR of 33 dB. In this worst-case scenario of a scheduler where a low number of RBs are allocated to the edge of the channel bandwidth, the ACLR constraint becomes stronger than the SEM constraint. OFDMA and Precoded OFDMA still have lower performance than SC-FDMA, and an OBO of 8.4 dB is necessary to meet the ACLR constraints for 4 localized RBs. This represents a loss of 1.2 dB with respect to SC-FDMA. Note that all numerical results in this subsection strongly depend on the HPA.

#### 4.3. BER Degradation and Overall Degradation

Let us now evaluate the degradation caused by the nonlinearity in terms of BER. Fig. 5 depicts the BER performance (for a target BER of  $10^{-4}$ ) for a SC-FDMA system employing 16 QAM with a 3/4 code rate and 2 distributed RBs. When the OBO decreases, the mean power of the signal going through the HPA increases with respect to the HPA saturation level; consequently, more and more signal samples undergo nonlinear distortion and/or clipping, which leads to increasing performance degradation. Even though there is virtually no performance loss (with respect to a linear system with no HPA) for an OBO of 8.1 dB, we can lose up to 1.5 dB in terms of  $E_b/N_0$  with an OBO of 4 dB. In system

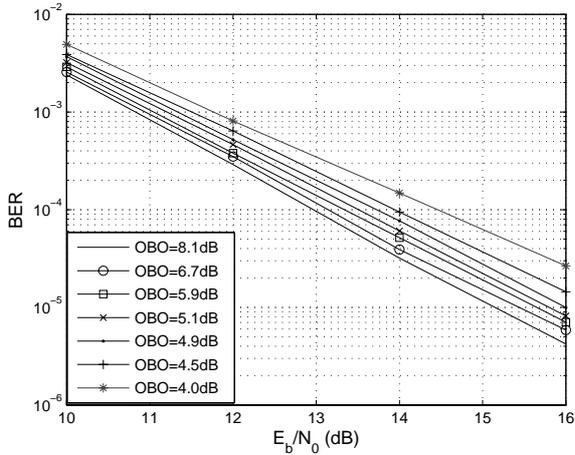


Figure 5. BER performance, SC-FDMA, 16QAM 3/4 with Rapp HPA, 2 distributed RBs, AWGN channel.

configurations with very permissive spectral requirements the  $E_b/N_0$  degradation can become the strongest constraint.

Let us further investigate the scenario described in the previous subsections. The impact of the nonlinear HPA on the system is given by the total degradation ( $OBO + \Delta E_b/N_0$ ) with respect to an ideal system where no HPA is present. In the studied case, where rather high back-offs are imposed by the spectral constraints and we use a coded system,  $\Delta E_b/N_0$  is negligible with respect to the necessary amount of OBO (for 2 distributed RBs, the spectral constraints impose an OBO of 7.2 dB, but the performance degradation  $\Delta E_b/N_0$  is on the order of 0.2 dB only). We can see that SC-FDMA gains roughly the 1.2 dB that we evaluated in the previous section over OFDMA and Precoded OFDMA. Let us now revisit the interpretation of Fig. 3. An OFDMA system operating at an IBO of 8.2 dB has a probability of  $10^{-3}$  that the signal samples go into saturation; in order to keep the same clipping probability of  $10^{-3}$ , a SC-FDMA system would need to function at an IBO of only 6.4 dB. This indicates a potential gain of 1.8 dB, which is larger than the 1.2 dB measured above. The explanation consists in the nature of the nonlinearity: The performance gain predicted by the CCDF of INP can be directly interpreted in terms of (input) back-off difference only in the case of an ideal (clipper-type) HPA, where all the unclipped samples remain undistorted. With the considered Rapp HPA, some of the samples that do not go into saturation suffer from nonlinear effects, and this is more pronounced at low back-offs. With a realistic HPA, a back-off difference given by CCDF of INP curves should only be seen as an upper bound of performance gain. Note that SC-FDMA

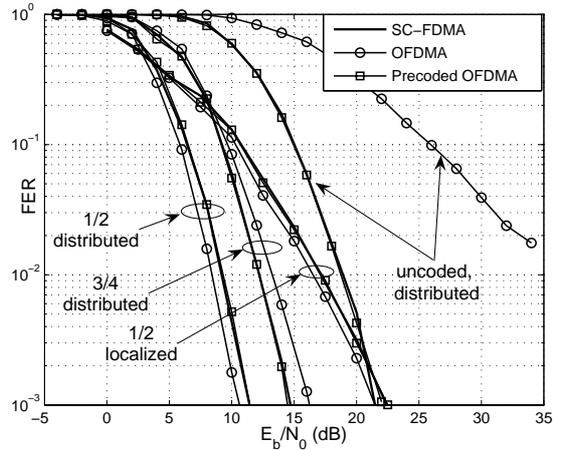


Figure 6. FER performance, QPSK, 2RBs, no HPA, COST 259 channel.

has a higher potential gain with respect to OFDMA when QPSK is employed, as it can be seen in Fig. 2. The potential gain diminishes when the size of the employed modulation increases.

## 5. PERFORMANCE ON FREQUENCY SELECTIVE CHANNELS

Let us now investigate the performance of SC-FDMA, OFDMA and Precoded-OFDMA on a single-input single-output frequency selective channel with Typical Urban COST259-like power delay profile (20 paths, maximum delay spread of 2.140  $\mu$ s). Since we want to separate the impact of the nonlinearities from the impact of the frequency selectivity, we assume in this section that no HPA is present at the transmitter. Let us first analyze the results in Fig. 6, where QPSK is employed. SC-FDMA and Precoded OFDMA have similar Frame Error Rate (FER) performances because they both tend to recover the frequency diversity thanks to their symbol energy spreading property. Since OFDMA has no built-in diversity, its performance is very dependent on the coding rate. When a low coding rate or an uncoded system is employed, OFDMA performs poorly because coding does not manage to compensate the influence of carriers with a low SNR. When stronger coding is present (e.g., rate 1/2), OFDMA benefits from the coding diversity and thus it recovers the difference and even outperforms SC-FDMA/Precoded OFDMA by 0.5 dB at  $FER = 10^{-1}$ . We also observe that localized subcarrier mapping has poorer performance as it recovers less diversity than distributed

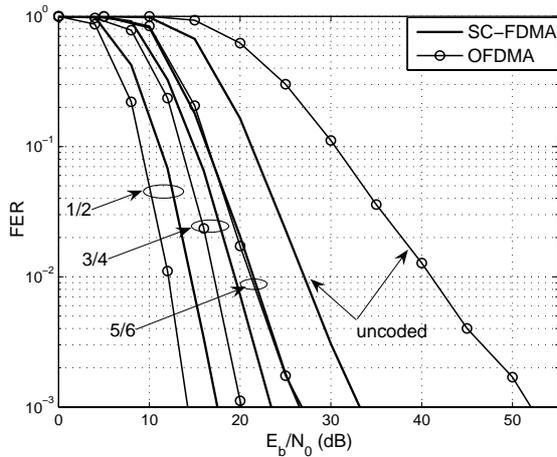


Figure 7. FER performance, 16 QAM; 2 distributed RBs at different coding rates.

mapping. In practice, frequency hopping techniques are used to compensate for this diversity loss in distributed mapping systems. Since channel estimation is much more difficult in the distributed case (which is also more vulnerable to Doppler and frequency offsets), localized carrier mapping with frequency hopping is preferred in practical applications.

With higher level modulations, there is a tradeoff [14] between the frequency diversity gain (due to the spreading performed in SC-FDMA / Precoded OFDMA) and the coding gain. Let us examine the Frame Error Rate (FER) results in Fig. 7, 8 centered on a target FER of 10% (we omitted the performance of Precoded-OFDMA since it is equivalent to that of SC-FDMA). The numerical results reported in Table 1 show the gain of OFDMA over SC-FDMA at 10% FER. SC-FDMA has difficulties to recover the frequency diversity when the modulation order increases (16 QAM, 64 QAM). In that case, OFDMA, which does not suffer from any inter-symbol interference, has better performance. Before closing this section, consider a user terminal at cell edge suffering from bad propagation conditions and which needs to transmit using the maximum authorized power. The base station would typically allocate to this user a small number of

Table 1: Relative gain of OFDMA over SC-FDMA for different coding rates at FER 10%.

FER = 10 <sup>-1</sup>	QPSK	16 QAM	64QAM
1/2	0.5 dB	3.1 dB	4.5 dB
3/4	-0.5 dB	1.5 dB	4.3 dB
5/6	-2.2 dB	0 dB	1.1 dB
uncoded	-11 dB	-9 dB	-8.8 dB

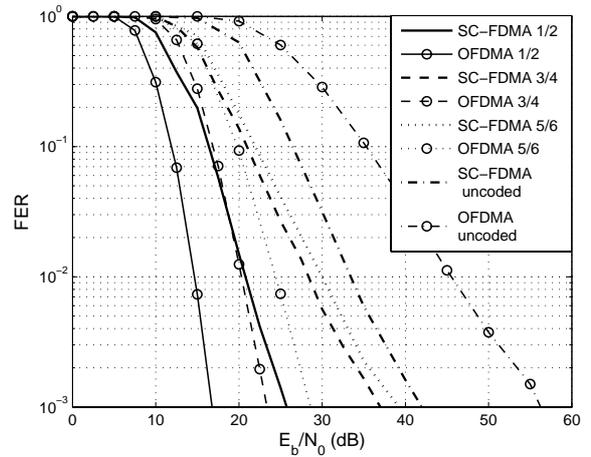


Figure 8. FER performance, 64 QAM; 2 distributed RBs at different coding rates.

RBs with QPSK and strong coding. The performance of OFDMA and SC-FDMA are comparable in this case, but the analysis of the previous section shows that SC-FDMA has a significant advantage over OFDMA in this scenario, because of its lower PAPR (up to 2.3 dB of potential gain read on the curves in Fig. 2, depending on the amplifier). On the other hand, a user that is close to the base station benefiting from good propagation conditions can decrease the transmitted power, and thus the PAPR problem is no longer an issue in that case. Moreover, the potential PAPR gains are much lower than in the case of QPSK. Therefore, OFDMA should be preferred in this scenario as it leads to a better throughput. Precoded-OFDMA has neither the advantage of PAPR in the first case, nor the advantage of better BER performance in the second.

## 6. CONCLUSIONS

In this paper, we have analyzed three multiple access techniques which are potential candidates for the uplink of future cellular communications systems: OFDMA, WH-Precoded OFDMA and SC-FDMA. We first investigated the impact of HPA nonlinearity on the performance of these schemes taking into account the constraints of practical systems (spectrum mask and ACLR). The analysis confirmed the potential gains of SC-FDMA over OFDMA in situations where the PAPR is a significant issue. Next, BER performance on frequency selective channels was investigated. With the QPSK signal format, SC-FDMA / Precoded OFDMA and OFDMA at usual coding rates have rather similar performances, and SC-

FDMA is preferred due to its PAPR gain. In contrast, OFDMA has superior performance in coded systems with higher order modulations, where the orthogonality loss of SC-FDMA and Precoded-OFDMA becomes a problem. We conclude that neither of the three multiple access techniques has a clear advantage in all situations. While SC-FDMA can have some advantages near the cell edge, where typically the QPSK signal format with low codes rates (e.g. rate 1/2) is employed, OFDMA turns out to have some significant advantages whenever high-level QAM signal formats can be used.

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