

UPLINK MODULATION STRATEGIES IN 4G WIRELESS CELLULAR SYSTEMS

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ABSTRACT

New upcoming wireless communication standards utilizing Orthogonal Frequency Division Multiplexing (OFDM) provide high data rates and good signal cell coverage that makes their application extremely promising in fourthcoming years. Despite of its widely recognized benefits, sensitivity to the nonlinear amplification remains still a special issue to be solved. Recent solution to overcome this problem has been introduced by 3GPP consortium in Release 8, where the particular precoded OFDMA scheme, a closely related OFDMA alternative, is considered. This approach is widely recognized as a Single Carrier Frequency Division Multiplexing (SC-FDMA) and is characterized by using Discrete Fourier Transformation (DFT) for the signal spreading/despreading purposes. In this paper, we present the mutual performance evaluation of discussed techniques performing over nonlinear AWGN channels and state some significant considerations resulting from this.

Keywords: nonlinear distortion, power amplifier, OFDMA, SC-FDMA

1. INTRODUCTION

Over the last decade, the demands for high data rates increased rapidly. Regarding to this fact, many techniques have emerged during this period. The earliest digital communication systems like GSM utilized time division multiple access [1]. The second generation and third generation of modern wireless communication systems employed direct sequence spread spectrum for both multiplexing and multiple access [1]. The next evolutions (4G) will bring OFDMA as a promising solution how to achieve the ubiquitous access to the source of information anywhere and anytime with high quality of services. Recently, two different OFDMA-based 4G techniques have appeared on the market. The former, WiMax, that is based on IEEE standard (802.16) adopts OFDMA transmission scheme in both forward link (uplink) as well as in reverse link (downlink) [2]. The latter approach has been introduced by 3GPP that firmed up specifications for Long-Term Evolution (LTE) [3]. LTE employs OFDMA in downlink scenario, which is important resemblance to WiMax, however SC-FDMA is used in the uplink [3].

SC-FDMA signals are characterised by the inherently lower peak-to-average power ratio (PAPR) than traditional OFDMA signals [4]. This fact motivates the manufacturers to introduce this method in the uplink of LTE, since reducing the sensitivity to nonlinear amplification is of special relevance to mobile terminals mostly (uplink). For the base station using expensive highly linear amplifiers, it is not such an important design key [3]. In general, we do distinguish between two different SC-FDMA concepts. SC-FDMA with blockwise subcarriers allocation is known as localised Localized Frequency Division Multiple Access (LFDMA) [4]. SC-FDMA systems with regularly interleaved subcarrier allocation is also known as Interleaved Frequency Division Multiple Access (IFDMA) [4], [5], [6]. Since only LFDMA concept is proposed to use in the 3GPP LTE specifications, we will be focused on this approach exclusively further in this paper.

Since the OFDMA signal results from the superposition of a large number of individually modulated data symbols, the OFDM signal envelope is characterised by the high fluctuation. Large peaks of the resultant signal will reach occasionally the saturation region of PA, which will further result in unacceptable BER increase as well as the out-of-band radiation [7]. There has been intensive research concerning nonlinear distortion and its effects for pure OFDMA signal. Some of the pioneer work on this topic was done in [8] for baseband OFDMA and in [9] for passband OFDMA where both introduced analytical derivation of nonlinear distortion in AWGN channels. From above given discussion we can claim, that the effects of the nonlinear distortion have been widely addressed recently and are verified by the analytical background. On the other hand SC-FDMA is relatively new standard and The Release 8 of 3GPP specifications do very little to explain the concept of SC-FDMA, there are still a lot of open issues also from the nonlinear distortion point of view to be discussed [10].

In this paper, we introduce the performance evaluation of traditional OFDMA concept with the upcoming SC-FDMA. In this area of research, there exist only several contributions concerning the sensitivity of SC-FDMA to nonlinear distortion, e.g. [4], [11], however we can claim that there still exists a little fuss about presented SC-FDMA. Therefore we find to be very attractive to do the fundamental comparison of above mentioned techniques in nonlinear AWGN environment from the BER point of view. Since SC-FDMA is characterised by inherently lower PAPR due to its single carrier nature, it is expected that SC-FDMA provides better performance results than OFDMA. However based on our observation, we can claim that OFDMA can give better BER performance in the uplink scenario for moderate number of subcarriers and higher signal-to-noise ratio (SNR) intervals than SC-FDMA. This is a special relevance for the users located near to the base station asking for the services such as high definition video real-time communication where application of OFDMA might have special interest.

2. OFDM OVERVIEW

OFDMA transmit signal is the sum of N independent sub-symbols (tones) with equal bandwidth and frequency separation $1/T$, where T is time duration of OFDMA symbol. The m -th of encoded bits is mapped into the complex valued OFDMA vector of QAM constellation points, $\mathbf{S}^m = [S_0^m, \dots, S_{N-1}^m]$ and the continuous time representation of the single multicarrier symbol is given by [12]:

$$s_{CP}^m(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k^m e^{j2\pi kt/T} \quad (1)$$

where m is a symbol index and S_k^m is the QAM value of k -th subsymbol or tone. The periodic extension of the symbol over the interval $[-T_{CP}, 0]$ is the cyclic prefix (CP) which simplifies the equaliser design in the presence of multipath fading.

In practise, OFDMA signals are generated using Inverse Discrete Fourier Transform (IDFT). The resulting T/N -spaced discrete time vector $\mathbf{s}^m = [s_0^m, \dots, s_n^m, \dots, s_{N-1}^m]$ = $IDFT(\mathbf{S}^m)$ is given by [12]:

$$\mathbf{s}^m = [s_0^m, \dots, s_n^m, \dots, s_{N-1}^m] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k^m e^{j2\pi kn/N} \quad (2)$$

For the remainder of this paper, we will omit the notation $[s_0^m, \dots, s_n^m, \dots, s_{N-1}^m]$, instead of this only s_n is used in analytical derivations for the concise structure of presented formulas.

3. SYSTEM STRUCTURE OF SC-FDMA

In SC-FDMA, the bit sequence is mapped onto N complex modulation symbols in the first step. Commonly used baseband modulation schemes in upcoming LTE standard include QPSK, 16-QAM and 64-QAM. In general, transmitter adopts the modulation scheme to match the particular channel conditions and characteristics for the certain time instance.

Afterwards, block of N data symbols is applied to a size N DFT. This operation is in the literature also described as a DFT-precoding operation [3]. Application of DFT-precoding at the transmitter side is a promising solution for the reduction of the envelope fluctuation of the original OFDMA signal. The next stage of SC-FDMA procedure is to shift the baseband DFT representation of SC-FDMA symbol to the desired part of the overall channel bandwidth. Since the signal is now represented as a DFT, assigning individual subcarriers to the user is only matter of frequency shifting and copying the N bins into a larger DFT M bins space that can be up to the size of the system channel bandwidth.

In LFDMA, each user terminal adopts consecutive adjacent subcarriers for the transmission. As a results of this fact, particular mobile terminal use only a fraction of the overall bandwidth and only a small fraction of frequency diversity is used (Fig. 1). This fact is of special relevance for the systems, where channel state information is perfectly known for the each time instant, hence no further kinds of diversity is necessary to use.

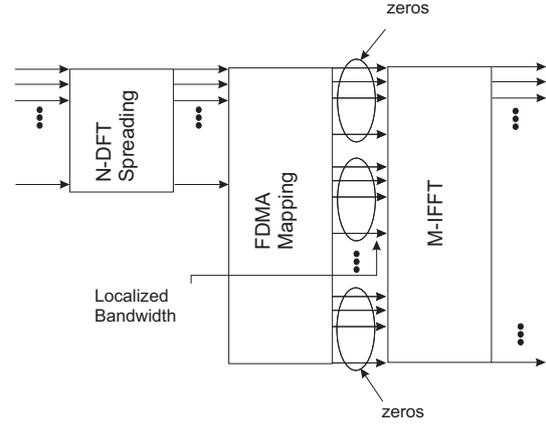


Fig. 1 Block scheme of SC-FDMA uplink transmission system

4. ANALYTICAL DERIVATION OF TIME DOMAIN SC-FDMA SIGNAL

Let $S_i, i = 0, 1, \dots, N-1$ be the complex data symbols according to the modulation alphabet, then the signal at the output of DFT-precoder block can be expressed as:

$$A_n = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} S_i e^{-j2\pi in/N} \quad (3)$$

Let us assume baseband OFDMA symbol $s(t)$ defined over the time interval $t \in [0, T_s)$,

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} A_k e^{j2\pi(k+k_0)t/T_s}, \quad (4)$$

where k_0 is the position of the first assigned subcarrier. For the sake of brevity, we assume k_0 to be $k_0 = 0$. If the signal $s(t)$ is sampled at a frequency LN/T_s , where $L = M/N$ is oversampling factor and N/T_s is the Nyquist rate, the signal at the output of LFDMA modulator can be expressed as:

$$s_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} A_k e^{j2\pi kn/M}, n = 0, 1, \dots, M-1. \quad (5)$$

From the (3) and (5) we get:

$$s_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \left(\frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} S_i e^{-j2\pi ik/N} \right) e^{j2\pi kn/M} \quad (6)$$

which results in:

$$s_n = \frac{1}{N} \sum_{i=0}^{N-1} S_i \sum_{k=0}^{N-1} e^{j2\pi k(n-Li)/M} \quad (7)$$

Let us briefly analyze the LFDMA signal at the sample positions multiple of the spreading factor. If $n = Lr$, the time domain signal in (6) reduces to [4]:

$$s_{Lr} = S_r \quad (8)$$

The derivation of this formula is beyond the scope of this paper and might be found in [4]. From (8) results, that the

$Lr - th$ sample of the time domain LFDMA signal is equal to the data symbol S_r . The samples at positions $n \neq S_r$ describe the transition of the time domain signal between values S_r and S_{r+1} . The presence of these transitions between modulated symbols restores the question of the fluctuation of the envelope and increase inherently PAPR.

5. NONLINEAR DISTORTION PROBLEM

PA are typically the most power-demanding components of transceiver structures. The design of PA, especially for linear, low-voltage operations, remains a difficult problem. In practical realisation, one takes the advantage of different predistortion schemes in order to compensate the PA nonlinearity. However, even if perfect predistortion is considered, the signal is commonly clipped at the threshold level A . On the other hand, using predistortion makes the PA characteristic linear up to the threshold level A . Thus, BER degradation may happen since the signal distortion like the clipping may be generated.

However, if the input signal resides in the linear region of PA, BER performance will be improved because of the linearization by predistorter. With aim to illustrate the typical behaviour of presented scheme, Soft Limiter model of PA is commonly used. Soft limiter can be seen as the device that is perfectly linear up to threshold level A and clip all samples exceeding the saturation point. Let $x_b = u_x e^{j\alpha_x}$ be the baseband signal at the input of soft limiter with A being the maximum output amplitude allowed than the baseband output signal becomes [12]:

$$y_b = \begin{cases} x_b, & \text{if } u_x < A \\ Ae^{j\alpha_x}, & \text{otherwise} \end{cases} \quad (9)$$

The PA operation in the region of its nonlinear characteristic causes a nonlinear distortion of transmitted signal, that subsequently results in higher BER and out-of-band energy radiation. The operating point of PA is defined by parameter input back-off (IBO) which corresponds to the ratio of saturated input power (P_{max}) and average input power (\bar{P}_x) [12]

$$IBO_{dB} = 10 \log_{10} \left(\frac{P_{max}}{\bar{P}_x} \right). \quad (10)$$

The measure of effects due to nonlinear PA could be decreased by the selection of relatively high value of IBO . However, this approach will result in inefficient use of PA performance that subsequently results in decreasing radius of the area covered by the effective OFDMA (SC-FDMA) signal. Therefore it is very essential to realise, that using extremely high IBO to decrease the nonlinear degradation is not realistic because then the specifications imposed by standards regarding, e.g. cell coverage, will not be fulfilled.

6. SIMULATION RESULTS

The intention of this part is to provide fundamental comparison of OFDMA and LFDMA in nonlinear AWGN environment. It is important to note here, that in real environment, transmitted signals are the subjects of fading ef-

fects due to the multipath environment. However, the provided comparison in nonlinear AWGN environment is actually not far from the real situation. Since LFDMA are characterised by the knowledge of channel state information at the transmitter side, the subcarriers suffering from deep fades are removed immediately from the transmission. If we make simplifying assumption (single user-single cell scenario), we can claim that mobile terminal will not suffer from the effects of multipath environment and the only sources of distortion are AWGN contribution and the effects of the nonlinearity.

The major reason for applying SC-FDMA systems in the uplink of LTE is their inherently lower envelope fluctuation in comparison with traditional multicarrier schemes. To verify this fact, we have introduced carefully selected computer simulations from the BER point of view. The simulation setup created for that purposes include 16-QAM ad 64-QAM baseband modulation. These modulations are being used in LTE and characterised by large sensitivity to nonlinear distortion. For QPSK it is not such an important issue.

In the uplink of upcoming LTE standard, only low number of subcarriers N is considered for transmission. Therefore, in order to provide relevant simulation results, following values of N have been chosen, $N = \{16, 64, 256\}$. Based on the results of our extensive simulation, BER performance of SC-FDMA does not change with different number subcarriers used for transmission, therefore only case of $N = 64$ shown. With aim to get general observations, a set of $IBO = \{2, 3, 4, 6\}$ parameters have been selected in simulation setup. No channel coding or any form of diversity is considered in order not to introduce other dependencies to the system performance.

Fig. 2 shows the BER performance of SC-FDMA and OFDMA at 16-QAM operating with a Soft Limiter at $IBO = 2dB$. It can be observed from this Figure, that SC-FDMA performs always better than OFDMA employing low $\{N = 16, 64\}$ and moderate $N = 256$ number of subcarriers. This fact is in accordance with our expectations and the application of SC-FDMA according to this scenario is absolutely favourable.

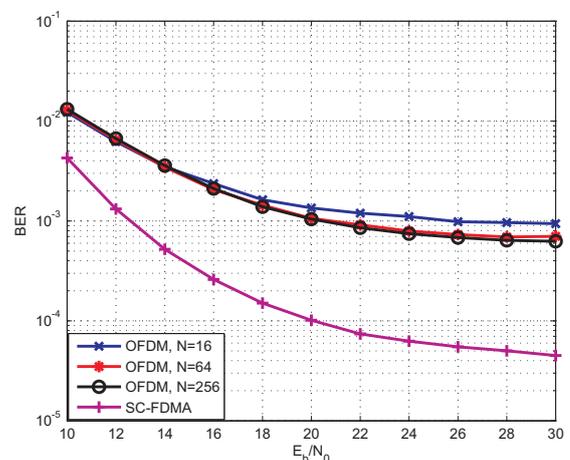


Fig. 2 BER performance of 16-QAM OFDMA and SC-FDMA systems operating with a soft-limiter at $IBO = 2dB$

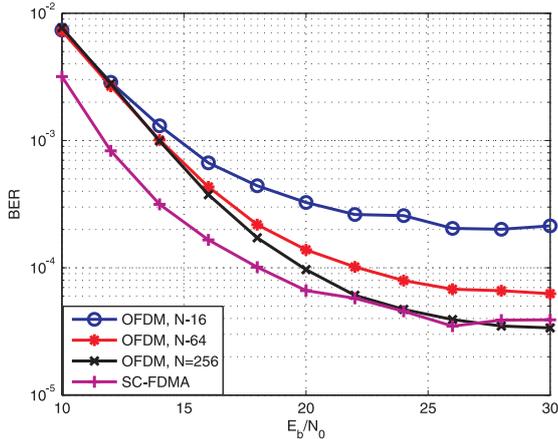


Fig. 3 BER performance of 16-QAM OFDMA and SC-FDMA systems operating with a soft-limiter at $IBO = 3dB$

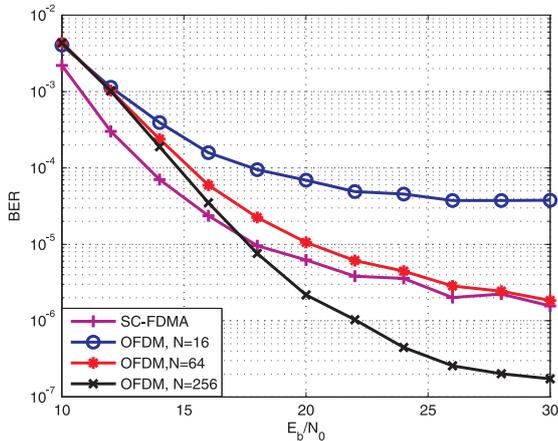


Fig. 4 BER performance of 16-QAM OFDMA and SC-FDMA systems operating with a soft-limiter at $IBO = 4dB$

However, with increasing parameter IBO , the situation has slightly changed. Simulation results depicted in Fig. 3 suggest that SC-FDMA performs always better than OFDMA employing low number of subcarriers $\{N = 16, 64\}$, on the other hand for high SNR, SC-FDMA provides similar results than OFDMA with $N = 256$. If we increase IBO parameter to $IBO = 4dB$ very interesting phenomena occurs, what is outlined in the Fig. 4. SC-FDMA outperforms OFDMA with $N = 16$ markedly, but provides only similar results than OFDMA with $N = 64$. As the opposite to this observation we can find the performance result of OFDMA employing $N = 256$ subcarriers that provides the positive gain of $5dB$ at $E_b/N_0 = 20dB$ in comparison with SC-FDMA.

In order to illustrate the existence of this effect even for 64-QAM, suitable parameters ($IBO = 6dB$) in Fig. 5 have been chosen. We can observe a gain of $7dB$ at $E_b/N_0 = 20dB$ in favour of OFDMA with moderate number of subcarriers.

An overall comparison leads to the conclusion that SC-FDMA is superior when the transmitted signal is largely

nonlinear distorted. However, if a nonlinear distortion is reduced at the transmitter side (application of high value of IBO , PAPR reduction methods) and mobile terminal is located near to the base station demanding for the high data traffic, it might be feasible to prefer OFDMA instead of SC-FDMA application. This analysis suggests that neither SC-FDMA or OFDMA has a clear advantage over the other in all conditions and the application of both of them depends on the particular system configuration and location in the cell edge. Presented results are very interesting from system design point of view, since OFDMA is less computational demanding and can be used at the specific conditions instead of SC-FDMA even in the uplink of multicarrier transmission schemes.

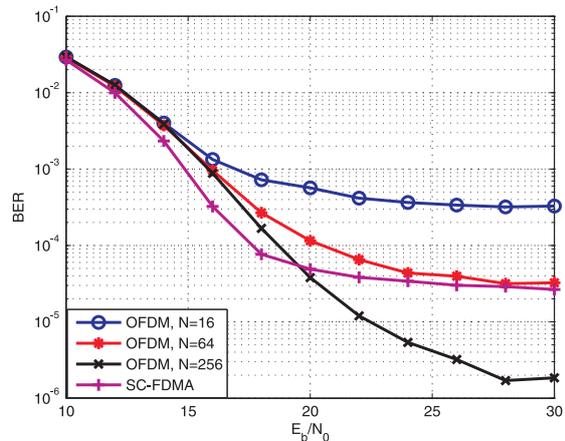


Fig. 5 BER performance of 64-QAM OFDMA and SC-FDMA systems operating with a soft-limiter at $IBO = 6dB$

7. CONCLUSIONS

In this paper, we introduced general comparison of traditional OFDMA concept with SC-FDMA from the BER point of view. As it was shown by means of computer simulations, the application of SC-FDMA is not always straightforward and there exist certain scenarios, typically for high SNR, where OFDMA can perform better than SC-FDMA. This is a special relevance of the upcoming next evolution of LTE, Advanced LTE, where OFDMA receives special interest even in the uplink of the cellular systems.

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