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Reduction Techniques of Peak-to-Average Power Ratio in MC-CDMA Systems

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ABSTRACT

The high peak-to-average power ratio (PAPR) is one of the main disadvantages of multicarrier code division multiple access (MC-CDMA) system. To reduce the PAPR of multicarrier CDMA signals, a lot of studies have been focused on the power characteristics of spreading sequences. This paper presents the main techniques to reduce the PAPR in MC-CDMA like Amplitude Clipping and Filtering, Coding, Selective Mapping, The adaptive predistortion technique and DFT Spreading. Then a comparison of all these techniques is done in order to clarify the main advantages and disadvantages of each technique.

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1. INTRODUCTION

The main feature of the next-generation wireless systems will be the convergence of multi-media services such as speech, audio, video, image, and data. This implies that a future wireless terminal, by guaranteeing high speed data, will be able to connect to different networks in order to support various services: switched traffic, IP data packets, and broadband streaming services such as video. The development of wireless terminals with generic protocols and multiple physical layers or software-defined radio interfaces is expected to allow users to seamlessly switch access between existing and future standards [1].

MC-CDMA allows one to benefit from several advantages of both multi-carrier modulation and spread spectrum systems by offering, for instance, high flexibility, high spectral efficiency, simple and robust detection techniques, and narrowband interference rejection capability [1].

However, any MC signal (including MC-CDMA) experiences a high “peak-to-average power ratio” (PAPR), i.e., the peaks of the instantaneous power are much higher than the average power level. Cosequently, the signal reveals vulnerable to nonlinear distortions induced by the high power amplifier (HPA) of the transmitter which entail both signal-to-noise ratio (SNR) degradation and out-of-band emission (OBE) [2].

This paper presents the main principles of MC-CDMA system and Peak-to-Average Ratio (PAPR) definition in section 2, while Origin of the Peak-to-Average Ratio Problem is discussed in section 3. The main techniques to reduce the Peak-to-Average Ratio are presented and explained clearly in both sections 4 and 5.Then, a comparison and summary of all these techniques are included in section 6; Finally the main conclusions in section 7.

2. MC-CDMA Signal AND PAPR DEFINITION

The basic MC-CDMA signal is generated by a serial concatenation of classical DS-CDMA and OFDM. Each chip of the direct sequence spread data symbol is mapped on to a different sub-carrier. Thus, with MC-CDMA the chips of a spread data symbol are transmitted in parallel on different subcarriers, in contrast to a serial transmission with DS-CDMA [3].

A principle downlink model of an MC-CDMA system is shown in Figure 1 . The system has K active users and for an each kth user $d(^{(k)} = [d_1{}^{(k)}, d_2{}^{(k)}, \ldots, d_M{}^{(k)}]$ denotes M number of quadrature phase shift keying (QPSK)- or quadrature amplitude modulation (QAM)-modulated data symbols, where $k = 1, 2, \ldots, K$. Each symbol of the user is multiplexed by a specific spreading code $c^{(k)} = [c_1{}^{(k)}, c_2{}^{(k)}, \ldots, c_J{}^{(k)}]$, where J denotes the spreading factor or spreading length. Many users' data can be transmitted in the same frequency space and at the same time because of the orthogonality of the spreading codes [4]. The spreaded symbol is summed element by element with the other users' symbols. Then, the symbols are interleaved in the frequency domain to suppress burst errors caused from the communication channel. After interleaving, the symbols become $X = [X_0, X_1, \ldots, X_{N-1}]^T$, where N is the number of sub-carriers. Finally, the interleaved symbols are input into the IFFT of size $N = M . J$. The transmitted continuous-time MC-CDMA signal is expressed by

$$x(t) = \frac{1}{\sqrt{N}} \sum_{m=1}^{M} \sum_{j=1}^{J} \sum_{k=1}^{K} d_m^{(k)} c_j^{(k)} \mathrm{e}^{j2\pi\{M(j-1)+(m-1)\}t/T_s} \quad (1)$$

where T_s is a symbol period of an MC-CDMA signal, in which $0 \le t \le T_s$ However, the PTS requires a discrete-time MC-CDMA signal, which is given by

$$x(n) = \frac{1}{\sqrt{N}} \sum_{m=1}^{M} \sum_{j=1}^{J} \sum_{k=1}^{K} d_m^{(k)} c_j^{(k)} \mathrm{e}^{j2\pi\{M(j-1)+(m-1)\}(n)/(LNT_s)} \quad (2)$$

where $n = 0, 1, \ldots, LN - 1$ and L is the oversampling factor. When the MC-CDMA signals are oversampled as $L = 4$, the value of the PAPR in the discrete-time is nearly the same with the PAPR in the continuous-time. At the end of oversampling, the vector transforms as $x = [x_0, x_1, \ldots, x_{LN-1}]$ and the PAPR of the symbols are defined as

$$\mathrm{PAPR}(x) = \frac{\max\limits_{0 \le n \le LN-1} \{|x_n|^2\}}{E\{|x_n|^2\}} \quad (3)$$

where E{.} denotes the mean value of $\{|xn|^2\}$. The complementary cumulative density function is a commonly used criterion to show the performance of the PAPR reduction performance and described as

$$\mathrm{CCDF} = \Pr\{\mathrm{PAPR}(x) . \mathrm{PAPR}_0 \quad (4)$$

where PAPR_0 is a certain level of the PAPR[4].

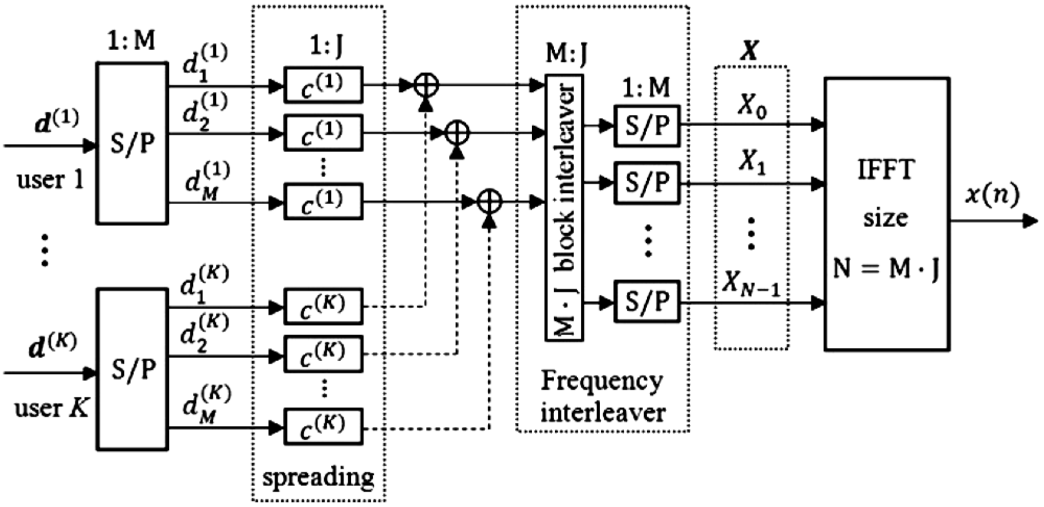

Figure 1 Block diagram of a downlink MC-CDMA system [4].

3. ORIGIN OF THE PEAK-TO-AVERAGE RATIO PROBLEM

One of the major problems of OFDM is that the peak amplitude of the emitted signal can be considerably higher than the average amplitude. This Peak-to-Average Ratio (PAR) issue originates from the fact that an OFDM signal is the superposition of N sinusoidal signals on different subcarriers.

On average the emitted power is linearly proportional to N. However, sometimes, the signals on the subcarriers add up constructively, so that the amplitude of the signal is proportional to N, and the power thus goes with N2. Thus anticipate the (worst case) power PAR to increase linearly with the number of subcarriers.

The contributions to the total signal from the different subcarriers can be viewed as random variables (they have quasi-random phases, depending on the sampling time as well as the value of the symbol with which they are modulated). If the number of subcarriers is large, the central limit theorem can be invoked to show that the distribution of the amplitudes of in-phase components is Gaussian, with a standard deviation $\sigma = 1/\sqrt{2}$ (and similarly for the quadrature components) such that mean power is unity. Since both in-phase and quadrature components are Gaussian, the absolute amplitude is Rayleigh distributed. Knowing the amplitude distribution, it is easy to compute the probability that the instantaneous amplitude will lie above a given threshold, and similarly for power. For example, there is a exp(.106/10) = 0.019 probability that the peak power is 6 dB above the average power. Note that the Rayleigh distribution can only be an approximation for the amplitude distribution of OFDM signals: an actual OFDM signal has a bounded amplitude (N^* amplitude of signal on one subcarrier), while realizations of a Rayleigh distribution can take on arbitrarily large values .

There are three main methods to deal with the Peak-to-Average Power Ratio (PAPR):

A. Put a power amplifier into the transmitter that can amplify linearly up to the possible peak value of the transmit signal. This is usually not practical, as it requires expensive and power-consuming class-A amplifiers. The larger the number of subcarriers N, the more difficult this solution becomes[5].
B. Use a nonlinear amplifier, and accept the fact that amplifier characteristics will lead to distortions in the output signal. Those nonlinear distortions destroy orthogonality between subcarriers, and also lead to increased out-of-band emissions (spectral regrowth – similar to third-order intermodulation products – such that the power emitted outside the nominal band is increased). The first effect increases the BER of the desired signal (see Figure 2), while the latter effect causes interference to other users and thus decreases the cellular capacity of an OFDM system (see Figure 3). This means that in order to have constant adjacent channel interference power amplifier performance can be traded off against spectral efficiency (note that increased carrier separation decreases spectral efficiency) [5].
C. Use PAR reduction techniques. These will be described in the next subsection.

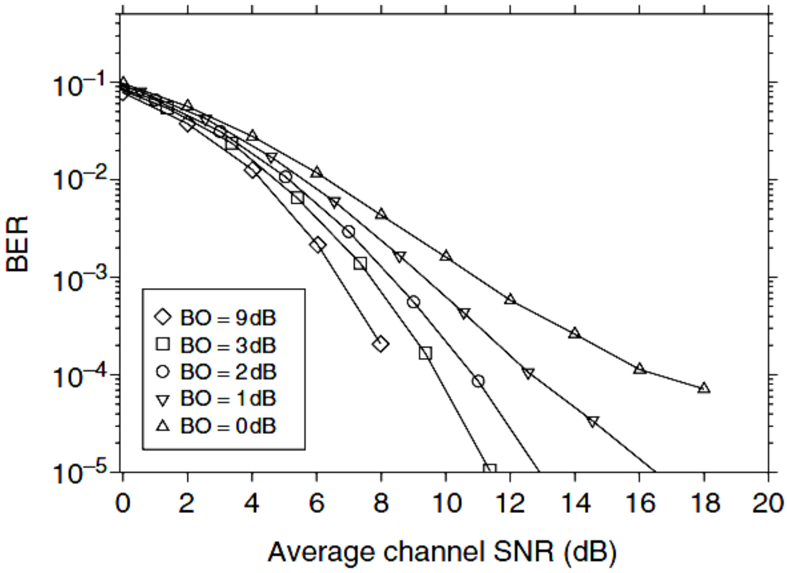

Figure 2 Bit error rate as a function of the signal-to-noise ratio, for different backoff levels of the transmit amplifier [5].

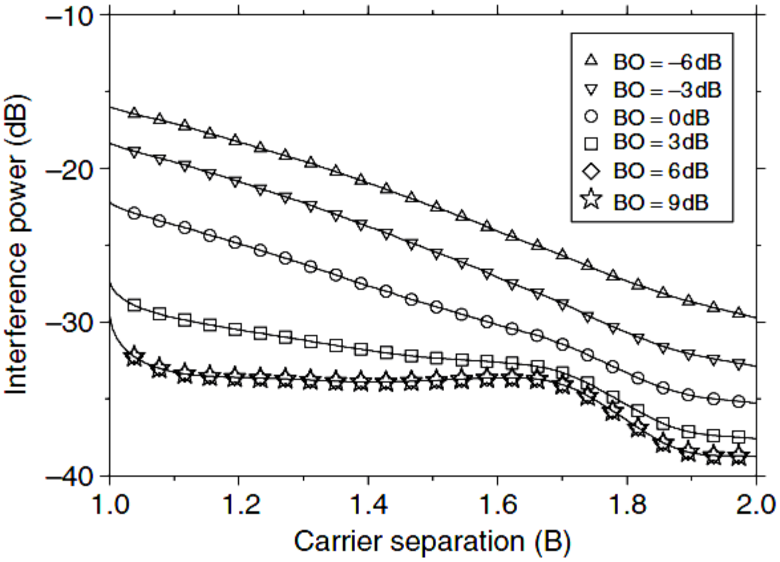

Figure 3 Interference power to adjacent bands (OFDM users), as a function of carrier separation, for different values of backoff of the transmit amplifier [5].

4. PAPR REDUCTION TECHNIQUES FOR MULTICARRIER TRANSMISSION

MC-CDMA systems are seen as special OFDM system when analyzing PAPR performance [6]. A wealth of methods for mitigating the PAR problem has been suggested in the literature. Some of the promising approaches are as follows [5]:

4.1 AMPLITUDE CLIPPING AND FILTERING

Figure 4 shows MC CDMA transmitter is combination of CDMA and OFDM transmitters. The MC CDMA transmitted signal is fed to Clipping followed by filtering then the signal is processed through DAC and HPA. Clipping is simple and effective by selecting optimum clipping ratio to remove the high amplitude peaks. But, it degrades system performance by introducing IBR and OBR, which can be reduced by filtering. This technique results in peak regrowth and distortion of the transmitted signal that can be reduced by repeated clipping and filtering.

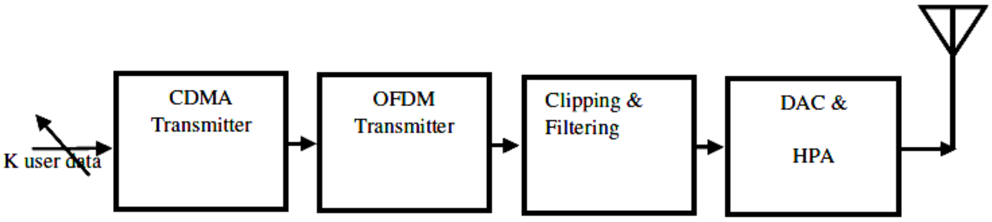

Figure 4. MC CDMA with clipping & Filtering

Using filtering technique improves IBR without degradation of BER. Using these technique additional blocks are used for clipping and frequency domain filtering at the transmitter, whereas receiver is unchanged. Transmitter complexity is increased by adding Fast Fourier Transform (FFT), IFFT filtering and computationally expensive [8].

4.2 CODING

Coding can also be used to reduce the PAPR. A simple idea is to select those codewords that minimize or reduce the PAPR for transmission [7]. This scheme requires storing best codes, need large look-up tables for encoding and decoding, especially for large number of subcarriers. This scheme also requires exhaustive algorithm for searching to find best codes from the look-up table. This scheme suffers from extensive calculations to find good codes and offsets. Huffman coding is used to reduce PAPR of OFDM transmitted signal for distortion-less scrambling technique by sending encoding table for accurate decoding at the receiver without reducing throughput. Block coding scheme to reduce the PAPR has many advantages such as no side information at the receiver, codes include error control capacity which can reduce BER at the receiver, reduce PAPR and provide good error correction capability having higher code rates [8]. Park et al have proposed using Walsh Hadamard (WH) code for PAPR reduction in MCM. The proposed Hadamard transform scheme may reduce the occurrence of the high peaks when compared with Original MCM signal. Using Hadamard transform reduces PAPR. In addition, it requires no side information at the receiver for MCM system (OFDM) .

Coding techniques can be used for signal scrambling, such as Golay complementary sequences , Shopire-Rudin sequences, and barker codes. They can be used efficiently to reduce the PAPR. However, with the increase in number of carriers, overhead is increased. More practical solutions of the signal scrambling techniques are block coding, selected mapping and PTS. Signal scrambling technique with side information reduces the throughput, since they introduce redundancy, more degradation and more vulnerable to errors. Error control selective mapping scheme (ECSLM) is more effective and avoids the need of side information. In ECSLM as number of control bits increase, the PAPR reduction increases, and complexity increases [8].

4.3 SELECTIVE MAPPING

Figure 5 shows the block diagram of selective mapping (SLM) technique for PAPR reduction [9]. Here, the input data block X =[X[0], X[1],….X[N-1]] is multiplied with U different phase sequences P^u= [P^u_0, P^u_1,…, P^u_{N-1}]^T where P^u_v= $e^{J\theta uv}$ and θ^u_v ϵ[0, 2π) for v = 0, 1,……, N-1 and u= 1, 2, …..,U, which produce a modified data block X^u =[X^u[1], X^u[2], . . . ; $X^{u[}$N-1]]^T . IFFT of U independent sequences {X^u[v]} are taken to produce the sequences x^u = =[x^u[0], x^u[1], . . . ; x^u[N-1]]^T, among which the one ~x = $x^{\sim u}$ with the lowest PAPR is selected for transmission, as shown as

$$\tilde{u} = \underset{u=1,2,\cdots,U}{\operatorname{argmin}}\left(\max_{n=0,1,\cdots,N-1}|x^u[n]|\right) \tag{5}$$

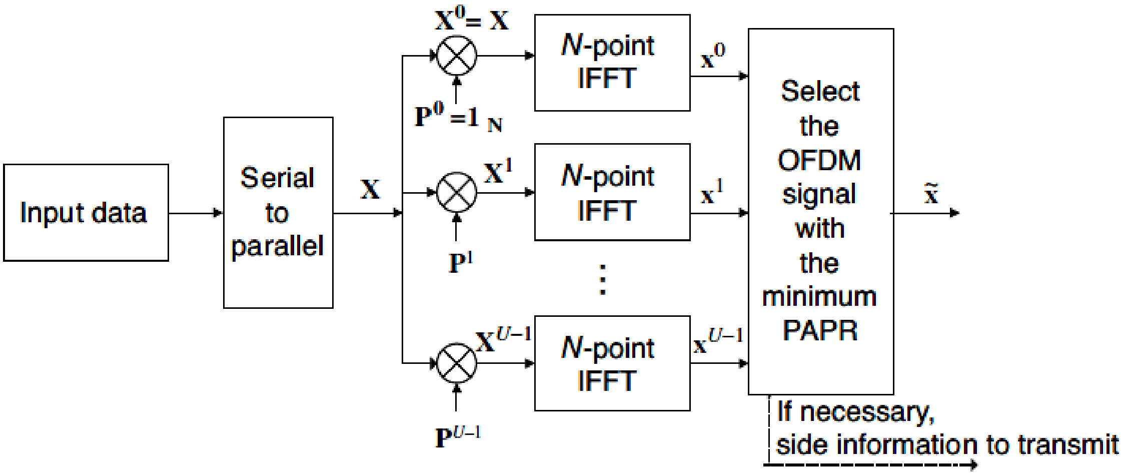

Figure 5. Block diagram of selective mapping (SLM) technique for PAPR reduction [9].

In order for the receiver to be able to recover the original data block, the information (index u) about the selected phase sequence P^u should be transmitted as aside information. The implementation of SLM technique requires U IFFT operations. Furthermore, it requires [$\log_2$ U] bits of side information for each data block where [x] denotes the greatest integer less than x [9].

4.4 THE ADAPTIVE PREDISTORTION TECHNIQUE

Signal pre-distortion techniques based on companding to reduce the PAPR have been proposed by several authors using different companding techniques such as µ-Law, exponential, modified exponential and linear companding [8]. The adaptive predistortion technique can compensate the nonlinear effect of a high power amplifier (HPA) in OFDM systems. It can cope with time variations of nonlinear HPA by automatically modifying the input constellation with the least hardware requirement (RAM and memory lookup encoder). The convergence time and MSE of the adaptive predistorter can be reduced by using a broadcasting technique and by designing appropriate training signals [9].

4.5 DFT SPREADING

Before discussing the DFT-spreading technique, let us consider OFDMA (Orthogonal Frequency-Division Multiple Access) system. As depicted in Figure 6, suppose that DFT of the same size as IFFT is used as a (spreading) code. Then, the OFDMA system becomes equivalent to the Single Carrier FDMA (SC-FDMA) system because the DFT and IDFT operations virtually cancel each other. In this case, the transmit signal will have the same PAPR as in a single-carrier system [9].

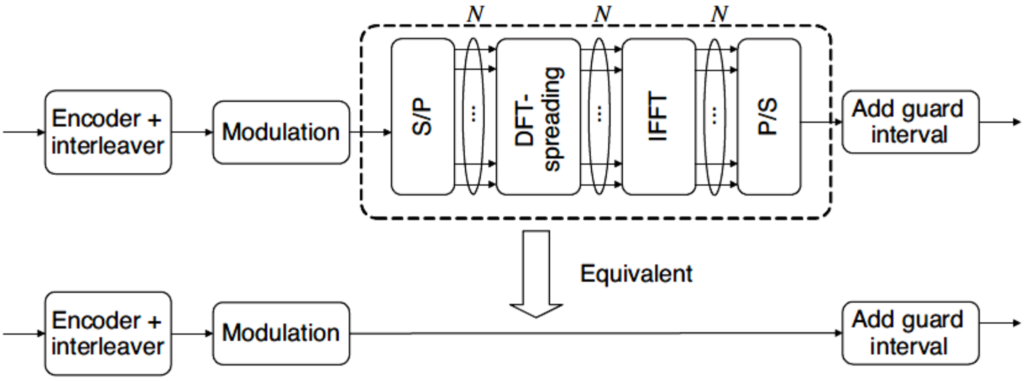

Figure 6. Equivalence of OFDMA system with DFT-spreading code to a single-carrier system [9].

In OFDMA systems, subcarriers are partitioned and assigned to multiple mobile terminals (users).Unlike the downlink transmission, each terminal in uplink uses a subset of subcarriers to transmit its own data. The rest of the subcarriers, not used for its own data transmission, will be filled with zeros. Here, it will be assumed that the number of subcarriers allocated to each user is M. In the DFT-spreading technique, M-point DFT is used for spreading, and the output of DFT is assigned to the subcarriers of IFFT. The effect of PAPR reduction depends on the way of assigning the subcarriers to each terminal. As depicted in Figure 7, there are two different approaches of assigning subcarriers among users: DFDMA (Distributed FDMA) and LFDMA (Localized FDMA). Here, DFDMA distributes M DFT outputs over the entire band (of total N subcarriers) with zeros filled in (N_M) unused subcarriers, whereas LFDMA allocates DFT outputs to M consecutive subcarriers in N subcarriers. When DFDMA distributes DFT outputs with equi-distance N/M = S, it is referred to as IFDMA (Interleaved FDMA) where S is called the bandwidth spreading factor [9].

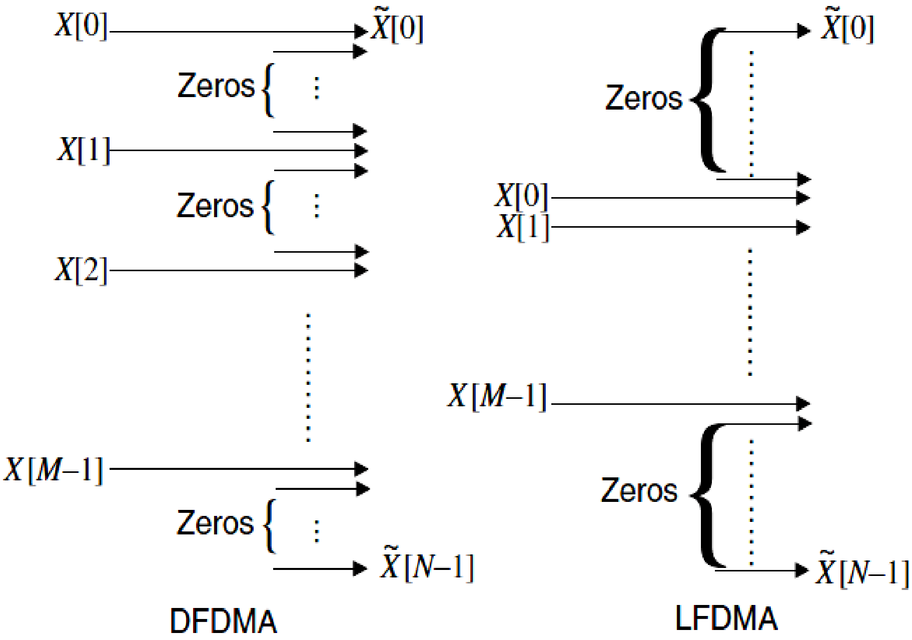

Figure 7. Subcarrier mapping for uplink in OFDMA systems: DFDMA and LFDMA.

Figure 8 illustrates the subcarriers allocated in the DFDMA and IFDMA with M = 4, S = 3, and N = 12. Furthermore, Figure 9 shows the examples of DFT spreading in DFDMA, LFDMA, and IFDMA with N = 12, M = 4, and S = 3. It illustrates a subcarrier mapping relationship between 4-point DFT and 12-point IDFT [9].

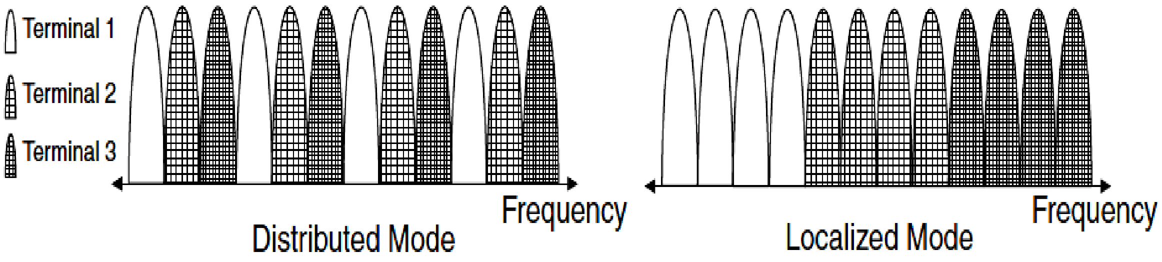

Figure 8. Examples of subcarrier assignment to multiple users: three users with N = 12, M = 4, and S=3 [9].

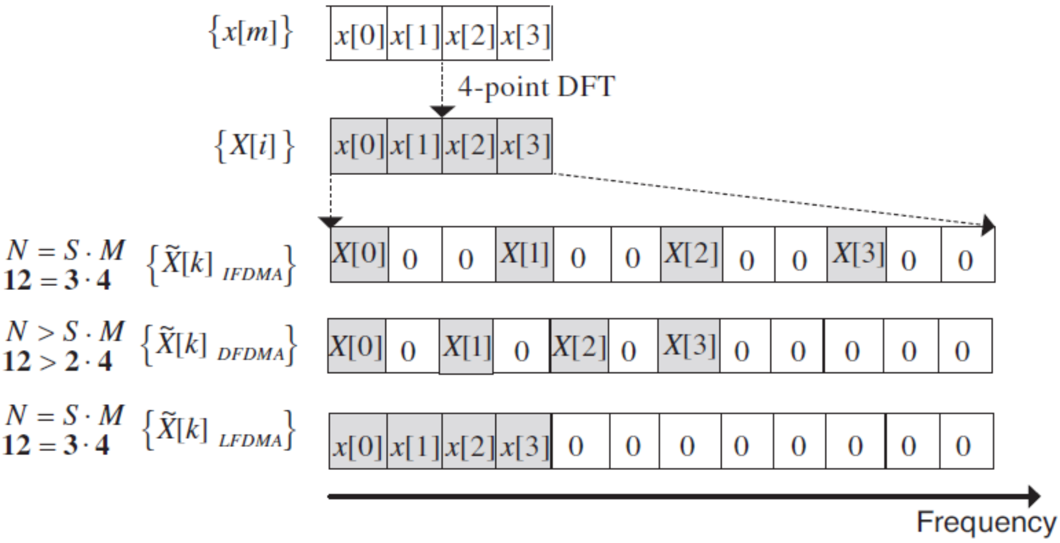

Figure 9. Examples of DFT spreading for IFDMA, DFDMA and LFDMA: three users with N = 12, M = 4, and S = 3.

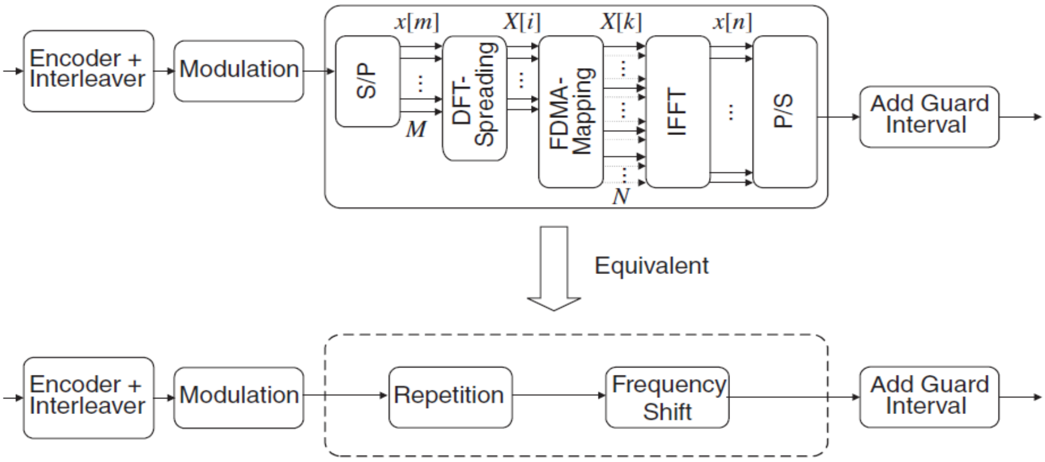

Figure 10. Uplink transmitter with DFT-spreading technique of IFDMA [9].

5. SUMMARY AND CONCLUSIONS

PAPR reduction techniques are classified into the different approaches: clipping technique, coding technique, probabilistic (scrambling) technique, adaptive predistortion technique, and DFT-spreading technique. The clipping technique employs clipping or nonlinear saturation around the peaks to reduce the PAPR. It is simple to implement, but it may cause in-band and out-of-band interferences while destroying the orthogonality among the subcarriers. This particular approach includes block-scaling technique, clipping and filtering technique, peak windowing technique, peak cancellation technique, Fourier projection technique, and decision-aided reconstruction technique [9].

The coding technique is to select such codewords that minimize or reduce the PAPR. It causes no distortion and creates no out-of-band radiation, but it suffers from bandwidth efficiency as the code rate is reduced. It also suffers from complexity to find the best codes and to store large lookup tables for encoding and decoding, especially for a large number of subcarriers. Golay complementary sequence, Reed Muller code, M-sequence, or Hadamard code can be used in this approach.

The probabilistic (scrambling) technique is to scramble an input data block of the OFDM symbols and transmit one of them with the minimum PAPR so that the probability of incurring high PAPR can be reduced. While it does not suffer from the out-of-band power, the spectral efficiency decreases and the complexity increases as the number of subcarriers increases. Furthermore, it cannot guarantee the PAPR below a specified level. This approach includes SLM (SeLective Mapping), PTS (Partial Transmit Sequence), TR (Tone Reservation), and TI (Tone Injection) techniques.

The adaptive predistortion technique can compensate the nonlinear effect of a high power amplifier (HPA) in OFDM systems. It can cope with time variations of nonlinear HPA by automatically modifying the input constellation with the least hardware requirement (RAM and memory lookup encoder). The convergence time and MSE of the adaptive predistorter can be reduced by using a broadcasting technique and by designing appropriate training signals.

The DFT-spreading technique is to spread the input signal with DFT, which can be subsequently taken into IFFT. This can reduce the PAPR of OFDM signal to the level of single-carrier transmission. This technique is particularly useful for mobile terminals in uplink transmission. It is known as the Single Carrier-FDMA (SC-FDMA), which is adopted for uplink transmission in the 3GPP LTE standard.

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