Multi-carrier OFDM, Single Carrier with Frequency Domain Equalization (SCFDE) and CDMA: Performance Comparison

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***Abstract*—The equalization in the frequency domain is common between multi-carrier OFDM and the single carrier with frequency domain equalization SCFDE systems as well as code division multiple access CDMA. Therefore, performances can be fairly compared. In this paper, we explain why the OFDM and CDMA systems demonstrate similar signal fluctuation as shown by simulation results in the literature. Furthermore, MC-CDMA, a combination of OFDM and CDMA is shown to be SCFDE; therefore, the same performance could be achieved with simpler instrumentation, and, the combination of SCFDE and CDMA is shown to be an OFDM system.**

***Index Terms*—CDMA; MC-CDMA; OFDM; SCFDE; Spread Spectrum.**

I. Introduction

The spread spectrum technology (SS) has been widely spread since its release and availability for the civil use. This transmission technique has much great immunity to interference and noise compared with conventional radio transmission techniques. Many of today's systems are inspired by or are either a direct or indirect application of the spread spectrum techniques. Applications for commercial spread spectrum range between wireless cellular systems and phones, WLAN, and wide area network WiMAX. Other related technology has been beside in focus at the same time. This technology is the orthogonal frequency division multiplexing (OFDM). OFDM, a broadband technique has attracted great attention and been very popular for the last decade due to the advance of the signal processing and the powerful processors being developed. OFDM is considered as an effective are modulation technique for high-speed digital transmission of many services. It participates in a wide range of applications, including, IEEE 802.11a, g, wireless LAN standards, digital audio broadcasting DAB and digital video broadcasting DVB [1].

On the other hand, in the last decade, there has been an emerging technique whose performance is proved to be similar to OFDM. This technique is known as single carrier transmission with frequency domain equalization (SCFDE) [2][3]. SCFDE has been adapted by IEEE 802.11 and HIPERLAN/2. The importance of SCFDE stems from the relative simplicity of instrumentation.

The fundamental difference between SCFDE and OFDM is the place of the inverse discrete Fourier transformation (IDFT). In OFDM, IDFT is taking place at the transmitter, while in SCFDE, it is shifted to the receiver side. For this reason, SCFDE is favored in up-link for the fact of power consumption reduction by the mobile terminals. Moreover, SCFDE is less sensitive to RF stage non-linearity [4].

In the subsequent sections, we discuss the multiple access techniques, in particular, CDMA as it represents an example of the spread spectrum techniques. In addition, the single carrier and the multicarrier systems including multicarrier CDMA (MC-CDMA), are discussed.

II. Multiple Access Techniques

Among the multiple access techniques, this paper must focus on CDMA. This technique enables several users to access the channel simultaneously and asynchronously. It supports a low-to-high data rate of multimedia services. In CDMA, various spreading codes are employed; however, we confine ourselves to the distinctive spreading code; Fourier codes, as a complex spreading code that is deduced from the discrete Fourier transformation matrix. Nevertheless, we do not tend to evaluate the CDMA scheme, but we review and focus on a combination of the multiple access and multi-carrier as well as a single carrier with frequency domain equalization [5][6].

The CDMA baseband signal can be described conveniently with a matrix-vector notation as [7][8]

$$\mathbf{r} = \mathbf{A}\mathbf{d} + \mathbf{n} \tag{1}$$

where $\mathbf{r}$ is the received vector of a CDMA system, $\mathbf{d}$ is the transmitted symbols $\boldsymbol{d} = (d^0, d^1, \ldots, d^{N-1})^T$ of K users. The matrix $\boldsymbol{A}$ comprises the effects of spreading and transmission over the multipath channel. It consists of $(NQ + L - 1) \times (NK)$ complex-valued elements, i.e., $\boldsymbol{A} \in C^{(NQ+L-1)\times(NK)}$. It can be broken into submatrices and each column in a submatrix is obtained by the convolution between the spreading code and the channel impulse response [7].

The received discrete signal $\boldsymbol{r}$ can also be expressed

$$\mathbf{r} = \mathbf{H}\mathbf{C}\mathbf{d} + \mathbf{n} \tag{2}$$

$\boldsymbol{H} \in C^{(NQ+L-1)\times(NK)}$ and $\boldsymbol{C}$ is the spreading matrix $\boldsymbol{C} \in C^{(NQ+L-1)\times(NK)}$

According to the matrix-vector notation, the signal received by the RAKE receiver can also be written as:

$$\hat{\mathbf{d}} = \mathbf{A}^{\mathbf{H}}\mathbf{r} = \mathbf{A}^{\mathbf{H}}\mathbf{A}\mathbf{d} + \mathbf{A}^{\mathbf{H}}\mathbf{n} \tag{3}$$

$(.)^H$ denotes matrix transpose conjugate. The multiuser detector inverts $\boldsymbol{A}$ matrix in order to extract the data vector. The detected data vector can be written in matrix-vector notation as:

$$\hat{\mathbf{d}} = (\mathbf{A^H A})^{-1} \mathbf{A^H r} \\ = \mathbf{d} + (\mathbf{A^H A})^{-1} \mathbf{A^H n} \quad (4)$$

However, the equalizer turns simply back the multipath channel into a perfect delta impulse. In the matrix-vector notation the output of the equalizer can be written as:

$$\mathbf{y} = (\mathbf{H^H H})^{-1} \mathbf{H^H r} \\ = \mathbf{Cd} + (\mathbf{H^H H})^{-1} \mathbf{H^H n} \quad (5)$$

Unlike the MUD, the equalizer does not invert the whole matrix **A**, but rather only the channel matrix **H**.

The effect of spreading is reversed by despreading on the output **y** of the channel equalization as:

$$\hat{\mathbf{d}} = \frac{1}{Q} \mathbf{C^H y} \quad (6)$$

In practice, orthogonal variable spreading codes OVSF are deployed in UMTS, whilst Walsh-Hadamard codes are used in the IS-95 system. Another spreading code applied in the uplink in LTE is the Fourier spreading codes [9][10]. At this point, we apply Fourier codes for demonstration purpose.

The spreading code for the k^{th} user are the columns or rows of the discrete Fourier matrix. The matrix entities are given by $c^k(q) = \frac{1}{N} e^{2\pi jqk/Q}$. However, it can be easily shown that the spreading matrix **C** is related to Fourier matrix **F** as follows:

$$\mathbf{C} = \mathbf{F^T} \quad (7)$$

$(.)^T$ denotes matrix transpose. Since **F** is symmetrical, therefore:

$$\mathbf{F} = \mathbf{F^T} = \mathbf{C} \quad (8)$$

The relations can be given now in relation to this fact such that

$$\hat{\mathbf{d}} = \frac{1}{Q} \mathbf{C^H y} = \frac{1}{Q} \mathbf{F^H y} = \frac{1}{Q} \mathbf{F^{-1} y} \quad (9)$$

Furthermore, Equation (2) can be also written

$$\mathbf{r} = \mathbf{HFd} + \mathbf{n} \quad (10)$$

Equation (5) can be written:

$$\mathbf{y} = \mathbf{Fd} + (\mathbf{H^H H})^{-1} \mathbf{H^H n} \quad (11)$$

and Equation (6) becomes:

$$\hat{\mathbf{d}} = \frac{1}{Q} \mathbf{F^H y} = \frac{1}{Q} \mathbf{F^{-1} y} \quad (12)$$

substituting for **y** in Equation (12) we get:

$$\mathbf{y} = \frac{1}{Q} \mathbf{F^{-1}} (\mathbf{Fd} + (\mathbf{H^H H})^{-1} \mathbf{H^H n}) \\ = \frac{1}{Q} \mathbf{d} + \mathbf{F^{-1}} (\mathbf{H^H H})^{-1} \mathbf{H^H} \frac{\mathbf{n}}{Q} \quad (13)$$

III. OFDM AND SC/FDE SYSTEM

Turning for SCFDE and OFDM systems which have in common the equalization carried in the frequency domain in two systems, and a conceptual physical layer SCFDE transceiver layout is shown in Figure 1. Replacing the inverse FFT process at the transmitter side in the Figure 1, we get the conceptual OFDM transceiver layout.

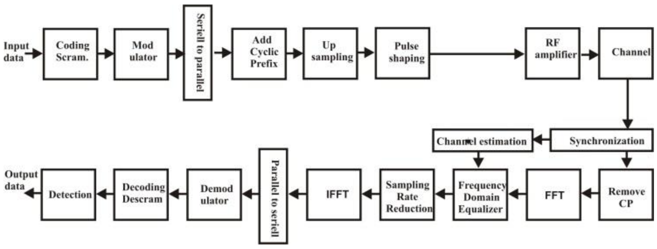

Figure 1: Conceptual physical layer layout of SCFDE transceiver

SCFDE is a block-based transmission, and a guard interval is inserted between the successive blocks. The time duration of the guard interval in order to be effective must be longer than the maximum delay spread of the concerned channel. In addition to the protection of the transmitted data against the interference which is caused by multipath channels guard intervals transform the linear convolution to a cyclic convolution which reduces the cost of the signal processing [11].

As depicted in Figure 1, we can write the following Equations. The output of an SCFDE system is:

$$\mathbf{y} = \mathbf{F^{-1} EF(Hd} + \mathbf{n}) \quad (14)$$

and in the OFDM system, the output is

$$\mathbf{y} = \mathbf{EF(HF^{-1}D} + \mathbf{n}) \quad (15)$$

E is the equalizer coefficients. The zero-forcing equalizer is given by

$$\mathbf{E} = \mathbf{H^{-1}} \quad (16)$$

H is the multipath channel circulant matrix. **D** represents the frequency domain input vector data, and **F** is the Fourier matrix.

IV. MULTICARRIER-SPREAD SPECTRUM

Spread spectrum techniques for second-generation mobile radio and OFDM for digital broadcasting and wireless LANs are combined advantageously. The two methods of combinations are first, multicarrier direct spread CDMA (MC-DS-CDMA), which suits the asynchronous up-link, where each data symbol is spread over Q chips and then modulates N subcarriers (N = Q) [12]. Second, multicarrier CDMA (MC-CDMA), in which the spread data of the active users is added before modulating the subcarriers as depicted in Figure 2 [5]. In this paper, we confine ourselves to MC-CDMA as it is appropriate to downlink and suits our discussion. This could lead to further investigations of the peak to average power ratio (PAPR). The PAPR of the signal after the summation sometimes is denoted as global PAPR (GPAPR) [13]. Figure 2 shows a typical MC-CDMA downlink transmitter [14][15].

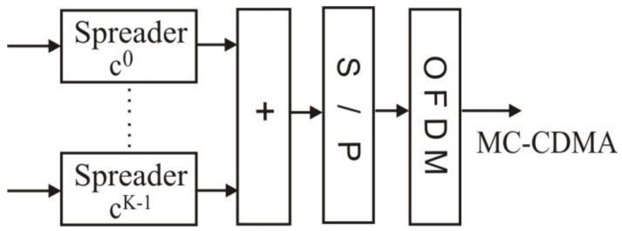

Figure 2: MC-CDMA downlink transmitter

Equation (7) is to be considered when combining CDMA with OFDM, and referring to Figure 3, the input data to be spread in order to get MC-CDMA as follows

$$\mathbf{r} = (\mathbf{F}^{\mathbf{T}})^{-1}\mathbf{EF}(\mathbf{HF}^{-1}\mathbf{F}^{\mathbf{T}}\mathbf{D} + \mathbf{n}) \tag{17}$$

The same can be applied SCFDE system. Spreading the input data in Equation (14) and we get SCFDE-CDMA as follows

$$\mathbf{r} = (\mathbf{F}^{\mathbf{T}})^{-1}\mathbf{F}^{-1}\mathbf{EF}(\mathbf{HF}^{\mathbf{T}}\mathbf{d} + \mathbf{n}) \tag{18}$$

Letting $\mathbf{F}^T = \mathbf{F}$ in Equation (17) we get the following

$$\begin{aligned} \mathbf{r} &= \mathbf{F}^{-1}\mathbf{EF}(\mathbf{HF}^{-1}\mathbf{FD} + \mathbf{n}) \\ &= \mathbf{F}^{-1}\mathbf{EF}(\mathbf{HD} + \mathbf{n}) \end{aligned} \tag{19}$$

Equation (19) which represents an SCFDE system is similar to Equation (14), as shown in Figure 3(a). We, therefore, highlight, the spreading of data using Fourier codes and then modulating the resulting signal through IDFT operators, we remain ultimately with a single carrier system SCFDE. Then it is concluded that the SCFDE is a special form of the OFDM signal. However, modulating the carriers is implemented via IDFT.

Similarly, letting $\mathbf{F}^T = \mathbf{F}^{-1}$ in Equation (18), we get the following

$$\mathbf{r} = \mathbf{EF}(\mathbf{HF}^{-1}\,\mathbf{d} + \mathbf{n}) \tag{20}$$

which is similar to Equation (14), it represents an OFDM system, as depicted in Figure 3(b).

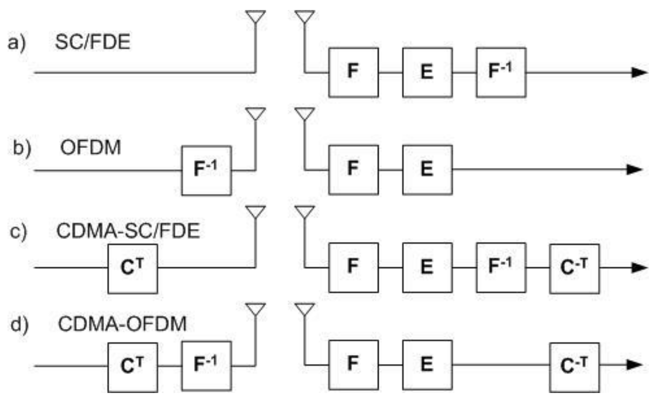

Figure 3: Block diagrams for (a) SCFDE (b) OFDM (c) SCFDE-CDMA (d) MC-CDMA systems

Figure 4 displays the simulation results from reference [7]. The purpose of the simulation is to compare the performance in terms of peak to average power ratio of OFDM and CDMA systems. Peak to average power ratio is a measure of signal fluctuation. The spreading factor in the simulation is Q = 256 for the CDMA, and N = 256 is the length of the FFT process. It is, therefore, full load system, and the spreading matrix is square in this case. It can be noticed from the Figure 4 that the curves of CDMA and OFDM for Q = 256 are just identical.

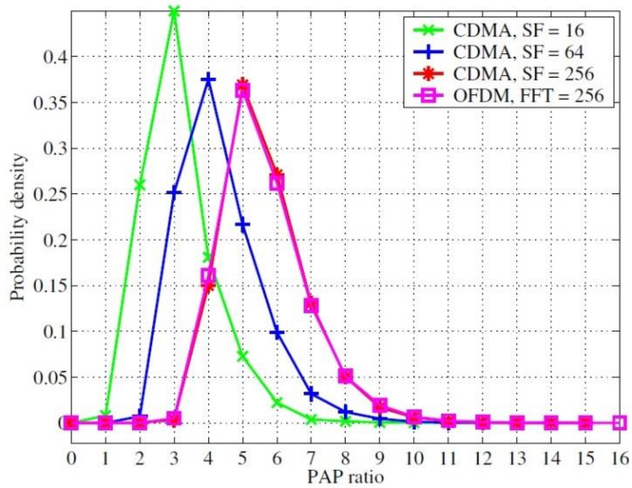

Figure 4: Simulation results of CDMA and OFDM comparison [7]

V. CONCLUSION

Simulation results reported in the literature showed that OFDM and CDMA have the same PAPR and hence the same signals fluctuations, however, there has been no explanation is provided. In this paper, we presented the analytical explanation for the equivalence of the PAPR behavior of OFDM and CDMA systems. We also showed that a combination of OFDM and CDMA knew as MC-CDMA is an SCFDE and vice versa, that the combination of SCFDE and-CDMA is an OFDM system.

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