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Spectrally Efficient Frequency Division Multiplexing in LTE Downlink

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Abstract: Spectral efficiency is a key design issue for all wireless communication systems. Orthogonal frequency division multiplexing (OFDM) is a very well-known technique for efficient data transmission over many carriers overlapped in frequency. The 3GPP has chosen the OFDM as the radio access technology due to its simple implementation in receiver and spectral efficiency. To enhance system's data rate a proposed system of using SEFDM instead of OFDM for LTE downlink air interface. SEFDM systems propose bandwidth savings when compared to OFDM systems by multiplexing multiple non orthogonal overlapping carriers. Two detection methods were used: Efficient Sphere Decoder (ESD) and ESD with Iterative Cancellation (IC). The efficacy of the proposed design is shown through detailed simulation of systems with different bandwidth compression values. The ESD-IC decoder proposed produces a very good result. The system is able to produce efficiency gains of up to 25% while maintain performance near to an OFDM. The performances of two systems (OFDM and SEFDM) were compared in terms of performance and throughput with fixing all the other parameters.

Keywords: LTE, OFDM, BCF, SEFDM, ESD, ESD_IC.

I. INTRODUCTION

Long-Term Evolution (LTE) is one of the latest standards for the fourth generation (4G) wireless networks [1]. It is an evolution of the Universal Mobile Telecommunications System (UMTS) standardized by the 3rd Generation Partnership Project (3GPP) in its 8th release for the development of wireless broadband networks with very high data rates [2]. LTE provides high speed data packet access for various deployment scenarios [3].It provides high speed data transmission, low latency, and high spectral efficiency as well as support for high mobility [4]. Technically, LTE provides a high data rate and can operate in different bandwidths ranging from 1.4MHz to 20MHz [5]. The air interface of LTE technology is based on Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the downlink and Uplink respectively to deliver the flexibility and increase data rate without additional bandwidth or increase transmit power [3].

OFDM is the technique used in the physical layer to pack overlapping but orthogonal sub-carriers. Since spectrum is a limited resource, techniques that can further improve spectral efficiencies, while guarantee system performance would be in high demand. To achieve better efficiency, non-orthogonal multicarrier communications are emerging [6]. In 5G standard explorations, non-orthogonal concepts are commonly mentioned as potential candidates for the air interface. Early application of such techniques, in multicarrier communications, can be traced back to 2003 [7] when the technique termed Spectrally Efficient Frequency Division Multiplexing (SEFDM) was proposed. Recently, this technique, detailed in [8], showing significant bandwidth saving with small power penalty. Spectrum saving in SEFDM is achieved by deliberately violating the orthogonality principle, which leads to non-orthogonal overlapping sub-carriers which allows bandwidth saving compared to OFDM. In LTE Downlink, the using of SEFDM technique for downlink instead OFDM is very important because of limited resources. When frequency spacing decreased, the number of subcarriers will increase per each allocated transmission bandwidth.

II. SPECTRALLY EFFICIENT FDM (SEFDM)

The Spectrally Efficient Frequency Division Multiplexing (SEFDM) system was proposed as a multicarrier modulation (MCM) scheme that promises better utilization of bandwidth than an equivalent Orthogonal Frequency Division Multiplexing (OFDM) system [8]. SEFDM achieves spectral savings by reducing the spacing of the subcarriers and/or transmission time, thus violating the orthogonality rule [6].The SEFDM signal consists of a stream of SEFDM symbols each carrying a block of N complex input symbols, denoted by $s = s_{Re} + s_{Im}$, and transmitted within T seconds. Each of the N complex input symbols modulates one of the non-orthogonal and overlapping subcarriers, hence, giving the SEFDM signal $x(t)$ as:

$$x(t) = \frac{1}{\sqrt{T}} \sum_{l=-\infty}^{\infty} \sum_{n=0}^{N-1} s_{l,n} e^{\left(\frac{j2\pi\alpha\,(t-lT)}{T}\right)} \qquad (1)$$

where Δf denotes the frequency separation between adjacent sub-carriers defined as $\Delta f = \alpha/T$, where α is the bandwidth compression factor (BCF), T is the period of one SEFDM symbol, N is the number of sub-carriers and $s_{l,n}$ the complex symbol modulated on the n^{th} sub-carrier in the l^{th} SEFDM symbol. α Determines bandwidth compressions and hence bandwidth saving equals to $(1 - \alpha) \times 100\%$. OFDM has $\alpha = 1$, and $\alpha < 1$ is for SEFDM [8].Higher throughput can be obtained if SEFDM is used

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instead of OFDM. The transmitter of SEFDM is implemented based on the IDFT design as proposed in [4]. The receiver obtains statistics of the signal by the DFT block as proposed in [8] and then applies joint equalization and detection methods to estimate the transmitted symbols. In this case the demodulated signal is expressed as [6]:

$$(\mathbf{R} = \mathbf{F}^{*}\mathbf{HFS} + \mathbf{W}_{\mathbf{F}^{*}}) \qquad (2)$$

Where R is the received vector, F is the subcarrier's matrix, H is the Channel State Information matrix (CSI), and W is the noise. There are two detection methods for SEFDM: they are Maximum likelihood (ML), and Sphere Decoder (SD). Efficient Sphere Decoder proposed (ESD) by in [9] can be used to reduce SD computations because it omits redundant calculations. Finally, Iterative Cancellation (IC) cancellation is applied after ESD method to get riding of ICI.

- **Maximum Likelihood (ML):** This requires an exhaustive search of all transmitted symbols combinations. The ML represented as [6]:

$$\hat{\mathbf{S}}_{\mathbf{ML}} = \min_{\mathbf{S}\in\mathbf{Q}^{\mathbf{N}}} \left\| \mathbf{F}^{*^{-1}}(\mathbf{R} - \mathbf{F}^{*}\mathbf{HFS}_{\mathbf{m}}) \right\|^{2} \qquad (3)$$

- **Sphere Decoder (SD):** It's a potential solution for small system size. However, its complexity increases rapidly with the enlargement of the system size and it is unsuitable for practical implementations. The SD represented as [6]:

$$\hat{\mathbf{S}}_{\mathbf{SD}} = \min_{\mathbf{S}\in\mathbf{Q}^{\mathbf{N}}, \|(\mathbf{R}-\mathbf{CS_m})\|^2 \le g} \left\| \mathbf{F}^{*^{-1}}(\mathbf{R} - \mathbf{F}^{*}\mathbf{HFS}_{\mathbf{m}}) \right\|^{2} \qquad (4)$$

- **ESD-IC**: Efficient Sphere Decoder (ESD) along with Iterative Cancellation (IC) can perform better. First, ESD is used then IC to remove ICI. The IC represented as [7]:

$$\mathbf{S}_{\mathbf{n}} = \mathbf{R} - (\mathbf{C} - \mathbf{I})\mathbf{S}_{\mathbf{n-1}} \qquad (5)$$

Where S_n is an N-dimensional vector of recovered symbols after n iterations, $S_{(n-1)}$is an N-dimensional vector of estimated symbols after n - 1 iterations, I is an N × N identity matrix.

III.SPECTRALLY EFFICIENT FDM (SEFDM) IN LTE DOWNLINK

A. Theoretical Analysis

LTE downlink frame structure is a 10 ms length. Each frame is divided into 10 sub-frames of 1 ms. Each sub-frame is further divided into two time slots, each with duration of 0.5 ms. Each time slot consists of either 7 or 6 OFDM symbols depending on the type of cyclic prefix (CP) whether (Normal or Extended) employed. The smallest modulation structure in LTE is one symbol in time vs. one subcarrier in frequency and is called a Resource Element (RE). REs are further aggregated into Resource Blocks (RBs), with the typical RB having dimensions of 7 symbols by 12 subcarriers. Frequency spacing (Δf) between subcarriers is 15 kHz which is the reciprocal of one OFDM symbol duration 66.7μs. The proposed research is to replace each OFDM symbol by SEFDM symbol to achieve smaller subcarrier bandwidth, higher number of subcarriers, higher number of resource blocks, hence more spectrally efficient system.

SEFDM is likely to be used in LTE downlink instead of OFDM in terms of spectrum. As the frequency spacing between subcarriers (Δf) decreases, the number of subcarriers Ns.c as well as the number of resource blocks RBs will increase. Table 1 shows the bandwidth of PRBs will decrease when Δf decrease and hence we can serve more users. Throughput can be greatly enhanced when SEFDM is used. When Bandwidth compression Factor BCF (α) decrease, the number of subcarriers increase and also throughput will increase too.

Table1. Different number of RBs for different BCF (α)

BCF (α)	**Δf (kHz)**	**PRB BW (kHz)**	**No. of RBs per Transmission B.W (MHz)**					
			1.4	**3**	**5**	**10**	**15**	**20**
1	15	180	6	15	25	50	75	100
0.8	12	144	7.5	18	30	60	90	125
0.75	10.5	126	8.5	21	35	71	107	142
0.6	10	120	9	22	37	75	112	150

Theoretical capacity C of the system can be represented with an AWGN channel and calculated according to Shannon capacity [10]:

$$C = F\ B.W\ log_2(1 + SNR) \qquad (6)$$

Here, SNR is the Signal to Noise Ratio, BW the bandwidth occupied by the data subcarriers as shown below, and F a correction factor. The bandwidth BW is calculated as [11]:

$$B.W = \frac{N_{SC} \cdot N_S \cdot N_{RB}}{T_{sub}} \qquad (7)$$

Where N_sc=12 is the number of subcarriers in one RB, N_s is the number of SEFDM or OFDM symbols in one sub-frame (usually equal to fourteen when the normal Cyclic Prefix (CP) is set), NRB is the number of RBs that fit into the selected system bandwidth (for example 6 RBs within a 1.4MHz system bandwidth in case of OFDM (α=1) but 9 RBs within the same bandwidth at (α=0.6)), and T_sub is the duration of one sub-frame equal to 1ms. The transmission of an OFDM or SEFDM signal requires also the transmission of a CP or a guard band to avoid Inter-Symbol-Interference and the reference symbols for channel estimation. Therefore, the well-known Shannon formula is adjusted in (8) by the factor F. This factor F as shown below, accounts thus for the inherent system losses and is calculated as:

$$F = \frac{T_{frame} - T_{cp}}{T_{frame}} \cdot \frac{\frac{N_{SC} \cdot N_S}{2} - 4}{\frac{N_{SC} \cdot N_S}{2}} \qquad (8)$$

Where Tframe is the fixed frame duration equal to 10 ms and TCP is the total CP time of all OFDM or SEFDM symbols within one frame [10].

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Table 2 shows the enhancement of system capacity with decreasing BCF value. Fig.1 shows the increasing number of subcarriers with decreasing BCF.

Table2. Theoretical Capacity for different values of (α)

SNR (dB)	Theoretical Capacity (Mbps)			
	α =1 (OFDM)	**α = 0.8**	**α =0.75**	**α =0.667**
0	**14.952**	**52.44**	**59.571**	**62.928**
10	**51.725**	**64.656**	**73.449**	**77.587**
20	**99.34**	**124.1**	**141.062**	**149.01**
30	**149**	**186.25**	**211.58**	**223.5**
50	**248.35**	**310.43**	**352.657**	**372.525**

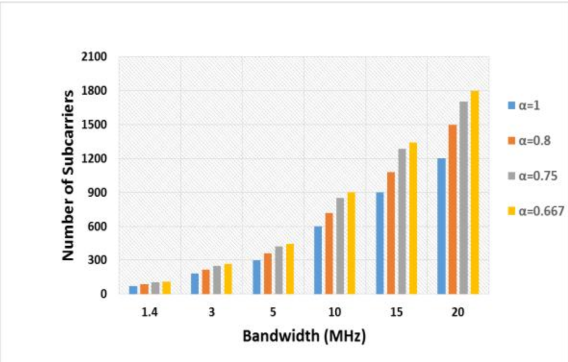

Fig.1. Different numbers of subcarriers for different BCF (α)

B. **Proposed System Model**

LTE transmitter and receiver consist of several stages like scrambling, Pre-coding …, OFDM Signal Mapper and Demapper. The proposed system is only deal with the last stage of LTE transceiver by substituting OFDM Signal Mapper and Demapper with SEFDM Signal Mapper and Demapper to obtain higher spectral efficiency. So, the proposed system is assumed to be perfectly encoded and decoded, there is no coding taken into account. IDFT implementation of SEFDM Transceiver was efficiently substituted by IFFT. Guard interval was taken to be normal. ITU Channel Models were used for the implementation of the system. The system was first assumed to be in case of perfect Channel State Information (CSI), and then Least Square (LS) method was used for channel estimation. At the detection stage, two methods were used. Efficient Sphere Decoder (ESD) and ESD_IC, which combines Efficient Sphere Decoder with Iterative Cancellation (IC).

IV. SIMULATION RESULTS AND DISCUSS

A. SIMULATION PARAMETERS

In this section, we will simulate and discuss the performance of an LTE system when SEFDM is used instead of OFDM as an LTE air interface. The simulations are carried out for frequency-selective channels modelled by ITU for Vehicular-A channel. Our simulations were performed using 1.4 MHz bandwidth. The simulation parameters used are listed in the Table 3.

Table3. Simulation Parameters

Parameters	Values
Bandwidth	1.4 MHz
Guard interval	Normal
Channel Estimation	Least Square (LS)
Channel Type	Vehicular-A (Veh-A) for Fast User Mobility
User Velocity	30 km/h for Veh-A
Receiver Detection Type	Efficient Sphere Decoder (ESD) Hybrid Detection
Simulation Length	100 subframe
Transmission Scheme	SISO
Modulation Type	4-QAM
Bandwidth Compression Factor (α)	1, 0.8, 0.75, 0.6
Frequency spacing (kHz)	15, 12, 11.25, 10

B. **Results**

It's clear from figures that the system needs higher power when (α) decreases to maintain the same performance as OFDM when (α = 1). There is a trade-off between increasing power and bandwidth savings. When comparing between the two detection methods (ESD and ESD-IC) used, it's clear that the system needs less power when ESD_IC method is used. It should be noted that for the same bandwidth saving, the performance of an ESD_IC is better than that of an Efficient Sphere Decoder with the same power consumption. Such performance improvement is attributed to the reduction of interference by iterative cancellation for the ICI after SD, but Hybrid Detection needs more complexity depending on the number of iterations in Iterative cancellation.

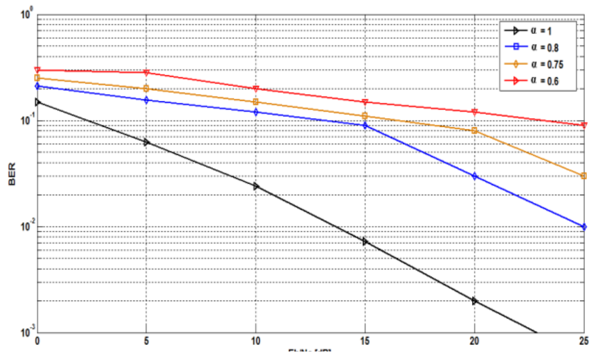

Fig.2. BER versus Eb/No using ESD-IC method with LS channel Estimation.

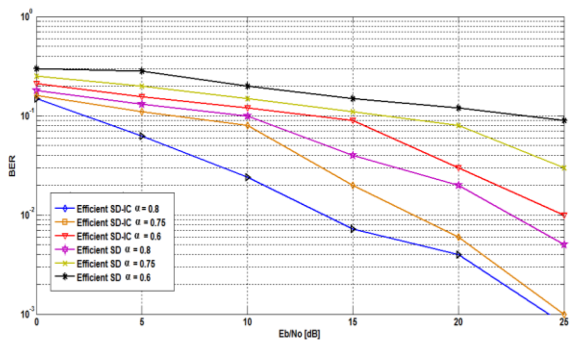

Fig3.BER versus Eb/No using ESD-IC method with LS channel Estimation

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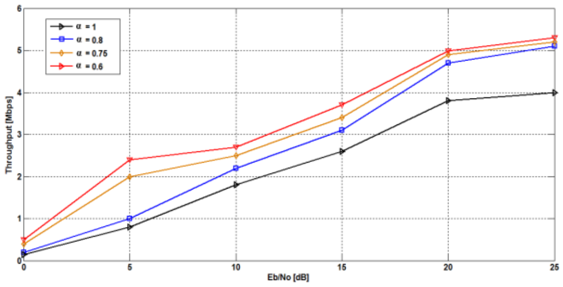

Fig.4.Throughput versus Eb/No using ESD method with LS channel Estimation.

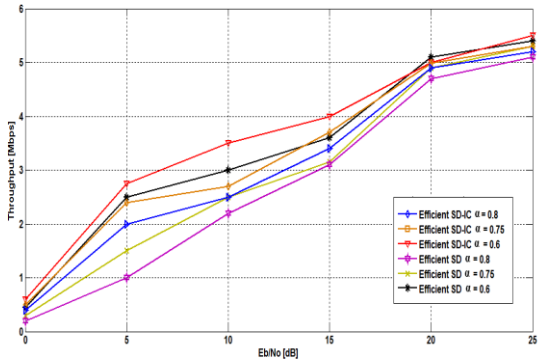

Fig.5.Throughput versus Eb/No using ESD-IC method with LS channel Estimation.

It's clear that SEFDM system can greatly enhance throughput. Throughput can be enhanced from 4-5.5 Mbps when α decrease from (1- to- 0.6) but system complexity will enhanced too. It should be obvious that for high Eb/No values both Efficient Sphere Decoder and Hybrid Detection methods will give the same peak throughput.

V. CONCLUSION

The main goal of this paper was to present the advancements achieved when SEFDM system substitutes by an OFDM in LTE Downlink. In this paper, we present the performance of OFDM and SEFDM systems in terms of bandwidth savings. We can see that when BCF (α) decreases throughput will increase and hence more number of users or higher throughput for a fixed number of users. Two Detection methods were used: ESD and ESD-IC. ESD can perform better than ESD only but its complexity is higher. On the other hand, higher throughput comes at cost. When BCF (α) decreases the system becomes more complex and the power is increased too. But there is some researches that discuss the power and complexity reduction for SEFDM system.

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