Single Carier FDMA as the uplink and OFDMA as the downlink for LTE-Advanced: Performance analysis in terms of PAPR and sensitivity with Carrier Frequency Offset and Timing Offset

Phuoc Vu
Division of Electrical Engineering
School of Electrical Engineering and Computer Science
Louisiana State University
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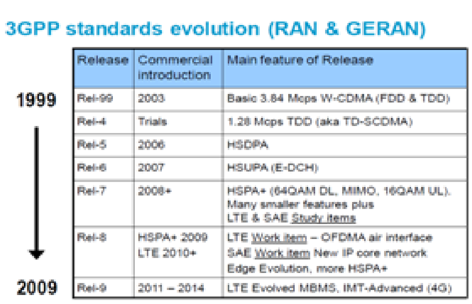
***Abstract*—Recently, OFDMA and SC-FDMA have been widely studied for the uplink of a mobile communication for 4th generation (4G) systems. While its parent generation used Code Division Multiple Access (CDMA), LTE implements Orthogonal Frequency Division Multiple Access (OFDMA) for its downlink and Single-Carrier Frequency-Division Multiple Access (SC-FDMA) for its uplink. The purpose of this project is to investigate the reasoning for this change between uplink and downlink modulation schemes. As a result, OFDMA has high PAPR (Peak-to-Average Power ratio) values and more sensitive in term of Bit Error Rate given non-zero carrier frequency offset (CFO) than SC-FDMA but SC-FDMA provides the same efficiency of OFDM system at a reduced power level. It is important to keep a low PAPR on the uplink. MATLAB simulations are also conducted to verify the performance of OFDMA and SC-FDMA and to learn the results that derived from the literature survey.**

I. Introduction

The 3rd Generation Partnership Project (3GPP) has released the Long Term Evolution (LTE) specifications to transit from 3G communications systems to meet the need of 4G systems. From that, LTE-Advanced has been chosen as the candidate for 4G systems. LTE use Orthogonal FDMA for


3GPP standards evolution (RAN & GERAN)

Release	Commercial introduction	Main feature of Release
Rel-99	2003	Basic 3.84 Mcps W-CDMA (FDD & TDD)
Rel-4	Trials	1.28 Mcps TDD (aka TD-SCDMA)
Rel-5	2006	HSDPA
Rel-6	2007	HSUPA (E-DCH)
Rel-7	2008+	HSPA+ (64QAM DL, MIMO, 16QAM UL). Many smaller features plus LTE & SAE Study items
Rel-8	HSPA+ 2009 LTE 2010+	LTE Work item – OFDMA air interface SAE Work item New IP core network Edge Evolution, more HSPA+
Rel-9	2011 – 2014	LTE Evolved MBMS, IMT-Advanced (4G)

Fig. 1: 3GPP evolution

transmission from base stations to mobile terminals while the LTE standard for uplink transmission is based on Single Carrier FDMA (SC-FDMA). Many literature have analyzed the performance of SC-FDMA and OFDMA in terms of capacity, power outage and PAPR and make such a comparison, for example [3]-[6]. However, there are not many papers dealing with the SER performance of these two schemes in terms of carrier frequency offset (CFO) and timing offset (TO), those topics are also of important to derive the comparison results of these two schemes. The organization of this report is as following: in section 2, two modulation schemes OFDM and Single Carrier Frequency Division Multiplexing (SC-FDE) are revisited. Section 3 is the basis for the multiple access versions of OFDM and SC-FDE, namely OFDMA and SC-FDMA. The performance of two transmission schemes in terms of PAPR is compared and analyzed based on MATLAB simulation results. Section 4 is about sensitivity of OFDMA and SC-FDMA on Symbol- error- rate (SER) to CFO and TO with the baseline assumptions made so that the comparison can be fair. Then the synchronization techniques are investigated and reviewed from literature survey to handle the effects of CFO and TO in these systems. Last, section 5 sums up the results and suggests future work.

II. Modulation schemes: OFDM and SC-FDE

It is obvious that today's wireless broadband communications systems are characterized by very dispersive channels. To face this phenomenon, two modulation techniques can be used: single carrier (SC) modulation with frequency-division equalization (SC-FDE), or multicarrier modulation with orthogonal frequency-division multiplexing (OFDM). The following diagram shows the basic differences between the two modulation schemes. In this section, the differences between an OFDM system and an SC-FDE system are listed and then comparisons in terms of the performance of these two systems by simulations.

A. OFDM

OFDM is a special type of multicarrier modulation, in which a single high rate bit stream is divided into multiple low rate substreams and transmit each slower signal in a separate frequency band. The transmitter and receiver architecture of a multicarrier modulation scheme is illustrated here: Multicarrier transmission scheme has been studied in the IEEE archive

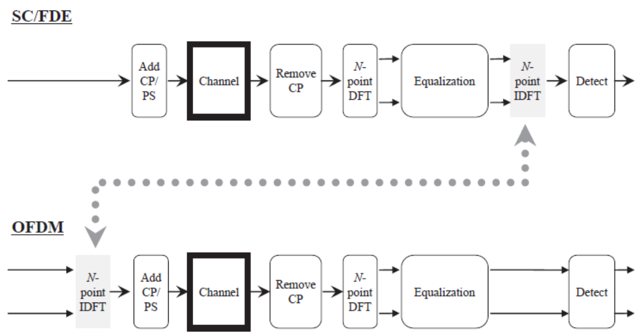


Fig. 2: OFDM vs. SC-FDE modulation

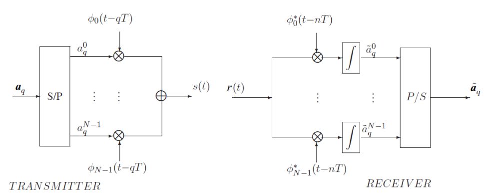


Fig. 3: Multicarrier modulation transmitter and receiver

since the paper of Chang and Gibby [4]. Weinstein and Ebert [5] came up with the idea of using DFT to implement OFDM, instead of using banks of subcarrier oscillators and coherent demodulators as shown in the . This idea, together with the very fast implementation of DFT in hardware using FFT, make OFDM a very attractive modulation scheme. We consider the following structure of an OFDM transmitter:

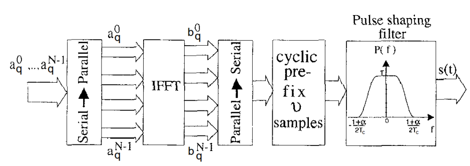


Fig. 4: OFDM transmitter

The input samples at the q-th symbol a_q^i come in at rate 1/Tc. N of those samples are processed at a time using an IFFT block. The outputs of the IFFT block, b_q^i, are converted to a serial stream and passed through a cyclic prefix block which adds the last W samples to the beginning of the symbol, as in above figure. The serial baseband output is then fed to a pulse shaping filter with impulse response p(t). The role of the cyclic prefix is two fold: 1) it turns linear convolution as is naturally done by the channel into circular convolution, which greatly simplifies the receiver. 2) it provides a guard time to counteract ISI. The OFDM receiver structure is described below[7].

The received signal is matched filtered with the transmitted pulse shape. The output of the matched filter is sampled at instants nTc + $\hat{\tau}$ where $\hat{\tau}$ is the estimate of the time delay. The cyclic prefixed is removed and the block of N samples is fed to the FFT. The frequency equalizer (FEQ) scales and rotates each FFT output sample to compensate for the channel. One important feature of OFDM is its ability to equalize in

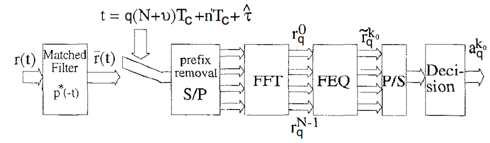
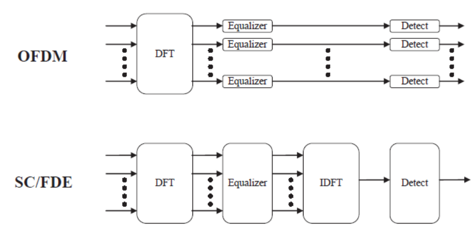


Fig. 5: OFDM receiver

frequency domain. Two different ways of equalizing are the zero-forcing (ZF) equalizer and the minimum mean square error (MMSE) equalizer. While they both correctly recover the phase of the signal, the ZF equalizer causes noise enhancement and the MMSE equalizer causes time distortion in the signal. These effects of the equalizers will be examined in the following sections.

B. SC-FDE

A variation of OFDM is SC-FDE, a modulation scheme that contains all the same blocks but moves the IFFT from the transmitter to the receiver, just like in Fig. 3. The difference between this system and OFDM is that the constellation mapping takes place in time domain, and the CP is the last time samples added to the beginning of the signal. In the receiver, OFDM performs data detection on a per-subcarrier basis in the frequency domain whereas SC/FDE performs data detection in the time domain after the additional IDFT operation, as shown below[19].



receiver.png

Fig. 6: SC-FDE vs. OFDM receiver

Hence, OFDM is more sensitive to a null in the channel spectrum and it requires channel coding or power/rate control to overcome this vulnerability. In section (4) it is shown also OFDM is more sensitive to carrier frequency offset than SC-FDE. Here we employ simulations to obtain the SER performance of SC-FDE system since analytical results are difficult to derive as well as the OFDM system.

C. Performance comparison between two modulation schemes

In this section, MATLAB simulation has been conducted to compare the performance of both modulation schemes. In these simulations, the ideal transmission assumptions are made, i.e. we assume that there is no carrier frequency offset or timing offset in the system, the symbol rate is fixed and the simulation parameters set up are shown below. For each simulation, 10000 independent trials were run in MATLAB with multipath coefficients following the LTE multipath propagation model. Our simulation shows QPSK as the data modulation format, without Pulse shaping filter nor channel coding and the system bandwidth is chosen to be 5MHz. The transmitter IFFT size is 512 and there are 20 cyclic prefix samples at the modulator. The number of subcarriers is, hence, 512. The simulation is applied to both zero forcing equalization and MMSE equalization with the number of iterations is 10000. Figure

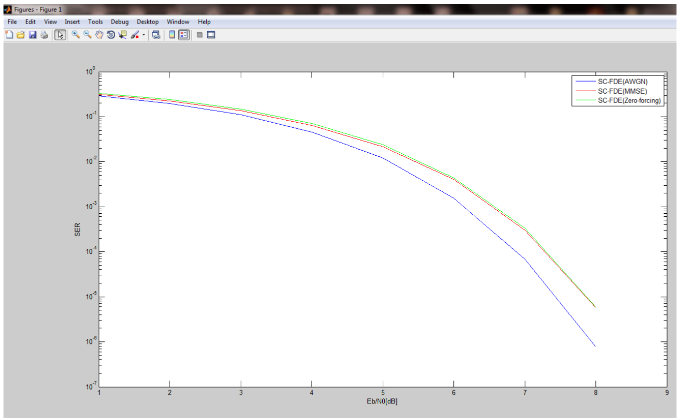


Fig. 7: Symbol error rate performance of SC/FDE system with different types of equalization method

7 shows the SER performance of the SC/FDE system with different types of channel equalization method. We can see that MMSE equalization gives better performance than the zero forcing equalization because of its robustness against noise during the equalization processing. Other advanced equalization methods,such as decision feedback equalization (DFE) and turbo equalization,should give performance approaching the AWGN channel. Similar plot was also given for the OFDM system. Again, we see that MMSE equalization performs

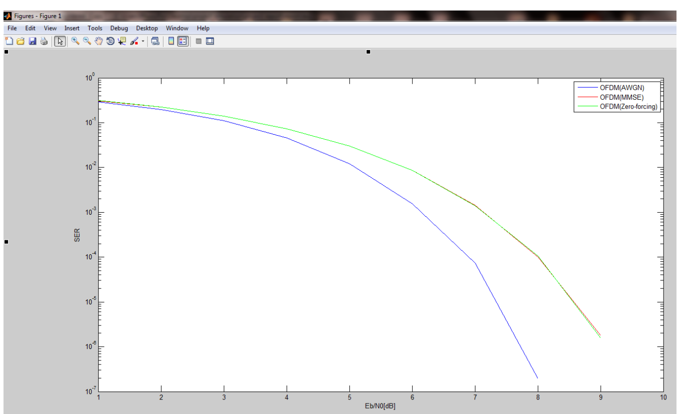


Fig. 8: Symbol error rate performance of OFDM system with different types of equalization method

slightly better than the zero forcing equalization but both are more sensitive to symbol error rate than the AWGN channel. To compare the performance of the OFDM and SC-FDE modulation scheme, the following figure is plotted. Figure 9 compares the SER performance between SC/FDE and OFDM. For the AWGN channel, we can see that they essentially have the same performance. For MMSE and ZF equalization we can see that SC/FDE outperforms OFDM because of the inherent frequency. An OFDM system needs a good channel coding or channel adaptive modulation scheme to overcome

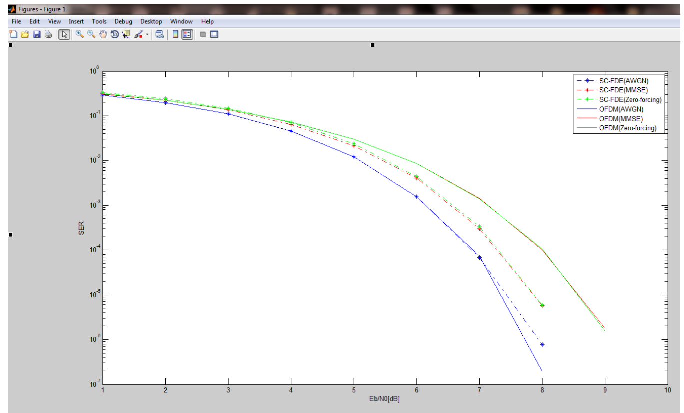


Fig. 9: Comparison of symbol error rate performance of OFDM and SC-FE system with different types of equalization method

this limitation. Figure 10 shows the effect of not using the CP

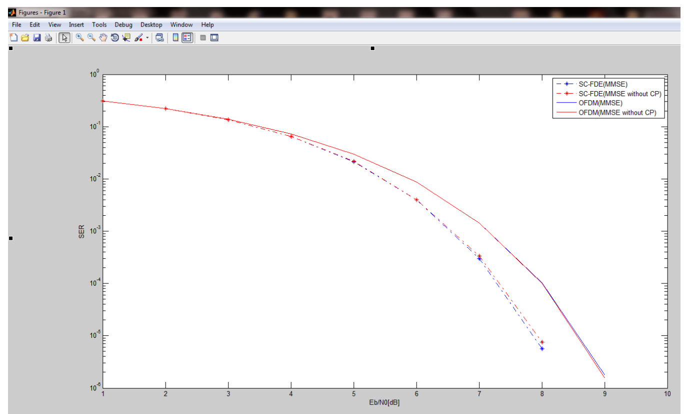


Fig. 10: Symbol error rate performance of SC-FDE/OFDM system without Cyclic Prefix

for the SER performance of SC-FDE and OFDM system that degrades significantly in the high SNR regime when the length of the CP is zero. This illustrates the critical role of CP in the presence of a multipath channel.

III. Multiple Access version: OFDMA and SC-FDMA

OFDMA and SC-FDMA are multiple access transmission versions of the two modulation schemes: OFDM and SC-FDE. The following figure shows the transmitter/ receiver structure of OFDMA and SC-FDMA systems. We can see from the above figure that OFDMA and SC-FDMA transmitters and receivers perform many common signal processing functions: they use the same number of subcarrier symbols, both use frequency domain channel equalization and use cyclic prefix. However, there are distinct differences that lead to different performance. The most obvious is that OFDMA transmits a multicarrier signal whereas SC-FDMA transmits a single carrier signal. Because of this, SC-FDMA has a lower peak-to-average power ratio (PAPR) than OFDMA. In this section, we

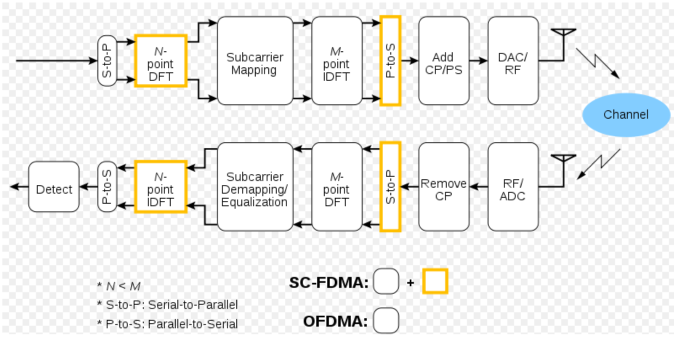


Fig. 11: Transmitter and receiver structure of SC-FDMA/ OFDMA

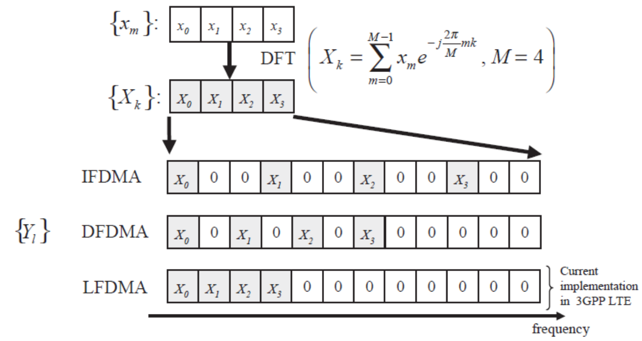


Fig. 12: Different subcarrier mapping schemes for M = 4, and N = 12

also do not mention the effect of frequency offset and timing offset to the performance of the two systems.

A. OFDMA

One big advantage of OFDMA for the adpoption as LTE downlink is its robustness in the presence of multipath signal propagation[2]. The immunity to multipath derives from the fact that an OFDMA system transmits information on M orthogonal frequency carriers, each operating at 1/M times the bit rate of the information signal. On the other hand, the OFDMA waveform exhibits very pronounced envelope fluctuations resulting in a high peak-to-average power ratio (PAPR). Another problem with OFDMA is its high sensitivity to frequency offset [19]. In OFDMA, since many users transmit symbols simultaneously, each with their own estimates of the subcarrier frequencies, a frequency offset is inevitable and multiple access interference occurs as users power leaks into subcarrier bands.

B. SC-FDMA

From Fig. 12, the input of the transmitter and the output of the receiver are complex modulation symbols. In the real systems to dynamically adapt the modulation technique to the channel quality, binary phase shift keying(BPSK) in weak channels and up to 64-level quadrature amplitude modulation (64-QAM) in strong channels are used [19]. The M-point discrete Fourier transform (DFT) produces M frequency domain symbols that modulate M out of N orthogonal subcarriers spread over the given bandwidth. The bandwidth spreading factor is N/M. There are three approaches to assigning mobile terminals to subcarriers: localized FDMA (LFDMA), distributed FDMA (DFDMA), and interleaved FDMA (IFDMA), a special case of distributed FDMA. The following figure shows for example, different subcarrier mapping schemes for M = 4, and N = 12[19]. For channel equalization, while OFDMA performs equalization and data detection separately for each subcarrier, SC-FDMA performs equalization across the entire channel bandwidth. It then uses the IDFT to transform the signal from one terminal to the time domain prior to detection of the modulated symbols. The IDFT prior to symbol detection is necessary because, except for IFDMA, the transmitted signal consists of a weighted sum of all symbols in a block. The IDFT retrieves the original symbols from the composite signal. Because SC-FDMA effectively spreads each modulated symbol across the entire channel bandwidth, it is less sensitive to frequency-selective fading than OFDMA, which transmits modulated symbols in narrow sub-bands[19]

C. PAPR analysis of OFDMA and SC-FDMA

- It is difficult to compute the values of the PAPR of the time domain signal analytically for a given set of constellations for OFDMA system. [4] assumes that the constellations map to complex Gaussian random variables with variance σ^2 in the time domain. Hence, the complementary cumulative distribution function (CCDF) of the PAPR is:

$$Pr(PAPR \geq w) = 1 - (1 - \exp(-w))^N \tag{1}$$

N is the number of subcarriers per block

- For the SC-FDMA system, the PAPR is defined as the ratio of peak power to average power of the transmitted signal in a given transmission block. Without pulse shaping, that is, using rectangular pulse shaping, symbol rate sampling will give the same PAPR as the continuous time domain case since an SC-FDMA signal is modulated over a single carrier. The PAPR of SC-FDMA signals is analyzed in [19] but we consider here the case for interleaved FDMA only. MATLAB simulation has been conducted to compare the performance of PAPR of both SC-FDMA and OFDMA system. In these simulations, the ideal transmission assumptions are made, i.e. we assume that there is no carrier frequency offset or timing offset in the system, the symbol rate is fixed and the simulation parameters set up are shown below. Our simulation shows QPSK as the data modulation format, without Pulse shaping filter nor channel coding and the system bandwidth is chosen to be 5MHz. The transmitter IFFT size is 512 and there are 20 cyclic prefix samples at the modulator. The number of subcarriers is, hence, 512. The simulation is applied to both zero forcing equalization and MMSE equalization with the number of iterations is 10000.We compare the PAPR value that is exceeded with the probability less than 0.001 or 99.9-percentile PAPR. We can see that all the cases for SC-FDMA have indeed lower PAPR than that of OFDMA.

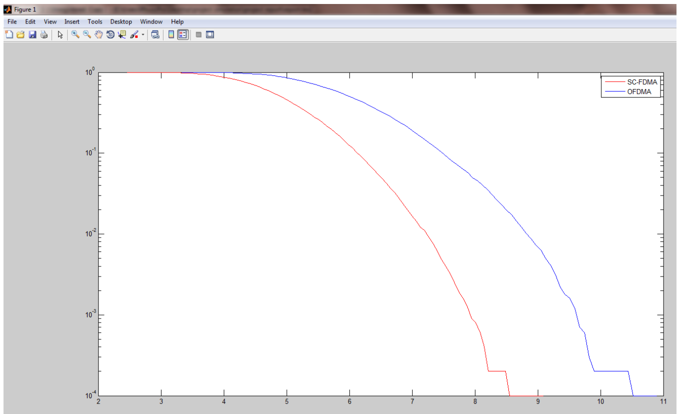


Fig. 13: Different subcarrier mapping schemes for M = 4, and N = 12

IV. OFDMA and SC-FDMA Sensitivity to Carrier Frequency and Timing Offsets

There have been multiple analyses in the literature on the effect of time and frequency offset on the performance (e.g. the receiver SNR) of an OFDM system, as in [9] [21] [22]. The main synchronization errors are:

- Timing offset: Caused by delay in the channel, results in sampling at incorrect instants, which in turn causes ICI.
- Phase offset: Caused by phase rotation of the channel,results in a constant phase error over all subcarriers.
- Carrier frequency offset: Caused by the asynchronous local oscillators at the transmitter and receiver. Later it is shown that this offset results in a loss in SNR which is independent of the subcarrier index.

All of them will degrade the performance of OFDMA and SC-FDMA in terms of BER. We consider here only the cases for Carrier frequency offset and timing offset. We want to compare BERs for the OFDMA and SC-FDMA systems in the presence of CFO under the AWGN channel. For OFDMA systems. the IC1 is approximated as Gaussian noise. Also we employ simulation to obtain the BER performance of SC-FDMA and OFDMA systems since analytical results are difficult to derive.

A. Effects of time and frequency synchronization error

1) OFDM with CFO: The following figure shows the general structure of OFDM systems in the presence of CFO. At the output of the modulation block, IDFT is used on the current symbol, which includes N data samples X_0^k, for k=0,1,2,..,N-1 to produce the corresponding signals in the time domain. Then cyclic prefix is added to the beginning of the output stream. The time domain signal is given by:

$$x_0(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_0(k) \exp(j * 2 * \pi * n * k * \frac{1}{N}) \quad (2)$$

where n is from N_g to N-1 At the receiver side, down-converting RF introduces carrier frequency offset $\triangle f$ into

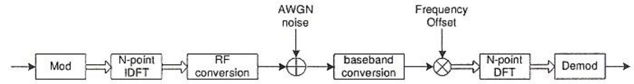


Fig. 14: OFDM system with carrier frequency offset(CFO)

the receiver signals. By removing the CP, the discrete signal expression of the nth sample is shown to be:

$$y_0(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_0(k) \exp(j2\pi n(k+\varepsilon)/N) + z_0(n) \quad (3)$$

where $\epsilon = \Delta f T$ is the normalized CFO of the system and $z_0(n)$ denotes the AWGN samples. The following figure plots sensitivity of OFDM sub carriers with Carrie frequency offset(CFO). Presence of CFO changes position of sub-carriers.

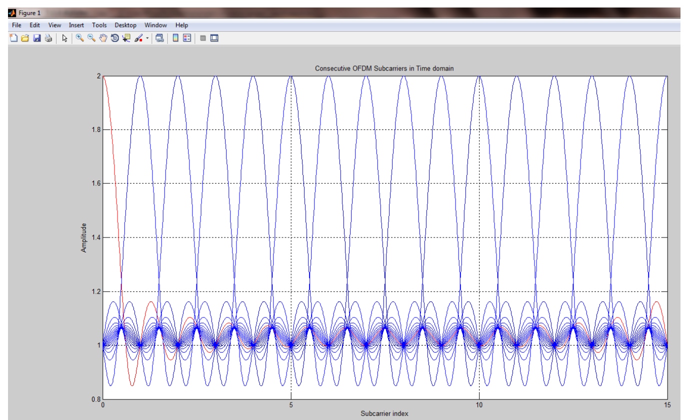


Fig. 15: OFDM sub carriers with Carrie frequency offset(CFO)

Also, the following figures show the OFDM system simulation with various CFO values under AWGN channel.

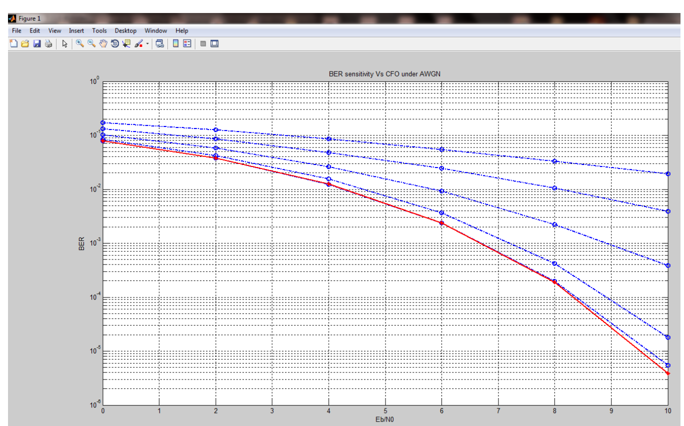


Fig. 16: BER sensitivity of OFDM vs. CFO under AWGN

We can see that as in high SNR regime the carrier frequency offset significantly increases the BER of OFDM system.

2) SC-FDE with CFO: The system structure of SC-FDE is shown below. Assume that the similar parameters of OFDM

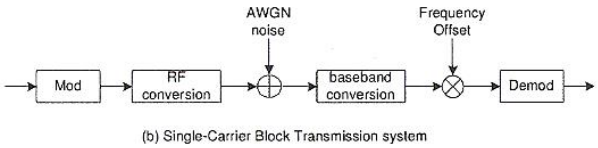


Fig. 17: SC-FDE system with carrier frequency offset(CFO)

have been chosen for the SC-FDE system, especially the same normalized CFO ϵ. Hence the SC-FDE system can be described as:

$$y_s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_s(k) \exp(j2\pi n(k+\varepsilon)/N) + z_s(n) \quad (4)$$

B. Comparison of OFDMA and SC-FDMA with sensitivity to CFO

Again under the same set of assumption: the same bandwidth is allocated, the normalized CFO ϵ of the two systems are the same, the sample rate and number of subcarriers are the same we made a fair comparison of the effects of CFO with the two systems. The simulation set up is the same in the previous section with the added CFO factor $\epsilon = 0.1$. The following figure shows the effects of CFO with both modulation schemes.

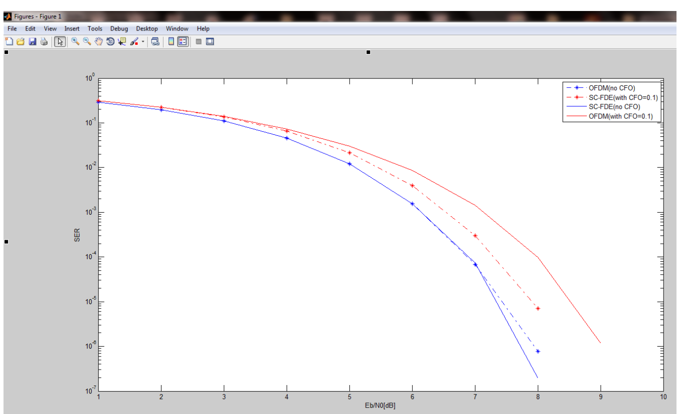


Fig. 18: SER sensitivity of OFDMA and SC-FDMA with carrier frequency offset(CFO)

We can see that OFDMA system is obviously more sensitive to CFO than the SC-FDMA system. This result is also confirmed in other papers. A simulated coded block error rate performance comparison between SC-FDMA with frequency domain MMSE equalization and OFDMA, evaluated for various modulation and coding sets specified in UTRA LTE, is presented in [8]; OFDMA is shown to perform better than SC-FDMA for some modulation and coding sets. Subsequently, the same authors, in [9], proposed a iterative equalization and decoding (turbo equalization) scheme, and showed that SC-FDMA with turbo equalizer performed better than (or same as) OFDMA for all modulation and coding sets considered. On a similar line, the authors in [10] proposed a soft-output trellis based equalizer that takes into account the cyclic inter-symbol interference (ISI) structure arising in SCFDMA, and showed that SC-FDMA with trellis based equalizer performed better than SC-FDMA with MMSE equalization. An approximate performance analysis of the BER of SC-FDMA with frequency domain equalization is presented in [11]. In [12], a PAPR and BER performance comparison between SC-FDMA, OFDMA and Walsh-Hadamard precoded OFDMA is presented, where the PAPR advantage of SC-FDMA in the presence of power amplifier non-linearity has been analyzed.

C. Synchronization techniques

OFDM synchronization techniques can be put in 2 categories:

- 1) non data-aided: make use of the correlation between the CP and the end of the symbol; and
- 2) data-aided: make use of additional data such as preamble and pilot tones.

Exploiting the redundancy created by the CP, we can estimate time and frequency parameters. This is most commonly done by averaging the correlation of the CP and the end of the OFDM symbol. Van de Beek et al. has analyzed this scheme [8] using a maximum likelihood estimator. Intuitively, this technique would perform badly in a multipath channel because the CP is distorted by ISI.

The correction of time and frequency offset is so important to an OFDM system that in most cases it is justified to lose some amount of bandwidth for synchronization. This bandwidth can take the form of a preamble, some pilot tones in each OFDM symbol, or a combination of the two. The most popular synchronization technique for OFDM systems is due to Schmidl and Cox [10] which has the accuracy close to the Cramer-Rao bound. There have been numerous work either trying to improve, or based on this algorithm. Almost all new techniques have a comparison to Schmidl and Coxs.

Pilot tones techniques: The use of pilot tones in each OFDM symbol was initiated by D. K. Kim et at. [11]. The underneath idea is that the phase offset between 2 subcarriers depends only on the frequency difference between those subcarriers.

V. Conclusion

In this report, we have analyzed and made a comparison of the performance between two transmission schemes SC-FDMA and OFDMA. Single carrier FDMA (SC-FDMA) is a multiple access technique that utilizes single carrier modulation, orthogonal frequency multiplexing, and frequency domain equalization. It has similar performance and essentially the same overall complexity as orthogonal frequency division multiple access (OFDMA). One prominent advantage over OFDMA is that the SC-FDMA signal has better peak power characteristics because of its inherent single carrier structure. SC-FDMA is also shown to be less sensitive with carrier frequency offset and

- One of the disadvantages of SC-FDMA over OFDMA is that channel adaptive subcarrier bit and power loading is impossible for SC-FDMA [5]. By adapting the symbol modulation and power for individual subcarriers, OFDMA is able to come close to the upper bound of the capacity limit for a given channel. Hence this might be one reason OFDMA chosen for down-link transmission.

- SC-FDMA has drawn great attention as an attractive alternative to OFDMA, especially in the uplink communications where better peak power characteristics greatly benefit the mobile terminal in terms of transmit power efficiency and manufacturing cost. Because of its merits, SC-FDMA has been chosen as the uplink multiple access scheme in 3GPP Long Term Evolution (LTE).

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