OFDMA in High-speed Mobile Systems, Pilots and Simulation Problems

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Abstract— **A proposal is put forward for an innovative method of multiple access, termed Frequency Bank Signal (FBS). The major advantage of FBS is that the error probability is almost non-sensitive to, either, the Doppler Effect, separate signal delay or to the negative effect of reflected signals. In addition, FBS signals do not require special pilots or equalization signals. Two methods, based on Frequency stuffing and time stuffing, for simulation of OFDMA systems are proposed. Both methods are characterized by enhance resolution and allow for monitoring of the influence of impairments such as orthogonality disturbance, non-ideal synchronization and jitter in the receiver.**

Keywords— OFDM, Doppler, Multipath, Pilot, FBS, Simulation

I. INTRODUCTION

Nowadays, the OFDM (Orthogonal Frequency Division Multiplexing) technology is widely adopted as a modulation scheme for many WLAN standards such as IEEE802.11a and HIPERLAN2 and also DAB, DVB-T, DVB-H, WiMax, Wi-Fi. There is now a generally accepted opinion that also the next generation of mobile/wireless systems will be based on this technology [1-4]. The main advantages of OFDM are its spectrum efficiency and robustness against fading in multipath propagation. Reflection signals in OFDMA change the phase and amplitude of information symbols and this influence is compensated by pilot signals.

The performance of an OFDM system heavily relies on its timing and frequency synchronization. In the presence of Doppler effects, the receiver synchronization system is not able to react immediately and hence received symbols cannot be corrected during their symbol time. Moreover, in the case of OFDMA systems, frequencies of different carriers can be shifted in different directions, leading to a large Doppler spread. In absence of a fast response synchronization system in the receiver, symbol arrival time will be unsynchronized due to Doppler effects. This leads to an additional phase shift, which we shall refer to as a short delay. As the automatic frequency control system in a receiver cannot correct the decoding parameters of the FFT instantly, the receiver can detect signals whose frequencies are shifted by the transmitter and fails to synchronize with frequencies shifted due to Doppler effects. Demodulation of the OFDM signals with an offset in their frequencies can lead to a high bit error rate.

Orthogonality deterioration caused by Doppler effects introduces Inter Carrier Interference (ICI). Due to ICI, the phases of Pilot signals are affected by neighboring carrier's phases, in addition to channel conditions.

There are some problems in simulation methods employed to study the Doppler effects in OFDM systems. The OFDMA signal spectrum does not include intermediate points between spectral components, so that it is impossible to simulate the frequency shifts resulting from Doppler effects. Usually, these simulations are done by the MATLAB's "Doppler Filter", which can change the signal phases, but is unable to simulate the more significant problem, namely the orthogonality deterioration. Another problem is the simulation of the jitter influence.

A combination of principles used in PAL TV, OFDMA and CDMA named Frequency Bank Signal (FBS) provides solutions to the above problems without having to use additional signals, such as a pilot or test signal for the equalizing process.

In this paper we present two simulation methods based on frequency stuffing and time stuffing, aimed at increasing the simulation resolution, and hence allowing for investigation of OFDMA peculiarities. These methods are used for a comparative study of the common OFDMA method and the FBS method.

II. THE FREQUENCY STUFFING SIMULATION METHOD

It is possible to show that owing to the high central frequency and the small frequency spacing between subcarriers, the Doppler shift is the same on all OFDMA carriers and is restricted to a few percents.

Frequency stuffing means to add s -1 'zeros' ($s = 2^n$) between each carrier. Let us describe this method by means of an example, for the case of N=8 subcarriers. We can decide the real spectrum in FFT dimension (N/2) to be 16 bits, where eight bits are used for transmitting information bits and pilot signals (see Fig 1A).

Now, we introduce frequency stuffing as illustrated in Fig. 1B. This means that s-1 points are added between all subcarriers (see Fig. 1C).

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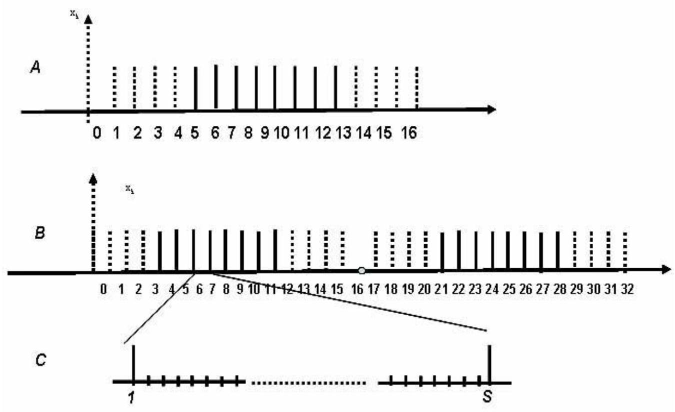

Figure 1.Frequency stuffing .

Now we can introduce a frequency shift corresponding to the Doppler Effect with a resolution of 1/s. After IFFT, we receive a time signal with Ns samples.

For transmitting, we use only N first samples. Since, the receiver is not aware of frequency changing, FFT is performed on the transmitted frequencies, and we obtain all the influences of Doppler effects including ICI.

The proposed frequency stuffing method is confirmed by following mathematical analysis.

The discrete Fourier transform (DFT) of x_n is defined by:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi j}{N}kn}, \qquad k = 0,\dots,N-1 \qquad (1)$$

The inverse discrete Fourier transform is defined by:

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{\frac{2\pi j}{N}kn}, \qquad n = 0,\dots,N-1 \qquad (2)$$

It can be useful to denote:

$$t_n = \frac{T}{N}n, \quad \omega_k = \frac{2\pi}{T}k, \quad x_n = x(t_n),$$

then

$$X_k = X(\omega_k) = \sum_{n=0}^{N-1} x(t_n)e^{-j\omega_k t_n},$$
$$k = 0,\dots,N-1 \qquad (3)$$

$$x_n = x(t_n) = \frac{1}{N}\sum_{k=0}^{N-1} X(\omega_k)e^{j\omega_k t_n},$$
$$n = 0,\dots,N-1 \qquad (4)$$

Due to the Doppler shift, the new frequencies are $\tilde{\omega}_k = \omega_k + \Delta\omega$,

where $\Delta\omega = \frac{2\pi}{T}\delta$

(δ denotes relative shift). Then the new signal is

$$\tilde{x}_n = \tilde{x}(t_n) = \frac{1}{N}\sum_{k=0}^{N-1} X(\omega_k)e^{j\tilde{\omega}_k t_n}$$
$$= \frac{1}{N}\sum_{k=0}^{N-1} X(\omega_k)e^{j(\omega_k+\Delta\omega)t_n}$$
$$= \left(\frac{1}{N}\sum_{k=0}^{N-1} X(\omega_k)e^{j\omega_k t_n}\right)e^{j\Delta\omega t_n}$$
$$\tilde{x}_n = x(t_n)y(t_n) = x_n y_n, \qquad n = 0,\dots,N-1 \qquad (5),$$

where $y_n = y(t_n) = e^{j\Delta\omega t_n} = e^{j\frac{2\pi}{N}n\delta}$.

Let us denote the Discrete Fourier Transform of y_n by Y_k,

i.e. $$Y_k = \sum_{n=0}^{N-1} y_n e^{-\frac{2\pi j}{N}kn} = \sum_{n=0}^{N-1} e^{\frac{2\pi j}{N}(\delta-k)n},$$
$$k = 0,\dots,N-1 \qquad (6)$$

By the convolution theorem, the DFT of the new signal is

$$\tilde{X}_k = (X \otimes Y)_k = \frac{1}{N}\sum_{i=0}^{N-1} X_{k-i}Y_i \qquad (7).$$

Note that if there is no shift, i.e. if $\delta = 0$, then $\Delta\omega = 0$ and $y_n = 1, \quad n = 0,\dots,N-1$.

Thus, if there is no shift, then

$$Y_k = \sum_{n=0}^{N-1} y_n e^{-\frac{2\pi j}{N}kn} = \sum_{n=0}^{N-1} e^{-\frac{2\pi j}{N}kn},$$

$$Y_k = \begin{cases} N, & k = 0 \\ 0, & k = 1,\dots,N-1 \end{cases} \qquad (8)$$

and so $\tilde{X}_k = (X \otimes Y)_k = \frac{1}{N}\sum_{i=0}^{N-1} X_{k-i}Y_i = X_k$,

i.e. the spectrum is not changed, as expected.

Now we will get explicit expression of the spectrum of the shifted signal according to formula (7) for the case $\delta \neq 0$.

First, let us compute Y_k by using (6):

$$Y_k = \sum_{n=0}^{N-1} e^{\frac{2\pi j}{N}(\delta-k)n} = \frac{1-e^{\frac{2\pi j}{N}(\delta-k)N}}{1-e^{\frac{2\pi j}{N}(\delta-k)}} = \frac{1-e^{2\pi j(\delta-k)}}{1-e^{\frac{2\pi j}{N}(\delta-k)}};$$

$$Y_k = \frac{1-e^{2\pi j\delta}}{1-e^{\frac{2\pi j}{N}(\delta-k)}}, \qquad k = 0,\dots,N-1 \qquad (9),$$

so $$Y_i = \frac{1-e^{2\pi j\delta}}{1-e^{\frac{2\pi j}{N}(\delta-i)}}, \qquad i = 0,\dots,N-1 \qquad (10).$$

Thus, by (7)

$$\tilde{X}_k = \left(X \otimes Y \right)_k = \frac{1}{N} \sum_{i=0}^{N-1} X_{k-i} Y_i ;$$

$$\tilde{X}_k = \frac{1-e^{2\pi j\delta}}{N} \sum_{i=0}^{N-1} \frac{X_{k-i}}{1-e^{\frac{2\pi j}{N}(\delta - i)}} \qquad (11) .$$

Formula (11) is exact.

Linear Approximation.

The linear approximation of Y_k ($0 < |\delta| << 1$) is found by:

$$Y_0 = \frac{1-e^{2\pi j\delta}}{1-e^{\frac{2\pi j}{N}\delta}} \cong N + \frac{N(N-1)}{2} \cdot \frac{2\pi j}{N} \delta ;$$

$$Y_0 \cong N + j(N-1)\pi\delta \qquad (12) .$$

$$Y_k \cong \frac{1-e^{2\pi j\delta}}{1-e^{-\frac{2\pi j}{N}k}} \cong -\frac{2\pi j\delta}{1-e^{-\frac{2\pi j}{N}k}} ,$$

$$k = 1, \ldots, N-1 \qquad (13)$$

(Or $\quad Y_i \cong -\dfrac{2\pi j\delta}{1-e^{-\frac{2\pi j}{N}i}}, \quad i = 1, \ldots, N-1$)

Hence, by (7):

$$\tilde{X}_k = \left(X \otimes Y \right)_k = \frac{1}{N} \sum_{i=0}^{N-1} X_{k-i} Y_i ,$$

$$= \frac{1}{N} \left(X_k Y_0 + \sum_{i=1}^{N-1} X_{k-i} Y_i \right)$$

$$\tilde{X}_k = X_k \left(1 + \pi j \frac{N-1}{N} \delta \right) +$$

$$+ \frac{2\pi j\delta}{N} \sum_{i=1}^{N-1} \frac{X_{k-i}}{1-e^{-\frac{2\pi j}{N}i}} \qquad (14)$$

So, for known values of $\Delta\omega$ or δ, we can compute by (14) the amplitudes and phases of all components after Doppler Effect influence.

A comparison between frequency stuffing simulation methods and analytical method shows identical results.

III. THE JITTER TIME STUFFING SIMULATION METHOD

In contrast to Doppler effects, jitter can influence on intermediate or base band frequencies. In this case OFDMA carriers are different and the same time changing results different phase changing.

Time stuffing means to add s -1 'zeros' ($s = 2^n$) in the centre of the OFDMA spectrum. Let us describe this method using an example for the case on N=8 subcarriers. We can decide the real spectrum in FFT dimension (N/2) to be 16 bits, where eight bits are used for transmitting information bits and pilot signals (see Fig 2A).

Now we have to modify this spectrum to a complex form such as in Fig 2B. For the purpose of frequency changing, we make a stuffing. That is, Ns-1 points are placed in spectrum centre (see Fig. 2C).

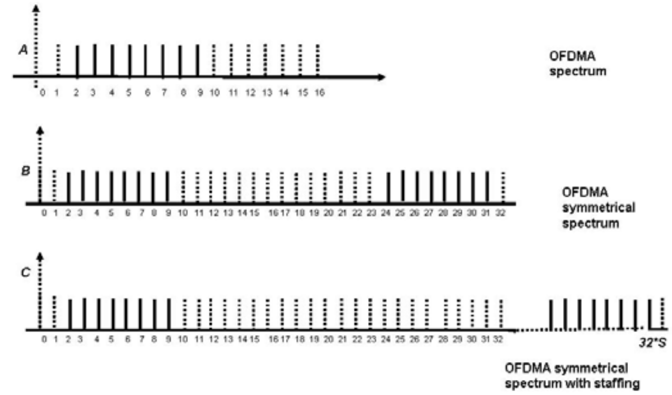

Figure 2. Jitter in OFDM simulation opportunity.

In frequency stuffing method we shift frequency carriers by the same percents of different between carriers and we receive approximately the same phase shift. If the frequency shift is higher than several percents, the phase shifts will not be equal. In the case of jitter and if we are working on base band signal (homodyne receiver) the phase shift will be different on all carriers. Let we have OFDMA signal with N/2 = 8 and carrier frequencies as shown in Fig. 3.

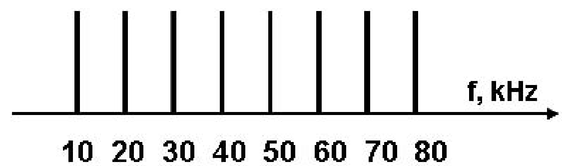

Figure 3. OFDMA spectrum example.

Assume that the symbol time, which is equal to 10^{-4} s, change by 1%. In this case each phase carrier has different phase change. For example:

$$\Delta\varphi_1 = 2\pi \cdot 10 \cdot 10^3 \cdot 10^{-4} \cdot 10^{-2} = 2\pi \cdot 10 \cdot 10^{-3} = 3.6^0$$

$$\Delta\varphi_2 = 2\pi \cdot 20 \cdot 10^3 \cdot 10^{-4} \cdot 10^{-2} = 2\pi \cdot 11 \cdot 10^{-3} = 7.2^0$$

Fig. 4 shows the simulation results for the phase shift as a function of frequency in the case of a small Doppler shift and small jitter. Here, the Doppler Shift is 3% of the carrier spacing and the Jitter is about 0.5 – 1% of the symbol duration. Symbol number in each simulation is 1024.

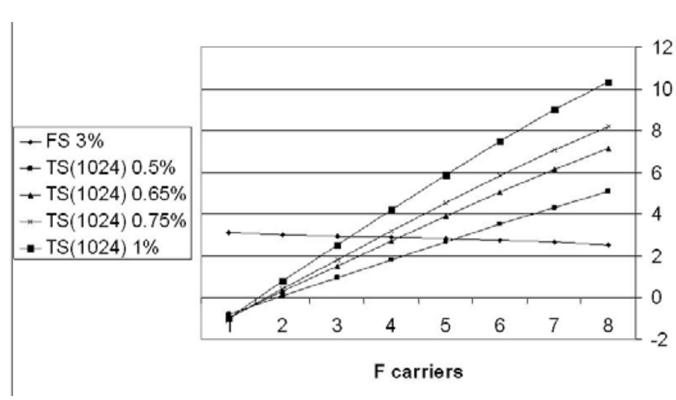

Figure 4. Phase shifts (grad.) due to Doppler Effect by Frequency Shift (FS) simulation and due to Jitter by Time Shift (TS) simulation in OFDMA

IV. FBS SYSTEM

In [5, 6], we proposed a new method called the Frequency Bank Signal (FBS-I) method, which is a modification of the OFDM method combined with MPSK modulation. FBS-I employs a precoding scheme based on the Walsh sequence, to enhance the performance of OFDM-MPSK signaling. In [7, 8], the FBS-I method is extended to allow for the application of the precoding method in MQAM-OFDM signaling. This new method is referd to a the FBS-II or simply the FBS method.

The FBS principles can be explained by the following example. Assume a single carrier MPSK or MQAM modulated signal, with a transmission rate of Rs. In the FBS method, this signal is transmitted on K sub-carriers using the OFDM method. On each sub-signal symbol, the rate will be R_S/K. The frequency difference between carriers will be $1/T_S$, where T_S is the symbol duration on each sub-carrier.

Let us assume the first symbol of first sub-signal x(t) to be:

$$x(t) = A\cos(\omega t + \varphi)$$

which can be presented by I and Q components:

$$I = A\sin\varphi \quad and \quad Q = A\cos\varphi$$

We can transmit I and Q values on K sub-carriers corresponding to one Walsh function pair selected from a K×K Walsh-Hadamard matrix. For example, for one of K = 8, pair: 1 -1 -1 1 -1 1 1 -1 and 1 -1 1 -1 1 -1 1 -1

the following I and Q values will, in reality, be transmitted:

I –I –I I –I I I –I
Q –Q Q –Q Q –Q Q –Q

FBS symbol can be presented as a sum of two projections of two rotating phasors, and .

$$\left.\begin{aligned} I_{i,j} &= A_{i,j}\sin\left(\varphi_{i,j}+\theta_j\right) \\ Q_{i,j} &= A_{i,j}\cos\left(\varphi_{i,j}+\theta_j\right) \end{aligned}\right] \qquad (23),$$

where θ_j is the initial phase, chosen for the j^{th} signal.

Using line l of the Walsh-Hadamard matrix for I_j and line m of this matrix for Q_j, we can present FBS signal for transmitting this symbol as follows:

$$S_{i,j} = \sum_{k=1}^{K}\left\{ I_{i,j}\left(-1\right)^{W_{l,k}}\cos 2\pi f_k t + Q_{i,j}\left(-1\right)^{W_{m,k}}\sin 2\pi f_k t \right\} \quad (24)$$

where $W_{l,k}$ is the k^{th} value in line l of the Walsh-Hadamard matrix, $W_{m,k}$ is the k^{th} value in line m of the Walsh-Hadamard matrix.

For receiving the transmitted sub-signals we must conduct the opposite processing with the aid of the same pair of Walsh functions. The sum of all values in the first line is 8I and the sum of all values in the second line is 8Q. Using the values of I and Q we can find the values of A and φ. On the same k carriers we can transmit k/2 signals without mutual influences due to orthogonality of the Walsh function. For transmitting the same value of information on the same number of sub-carriers in OFDM and in FBS, we must double M in the case of FBS. For example, instead of QPSK in OFDM, we use 16QAM in FBS.

It is recognized that a change from QPSK to 16QAM must include an increase of power by 4dB [15-16]. Power efficiency of OFDM systems can be improved by Peak Factor or Peak to Average Power Ratio (PAPR) reduction [17], even though this method can be implemented without pilot signals. Subsequently, the frequency band becomes twice as narrow. In our case, the frequency band remains at the same frequency since we have made use of the same sub-carriers. In addition, the signal to noise ratio does not change. Actually, the same information is transmitted on K sub-carriers. Essential information (I and Q) is summed using an arithmetical method. However, noise components are summed using a root mean-square method.

Besides, in real systems E_b/N_0 levels decrease due to pilot noise influence on the detected result. However, this decrease does not depend on the pilot rate. Typically, the pilot signal level is greater than the information level by 3 – 9 dB. For correct comparison, we must take the power of all the OFDMA signals (including pilots) and FBS signals to be the same. For pilot rate Rp and pilot signals level in excess of 6dB, we have to increase E_b/N_0 in the case of OFDMA by 1dB if Rp = 1/10 and by 4dB if Rp = 1/2. Consequently, the desired power in OFDM – QPSK and in FBS – 16QAM will be approximately the same. It is correct for conditions without MPP, Doppler Effect and Short Delay.

V. SIMULATION RESULTS

Simulations were accomplished using the MATLAB software package. A typical situation was implemented in order to perform a comparison between OFDMA-QPSK and the FBS-16QAM systems. All channel conditions were the same. Four OFDMA signals were simulated; without pilot signals and with pilot signals at rates 1:10. 1:5 and 1:2. Pilot power was 3dB more than the power of information signals.

A transmitter is situated in the center of the zone. All receivers can move with speeds of 120 km per hour. For the purpose of the simulation, the symbol duration T is assumed to be as large as ten times the maximal delay. The Guard interval is 20% of T. Moving Rx's cause Short Delay and Doppler shift. There were two reflected signals with amplitude 0 – 0.3 of the direct signal amplitude. Frequency, phase, and time recovery in receiver were set not ideal. Signals are transmitted by frames of 100 - 1000 symbols. Each frame starts with one synchronizing symbol.

The main problem is accumulation of phase variations of SD from symbol to symbol. The receiver synchronization system is able to correct the symbol duration and change the frequency after several symbols.

Reflected signals contain three phase shift components: a constant Δφ, which is the same on all carriers; a variable Δφ which is proportional to carrier number, and a phase shift due to short delay. Reflected signals also contain Doppler Shift. In the simulations the receiving signals have some Jitter and phase noise. All conditions vary from frame to frame within the above limits. Detailed simulation conditions and simulation results can be found in [9 – 11]]. Fig. 5 - 7 compares the performance of FBS and OFDMA by simulation results for BER as a function of Eb/N0. Fig. 8 clearly shows that FBS has significant advantages over OFDM even for the case of high pilot rates. For example, for OFDMA requires pilot rate Rp=1/2 and pilot power 3 dB higher that information signals. That is, one should increase the power of transmitting signals by 3 dB and decrease bit rate by 50%.

At the instance of one of OFDMA specialist we carried out additional comparison between OFDMA and FBS.

We have chosen one of results from the FBS presentation (see Fig. 8.)

With the same conditions we implemented convolution code with rate ½ and length 7. We added the case with pilot rate 2/3 (two sub carriers and one pilot with 3 dB enlarged power). Overall power (including pilots) and frequency bands in cases OFDMA and FBS are the same (see Fig. 9).

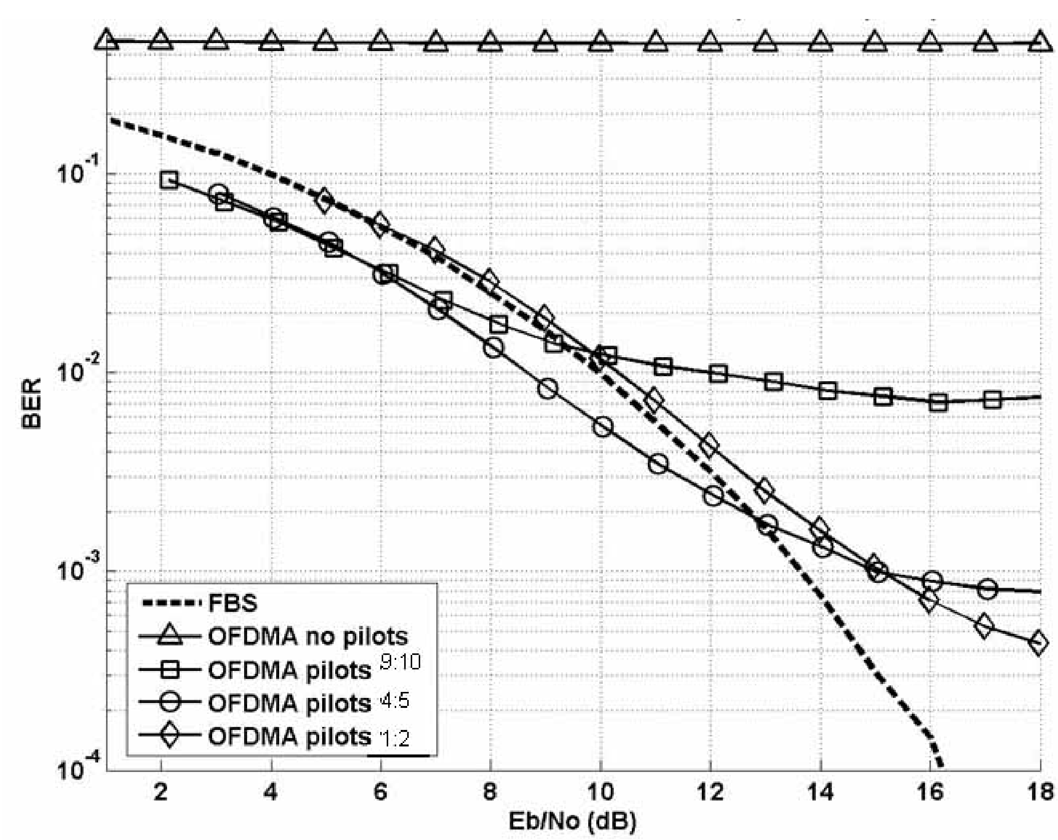

Figure 5. OFDMA and FBS systems after Doppler Effect (1%), MPP and phase noise (the standard deviation of random phase variation was 5°). Pilot/direct signal amplitude ratio in OFDMA is 2.

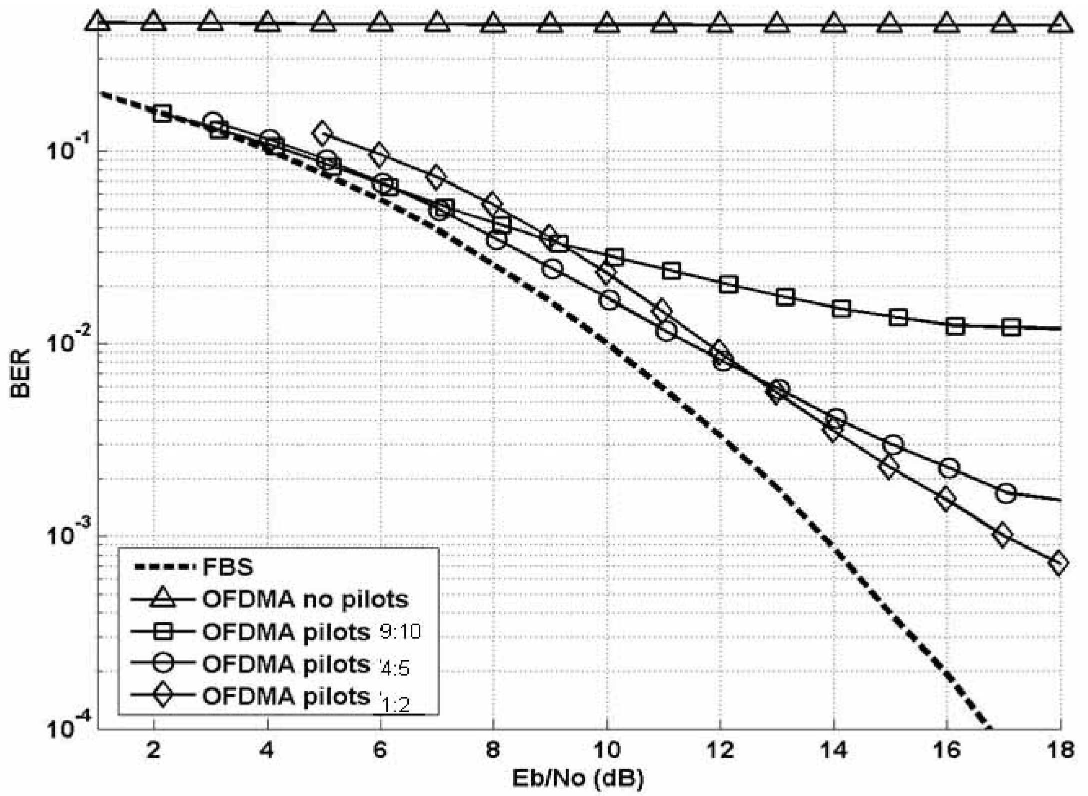

Figure 6. OFDMA and FBS systems after Doppler Effect (1%), MPP, jitter and receiver phase noise influence (mean value is 7.5°). Pilot/direct signal amplitude ratio in OFDMA is 1

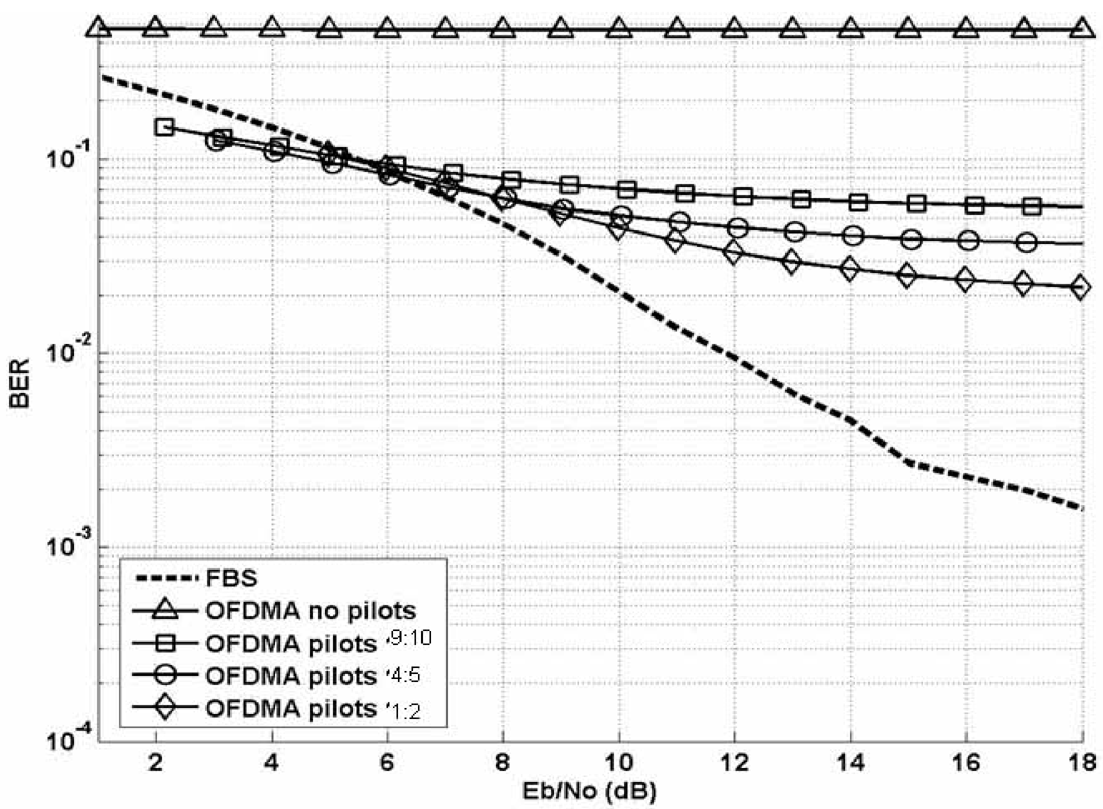

Figure 7. OFDMA and FBS systems after Doppler Effect (2%), MPP, jitter and receiver phase noise influence (mean value is 15°). Pilot/direct signal amplitude ratio in OFDMA is 2.

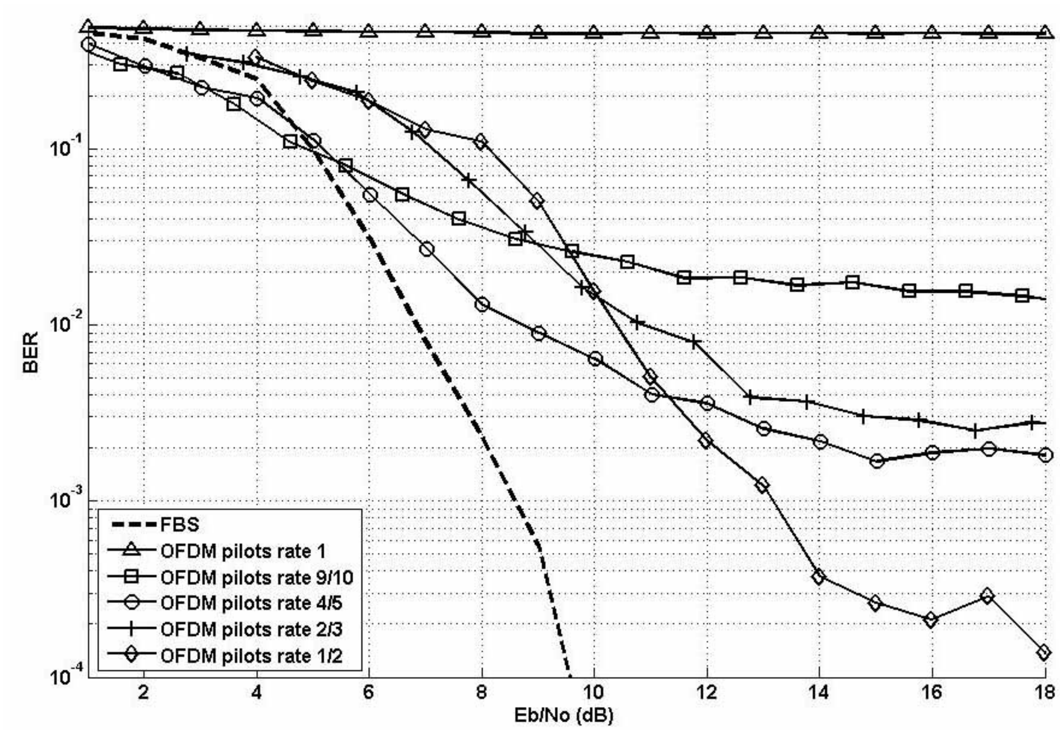

Figure 8. OFDMA and FBS systems with convolution code with rate ½ and length 7, after Doppler Effect (2%), MPP, jitter and receiver phase noise influence (mean value is 15°). Pilot/direct signal amplitude ratio in OFDMA is 2.

VI. CONCLUSION

This simulation results shows that at high levels of Eb/N0 the BER in FBS system decreases as a higher rate, as compare to OFDMA system.

Here we have presented two simulation methods allowing for investigation of Doppler effects in wireless channels. These methods consider orthogonal disturbance, influences of non-ideal transmitter and receiver stability, non-ideal carrier and time clock recovery. The proposed simulation methods are used to carry out a comparative study of the of OFDMA and FBS systems. The high performance of the FBS systems, as shown by the simulations, proves that it is possible to cancel the pilot signals in OFDMA and yet maintain a high performances communication link.

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