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Doppler Effect limiting values in OFDMA cellular systems

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Abstract *- This article puts forward an examination of using OFDMA method like WiMax for future cellular systems. The main goal of investigation and simulation is Doppler Effect influence on orthogonality disturbance in critical but real situations. The simulation results, allow coming to conclusion that Doppler Effect influence on pilot signals leads to BER increasing. The paper proposes Doppler Effect limiting values for pilot signals using and another solutions for decreasing Doppler Effect influences on OFDMA systems. One of possible solutions can be FBS method.*

Keywords: *OFDMA, Cellular, Doppler, Multipath, Pilot, FBS*

1 Introduction

Successful implementation of the OFDMA method [1-4] in some systems such as in DAB, DVB-T, DVB-H, WiMax and WiFi have in the past raised expectations that a new cellular system could be based on this method [5,6]. The main purpose of this article is to bear out the enormous difficulties with which OFDMA is implemented in cellular systems. Problems associated with mobile communication systems (TDMA, CDMA and OFDMA) such as Multipath Propagation (MPP) and Doppler Effect (DE) have been increased in recent times. These problems are more evident with the increase of frequency to up to 10 GHz, and vehicle speed to up to 300 km/h. To date, these problems are treated using channel estimations, pilot signal transmission and by effective Error Correction Codes (ECC). However, these methods significantly reduce system spectral efficiency, sometimes up to 50%. The high level of reflected signals found in any modern big city are a main reason for the use of increased symbol duration, which, as a result, makes the system more sensitive to DE. In the case shown below, DE causes orthogonality deterioration. Orthogonality deterioration, in turn, leads to the appearance of Inter Carrier Interference (ICI), since the phase of Pilot signals is dependent not only on channel conditions but also on neighboring carrier phases. Therefore, pilot signals do not function as it is expected. Moreover, in order to reduce the effect of noise on pilot signals, they are transmitted at high powers so that the power of the information signals is reduced in order to maintain the same average output power, and therefore BER increases.

THE INFLUENCE OF DOPPLER EFFCTS ON OFDMA SYSTEMS

It is well-known, that conditions for orthogonality of OFDMA are as follows:

- $\Delta f \cdot T = 1$, where Δf is subcarrier spacing and T is a symbol duration;
- The number of periods in the symbol of each subcarrier must be a whole number

In the case of mobile communication, the main influence of DE is in increasing or decreasing the distance between Tx and Rx during T due to the motion of the car (the start and end times of the symbol correspond to different distances), which causes a change in the receiving symbol duration by factor k_d

$$k_d = 1 + \frac{V}{c}\cos\varphi,$$

where V is the velocity of Rx relative to Tx, c is the light velocity and φ is the angle between velocity vectors of Tx and Rx. Therefore, T and carrier frequency f are changed by k_d

$$f \to f \cdot k_d \quad and \quad T \to T / k_d$$

The frequency spacing between two neighboring carriers with and without DE is

$$(f_{k+i+1} - f_{k+i})T = [(f_{i+1} - f_i) \cdot k_d] \cdot T[/ k_d] = 1 \qquad (1)$$

Therefore, DE does not affect orthogonality between sub carriers. However, it is true only in the case where the Rx uses a faultless synchronization system. In reality, the receiver does not change its symbol time and FFT parameters instantly due to sluggishness of its symbol synchronization system. For this reason, we can assume that in the presence of DE, T is constant for the duration of a symbol. In this case, we have:

- An additional phase shift $\Delta\varphi_{delay}$, hereafter termed Short Delay (SD) caused by incompatibility between the symbol time of arrival and the values of T due to lack of a fast response of a synchronization system in Rx. One can calculate SD (in degrees) by

$$SD \approx \frac{360^0 L}{\lambda} \qquad (2),$$

where L is a car shift during symbol duration T.

SD is accumulated after each symbol. The subcarrier spacing Δf changes under constant decoding duration T that causes ICI due to orthogonality deterioration. Let us take one carrier and make FFT without DE influence (see Fig.1a). Spectral components on all adjacent carriers are absent. In the case of DE influence, spectral components on adjacent carriers appear. (See Fig 1b)

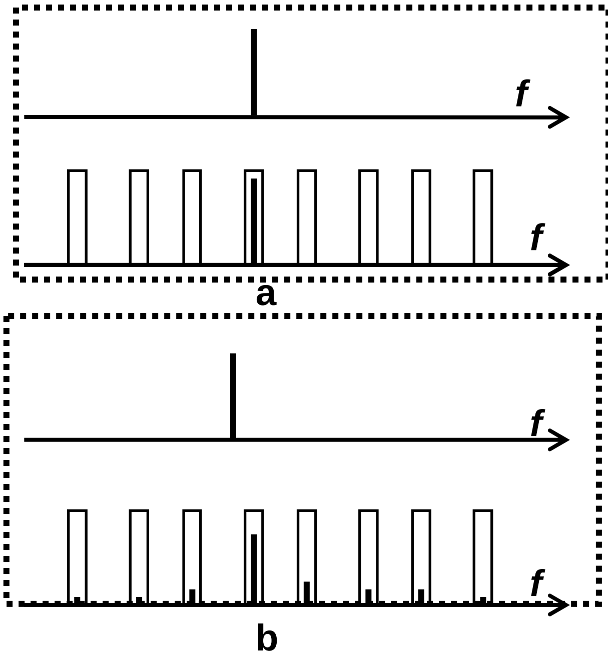


Figure 1. FFT result in the case without DE (a) and with DE (b)

- The number of periods in the symbol of each sub carrier is not a whole number due to DE influence, which is an additional factor for the appearance of ICI.
- ICI causes Pilot signal phase and amplitude fluctuations due to phase variations in the information carriers.

Many investigations do not draw attention to orthogonality deterioration. For these simulation problems one can use the well-known Doppler Filter, which provides phase changing only and ignores frequency changing. Frequency changing alone, under constant symbol duration, can cause orthogonality deterioration. The DE simulation problem is that it is difficult to simulate very small frequency variations. The OFDM modulator houses the IFFT processor. In addition, the OFDM spectrum does not have intermediate points between carriers. Therefore, it is impossible to change the frequency in sections that are smaller than the frequency distance between carriers. Special methods of calculation are used to solve this problem [7]. A discrete Fourier transform is defined by:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi j}{N}kn}, \qquad k = 0,\ldots,N-1. \qquad (3)$$

Inverse Discrete Fourier transform is defined by:

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{\frac{2\pi j}{N}kn}, \qquad n = 0,\ldots,N-1. \qquad (4)$$

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

$$X_k = X(\omega_k) = \sum_{n=0}^{N-1} x(t_n) e^{-j\omega_k t_n}, \quad k = 0,\ldots,N-1 \qquad (5)$$

$$x_n = x(t_n) = \frac{1}{N}\sum_{k=0}^{N-1} X(\omega_k) e^{j\omega_k t_n}, \quad n = 0,\ldots,N-1. \qquad (6)$$

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). Consequently, the new signal is

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

$$\tilde{x}_n = x(t_n) y(t_n) = x_n y_n, \qquad n = 0,\ldots,N-1 \qquad (7)$$

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

Thus, the new spectral components of the signal effected by the Doppler Shift, can be computed according to the following formula:

$$\tilde{X}_k = X_k\left(1 + \pi j \frac{N-1}{N}\delta\right) + \\ + \frac{2\pi j\delta}{N}\sum_{i=1}^{N-1}\frac{X_{k-i}}{1 - e^{-\frac{2\pi j}{N}i}}. \quad (8)$$

Therefore, for known $\Delta\omega$ or δ, we can compute the new spectrum by (8) [7]. The frequency stuffing method was implemented in the simulations described below [7]. Both methods of calculation and stuffing gave the identical results.

3. OFDMA SIMULATION MODEL AND RESULTS

We have chosen three possible cases of DE influence in OFDMA systems where symbol duration T = 0.1 ms (Δf = 10 kHz), central frequency *is* f and car velocity is V (see table 1).

Table 1

	F (GHz)	V (km/h)	D (%)	Short Delay SD (deg)
Weak DE	1	120	1	+/- 4
Mean DE	2.4	120	2.4	+/- 9.6
Strong DE	2.4	300	6	+/- 24

The main parameter of DE is the ratio D in percentage of the carrier frequency shift to Δf. The following model is used for clarification of DE influence on orthogonality deterioration. Basic FFT size is 64 points, number of signals is seven, each signal consists of eight carriers, carrier distribution the same as PUPS mode of standard 802.16e, modulation method is QPSK, symbol duration is 0.1 ms, guard interval is 0.1T, sign of DE at signals is alternate (for example + - + - + - + -), pilot signals power to information signal power ratio (R_{ps}) is 1 or 4, relative number of pilot signals (pilot ratio) is 6/8 or 4/16 (see fig. 2)

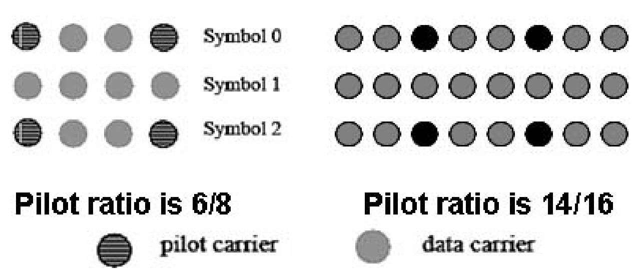


Figure 2. Pilot signal distribution.

In the case of R_{ps} = 4, the power of signals and pilots decreases by 2.4 dB (pilot ratio 6/8) and by 1.4 db (pilot ratio 14/16).The simulation results presented in the two figures below include only one of the possible impairments, namely DE, without an error correction code (fig 3) and with a convolution , rate 1/2 (fig 4).

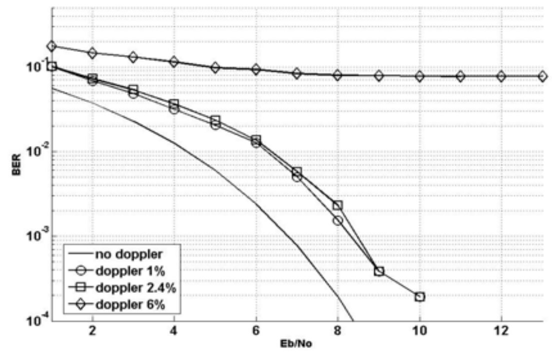


Figure 3. BER versus E_b/N_0 withot convolutional code

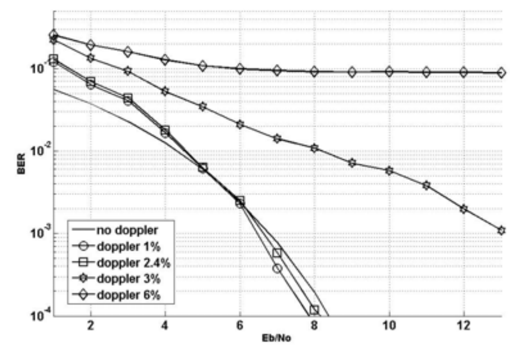
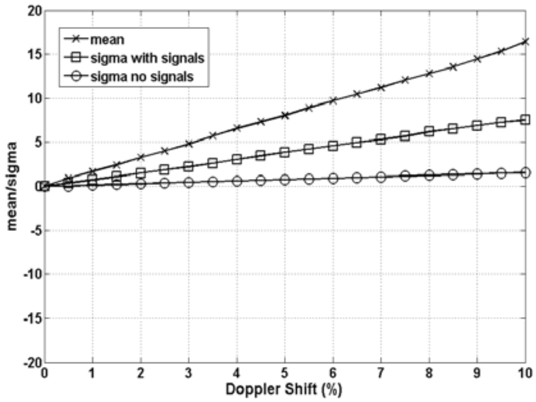
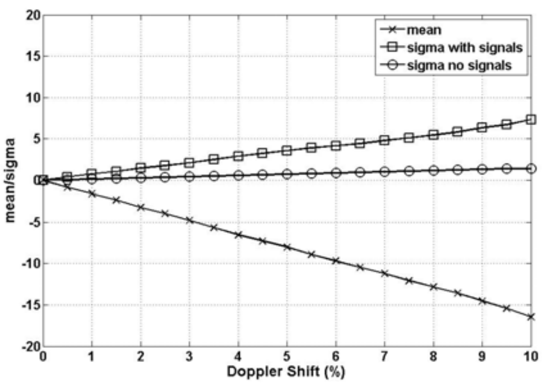


Figure 4. BER versus E_b/N_0 with convolutional code (rate1/2)

The figures show BER curves versus E_b/N_0 with various DE values and without DE (unbroken curve) in the case of (R_{ps} = 4 and pilot ratio 14/16). Taking into account that BER values of all signals for each DE are the same, they are shown as one curve. To clarify the influence of orthgonality disturbance, pilot signals phase shift dispersion was calculated. In this case the phase shift is the difference between the pilot signal phase after FFT and the pilot signal phase after SD before FFT. In other words, the pilots phase shift reflects phase changing due to frequency changing. The simulation was made for positive and negative DE and for pilot signals with or without the presence of information signals. This means that there is no influence on orthogonality disturbance in the case where the information signal is absent. In both cases: the positive DE (Fig. 5a) and negative DE (Fig. 5b) phase shift mean values correspond to approaching phase shift directions. Actually, there are no accidental phase shifts in the pilot signals. On Fig 5 one can see a standard deviation of phase shift distribution (σ) versus DE %.



a



b

Figure 5 Pilot signal phase shift versus DE

This "accidental" change in phase is equivalent to the addition of noise with power σ^2. When comparing the Gaussian channel without DE, the results received were of phase standard deviation versus E_b/N_0, shown in Fig 6 (unbroken curve). In addition, this figure illustrates the minimum phase shift value for 1% of maximal values.

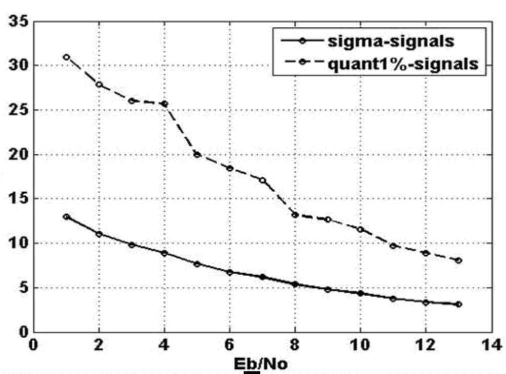


Figure 6. Information signal phase shift due to noise influence.

When comparing between Fig 5 and Fig. 6 we see that commencing from 3% DE essentially bears influence on BER. If D = 6% the noise power is doubled. In other words, even without noise BER will be worse than 10^{-3} - 10^{-4}. The deterioration in orthogonality causes a change in pilot signals in addition to a change in carrier phase. The simulation shows that the phase shift on all carriers and the pilot phase after interpolation do not match (in this case the correction by pilots is useless). Moreover, when DE is more than 3% and when the symbol serial number within the frame is more than seven the above phase shifts are even at opposite ends of each other. This situation leads to errors even without noise. In fact, BER will be much worse due to the influence of impairments such as multi path propagation, jitter, LO phase noise, etc. All of these influences cannot be corrected by the use of pilot signals due to orthogonality deterioration. Taking into account the advantages of OFDMA such as the minor influence of reflection signals and good possible throughput, the opportunity may arise for using the proposed version of the OFDMA system with no need to implement pilot signals. One possible idea is returning to Differential MPSK method [12], like in DAB system. Other methods may be based on estimation signals inserted at the beginning of a frame [8, 9] or methods, such as in FBS.

4 Frequency Bank Signal (FBS)

To deal with the above-mentioned problem, authors proposed a novel method called the Frequency Bank Signal (FBS) [7, 10, 11, 13]. The FBS principles can be explaned by the following example (for a detailed description of the FBS method see FBS site in [13]).
Assuming a single carrier MPSK or MQAM modulated signal, with symbol rate R_S, is transmitted on K sub-carriers using the OFDM method. As a result, for each carrier, 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 the first sub-signal x(t) to be:

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

This signal consists of orthogonal components I and Q, as follows:

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

The I and Q components are transmitted on K sub-carriers corresponding to one Walsh function pair selected from a Walsh-Hadamard matrix. For example, for one of K = 8 pairs:

1 -1 -1 1 -1 1 1 -1 and
1 -1 1 -1 1 -1 1 -1

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

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

FBS symbol can be presented as the sum of two following orthogonal components:

$$\left.\begin{aligned} I_{i,j} &= A_{i,j}\sin\left(\varphi_{i,j}+\theta_j\right) \\ Q_{i,j} &= A_{i,j}\cos\left(\varphi_{i,j}+\theta_j\right) \end{aligned}\right] \qquad (9),$$

where θ_j is the initial phase, chosen for the j^{th} signal.
Using the row l of the Walsh-Hadamard matrix for I_j and the row m of the Walsh-Hadamard matrix for Q_j, we can present FBS signal for transmitting this symbol as follows:

$$S_{i,j} = \sum_{k=1}^{K} \left\{ \begin{aligned} & I_{i,j}\left(-1\right)^{W_{l,k}} \cos 2\pi f_k t + \\ & Q_{i,j}\left(-1\right)^{W_{m,k}} \sin 2\pi f_k t \end{aligned} \right\} \quad (10)$$

where $W_{l,k}$ is the k^{th} value in row l and $W_{m,k}$ is the k^{th} value in row m of the Walsh-Hadamard matrix.
In the receiver the reverse process using the same pair of Walsh functions carried out. The sum of all values in the first row is 8I and the sum of all values in the second line is 8Q. Using the I and Q values, we can find the values of amplitude A and phase φ. On the same K carriers $K/2$ signals can be transmitted 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, the M value must be doubled, e.g. using 16QAM in FBS instead of QPSK in OFDM.

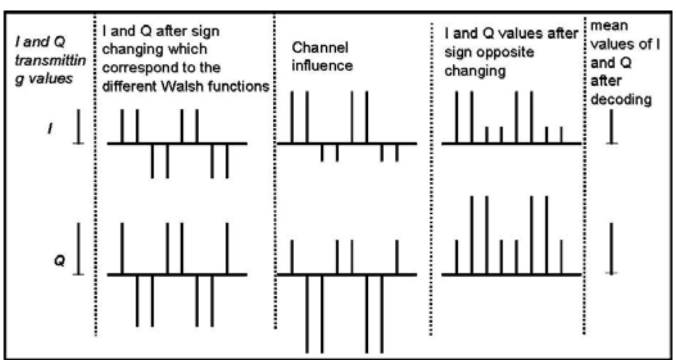


Figure 7. Channel influence on I and Q components in FBS

The main goal of FBS is to cancel all channel influence during decoding process, as illustrated in Fig. 7

5 OFDMA and FBS SIMULATION RESULTS

Comparison between OFDMA and FBS was carried out. One of the results from the FBS presentation [12] is shown here in Fig. 8.
A convolution code with rate ½ and length 7 was implemented in compared systems, under the same conditions and various OFDMA pilot ratios 1/2, 2/3,4/5 and 9/10 (numerator is the number of information carriers, and denominator is a total number of carriers, including pilots with 3 dB enlarged power). These results correspond to Doppler Effect Mean value (row 2 in table 1) and the influence of impairments such as multi path propagation, jitter and LO phase noise. Overall powers (including pilots) and frequency bands in both cases (OFDMA and FBS) are the same.

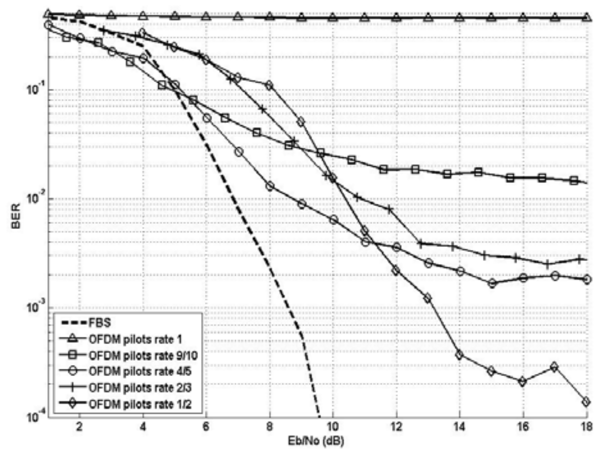


Figure 8. Comparison between OFDMA and FBS in moving conditions.

6 CONCLUSIONS

In comparison to the OFDM method the FBS method allows transmission of the same quantity of information in the same frequency band and with the same power. The main FBS advantages are:

- A significant decrease of the Doppler shift effects, as well as the time delays and multi-paths influences.
- FBS removes the need for conducting tests or using pilot signals and/or equalizing processes.,
- Eliminating prolonged selective fading by means of randomly shifting sub-carriers frequencies.
- The FBS method can be implemented in different wireless communication systems, using various modulation techniques.[3,8]
- FBS allows to keep the performances even in communication with very high speed vehicles [4, 13].

All these advantages are achieved without any extra cost in frequency band and without an increase in the system power. Implementation of the FBS system will result in a significant increase throughput affording very fast internet also.
The main conclusion concerning OFDMA is the following: increasing pilot's number more than 4/5 spoils BER value greatly.

The presented results show that it is almost impossible to develop an OFDMA cellular system based on the principle of pilot signals. This is mainly because of orthogonality disturbance due to Doppler Effect influence. 3% Doppler Shift is a real situation and 3% Doppler Shift is also a real situation.

Under these conditions, pilot signals do not improve the decoding process and may even lead to deterioration in the decoding process.

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