Investigation of the Impact of Pilot Signals on the Performance of OFDMA Systems

M. HARIDIM, M. BANK, V.VULFIN

***Abstract*—**We introduce a new simulation method for OFDMA systems. The proposed method allows for the study of the impact of deterioration of subcarriers orthogonality, non-ideal synchronization and the phase noise of local oscillators. Using the proposed simulation method we have studied the impact of pilot signals on OFDMA performance. Results are compared to the performance of FBS systems which are a modified version of OFDMA systems using no pilot signals.

***Keywords*—**OFDMA, pilots, Doppler, FBS, simulation.

I. INTRODUCTION

The Orthogonal Frequency Division Multiplexing technology (OFDM) systems are now 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 requirement for achieving a good agreement between simulations and the real situation has been always a challengeable problem. In the field of the mobile communications, this problem is becoming more complicated with the current tendency of increasing the carrier frequencies, increasing the moving speed, increasing the transmitting bite rate, and using highly compressed signals, which are more vulnerable to errors [1-4]. Compared to single carrier systems, OFDMA systems suffer from an additional problem, namely the orthogonality deterioration which can lead to Inter Carrier Interference (ICI) effects. Currently, the main method to combat the aforementioned impairments is use of pilot signals [5-7]. In the presence of ICI, the phase of pilot signals is influenced also by neighbouring carriers' phases, in addition to impairments caused by channel conditions. Pilot signals also decrease the signal to noise ratio (S/N). Under these situations the pilot signals can not fulfill their task, i.e. carrier frequency offset estimation, channel estimation, and frame detection. Simulations of the Doppler Effect involve some difficulties associated with the achievable frequency resolution. The OFDM spectrum produced by the IFFT processor in the OFDM modulator does not include intermediate points between carriers. Therefore, Doppler frequency changes smaller than the carriers' frequency spacing are not resolvable. To solve this problem, we propose a stuffing based simulation method with enhanced resolution so that it allows checking the influence of different impairments on OFDMA signal components including the pilots. Moreover, this method allows investigating the impact of pilot signals impairments on the information signals decoding process.Doppler effects are not restricted only to frequency shift, and may influence the receiver's synchronization system and result in random symbol delays or forestalling and additional errors due to jitter and phase noise. In this work we will focus on the frequency shift only.

Manuscript received November 1, 2007, Revised version received December 28, 2007
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II. EXPERIMENTAL EVIDENCE FOR DE

Below, we'll present experimental results for DVD-T signals subjected to the DE.Experiments were performed in collaboration with the Measurement Laboratory of the Israeli Communication Co. - Bezeq (Fig 1). The Bezeq mobile laboratory allows measurements of electromagnetic field strength and post decoding (Viterbi codes) Bit Error Rate (BER). In addition, the equipment enables the observation of image quality including synchronization disturbances.

Figure 1. Apparatus for measurements under moving conditions.

Figure 2 shows the mean value as well as the standard deviation of carrier phase variations corresponding to the relative frequency change $\Delta f/(f_i - f_{i-1})$.

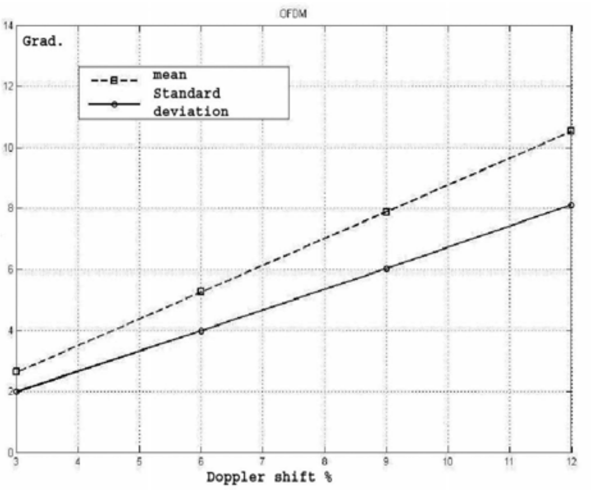

Figure 2. Phase variations due to Doppler Shift

It is interesting to note that the standard deviation in Fig. 2, is of the same order of magnitude as the mean values implying that there is no correlation between the phase variations of different carriers (including pilots), In effect, these random variations of the pilot signal phase result in severe deterioration of the signal-to-noise ratio, independent of the amplitude of the pilot signal.

As shown in Fig. 3 the section of road chosen for the experiments, is quite a straight path. Traffic during the experiments was not heavy.

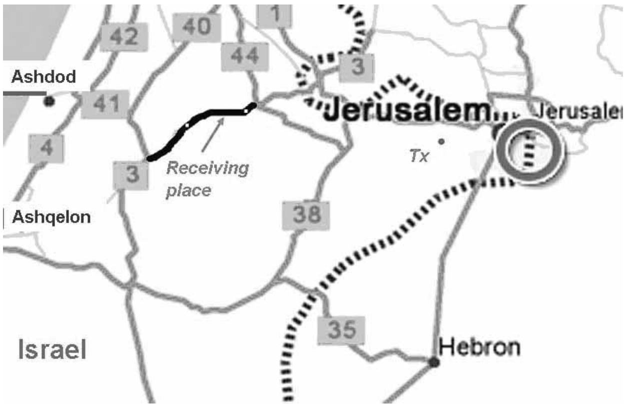

Figure 3. Place of measurements.

Two sets of measurements were accomplished for two speeds: (A) V=40km/h, (B) V=20 km/h.

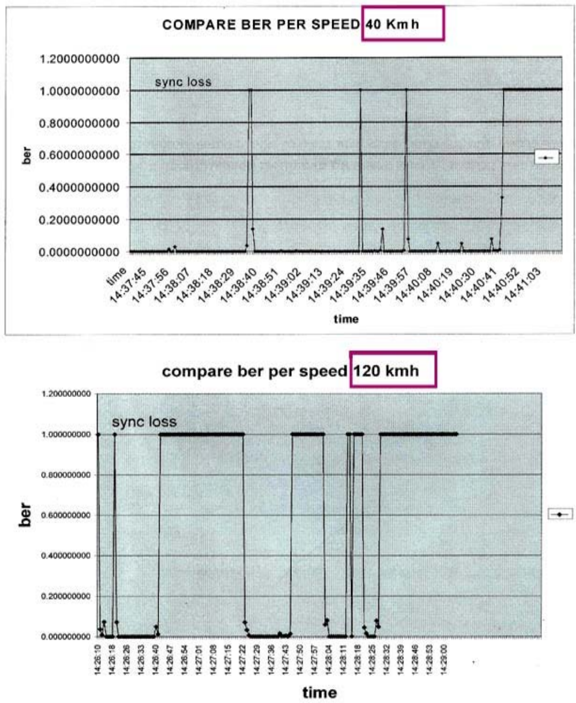

Figure 4. Measurement results: A- high speed, B-low speed

In both cases, the electromagnetic field strength was higher than the receiver sensitivity. The results clearly show that the number of synchronization losses increases proportionally with the vehicle speed because of DE. In addition, because of disturbances to TV reception it was impossible to view television for speeds approaching 120 km/h for over 50% of the traveling time.

III. THE STUFFING BASED SIMULATION METHOD

OFDM modulation starts with constructing an orthogonal spectrum which consists of L complex components, where L is an integer power of 2. For L = 4 (see Fig 5.A).

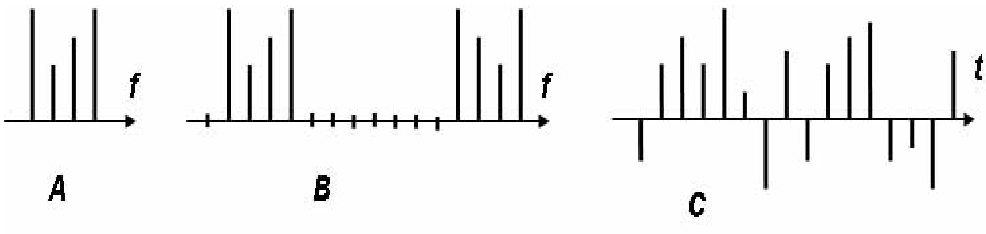

Figure 5. OFDMA Matlab simulation process.

The OFDM signal in the time domain is a real signal. So its spectrum must be complex conjugate where the symmetry is in the muddle of the spectrum. It's also has a DC component that is the first sample. But we note (Fig1.A) the spectrum isn't complex conjugate and there is no DC component. In order to use the Matlab IFFT command to get a real signal in time domain we must:

- Include a DC component (is set to zero) in the beginning of the spectrum
- Include complex conjugate samples

It should be noted that the Matlab IFFT function returns the discrete Fourier transform (DFT) of a vector, computed with a fast Fourier transform (FFT) algorithm. So if we use the Matlab's IFFT function for a sequence where number of samples is 2m (where m is an integer) the time computation of the algorithm should be faster if we compare it to the case where the number of samples isn't 2m. We checked time difference in computation for two different cases where *m* has an integer-value or a non-integer value. The number of samples in frequency domain is chosen to be 128 or 140 and the time difference was about 10ms (the computation where done by Intel(R) Core(TM)2 CPU 6400 @2.13 GHz, 1 GB of RAM). It's possible to get 2m (m integer) spectrum samples but we need to make a zero padding in the middle of the spectrum. Zero padding in the frequency domain will cause an interpolation in time domain. If the ratio q between number of zeros we padded and the number of samples in the original spectrum (included DC and complex conjugate samples) isn't an integer number we won't get the correct time domain signal. In other words, in order to allow for correct reconstruction of the time domain signal, we must choose an integer ratio q. We should also multiply the amplitude of the time domain signal by factor q+1 in order to preserve the original signal's amplitude. So, for simulation purposes we should use an algorithm with a little slower computation time but then we get more accurate signals in time domain.

To meet these conditions we built a spectrum with range N = 4L+2 with the following structure: 0, [L complex numbers], [(2L + 1)*q zeroes], [L conjugate numbers] (see Fig. 5B). After IFFT we will get N real samples (see Fig. 5C). Now we will expand our method of simulation. Our proposed stuffing simulation method consists of inserting S zeroes after each spectral component of the signal (see Fig. 6). The number of inserted zeros must be N*p where p is some integer number. This will result in p copies of the original signal in the time domain.

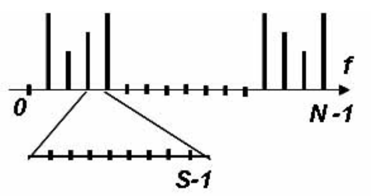

Figure 6. Stuffing process in OFDM simulation.

After IFFT we will get N*(q + 1)*(p + 1) real samples (time domain signal). In order to maintain the original signal length, we will transmit only first N samples. We need to multiply the amplitude of the time domain signal by the p+1 factor in order to get the correct amplitude.

Now we can introduce frequency shifts corresponding to the Doppler Effects with resolution 1/S. Since the receiver performs FFT with the original (uninfluenced) frequencies, the output signal reflects all influences of the Doppler Effect including ICI. Our simulation results are identical to those achieved by mathematical calculations.

The Matlab code in this stage will be:

```
M = 16 ; %M = 2 – BPSK; M = 4 – QPSK; M = 16 – 16QAM

L = 4 ;   % Number of complex components

x1 = randint( L , 1 , M ) ; % raffle decimal numbers

X1 = pskmod( x1 , M ) ; % for BPSK and QPSK ; One Sided Spectrum

X2 = [ 0 ; X1 ; fliplr( conj( X1' ) )'] ;% Two Sided Spectrum

x2 = ifft( X2 ) ; % Time Domain

q = 1 ; % Number of integer multiplies of 2L+1

X3 = [ 0 ; X1 ; zeros( ( ( 2 * L + 1 ) * q ) , 1 ) ; fliplr( conj( X1' ) )' ] ;  % Two sided spectrum padded in

% the middle

x3 = ( q + 1 ) * ifft( X3 ) ; % Time Domain

p = 1 ;  % Number of integer multiplies of 2L+1 padded between the samples

X4 = conj( reshape( [ X3 , zeros( length( X3 ), p ) ]' , ( p + 1 ) * length( X3 )  , 1 ) ) ; % Two sided

% spectrum padded in the middle with stuffing

x4 = ( q + 1 ) * ( p + 1 ) * ifft( X4 ) ;  % Time Domain
```

IV. BASE-BAND SIMULATIONS USING THE STUFFING METHOD

In the receiver, a bandpass OFDMA signal corresponding to carrier k, without Guard interval, can be written as:

$$s_k(t) = A_k \sin[2\pi(n+k)\frac{1}{T}t + \varphi_k] \qquad (1)$$

where: - n* 1/T is the first carrier frequency

k is carrier number inside the OFDMA signal, amplitude A_k and phase φ_k depend on transmitting information.

Let us examine these problems by means of an example.

Distance variations caused by the Doppler effects lead to a variation of the received symbol duration T:

$$f \to f \cdot k_d \quad and \qquad T \to \ T/k_d$$
$$where \ \ k_d = 1 + \frac{V}{C}\cos\varphi, \qquad (2)$$

Where φ is the angel between the moving direction and the Tx – Rx direction. In the receiver, on the other hand, T is kept unchanged due to symbol synchronization system. Thus

$$\Delta f_k = \frac{1}{T}(n+k)k_d - \frac{1}{T}(n+k) =$$
$$\frac{1}{T}(n+k)(k_d - 1)$$
$$\Delta f_{k+m} = \frac{1}{T}(n+k+m)(k_d - 1) =$$
$$\frac{1}{T}n(k_d - 1) + \frac{1}{T}(n+k)(k_d - 1) \qquad (3)$$

Therefore, the Doppler frequency shift consists of two parts:

A constant part common for all frequencies $n(k_d-1)/T$, and a small part proportional to carrier number k.

$$\frac{1}{T}(k+m)(k_d - 1)$$

For example:

$T = 100\ \mu s = 10^{-4}$, $\Delta f = 1/T = 10^{4}$, $f = 1GHz$,

$n = 10^{9}/10^{4} = 10^{5}$, $k_{d,\cos\varphi=1} = 1 + \frac{1/30}{300000} = 1 + 10^{-7}$

$\Delta f_1 = 10^{4} \cdot 10^{5} \cdot 10^{-7} = 100.000\ Hz$

$\Delta f_2 = 10^{4} \cdot (10^{5} + 1) \cdot 10^{-7} = 100.001\ Hz$

Apparently, the frequency shift on all carriers (Δf_d) and the corresponding phase shifts are approximately the same. That is, despite the fact that Doppler Shift is proportional to carrier frequency, we can make frequency shift in base band simulation by the same value.

Our simulations are based on the following algorithm and parameters.

- The signal must be built by 50 frames with 100 symbols a piece;
- Number of different signals: 4;
- Number of information carriers for all signals: 8;
- FFT dimension (N/2): 16;
- Zeros stuffing number: 128;
- AGC control signal is calculated by 9 samples;
- First signal in each frame is test signal with in 4 times bigger then direct signal amplitude;
- Pilot/direct Signal Amplitude Ratio in OFDMA : 2 or 1;

VI. SIMULATIONS RESULTS.

Fig.'s 7 – 10 show some results of stuffing method simulations. We checked the influence of the Doppler effects on the components phase shift. The value of Doppler shift is calculated as the ratio between the frequency change and the carriers frequency spacing without guard intervals, at the decoder input. In Fig. 3 one can see an OFDM signal with no pilots, in which all carriers change in the same direction. A shown, ….

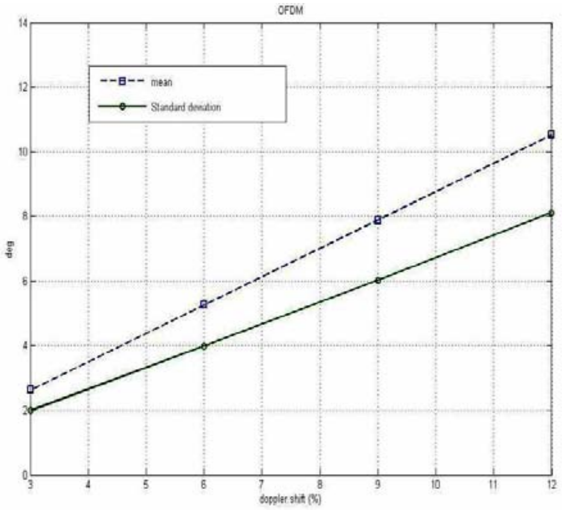

Figure 7. Doppler Effect influence on OFDM signal phases.

Fig. 8 shows an OFDMA signal with no pilots, in which the frequency shifts are random.

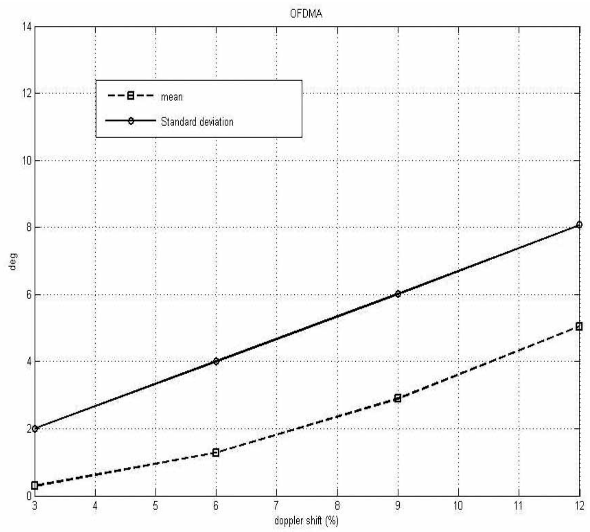

Figure 8. Doppler Effect influence on OFDMA signal phases

OFDMA has a lower phase shift mean value compared to OFDM. But, their standard deviation is the same. The phase shift standard deviation is more important as it is equivalent to noise level. In Fig. 9, one can see the influence of Doppler effects on pilot signals in OFDM signals, where amplitude of pilot signals is 6dB higher than information signals amplitudes.

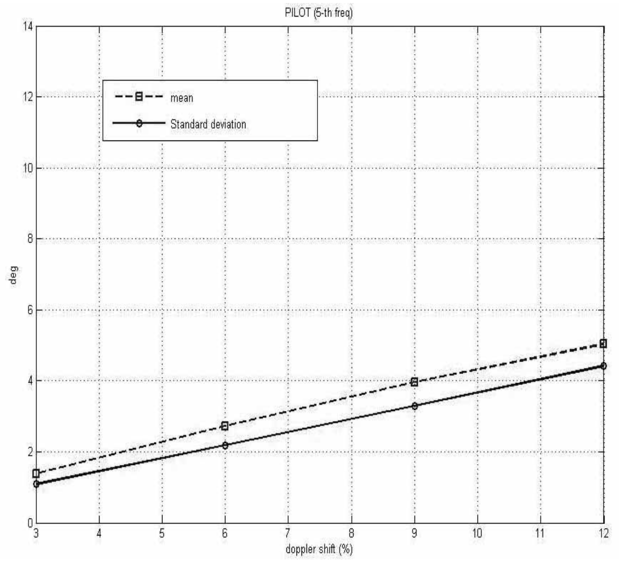

Figure 9. Doppler Effect influence on OFDMA pilot signal phases.

Strong pilot signals indeed lead to decreased values of phase variations, but they intensify the influence of these phase variations on neighboring information carriers phases (see Fig. 6)

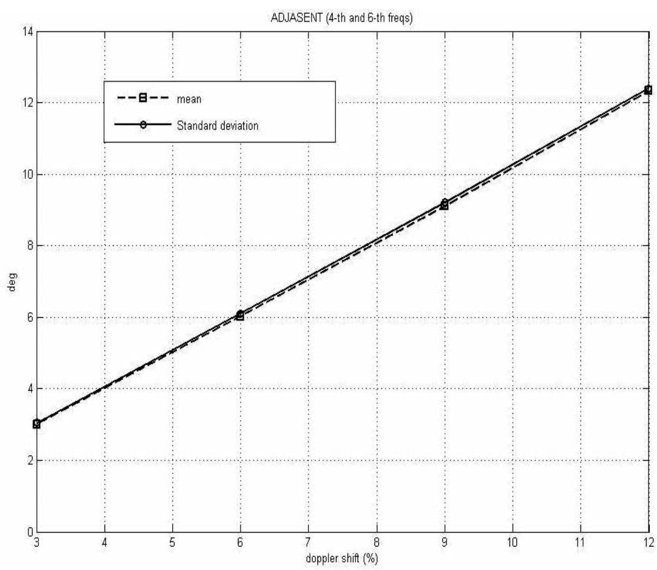

Figure 10. Pilot signal phases changing influence on information carrier's phases.

The main goal of using strong pilot signals is to combat signal to noise ratio deterioration due to use of pilot signals. However, as it is shown by the simulation results in Fig. 10, Strong pilot signals have a negative impact on impairments stemming from Doppler effects.

This is only one example which shows that in case of very difficult situations, pilot signals do not improve the situation and make things worse. Each pilot signal is used as a reference for decoding few symbols. So, if this reference is impaired few symbols will suffer. In such cases, it may be beneficial to implement an OFDMA system without pilot signals, for example FBS system.

VI. THE FBS SYSTEM

In [8 – 12], the authors have proposed a novel method called the Frequency Bank Signal (FBS). The FBS principles can be explained by the following example (for a detailed description of the FBS method see [12]). Assuming a single carrier MPSK or MQAM modulated signal, which transmits at the symbol rate RS, one can transmit this signal on K sub-carriers using the OFDM method. As a result, for each carrier, the rate will be RS/K. The frequency difference between carriers will be 1/TS, where TS is the symbol duration on each sub-carrier. Let us assume the first symbol of the first sub-signal x(t) to be:

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

We can break down this signal by orthogonal components I and Q, as follows:

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

We can transmit I and Q values on K sub-carriers corresponding to one Walsh function pair selected from a 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:

$$\left.\begin{aligned} I_{i,j} &= A_{i,j}\sin\left(\varphi_{i,j} + \theta_j\right) \\ Q_{i,j} &= A_{i,j}\cos\left(\varphi_{i,j} + \theta_j\right) \end{aligned}\right] \qquad (4),$$

where θj is the initial phase, chosen for the jth signal.

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

$$S_{i,j} = \sum_{k=1}^{K} \left\{ \begin{array}{l} I_{i,j} \left(-1\right)^{W_{l,k}} \cos 2\pi f_k t + \\ Q_{i,j} \left(-1\right)^{W_{m,k}} \sin 2\pi f_k t \end{array} \right\} \quad (5)$$

where Wl,k is the kth value in line l of the Walsh-Hadamard matrix, Wm,k is the kth value in line m of the Walsh-Hadamard matrix.

In the receiver, we must conduct the opposite processing using 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 I and Q values, 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-II, e.g. by using 16QAM in FBS instead of QPSK in OFDM.

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

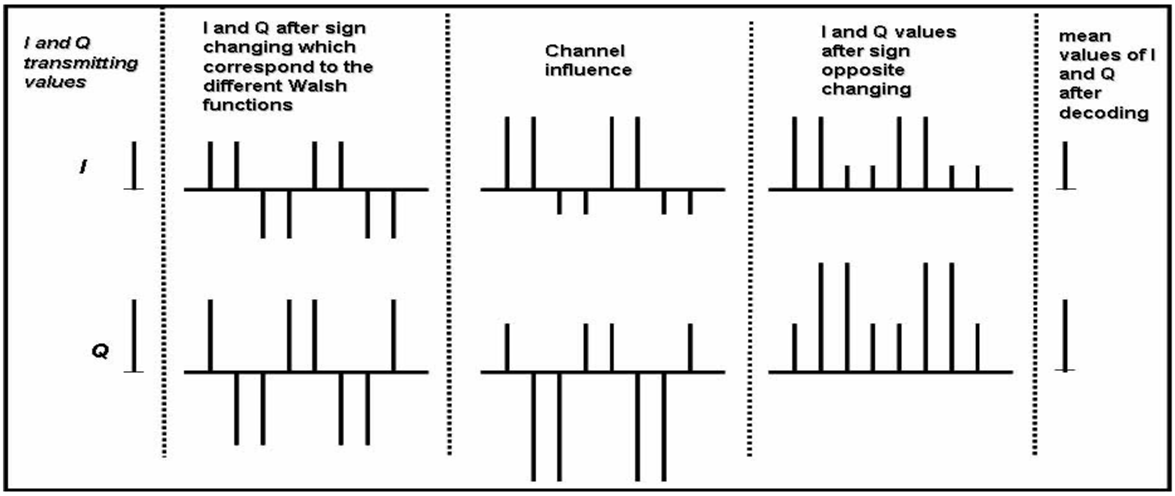

Figure 7. Channel influence on I and Q components in FBS.

VII. CONCLUSIONS

We have used a new simulation method allowing for investigation of the impact of Doppler effects in the OFDM systems. It is shown that Pilot signals used in OFDM systems can result in degradation of the system performance in certain situations. A modified version of the OFDMA method, called the FBS method, is presented. is propose. It is shown that the FBS method, using no pilot signals, is capable of combating the deterioration of the orthogonality between subcarriers. Comparison between the FBS and the ordinary OFDM, show that under certain practical situations, the former method gives superior performance over the latted one. is also shown that the need for pilot signals can be removed by the novel FBS method, which is based on transmitting the same information on

some carriers with possibility to compensate channel influence without bandwidth widening. The main advantage of FBS is the enhanced system throughput.

Acknowledgements

The authors would like to thank Boris Hill for developing and carrying out numerous Matlab simulations and Dr. Miriam Bank for the mathematical examination of the proposed simulation method.

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