New Solution for Reducing Doppler Shift in the MB-OFDM System Over High Mobility Multipath Channel for V&I Communication

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Abstract: The MB-OFDM has been proposed as a good candidate to ensure Vehicle to Infrastructure communication (V&I). Fast moving vehicles present challenges for the proposed system especially for high mobility (250 km h⁻¹). The main objective in this study is to study and investigate the impact of Doppler shift on the quality of transmitted/received signal in terms of Bit Error Rate (BER) and the transmission range. A new solution based on the association of Maximum Likelihood (ML) and Extended Kalman Filter (EKF) algorithm is proposed and computer simulations are performed to confirm the reduction of Doppler impact on the signal quality. Also it is shown that for high value of speed, the new solution can effectively improve the transmission range of the MB-OFDM system.

Keywords: MB-OFDM, Multipath Channel, Doppler Effect, Performance Analysis, EKF, ML

Introduction

The MB-OFDM has been selected by several key industry organizations: Multiband OFDM Alliance, WiMedia, Wireless Universal Serial Bus (USB), because of its very good technical characteristics for the diverse set of high performance that are eagerly anticipated for different applications (Kabil et al., 2014; 2011). However, in the wireless mobile environment, Doppler shift emerges due to the motion of a transmitter relative to a receiver (Albarazi et al., 2011; Kabil et al., 2013). When a vehicle transmits/receives a signal while moving, the transmitted/received signal is subjected to an offset in its frequency. The higher the vehicle speed, the larger frequency distortion (Albarazi et al., 2011) as a result, frequency shifting increases and leads to a loss in orthogonality between subcarriers causing Inter-Carrier Interference (ICI) (Albarazi et al., 2011; Kabil et al., 2013).

For higher values of speed especially for 250 km h⁻¹, the signal restoration becomes extremely difficult (Kabil et al., 2013). Therefore, several methods have been proposed to provide an estimation of Doppler shift for OFDM communication systems (Kabil et al., 2013; Kumar and Pandey, 2013; Kumar et al., 2009; Rahman et al., 2012). Previously in article (Kabil et al., 2013), the Extended Kalman Filter (EKF) has been proposed as a good method for the MB-OFDM system. Significant gains of the performance can be achieved using EKF method for high and low speeds in terms of BER (Kabil et al., 2013).

The critical limitation in the MB-OFDM system is their relatively short range (Qiyue et al., 2007; Batra et al., 2004). The desired range is around 20 m for 200 Mbits/s, it can be reduced in the presence of Doppler shift (Kabil et al., 2014). To push the MB-OFDM as a good candidate to ensure V&I communications proposed in (Kabil et al., 2013), it is important to improve the extremely short transmission range limit. The main objective of this article is to study and investigate the performance of the MB-OFDM system with the new solution for reducing the ICI Effect based on the association of EKF and ML over radio channel in terms of BER and transmission range.

This paper is organized as follows: We give a brief review of the MB-OFDM system. Then, we illustrate how the new compensation of Doppler Effect can be
exploited and also analyzed its performance in terms of BER and transmission range.

Materials and Methods

MULTIBAND-OFDM System

The available spectrum (3.1-10.6 GHz) (Avila and Thenmozhi, 2014) is divided into 14 sub-bands (Qiyue et al., 2007), each one occupying 528 MHz (Kabil et al., 2011; Avila and Thenmozhi, 2014). The structure of the MB-OFDM solution is very similar to that of a conventional wireless OFDM physical layer, the main difference is the use of Time-Frequency Codes (TFC) (Kabil et al., 2013). The structure of the MB-OFDM system offers data rates of [55, 80, 110, 160, 200, 320 and 480] Mbits/s (Kabil et al., 2014).

The fundamental transmitter and receiver structure of an MB-OFDM system is illustrated in Fig. 1. At the transmitter, the bits from information sources are first encoded by the convolution encoder. To exploit time-frequency diversity and combat multi-path fading, the coded bits are further interleaved according to some preferred time-frequency patterns and the resulting bit sequence is mapped into constellation symbols and then converted into a block of N symbols by the serial-to-parallel converter (Qiyue et al., 2007; Kabil et al., 2011).

The IFFT size is 128 and the total number of used subcarriers is 122. The useful duration of each OFDM symbol is 242 ns, leading to subcarrier frequency spacing of ∆f = 4.125 MHz (Kabil et al., 2013). In order to avoid inter-symbol interference between two consecutive OFDM symbols, a Zero Padding (ZP) guard interval of 70.08 ns duration is added at the end of each OFDM symbol.

To provide increased performance for low data rates, the MB-OFDM system includes support for frequency and time spreading, which provide repetition of the same data symbols over multiple subcarriers and/or OFDM symbols. Frequency-Domain Spreading (FDS) repeats the same data symbol over two different subcarriers in the same OFDM symbol, while Time-Domain Spreading (TDS) repeats the entire OFDM symbol in two consecutive time slots (Kabil et al., 2013; Christopher, 2003). The OFDM symbol is passed through a Digital-to-Analogue Converter (DAC) resulting to an analogue baseband OFDM signal (Sadough, 2008).

At the demodulator, the used of ZP requires to make the operation called Overlap and Add (OLA) before the Fast Fourier Transform (FFT) in order to restore the orthogonality between subcarriers (Kabil et al., 2014). The obtained N symbols are then mapped into bits and the resulting bit sequence is de-interleaved and decoded to get back the information bits (Mohammad, 2007).

Results and Discussion

New Solution for Reducing the ICI Effect

The section covers the new solution’s studies for MB-OFDM system over high mobility multipath channel in order to improve the signal quality and the transmission range for 200 Mbits/s.

Improving the Performance of MB-OFDM System in Terms of BER

An OFDM signal represented in the time domain as in Equation 1:

\[ x(t) = \sum_{k=1}^{N} X_k e^{j2\pi f_k t} 0 \leq t \leq T_u \]

With:

\[ X_k \] = The complex signal modulating for the kth subcarrier

\[ f_k = f_0 + k\Delta f \] = The frequency of the kth subcarrier, \( f_0 \) is the starting frequency of the MB-OFDM signals

\[ \Delta f \] = The frequency separation between two adjacent subcarriers, \( \Delta f = \frac{1}{T_u} \)

\[ T_u \] = Useful duration

The complex baseband representation of the time variant impulse response model of the multipath channel in mobile radio environments is defined as (Albarazi et al., 2011):

\[ h(t, \tau) = \sum_{i=0}^{\infty} a_i e^{j2\pi f_{ik} t} \delta(t - \tau_i) \]

\[ f_{ik} = (f_u + k\Delta f) \frac{v}{c} - \cos \theta_i \]

Where:

\[ a_i \] = The multipath gain coefficients of i-th scatter

\[ \tau_i \] = the delay of i-th scatter

\[ F_{dk} \] = Doppler shift of the kth subcarrier received from the i-th scatter in the direction \( \theta_i \)

\[ v \] = The speed difference between the source and receiver

\[ c \] = Speed of light

We have been proposed a multipath channel model with two paths. The model of Saleh-Valenzuela (SV) has been adopted as the reference model of Outdoor UWB channel specified in the IEEE802.15.4a (Albarazi et al., 2011).

For the proposed channel with two paths and in the presence of the shadowing, the impulse response becomes:
Fig. 1. Block diagrams of the transmitter of an MB-OFDM system

\[ h(t, \tau) = X \sum_{i=1}^{2} \alpha_i e^{j2\pi f\tau} \delta(t - \tau) \]  

(4)

where, the X represents the lognormal shadowing with the parameter of shadowing is \( \sigma_x \).

The received signal with the proposed channel is:

\[ y(t) = X \sum_{i=1}^{2} \alpha_i \sum_{k=0}^{N-1} X_k e^{j2\pi f(t - \tau)} + w(t) \]  

(5)

\[ y(t) = e^{j2\pi f\tau} \left( X \sum_{i=1}^{2} \alpha_i \sum_{k=0}^{N-1} X_k e^{j2\pi f(t - \tau)} \right) + w(t) \]  

(6)

If the \( y(t) \) is sampled by Nyquist rate, the Equation 6 becomes.

The normalized Frequency Offset (FO) is \( \varepsilon = f_d T \) (Kabil et al., 2013):

\[ y(n) = e^{j2\pi n T} \left( X \sum_{i=1}^{2} \alpha_i \sum_{k=0}^{N-1} X_k e^{j2\pi f(t - \tau)} \right) N T + N T \]  

(7)

\[ y(n) = z(n) e^{j2\pi n T} + w(n) \]  

(8)

\[ y(n) = X \sum_{i=1}^{2} \alpha_i \sum_{k=0}^{N-1} X_k e^{j2\pi n T} \]  

(9)

The problem with OFDM systems is sensitive to the Frequency Offset (FO) between transmitter and receiver signals caused by the relative motion between transmitter and receiver and scattering environment, induces Doppler spread (Albarazi et al., 2011; Sreekanth and GiriPrasad, 2012). These frequency errors causes the loss of orthogonality between the subcarrier and signal transmitted on each carrier are not independent to each other, leading to the Inter-Carrier Interference (ICI), so that system performance may be considerably degraded (Albarazi et al., 2011). The degradation of the performance for the MB-OFDM in terms of BER is important and becomes worse with high speed (250 km h\(^{-1}\)) (Kabil et al., 2013).

Kabil et al. (2013), the Extended Kalman Filer (EKF) and the Maximum Likelihood (ML) estimation with ZF equalizer have been proposed and have been compared in order to combat the ICI effect. It is seen that the use of EKF or ML gives good results for 50 km h\(^{-1}\) and 150 km h\(^{-1}\), however, for 250 km h\(^{-1}\), the EKF gives a good results then the ML method and is about \( E_b/N_0 = 9.617 \) dB at BER = 10\(^{-3}\) compared to ML method we need \( E_b/N_0 = 20 \) dB for the same BER.

To increase the performance of the MB-OFDM system in terms of BER, we propose a new solution based on the association of the EKF and ML methods as shown in Fig. 2. These ICI cancellation methods are used without ZF equalizer.

The Equation 8 becomes:

\[ y(n) = (z(n)e^{j2\pi n T} + w(n)) e^{j2\pi f\tau} \]  

(10)

\[ y(n) = (z(n)e^{j2\pi n T - j2\pi f\tau} + w(n)) e^{j2\pi f\tau} \]  

(11)

Replacing \( \varepsilon = (\hat{\varepsilon}_{EKF} - \hat{\varepsilon}_{ML}) \) by \( \varepsilon = (\hat{\varepsilon}_{EKF} - \hat{\varepsilon}_{ML}) \), the Equation 11 becomes:

\[ y(n) = (z(n)e^{j2\pi n T} + w(n)) e^{j2\pi f\tau} \]  

(12)

Figure 3 illustrates the BER simulation results as function of \( E_b/N_0 \) for 200 Mbits/s for the EKF algorithm and ML method and the new solution based on the association of the EKF and ML over the proposed channel with Doppler Effect of 250 km h\(^{-1}\). The \( E_b/N_0 \) is varying between -6 and 50 dB.
According to the simulation results of the Fig. 3, it is observed that the new solution gives good results in terms of BER compared to EKF and ML methods. At BER = 10^-3, the association of the EKF and ML
algorithms gives a $E_b/N_0 = 3.169$ dB however, with EKF algorithm we need $E_b/N_0 = 9.371$ dB for the same BER.

Range Improvement

Range Improvement with ICI Reduction Methods

The equation of the SNR as function of the transmission range for multipath channel with Doppler Effect as (Qiyue et al., 2007; Sathananthan et al., 2000) is Equation 13:

$$\text{SNR} = P_{TX} - 20 \log_10 \left( \frac{4nf_d}{c} \right) - (-174 + 10 \log_{10}(R_b))$$

$$- 6.6 - 2.5 + 10 \log_{10}(E(\left| H[k]\right|^2)) + 10 \log_{10}(\sin^2(\epsilon))$$

$$- 10 \log_{10}\left( 1 + \frac{4}{3} \sin^2(\pi x N_e) \right) (\text{dB})$$

With:

- The term $10 \log_{10}(E(\left| H[k]\right|^2))$ is the fading gain that is captured by the IEEE 802.15.4a channel model and calculated as (Qiyue et al., 2007):

$$E(\left| H[k]\right|^2) = \exp(0.0265 \sigma_x^2)$$

(14)

- $10 \log_{10}(\sin^2(\epsilon)) - 10 \log_{10}\left( 1 + \frac{4}{3} \sin^2(\pi x N_e) \right)$: The degradation due to the Doppler Effect in dB as shown in (Sathananthan et al., 2000)

- $f_g$: The geometric average of the lower and upper frequencies defined as $\sqrt{f_L f_U}$ with $f_L$ is the lower frequency and $f_U$ is the upper frequency

The transmitted signal power is equal to (Qiyue et al., 2007; Batra et al., 2004):

$$P_{TX} \leq -41.25 + 10 \log_{10}(f_{tx} - f_{rx})(\text{dBm})$$

(15)

$G_{TX}$, $G_{RX}$ Gains of the transmitting and receiving antenna respectively and are assumed equal to 0 dB (Batra et al., 2004).

At the receiver, the average noise power can be calculated using the formula: $-174 + 10 \log_{10}(R_b)$ (in dBm). Here, $R_b$ is the data rate in bits per second and equal to 200 Mbits/s and -174 comes from $k_b T$ calculated at room temperature as the thermal noise power per hertz, where $k_b = 1.38 \times 10^{-23}$ J/K is the Boltzmann’s constant and $T$ is the temperature in Kelvin. We assume that the noise figure of the antenna and the receiver RF chain is 6.6 dB and the implementation loss in the digital baseband is 2.5 dB (Qiyue et al., 2007):

$c$ = Speed of light

$d$ = Distance between transmitter and receiver measured in meters

After adding the reduction algorithms: ML or EKF, the equation of SNR as function of the distance for an AWGN channel with Doppler Effect is as:

$$\text{SNR} = P_{TX} - 20 \log_{10} \left( \frac{4nf_d}{c} \right) - (-174 + 10 \log_{10}(R_b))$$

$$- 6.6 - 2.5 + 10 \log_{10}(E(\left| H[k]\right|^2)) + 10 \log_{10}(\sin^2(\pi x - \hat{\epsilon}))$$

(16)

$$- 10 \log_{10}\left( 1 + \frac{4}{3} \sin^2(\pi x - \hat{\epsilon}) N_e \right) (\text{dB})$$

The Fig. 4 illustrates the evaluation of the BER curves as function of the distance for the MB-OFDM system over the proposed channel with Doppler Effect for 250 km h$^{-1}$ with the algorithms: ML, EKF in comparison with the results of the BER for the proposed channel with Doppler Effect and without reduction algorithms. The distance varies between 1 and 25 m.

By comparing the results of the BER curves as a function of the distance presented in Fig. 4, we note that despite the using of the ICI reduction methods, the transmission range is still extremely short, the distance is $d = 3.325$ m for a BER $= 10^{-3}$ in the case of EKF filter.

Range Improvement with new Solution for Reducing ICI Effect

After adding the new solution based on the association of the ICI reduction algorithms: ML and EKF, the Equation 13 of SNR as function of the transmission range over the multipath channel with Doppler Effect becomes:

$$\text{SNR} = P_{TX} - 20 \log_{10} \left( \frac{4nf_d}{c} \right)$$

$$- (-174 + 10 \log_{10}(R_b)) - 6.6 - 2.5 + 10 \log_{10}(E(\left| H[k]\right|^2)) + 10 \log_{10}(\sin^2(\pi x - \hat{\epsilon}) - \hat{\epsilon}_{sl})$$

(17)

$$- 10 \log_{10}\left( 1 + \frac{4}{3} \sin^2(\pi x - \hat{\epsilon}) N_e \right) (\text{dB})$$

The Fig. 5 illustrates the simulation results for the MB-OFDM system over the proposed channel with Doppler shift for 250 km h$^{-1}$ with ICI reduction algorithms: ML and EKF. The distance is between 1 and 25 m.

It will be seen that with the new solution, the transmission range can be enlarged from $d = 3.325$ m to $d = 13.960$ m for the MB-OFDM system with data rate of 200 Mbits/s over high mobility multipath channel.
Fig. 4. Curves of the BER performance with the MB-OFDM system as function of distance for multipath channel with and without the reduction algorithms for 250 km h$^{-1}$

Fig. 5. Curves of the BER performance with the MB-OFDM system as function of distance for multipath channel with and without the reduction algorithms for 250 km h$^{-1}$
Conclusion

In this study, we have proposed a new solution based on the association of the EKF and ML methods for reducing ICI Effect in the MB-OFDM system over high mobility multipath channel especially for 250 km h$^{-1}$, to improve the signal quality and the transmission range. The new solution has been compared to the EKF and to the ML with ZF equalizer. It is shown that the new solution performs better than the EKF and ML methods and offers much improvement in the performance in terms of BER and transmission range. It will be seen that the transmission range can be enlarged to 13.960 m for 250 km h$^{-1}$.

Perspectives

In the future work we plan to:

- Study the effect of multi-user associated with the Doppler Effect
- Optimizing the receiver for reducing the processing time with good performance required by the application of transport

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Author’s Contributions

Sanaa Kabil: Participated in all experiments, coordinated the data-analysis and contributed to the writing of the manuscript.

Raja Elassali: Designed the research plan and organized the study.

Fouzia Elbahhar: Coordinated the data-analysis and contributed to the writing of the manuscript.

Brahim Ait Essaid: Participated in all experiments, coordinated the data-analysis and contributed to the writing of the manuscript.

Abdellah Ait Ouahman: Coordinated the data-analysis and contributed to the writing of the manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of other authors have read and approved the manuscript.

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