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Adaptive pulse shaping for CP-OFDM synchronization

By

Haitham El-Sayed Akah* Prof. Aladin Kamel** Prof. Hadia El-Hennawy**

Abstract:

This paper presents a new algorithm for blind timing offset estimation in cyclic prefix-orthogonal frequency division multiplexing (CP-OFDM) systems. The new algorithm allows the use of the simple non-dispersive Maximum likelihood (ML) time and frequency offset estimator in dispersive channels instead of the very complex dispersive ML time and frequency offset estimators. This new algorithm makes use of the data obtained from channel estimator to generate an adequate pulse shape, which reduces the error of the non-dispersive ML estimator significantly. Such adaptive pulse shaping could be used in mobile full-duplex systems where simplicity translates to less power and lighter weight.

Keywords:

Timing Offset estimation, CP-OFDM, Pulse Shaping, Adaptive systems, Blind algorithm, orthogonal frequency division multiplexing.

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* National Authority of remote sensing and space science
** Faculty of engineering, Ain-Shams University, Cairo, Egypt

1. Introduction:

Recently, orthogonal frequency division multiplexing (OFDM) systems have dominated the communication systems [1], such as digital video broadcast (DVB), wireless local area networks (WLAN) and ultra wide band systems (UWB). The simplicity of its channel equalization process and immunity to inter symbol interference (ISI) gain more attention each day especially in frequency selective fading environments. Such immunity to ISI can be credited to the cyclic prefix between two symbols that eliminate ISI. On the other hand such framing structure necessitates the identification of each frame start point. This synchronization problem has been subject of research for some time [2]-[14].

There are two main approaches to solve the OFDM symbols synchronization problem. The first one is by using pilot symbols to synchronize the receiver [2]-[4]. Such approach wastes bandwidth and necessitates the transmission of ideal sequences when there are no data to transmit. The second approach is to use the signal statistical information, power profile and the correlation between cyclic prefix part and the end of OFDM symbol, to blindly estimate the timing offset of each frame, which saves bandwidth and can handle burst transmission. [5]-[14].

However, the blind timing offset estimators proposed to date can be categorized into non-dispersive channel estimators and dispersive channel estimators. The dispersive channel timing offset estimators are very complex to implement in mobile communications, while the non-dispersive channel timing offset estimators are erroneous when used in dispersive channels.

This paper presents a new algorithm to improve the performance of the non-dispersive blind timing offset estimator employing pulse shaping proposed by Jan-Jaap de Beek, et al…[14] in dispersive channels. The new algorithm makes use of the information obtained from the channel estimator in OFDM systems, that is used usually to equalize the channel effect on the data, to select an adequate pulse shape for OFDM symbols. It can compensate most of the ISI effect on the simply non-dispersive timing offset estimator. The new algorithm is much simpler than other dispersive channel timing offset estimators, which makes it more feasible and suitable for mobile communication. On the other hand such an algorithm may not meet the expected results at very dispersive channels where the signal reflections nearly equal to the main signal path

In section 2, the signal model, the used estimator and the idea of improving the performance of this estimator in dispersive channels through the use of pulse shaping are introduced. In section 3, the numerical solution used to find these pulse shapes are presented with some examples of its outcome compared to raised cosine. Section 4 describes the synchronization algorithm and the adaptive pulse shaping system. Section 5 compares the performance of the new proposed algorithm compared to the raised cosine (RC) pulse shaping in deferent channels and analysis the results. Finally, section 6 concludes the work.

2. Signal Model:

The synchronization process requires that the receiver estimates the arrival time of the OFDM symbol. This paper is concerned with the using the ML timing offset estimator for non-dispersive channel in dispersive channels. The received signal model assumed by this estimator is as follows:

$$r(k) = g(k-\theta)s(k-\theta)e^{j2\pi\varepsilon k/N} + n(k) \tag{1}$$

where $s(k)$ is the transmitted OFDM signal, $g(k)$ is the pulse shape, $n(k)$ is the AWGN and θ the timing offset. The CP-OFDM system under consideration has an M sub-carrier and a CP of length L, so that $s(k)=s(k+M)$ for $0\leq k\leq L$ where M is the symbol length. The maximum likelihood estimators θ_{est} is given by

$$\theta_{est} = \arg\max_{\theta}\left\{\left|\gamma_N(\theta)\right| + \gamma_0(\theta)\right\} \tag{2}$$

where

$$\begin{aligned} \gamma_N(\theta) &= \sum_{k=-\infty}^{\infty} h_N(k-\theta)r(k)r^*(k+M), \\ \gamma_0(\theta) &= \sum_{k=-\infty}^{\infty} h_0(k-\theta)\left|r(k)\right|^2, \end{aligned} \tag{3}$$

$$h_N(k) = \frac{2SNRg(k)g(k+M)/\sigma_n^2}{SNR(g^2(k)+g^2(k+M))+1}, 0 \leq k < L \tag{4}$$

$$h_0(k)=\begin{cases}\rho\dfrac{SNRg^2(k+M)+1-g^2(k)}{SNR(g^2(k)+g^2(k+M))+1} & ,0\le k<L\\ \rho\dfrac{1-g^2(k)}{SNRg^2(k)+1} & ,L\le k<M\\ \rho\dfrac{SNRg^2(k-M)+1-g^2(k)}{SNR(g^2(k)+g^2(k-M))+1} & ,M\le k<M+L.\end{cases} \tag{5}$$

Where $\rho=-\dfrac{\sigma_s^2}{\sigma_s^2+\sigma_n^2}\dfrac{1}{\sigma_n^2}$ and $SNR=\dfrac{\sigma_s^2}{\sigma_n^2}$.

This is a simple estimator consisting of two filters depending on the choice of pulse shape and on the SNR. Rewriting the signal model for a dispersive channel:

$$\begin{aligned} r(k)&=h(k)*\left[g(k-\theta)s(k-\theta)\right]+n(k) \\ &=A_0g(k-\theta)s(k-\theta)+\sum_{l=1}^{l_0}A_lg(k-l-\theta)s(k-l-\theta)+n(k)\end{aligned} \tag{6}$$

where l is the reflection path index, A_l is the normalized l_{th} reflection amplitude and l_0 is the index of the last reflection path. The first and third terms in this equation are identical to Eq. (1), while the second term is treated as a noise in the estimator under consideration producing an error floor in timing estimation [15]. The pulse shape $g(k)$ can be used to reduce the effect of this term and its corresponding error floor for a specific channel response. Since the pulse shape is included in the estimators filters h_0 and h_N, the separation of $g(k)$ is done numerically.

Thus, the simplicity of the timing offset estimator is maintained while improving its performance as shown in section 3.

3. Numerical solution of pulse shape effects:

Before starting with the solution some CP-OFDM symbols parameters should be defined. The number of sub-carriers in each symbol is 64 (M=64). The cyclic prefix length is 20 samples (L=20) half of them is pulse shaped (pulse shape =10) while the rest of the symbol is left unchanged. These numbers were selected to speed the execution time of the simulation but other higher value were tested and produced the same results (M=1024 and L=128).

In order to numerically find the pulse shape $g(k)$ that minimizes the error of the timing estimator, we make use of a global optimization algorithm. The algorithm of choice here is genetic algorithm (GA). This algorithm takes a pool of few pulse shapes and treats them as chromosomes from different parents, and then it starts reproducing these chromosomes to generate the next generation of parents and so on. Each reproduction step include some sort of mutation and crossing over two chromosomes from two different parents as would happen in real life. Only the fittest parents, with minimum error, will survive to the next generation and the rest of them are eliminated. The pool for GA was 24 pulses with four elite members; the best four parents are allowed to survive to the next generation [16]-[17].

The cost function to evaluate the fitness of each pulse shape consists of 8000 pulse shaped CP-OFDM symbol, grouped into 100 burst of 80 symbol. Each burst was shifted randomly, filtered by the channel impulse response and supplied to the estimator under consideration, then the mean square error of the symbols timing offset estimation is calculated and supplied to the GA as a fitness parameter for each pulse.
The channel under consideration is supplied to the system then the GA starts to evaluate the fitness of the initial 24 pulse for this channel and breed them for 10000 generation. The best pulse in the last generation is considered to be the suitable pulse shape for the supplied channel impulse response. Pulses amplitude in the range from -1 to 1 are allowed maintaining the same power profile of the signal.

Figures 1 and 2 are examples of the result obtained for line of sight (LOS) and non line of sight (NLOS) channels with multiple reflections respectively.

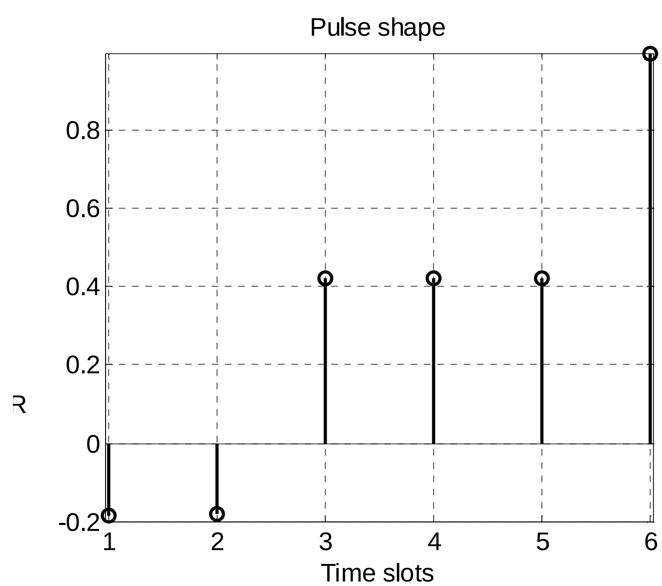

Figure (1): *Obtained Pulse for LOS channel*

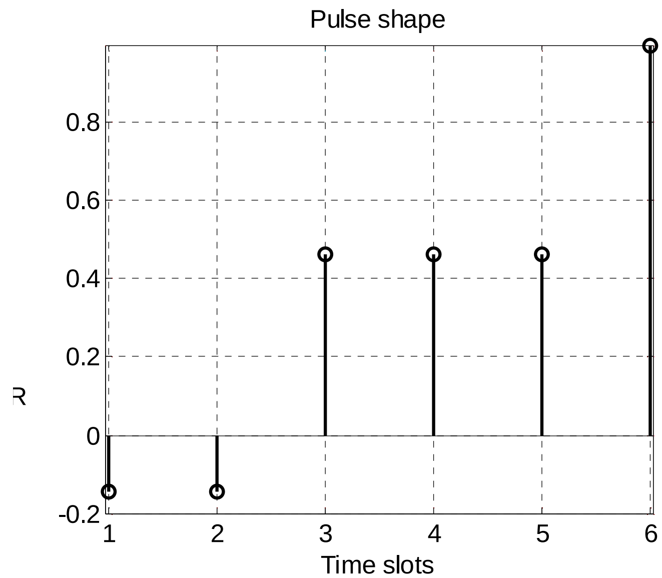

Figure (2): *Obtained Pulse for NLOS channel*

A comparison between the timing offset estimator variance for the obtained pulse shapes, raised cosine (RC) and rectangular (Rec.), no pulse shaping, against signal to noise ratio (SNR) are given in Figures 3 and 4 for LOS and NLOS respectively. It can be noticed that the obtained pulse shape outperforms the other pulse shapes for high SNR, but at low SNR the third term in Eq. (6), additive white Gaussian noise (AWGN) term, becomes more dominant and the pulse shape effect on the estimation process is wakening.

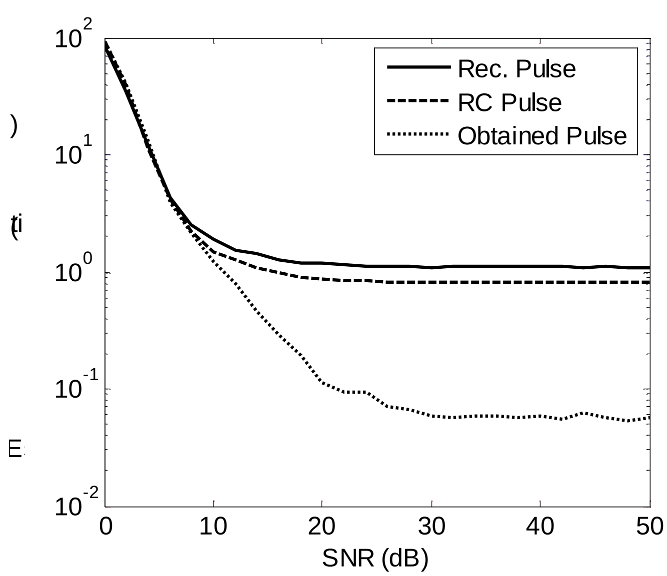

Figure (3): *Obtained Pulse for NLOS channel*

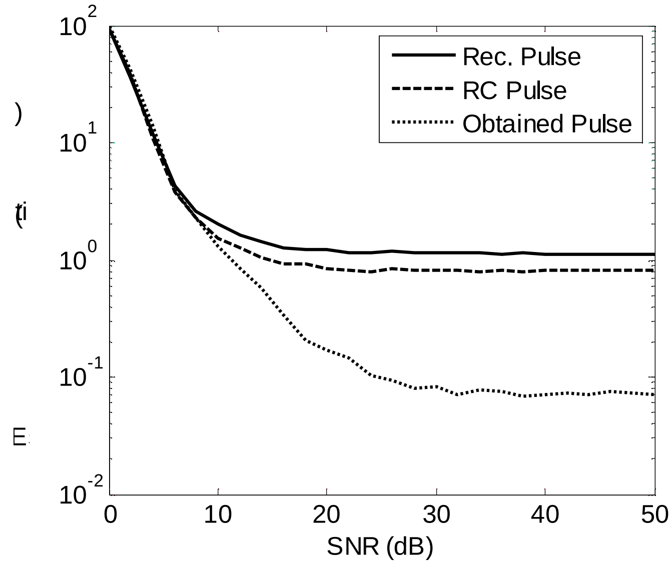

Figure (4): *Obtained Pulse for NLOS channel*

4. Proposed synchronization algorithm:

In this section the proposed algorithm for timing offset estimation of CP-OFDM system with adaptive pulse shaping is described. Figure 5 presents the proposed adaptive pulse shaping system.

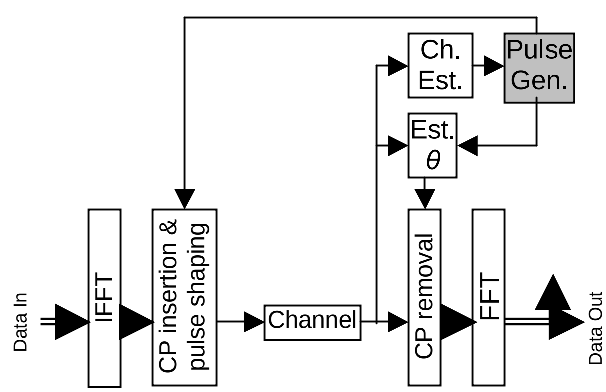

Figure (5): *Adaptive pulse shaping system block diagram*

This is a typical pulsed CP-OFDM system [14], where the transmitter modulates the data using OFDM-Modulator and sends the defined pulse shape through the channel. The receiver gets the signal plus the channel effects, noise and multi-path propagation; timing offset estimator estimates the start of each symbol and the channel estimator estimates the channel response to enable the receiver to compensate its effect on the

data. The timing offset and channel information are feed to the OFDM-demodulator to guide it during the demodulation process.
However using the non-dispersive timing offset estimator will produce an error floor as mentioned earlier. By adding the pulse generator block, that gets the estimated channel information and generates the corresponding pulse shape, this error floor will be reduced. This pulse shape is then sent back to the transmitter to use it with the next symbols.

The algorithm can be summarized as follow:

1. The transmitter and the receiver use the default pulse shape.
2. The receiver estimates the channel impulse response from the transmitted data.
3. The pulse generator finds the suitable pulse shape for that channel.
4. The receiver agrees with the transmitter to use this pulse shape.

Such pulse generator can be implemented using look up tables (LUTs) or a global optimization block

5. Numerical solution of timing offset estimation:

This section studies the performance of the proposed algorithm for different channels. As there are uncountable channels' combinations, a two ray model channels, only the main signal and a single image, was assumed. Each channel has two defining indices x and y, where x is the reflection time slot and y is the normalized amplitude of the reflection.
Here x ranging from 1 to 10, as the pulse shape length is 10 time slots, 5 at each end of the OFDM symbol, with step equals one and y ranging from 15% to 75% with step equals 0.05.
The pulse shape corresponding to each channel was calculated and the estimated variance for each case was recorded. These variances were plotted in 3D as can be seen in Figure 6.
Figure 7 compares the estimated variance for the proposed adaptive pulse shaping and the raised cosine pulse shaping, where it can be seen that the new algorithm improves the estimated performance significantly over RC pulse for most of the channels. It also compensates the channel effect for image of relative amplitude less than 45%, where the 10^{-4} is used instead of 0 due to the limit imposed by the number of OFDM symbols used in the simulation. It also shows that as the image amplitude approaches 100%, the effect of pulse shaping is weakened, as the image and the signal are affected almost equally by the pulse shape, and the use of adaptive pulse shaping becomes useless for images with relative amplitudes greater than 65%.

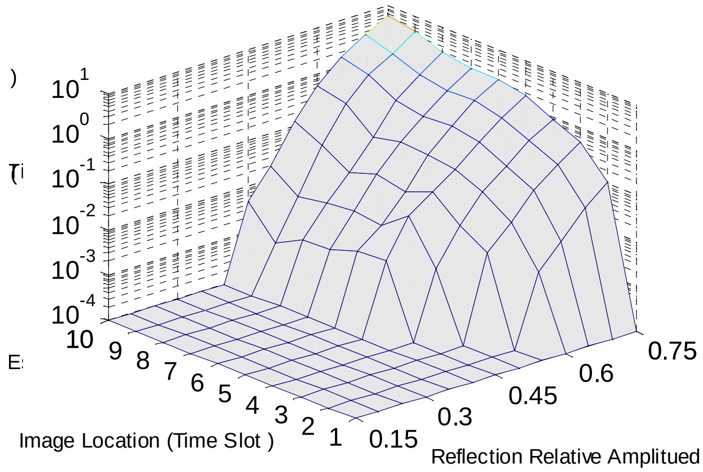

Figure (6): *Estimated variance for different channel image amplitudes and locations using the proposed algorithm*

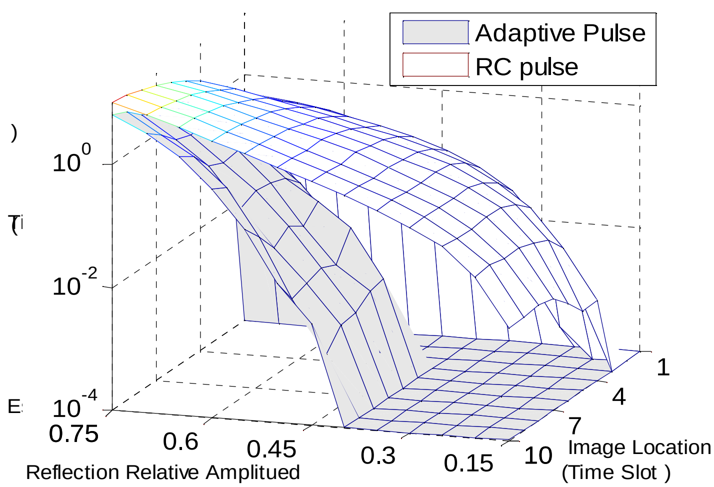

Figure (7): *Estimated variance for different channel image amplitudes and locations using the proposed algorithm and the RC pulse*

6. Conclusions:

At high SNR, the new generated pulse shapes are performing much better than both the raised cosine shape and the rectangular pulse shape. While at low SNR, where AWGN is becoming more dominant than ISI and since the AWGN does not depend on the pulse shape, all pulse shapes perform similarly.

The new algorithm compensates the channel effect for medium and low channel images, but as the channel images increase the effect of pulse shaping is weakening; this limits the usefulness of the proposed algorithm in highly dispersive channels.

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Nomenclatures:

$s(k)$	Transmitted OFDM signal
$g(k)$	Pulse shape
$n(k)$	AWGN
θ	Timing offset
M	Number of sub-carrier
L	CP length
k	Time slot
θ_{est}	Maximum likelihood estimators
l	Reflection path index
A_l	Normalized l^{th} reflection amplitude