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Title	**A Time Domain Equalizer (TEQ) for Channel Shortening in Project 802.16m SDD**
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Re:	IEEE 802.16m-07/040, “Call for Contributions on Project 802.16m System Description Document (SDD)”
Abstract	This contribution proposes a section/sub-section to describe a time domain equalizer to shorten the wireless channel with long delay spread in the Table of Contents (ToC) of IEEE 802.16m SDD for ISI mitigation in IEEE 802.16 system without increasing the length of cyclic prefix (CP).
Purpose	Propose to have a section/subsection “Time domain equalizer (TEQ)” in TGm SDD ToC.
Notice	
Release	
Patent Policy	

A Time Domain Equalizer (TEQ) for Channel Shortening in Project 802.16m SDD

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I. Introduction

The orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) are both multicarrier transmission techniques popularly used in IEEE 802.16 system. The OFDM / OFDMA divides the available signal band into many subchannels and allows a subcarrier used in each subchannel for data transmission. In general, a cyclic prefix (CP) is added in front of an OFDM / OFDMA symbol to avoid the intersymbol interference (ISI). The CP length is at least equal to or greater than the length of the channel delay spread (CDS). Since the CP will reduce the transmission efficiency, a large-size CP is not desirable. Thus, the choice of the CP size is often a compromise between the tolerated length of the CDS, and the data throughput. As a result, in some scenarios the length of the CDS will exceed the CP range. When it happens, the ISI is induced and the system performance is degraded. A simple method for this problem is to put a time domain equalizer (TEQ) in front of the FFT module such that the CIR can be shortened in the receiver side. Figure 1 shows a typical OFDM / OFDMA system, with a TEQ for the purpose of channel shortening.

Many algorithms have been proposed for the design of the TEQ [1], [2], [3]. Treating the TEQ design as a pure channel shortening problem, [2] proposed a criterion to maximize the shortening signal-to-noise ratio (SSNR), defined as the ratio of the energy of the TEQ shortened response inside and outside the CP range. This method was referred as the maximized SSNR (MSSNR) method, and the corresponding TEQ is called the MSSNR TEQ. For OFDM / OFDMA systems, no bit-loading is conducted and the purpose of the TEQ is just to reduce the ISI. Generally speaking, if the SSNR is larger, the ISI and the bit-error-rate (BER) become smaller. Thus, the MSSNR criterion is generally adequate in the OFDM / OFDMA systems.

One limitation of the MSSNR method is that the TEQ length must be smaller than or equal to the CP length [4]. Since the CIR of wireless channels is generally much more complex, the required TEQ length is usually much larger. In [4], a modified MSSNR TEQ method (called mMSSNR method here) was proposed to solve the problem. With this method, there is no limitation of the TEQ length. It was shown that as the tap length of TEQ increases, the SSNR also increases [4].

When the dimensionality of the TEQ is high, the required computational complexity becomes high. There are mainly two kinds of operations needed to perform in the TEQ problem. The first is the computations of the TEQ parameters, and the other is the TEQ filtering operations. The TEQ parameters may be computed once in a transmit packet, but the TEQ filtering process has to be conducted for each data sample. Thus, the computational complexity of the TEQ filtering process is more concerned in the TEQ design. Conventionally, the TEQ has a finite impulse-response (FIR) structure. However, this structure induces high computational complexity. In this contribution, we show a low-complexity TEQ for channel shortening by using an infinite-impulse-response (IIR) filter and compare the performance of different system schemes. It is well-known that, under some conditions, an IIR filer can be more efficient than an FIR filter. In other words, we can use fewer TEQ coefficients to achieve the same performance.

The rest of this contribution is organized as follows. The ensuing section describes the system model used and an algorithm for performance comparison. In Section III, we provide some numerical performance of the algorithms. Then, some concluding remarks are given in Section IV. Finally, proposed sections/subsections in the table of content (ToC) for IEEE 802.16m SDD are described in the last section.

II. System Model and Algorithm Description

Let *M* be the size of discrete Fourier transform (DFT), *L* the CP length, *K* = *M* + *L* the OFDM symbol length, *I* the CIR length and *N* the TEQ length. In addition, let $\mathbf{0}_p$ be the $\mathbf{0}_p$ zero column vector, $\mathbf{1}_p$ the $p \times 1$ unity column vector.

Figure 1 shows a typical OFDM / OFDMA transceiver model. At the IDFT output of the transmitter, the *i*th transmitted OFDM symbol is defined as $\mathbf{d}_i = [d_i(0), \cdots, d_i(M-1)]^T$. Adding the CP and conducting the parallel-to-serial conversion, we obtain the transmitted signal *x*(*n*), where *n* = *iK* + *l*, $x(n) = d_i(l+M-L)$ for $0 \le l \le L-1$, and $x(n) = d_i(l-L)$ for $L \le l \le K-1$. *x*(*n*) is transmitted over a finite impulse response channel with response $\mathbf{h} = [h(0), \cdots, h(I-1)]^T$ and corrupted by the additive white Gaussian noise (AWGN) $\eta(n)$. *x*(*n*) is assumed independent to the AWGN $\eta(n)$. Define $x_o(n) = x(n) * h(n)$ be the noise-free channel output signal. At the receiver side, both $x_o(n)$ and $\eta(n)$ are filtered by an *N*-tap TEQ filter with the coefficients $\mathbf{w} = [w(0), \cdots, w(N-1)]^T$, and their outputs are $y(n) = x_o(n) * w(n)$ and $v(n) = \eta(n) * w(n)$, respectively.

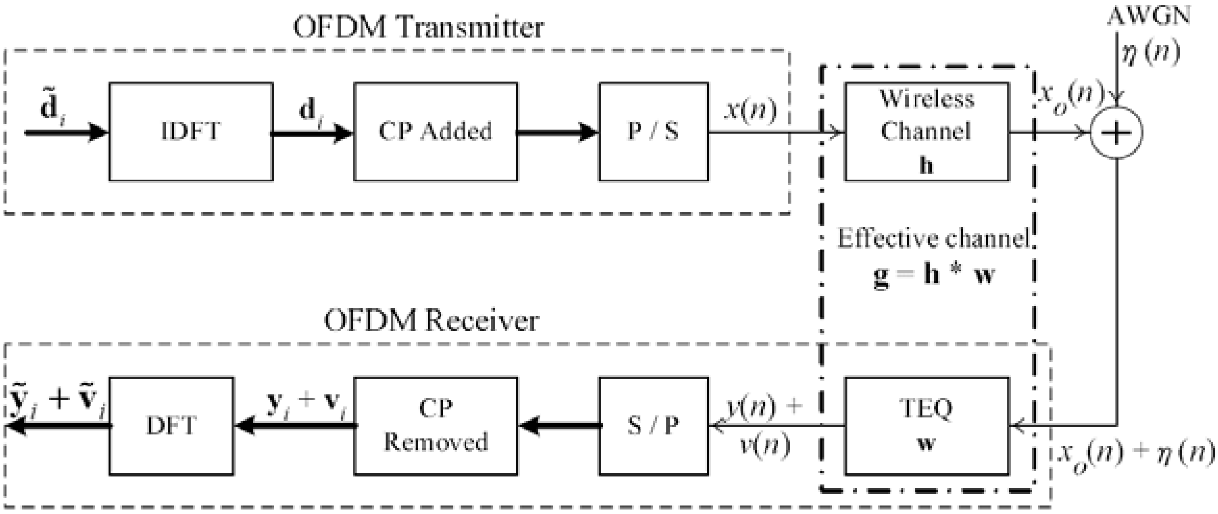

Figure 1. An OFDM / OFDMA system model for TEQ design

From Figure 1, *x*(*n*) passes *h*(*n*) and *w*(*n*). Let $g(n)$ be the equivalent channel response where $g(n) = h(n) * w(n)$, and $g(n)$'s length be $J = I + N - 1$. Here, we assume that *J* < *M*. Ignoring the synchronization delay, let $\mathbf{g} = [g(0), \cdots, g(J-1)]^T$. We can decompose g into $\mathbf{g} = \mathbf{g}_S + \mathbf{g}_I$, where $\mathbf{g}_S = [g(0), \ldots, g(L-1), \mathbf{0}_{J-L}^T]^T$ is the desired shortened channel response, and $\mathbf{g}_I = [\mathbf{0}_L^T, g(L), \ldots, g(J-1)]^T$ the residual ISI part. Next, we can rewrite $\mathbf{g}_S = \mathbf{D}_S \mathbf{H} \mathbf{w}$ and $\mathbf{g}_I = \mathbf{D}_I \mathbf{H} \mathbf{w}$, where $\mathbf{D}_S = \mathrm{diag}\left[\mathbf{1}_L^T, \mathbf{0}_{J-L}^T\right]$, $\mathbf{D}_I = \mathrm{diag}\left[\mathbf{0}_L^T, \mathbf{1}_{J-L}^T\right]$, and

$$\mathbf{H} = \begin{bmatrix} h(0) & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ h(I-1) & h(I-2) & \dots & h(I-N) \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & h(I-1) \end{bmatrix}_{J \times N} .$$

Here, $\mathrm{diag}[\cdot]$ denotes a diagonal matrix with the vector inside the bracket as its diagonal elements. The shortened signal-to-noise ratio (SSNR) at the TEQ output of the OFDM receiver is defined as

$$\mathrm{SSNR} = \frac{\mathbf{g}_S^T \mathbf{g}_S}{\mathbf{g}_I^T \mathbf{g}_I} = \frac{\mathbf{w}^T \mathbf{H}^T \mathbf{D}_S^T \mathbf{D}_S \mathbf{H} \mathbf{w}}{\mathbf{w}^T \mathbf{H}^T \mathbf{D}_I^T \mathbf{D}_I \mathbf{H} \mathbf{w}} = \frac{\mathbf{w}^T \mathbf{B} \mathbf{w}}{\mathbf{w}^T \mathbf{A} \mathbf{w}},$$

where $\mathbf{B} = \mathbf{H}^T \mathbf{D}_S^T \mathbf{D}_S \mathbf{H}$ and $\mathbf{A} = \mathbf{H}^T \mathbf{D}_I^T \mathbf{D}_I \mathbf{H}$.

The optimal TEQ of the MSSNR method can be obtained through maximizing the SSNR. The MSSNR TEQ method is to minimize the power term $\mathbf{w}^T \mathbf{A} \mathbf{w}$, under the constraint $\mathbf{w}^T \mathbf{B} \mathbf{w} = 1$. It was shown that the MSSNR TEQ is well behaved in an OFDM / OFDMA systems. However, the MSSNR method limits the TEQ length *N* to be not larger than the CP length *L*, $N \leq L$ [4].

Due to the channel inversion, the TEQ possesses the IIR properties. As a result, the IIR filer can reduce the computational complexity of the TEQ filtering significantly. We propose a simple two-stage approach to get a novel IIR TEQ with reduced complexity in the filtering operation as compared to the MSSNR TEQ. In the first stage, we first obtain the conventional FIR TEQ method MSSNR. In the second stage, a Steiglitz-McBride method (SMM) is applied to get the corresponding IIR coefficients which are identified from the FIR response. The Steiglitz-McBride method (SMM) is an iteration algorithm that finds an IIR filter with a prescribed FIR response in the time domain. In its original form, it minimizes a mean-square-error (MSE) criterion, leading a set of nonlinear regression equations for the optimal coefficients. The SMM transfers the problem into a set of linear equations, to be solved iteratively.

Finally, we use the resulting IIR TEQ in the receiver frontend to shorten the CIR. For easy reference, we call the proposed method as Steiglitz-McBride-MSSNR method, abbreviated as the SM-MSSNR method. The corresponding TEQ is called the SM-MSSNR TEQ.

III. Simulation Results and Discussions

The BER performance of the MSSNR [2], and the proposed SM-MSSNR methods are evaluated with simulations, as compared with that of system without TEQ. The DFT/IDFT size is set as 64, and the CP size as 16. The length of the wireless CIR is assumed to be 25, exceeding the CP size. The channel noise is modeled as the AWGN. The tap length of the MSSNR TEQ is 16, which is the largest tap size that can be used in the MSSNR TEQ. The tap length used in the SM-MSSNR TEQ is 6, 3 taps in the feedforward part, and 3 in the feedback part. The wireless channels are randomly generated for every OFDM packet. The channel is randomly generated. And all the simulations are evaluated with 30 OFDM packets, where each OFDM packet contains 60 OFDM symbols.

There are three curves for the simulations in Figure 2. The first one is the BER performance of the system without TEQ. It is clearly that if without the TEQ, the ISI degrades the BER performance significantly even if the noise is extremely smaller than the signal. The other two curves give the BER performance for the OFDM systems with the MSSNR TEQ and the SM-MSSNR TEQs fitted from the results of the MSSNR methods, respectively. In Figure 2, the BER performance of the MSSNR TEQ is much better than that of no TEQ. Furthermore, the performance of the SM-MSSNR TEQ is almost the same as that of the MSSNR TEQ. This result shows that the SMM can conduct a good fitting with sufficiently long FIR response. From the simulation result shown here, we can conclude that the proposed method can save up to 62.5% (which is 1 - 6/16,) of the computations in the TEQ filtering process without compromising performance. When the OFDM size becomes larger, the computational saving can be more significant.

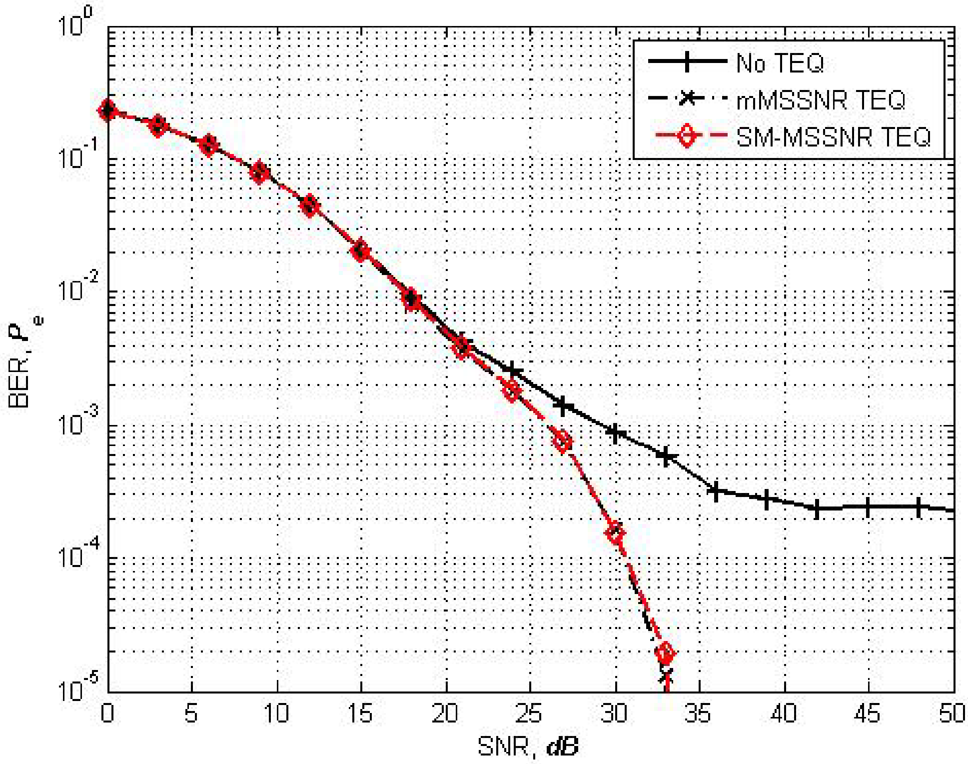

Figure 2. BER comparison for the channels

IV. Conclusion

We have compared a TEQ with IIR response, called the SM-MSSNR TEQ, with mMMSNR TEQ and non-TEQ schemes for the OFDM/OFDMA systems. Using the described approach, the IIR TEQ can be found straightforwardly. Simulation results show that the SM-MSSNR TEQ can have almost the same performance as that of the mMSSNR method but the required computational complexity for the filtering process is reduced significantly. Note that with TEQ, the error floor due to ISI can be removed under long delay spread wireless channel and the performance can be improved greatly.

V. Proposed Sections/Subsections in the Table of Content (ToC)

This contribution is to present a low-complexity time-domain equalizer (TEQ) for channel shortening and show that the applied scheme can effectively improve the system performance. According to IEEE 802.16 standard documents, current system does not support the function of time-domain equalizer (TEQ) to shorten a long delay spread channel for intersymbol interference (ISI) mitigation without increasing the length of cyclic prefix (CP). In some scenarios, the length of the channel delay spread (CDS) may exceed the CP range and thus it may induce serious ISI and degrades system performance. It is suggested to include this functionality in IEEE

802.16m system. As shown in this contribution, with TEQ at the receiver side, ISI can be suppressed to improve bit-error-rate (BER) performance without the loss of bandwidth efficiency. Required modifications to current system and proposed sections/subsections in ToC are shown as follows.

Proposed sections/subsections in ToC:

---Start of the Text---

[*Adopt the following text in the ToC of P802.16m System Description Document (SDD)*]

x.y Time domain equalizer (TEQ)

[*A cyclic prefix (CP) is added in front of an OFDM / OFDMA symbol to avoid the intersymbol interference (ISI). In some scenarios, the length of the channel delay spread (CDS) will exceed the CP range. When it happens, the ISI is induced and the system performance is degraded. To put a TEQ in front of the FFT module is a simple way such that the CIR can be shortened in the receiver side. Hence, the system performance can be improved significantly.*]

---End of the Text---

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