Low-complexity time-domain linear equaliser for single-carrier block transmissions

C.-Y. Ma and C.-C. Huang

Traditionally, frequency-domain equalisers have been used to equalise the single-carrier block transmission (SCBT) signals. However, to support the frequency-domain equaliser, two fast Fourier transform modules are required, which will increase the circuit complexity and chip area. A low-complexity time-domain linear equaliser for SCBT is proposed, which is less complicated than conventional frequency-domain equalisers, at the expense of an acceptable degradation in performance. For instance, for 60 GHz conference room non-line-of-sight channels, the complexity can be reduced by half at the expense of a 1.5 dB performance loss.

Introduction: Single-carrier block transmission (SCBT) has attracted a lot of attention in recent years mainly for three reasons. First, the SCBT signals can be simply equalised by a one-tap equaliser in the frequency-domain (FD) through the computational efficient fast Fourier transform (FFT) operation [1–4]. Secondly, since SC modulation is adopted, SCBT has relatively low peak-to-average power ratio compared with multicarrier modulation systems. Lastly, for SCBT, multipath diversity gain can be obtained if the equaliser is properly designed. Because of these advantages, SCBT has recently been employed in 60 GHz high data-rate communication systems, e.g. IEEE 802.11ad [5].

It is commonly believed that for SCBT, FD linear equalisers are much simpler than time-domain linear equalisers since computational efficient FFT operation can be applied to transform the signal from time-domain to FD. However, compared with orthogonal frequency division multiplexing (OFDM), which is also employed in IEEE 802.11ad, FD equalisation for SCBT requires an additional FFT operation. This requirement may lead to either considerable increase in the chip area or doubling of the circuit clock rate. For example, it is reported in [6] that 77% of the chip area of the communication baseband IC is occupied by the two FFT modules. Since the additional FFT module drastically increases the chip area and greatly raises the cost, designing low-complexity time-domain equalisers to avoid the use of the additional FFT module is of crucial importance.

Therefore, in this Letter, we propose a simple and well-performed time-domain linear equaliser to avoid the additional FFT operation. We consider the SCBT mode defined in IEEE 802.11ad [5] throughout this Letter, but the proposed method can be directly applied to other block transmission systems, for example, CDMA [4].

Conventional SC-FD equalisation: An SCBT system with block length N is considered in this Letter. The time-domain transmitted signal vector $\boldsymbol{x}$ is defined as

$$\boldsymbol{x} \triangleq \begin{bmatrix} x_1 & \cdots & x_N \end{bmatrix}^{\mathrm{T}} \tag{1}$$

We assume that the M leading samples in each block, namely $x_1, \ldots, x_M$, are used to transmit data symbols and $x_{M+1}, \ldots, x_N$ are used to transmit pre-defined reference signals. The frame format of IEEE 802.11ad SCBT signals is illustrated in Fig. 1. In each transmission block, $M = 448$ samples are used for data transmissions, and G_a64 is the pre-defined reference signal with 64 samples. Hence, the total block length N equals to $448 + 64 = 512$.

Fig. 1 *Frame format of IEEE 802.11ad SCBT transmitted signals*

Using the reference signals as the cyclic-prefix, the time-domain received signal vector $\boldsymbol{y} \triangleq \begin{bmatrix} y_1 & \cdots & y_N \end{bmatrix}^{\mathrm{T}}$ can be expressed as

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{z} \tag{2}$$

where $\boldsymbol{H}$ is the time-domain channel circular convolution matrix and $\boldsymbol{z}$ is the AWGN vector. We define $\boldsymbol{F}$ as the unitary FFT matrix. Then, the FD received signal vector $\boldsymbol{y}_F$ can be written as

$$\boldsymbol{y}_F = \boldsymbol{Fy} = \Lambda \boldsymbol{Fx} + \boldsymbol{Fz} \tag{3}$$

where $\boldsymbol{\Lambda} = \boldsymbol{FHF}^{\dagger}$ is a diagonal matrix representing the channel frequency response.

For the traditional single-carrier frequency-domain equaliser (SC-FDE) [1, 4], the received FD signal is equalised by a one-tap equaliser. Afterwards, the time-domain equalised output $\boldsymbol{r}$ is given by

$$\boldsymbol{r} \triangleq \begin{bmatrix} r_1 & \cdots & r_N \end{bmatrix}^{\mathrm{T}} = \boldsymbol{F}^{\dagger} \boldsymbol{W} \boldsymbol{y}_F \tag{4}$$

where $\boldsymbol{W}$, a diagonal matrix, is the equalisation matrix whose diagonal entries are the equaliser coefficients. In this Letter, we consider the MMSE equaliser; hence, the kth diagonal element of $\boldsymbol{W}$, namely $\boldsymbol{W}_k$, equals to $\left((\Lambda_k^*)/(|\Lambda_k|^2 + \sigma_z^2)\right)$, where Λ_k is the kth diagonal element of Λ and σ_z^2 is the AWGN power.

Finally, the time-domain equalised signal $\boldsymbol{r}$ is fed into an entry-wise minimum-distance symbol detector for data detection.

In summary, the block diagram of the conventional FDE is illustrated in Fig. 2. Compared with the OFDM receivers, the FDE for SCBT requires an additional FFT module (the shadow block in Fig. 2). Since the additional FFT module will greatly increase the chip area [6], we propose a time-domain equaliser to avoid the use of the additional FFT module in the following.

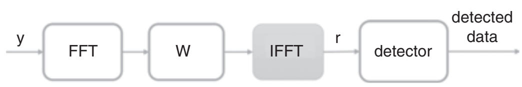

Fig. 2 *Block diagram of conventional FDE for SCBT*

Proposed time-domain linear equaliser: From (2) and (3), we can rewrite (4) as

$$\boldsymbol{r} = \boldsymbol{GHx} + \boldsymbol{Gz} = \boldsymbol{Gy} \tag{5}$$

where $\boldsymbol{G} = \boldsymbol{F}^{\dagger}\boldsymbol{WF}$ is a circular convolution matrix. Thus, the output $\{r_n\}_{n=1}^{N}$ in (5) can be interpreted as the circular convolution of the time-domain received signal $\{y_n\}_{n=1}^{N}$ with the discrete-time finite impulse response (FIR) filter $\{g_n\}_{n=1}^{N}$, where $\{g_n\}_{n=1}^{N}$ is the inverse FFT (IFFT) of $\{W_k\}_{k=1}^{N}$. That is to say, the conventional SC-FDE can be equivalently implemented in time-domain by convolving the time-domain receive signal $\{y_n\}$ with the time-domain FIR filter IR $\{g_n\}$. However, $\{g_n\}$ is, in general, an N-tap FIR filter, which is too complicated to implement in reality.

Therefore, we use a K-tap FIR filter $\tilde{\boldsymbol{g}}$ to approximate the desired response. The problem can be formulated as

$$\min_{\tilde{\boldsymbol{g}} \in \mathbb{C}^N} \|\boldsymbol{F}\tilde{\boldsymbol{g}} - \boldsymbol{Fg}\|_2^2 \quad \text{s.t. } \|\tilde{\boldsymbol{g}}\|_0 \le K \tag{6}$$

where $\boldsymbol{g} \triangleq \begin{bmatrix} g_1 & \cdots & g_N \end{bmatrix}^{\mathrm{T}}$. Since problem (6) is NP-hard, we solve the following optimisation problem instead, which is an approximation of (6) by using the Cauchy-Schwartz inequality

$$\min_{\tilde{\boldsymbol{g}} \in \mathbb{C}^N} \|\tilde{\boldsymbol{g}} - \boldsymbol{g}\|_2^2 \quad \text{s.t. } \|\tilde{\boldsymbol{g}}\|_0 \le K \tag{7}$$

Solving problem (7) is equivalent to finding the largest K elements of $\{|g_n|\}_{n=0}^{N-1}$, and this problem can be easily solved.

Comparison of computational complexity: The proposed algorithm involves an IFFT operation in the calculation of $\{g_n\}$. Since IEEE 802.11ad supports both SCBT and OFDM transmission modes, there is already an IFFT module, which is necessary for the OFDM transceiver, in the baseband communication circuit; namely, no additional FFT module is required for the proposed method. A K-tap FIR filter is required in the proposed method, but the increase in circuit area and computational complexity can be controlled by selecting an appropriate value of K at the expense of a tolerable performance degradation.

The computational complexity for the calculation of FD equalisation coefficients $\{\boldsymbol{W}_k\}$ and the time-domain K-tap FIR coefficients $\tilde{\boldsymbol{g}}$ is a minor issue. Typically, the channel coherent time for IEEE 802.11ad applications is so long that the complexity of the above-mentioned calculations can be ignored. Therefore, we only compare the computational complexity of the equalisation in the following.

To execute the FD equalisation, two N-point FFT operations and N complex multiplications are required. For convenience, we assume that an N-point FFT operation requires $N \log_2 N$ complex multiplications. Therefore, the number of complex multiplications required by the FD equalisation for IEEE 802.11ad SCBT mode is

$$\begin{aligned} & 2 \times \mathrm{FFT} + N \text{ (multiplications)} \\ & = 2 \times 512 \log_2 512 + 512 \text{ (multiplications)} \\ & = 9728 \text{ (multiplications)} \end{aligned} \tag{8}$$

On the other hand, the number of complex multiplications required by the proposed method with a K-tap FIR filter is

$$M \times K = 448 \times K \text{ (multiplications)} \tag{9}$$

It it noteworthy that the number of multiplications of the proposed time-domain equaliser will be approximately the same as the traditional FDE when $K = 21$.

Simulation results: The physical layer system parameters follow the IEEE 802.11ad specification [5], and QPSK is employed in our simulations. We use the conference room non-line-of-sight (NLOS) STA–STA sub-scenario of the 60 GHz channel model [7], which is suggested by IEEE 802.11ad, as our simulation channel model. All the channel-dependent parameters are set as the default values in [7].

Fig. 3 shows the bit error rate (BER) performance of the MMSE FDE and the proposed method with different values of K. It is obvious that the proposed method has a degradation in performance compared with FDE-MMSE, but the computational complexity can be greatly reduced. For example, for $K = 15$, there is about 1 dB performance loss at the BER level 10^{-3}, but the number of complex multiplications is reduced by 31%. Taking the case $K = 10$ as another example, the number of complex multiplications is reduced by 54% at the expense of a 1.5 dB performance loss at the BER level 10^{-3}.

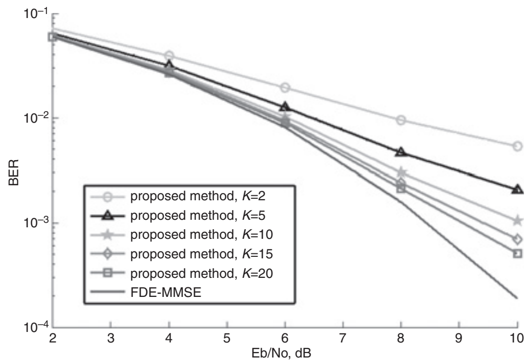

Fig. 3 *Performance of FDE-MMSE and proposed method with different values of K*

Conclusion: In this Letter, we propose a simple time-domain linear equaliser to replace the conventional FDEs for SCBT. The proposed equaliser can effectively reduce the computational complexity at the expense of an acceptable degradation in performance. Our simulation results show that in the 60 GHz conference room NLOS channels, the proposed method can reduce computational complexity by 54% at the expense of a 1.5 dB performance loss. In general, the proposed method provides an efficient way to make a trade-off between complexity and BER performance.

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C.-Y. Ma and C.-C. Huang (*Institute of Communications Engineering, National Chiao Tung University, Hsin-Chu, Taiwan*)

E-mail: ma_chun_ying.cm93@g2.nctu.edu.tw

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