AN EQUALIZATION TECHNIQUE FOR OFDM AND MC-CDMA IN A TIME-VARYING MULTIPATH FADING CHANNELS

*Won Gi Jeon, **Kyung Hi Chang, and *Yong Soo Cho

* Dept. of Electronic Engineering, Chung-Ang University, Seoul 156-756, Korea
** Electronics and Telecommunications Research Institute, Taejon 305-600, Korea

ABSTARCT

In this paper, an equalization technique for OFDM and MC-CDMA systems in a time-varying multipath fading environment is described. A loss of subchannel orthogonality due to time-variation of multipath channels leads to interchannel interference (ICI) which increases the error floor in proportion to Doppler frequency. A simple frequency domain equalizer which can compensate the effect of time-variation in a multipath fading channel is proposed by taking into account only the ICI terms significantly affecting the error performance and by modifying the previous frequency-domain equalization techniques. The effectiveness of the proposed approach is demonstrated via computer simulation by applying it to OFDM system when the multipath fading channel is time-varying.

1. INTRODUCTION

Recently, Orthogonal Frequency Division Multiplexing (OFDM) has attracted a great deal of attention for digital terrestrial broadcasting since the OFDM can mitigate the frequency selectivity of the channel using a simple one tap equalizer[1][2]. Furthermore the interchannel interference (ICI) and intersymbol interference (ISI) in OFDM can be easily prevented by inserting a guard interval before each transmitted block, longer than the largest delay spread[3]. The OFDM is generally known as an effective technique for high bit rate applications, such as digital audio broadcasting (DAB), digital video broadcasting (DVB), and digital HDTV broadcasting, due to its high spectral efficiency[2][4].

Another interesting approach, MC-CDMA, have received attention for the third generation mobile communication system, i.e., FPLMTS/IMT-2000, handling high data rates in wireless mobile radio environment [5][6]. Since the MC-CDMA technique can be considered as a multiple access technique based on OFDM, it has similar properties such as high bandwidth efficiency and robustness to multipath fading. However, most of the previous research concerning with the equalization for OFDM or MC-CDMA systems in a mobile environment have been investigated by assuming that the channel does not vary during a block period. Although the degree of channel variation over a block period becomes smaller as data rates increases, the loss of subchannel orthogonality due to a small change of multipath channel during a block period increases the error floor. The performance degradation due to the ICI becomes significant as the carrier frequency, block size, and vehicle velocity increase. In this paper, a simple frequency-domain equalizer which can compensate the effect of channel variation is described by assuming that the channel impulse response (CIR) varies in a linear fashion during a block period. Then, the ICI terms caused by the channel variation are compensated by a frequency-domain equalizer with minimum computational complexity. In section II, system models for OFDM and MC-CDMA are briefly discussed. In section III, the proposed equalization technique for OFDM and MC-CDMA in a time-varying multipath fading channel is described. After the effectiveness of the proposed approach is demonstrated by simulation in section IV, conclusion is made in section V.

2. OFDM AND MC-CDMA SYSTEMS

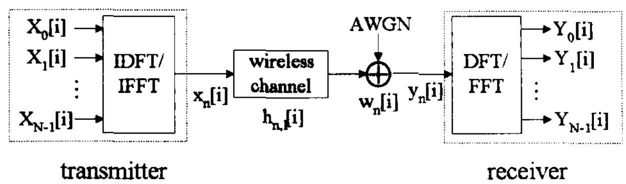

Fig. 1. A block diagram of an OFDM system

In Fig. 1, a block diagram of an OFDM system is shown. Several input bits are first encoded into one QAM symbol ($X_m[i]$), and then, N symbols are transferred by the serial-to-parallel converter (S/P) to the OFDM modulator. After each QAM symbol is modulated by the corresponding subcarrier, it is sampled and D/A converted. These blocks are omitted for simplicity in Fig. 1. Samples of OFDM signals, implemented by IDFT, can be expressed as follows:

$$x_n[i] = \sum_{m=0}^{N-1} X_m[i]\, e^{j2\pi mn/N}, \quad 0 \le n \le N-1 \tag{1}$$

where i denotes an index for OFDM blocks.

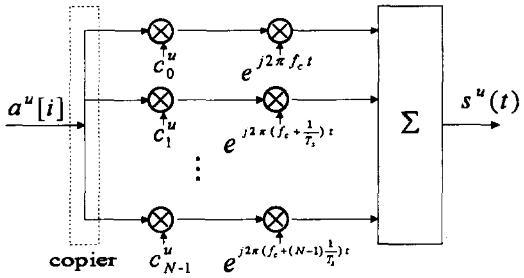

Fig. 2. Transmitter model for MC-CDMA system

A transmitter for MC-CDMA system is shown in Fig. 2. Here, $a^u[i]$ represents binary input data sequence (BPSK) of the u-th user at the i-th time. The i-th input data, $a^u[i]$, is first copied to N subchannels and, then, multiplied by the orthogonal Walsh-Hadamard code, c_m^u, corresponding to the u-th user as follows:

$$s^u(t) = a^u[i] \sum_{m=0}^{N-1} C_m^u e^{j2\pi(f_c + m\frac{1}{T_s})t}, \quad t \in [iT_s, (i+1)T_s] \tag{2}$$

This signal is modulated by N subcarriers and summed with other user's signals as

$$x(t) = \sum_{u=0}^{U-1} \sum_{m=0}^{N-1} a^u[i] C_m^u e^{j2\pi(f_c + m\frac{1}{T_s})t}, \quad t \in [iT_s, (i+1)T_s] \tag{3}$$

The resulting signal is sampled and transmitted to the wireless channel. Expression (3) can be rewritten by an equivalent discrete-time signal at baseband as follows:

$$x_n[i] = \sum_{n=0}^{N-1} X_m[i]\, e^{j2\pi mn/N}, \quad n = 0, 1, \cdots, N-1 \tag{4}$$

where $X_m[i] = \sum_{u=0}^{U-1} a^u[i] C_m^u$.

Since the transmitted sequence, $x_n[i]$, in (4) has the same form as the one in OFDM system except for multiuser capability, the following discussion will be applied to both OFDM and MC-CDMA systems. For notational convenience, the index, i, for OFDM blocks will be omitted.

Assuming that the multipath fading channel consists of L-path, the received signal can be expressed as

$$\begin{aligned} y_n &= \sum_{l=0}^{L-1} h_{n,l}\, x_{n-l} + w_n \\ &= h_{n,0}\, x_n + h_{n,1} x_{n-1} + \cdots + h_{n,L-1} x_{n-L+1} + w_n \end{aligned} \tag{5}$$

where w_n represents AWGN and $h_{n,l}$ represents the CIR of the l-th path at time n. The demodulated signal in frequency domain can be obtained by taking DFT or FFT of y_n as

$$Y_m = \sum_{n=0}^{N-1} y_n e^{-j2\pi mn/N} + W_m, \quad 0 \le m \le N-1 \tag{6}$$

where W_m denotes DFT of w_n given by

$$W_m = \frac{1}{N} \sum_{n=0}^{N-1} w_n e^{-j2\pi mn/N} \tag{7}$$

By substituting (5) into (6), the following equation is obtained:

$$Y_m = \sum_{k=0}^{N-1} \sum_{l=0}^{L-1} X_k H_l^{(m-k)} e^{-j2\pi lk/N} + W_m \tag{8}$$

where $H_l^{(m-k)}$ represent the DFT of time-varying channel, $h_{n,l}$, as follows:

$$H_l^{(m-k)} = \frac{1}{N} \sum_{n=0}^{N-1} h_{n,l}\, e^{-j2\pi n(m-k)/N} \tag{9}$$

Then, (8) can be rewritten as

$$\begin{aligned} Y_m &= \Big[\sum_{l=0}^{L-1} H_l^{\,0} e^{-j2\pi lm/N}\Big] X_m \\ &\quad + \sum_{k\ne m}^{N-1} \sum_{l=0}^{L-1} X_k H_l^{(m-k)} e^{-j2\pi lk/N} + W_m \\ &= \alpha_m X_m + \beta_m + W_m \end{aligned} \tag{10}$$

where

$$\alpha_m = \sum_{l=0}^{L-1} H_l^{\,0} e^{-j2\pi lm/N}, \tag{11}$$

$$\beta_m = \sum_{k\ne m}^{N-1} \sum_{l=0}^{L-1} X_k H_l^{(m-k)} e^{-j2\pi lk/N} \tag{12}$$

Here, α_m and β_m represent the multiplicative distortion at self-subchannel and ICI due to other subchannels, respectively[7].

If the channel can be assumed to be time-invariant during a block period, (9) can be simplified further as follows:

$$H_l^{(m-k)} = \frac{1}{N} h_l \sum_{n=0}^{N-1} e^{-j2\pi n(m-k)/N} \tag{13}$$

When $m \ne k$, $H_l^{(m-k)}$ in (13) vanishes, implying that there exists no ICI for time-invariant channels. Since $H_l^{(m-k)}$ becomes h_l for $m = k$, Y_m in (8) contains only multiplicative distortion at self-subchannel, which can be easily compensated by 1-tap frequency-domain equalizer. However, in order not to degrade the performance of OFDM or MC-CDMA systems in a time-varying multipath channel, the ICI terms as well as multiplicative distortion at self-subchannel must be taken into account for the design of frequency-domain equalizer.

3. AN EQUALIZATION TECHNIQUE FOR A TIME-VARYING MULTIPATH FADING CHANNEL

In general case where the multipath fading channel cannot be regarded as time-invariant during a block period, the vector equation for (7) can be expressed as

$$\mathbf{Y} = \mathbf{HX}+\mathbf{W} \tag{14}$$

where

$$\mathbf{Y} = [Y_0,\ Y_1,\ \cdots,\ Y_{N-1}]^T, \tag{15}$$

$$\mathbf{X} = [X_0,\ X_1,\ \cdots,\ X_{N-1}]^T, \tag{16}$$

$$\mathbf{W} = [W_0,\ W_1,\ \cdots,\ W_{N-1}]^T, \tag{17}$$

$$\mathbf{H}=\begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & & \ddots & \vdots \\ a_{N-1,0} & a_{N-1,1} & \cdots & a_{N-1,N-1} \end{bmatrix} \tag{18}$$

Here, $a_{m,k}$ in (18) is defined as

$$a_{m,k} = H_0^{(m-k)}+H_1^{(m-k)}e^{-j\pi k/N}+ \cdots + H_{L-1}^{(m-k)}e^{-j2\pi k(L-1)/N}$$

$$0\leq m,\ k\leq N-1 \tag{19}$$

To design an equalizer in the frequency-domain, one may use either of two widely-used criteria, resulting in[8]

$$\text{zero-forcing}: \ \mathbf{X} = \mathbf{H}^{-1}\mathbf{Y}^{\mathrm{T}} \tag{20}$$

$$\text{MMSE}: \ \mathbf{X} = \mathbf{H}^{*}\ [\mathbf{HH}^{*} + \sigma_w^2/\sigma_x^2]^{-1}\,\mathbf{Y}^{\mathrm{T}} \tag{21}$$

where σ_w^2 and σ_x^2 represent noise power and signal power, respectively.

In order to solve the equation in (20) and (21), we need both matrix calculation and estimation of $\mathbf{H}$ with a large size, which make it difficult to process in real time. However, when the channel can be considered to be slowly time-variant so that time variations of CIR, $h_{n,l}$, for all L paths are approximated by straight lines with low slopes during a block period, the matrix equation in (14) can be greatly simplified. Since most energy of a straight line with a small slope is constrained in the neighborhood of DC component in the frequency domain, the ICI terms which does not affect significantly Y_m in (10) can be ignored, i.e.,

$$a_{m,k} = 0 \qquad \text{for}\ \ |m-k|\geq \frac{q}{2} \tag{22}$$

where q denotes the number of dominant ICI terms which is not negligible. Then, the matrix equation given in (14) reduces to the one with a smaller size as

$$\mathbf{Y}_{m-\frac{q}{2}:m+\frac{q}{2}} = \mathbf{H}_{m-\frac{q}{2}:m+\frac{q}{2}}\ \mathbf{X}_{m-\frac{q}{2}:m+\frac{q}{2}} \tag{23}$$

where

$$\mathbf{X}_{m-\frac{q}{2}:m+\frac{q}{2}} = [X_{m-\frac{q}{2}} \cdots X_m \cdots X_{m+\frac{q}{2}}]^T, \tag{24}$$

$$\mathbf{Y}_{m-\frac{q}{2}:m+\frac{q}{2}} = [Y_{m-\frac{q}{2}} \cdots Y_m \cdots Y_{m+\frac{q}{2}}]^T, \tag{25}$$

$$\mathbf{H}_{m-\frac{q}{2}:m+\frac{q}{2}} = \begin{bmatrix} a_{m-\frac{q}{2},m-\frac{q}{2}} & \cdots & a_{m-\frac{q}{2},m} & \cdots & a_{m-\frac{q}{2},m+\frac{q}{2}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{m,m-\frac{q}{2}} & \cdots & a_{m,m} & \cdots & a_{m,m+\frac{q}{2}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{m+\frac{q}{2},m-\frac{q}{2}} & \cdots & a_{m+\frac{q}{2},m} & \cdots & a_{m+\frac{q}{2},m+\frac{q}{2}} \end{bmatrix} \tag{26}$$

In order to construct the matrix equation in (14) or (23), it is necessary to estimate $\mathbf{H}$ consisting of various transfer functions. However, accurate estimation of transfer function for each path requires complete knowledge of time-variation in CIR, $h_{n,l}$ for each block which is not the case in practical situation. By utilizing the above assumption that the CIR varies in a linear fashion during a block period, the estimation problem of $\mathbf{H}_{m-\frac{q}{2}:m+\frac{q}{2}}$ can also be greatly simplified since the value of slope of a straight line uniquely determines the ICI. The procedure for transfer function estimation is given as follows. First, time-domain pilot signal is inserted at the end of each block. Then, by comparing the CIR change between the previous block and current block for each path, the CIR variation during a block period can be estimated using the linear interpolation. Finally, the components of channel matrix, $\mathbf{H}_{m-\frac{q}{2}:m+\frac{q}{2}}$, are obtained by

$$H_l^{(k)} = \frac{1}{N}\sum_{n=0}^{N-1}\left\{p^l[i-1] + \frac{p^l[i]-p^l[i-1]}{N}\,n\right\}e^{-j2\pi nk/N} \tag{27}$$

where $p^l[i-1]$ and $p^l[i]$ denote the CIR of the previous block and current block for the l-th path, respectively. In practical situation, $H_l^{(k)}$ needs to be calculated for only a few k subcarriers, e.g., k = 0, 1, 2 for q = 2, or k = 0, 1, 2, 3, 4 for q = 4.

4. SIMULATION

To demonstrate the effectiveness of the proposed approach for a time-varying multipath channel, the following simulations are performed. The simulations are focused on the OFDM system since the performance of MC-CDMA, based on OFDM, in a time-varying environment can be interpreted in the same way except for multiuser interference. The considered mobile radio channel is a two-path fading channel with a multipath spread of 2 μsec. A bandwidth of 500 KHz with a carrier frequency at 1 GHz is considered for transmission. The total bandwidth is divided into 64 subband, hence the size of FFT becomes 64. An OFDM block is composed of 68 samples, one for cyclic prefix and three for pilot signals. The modulation scheme used for this simulation is 16-QAM. Doppler frequency is taken into account up to 200 Hz, resulting in the degree of time-variation, 0.00256 for 20 Hz, 0.0128 for 100 Hz, and 0.0256 for 200 Hz. Here, the degree of time-variation is defined as the ratio of block period (T_b) to the inverse of Doppler frequency (f_D). Perfect carrier and symbol synchronizations are assumed.

Fig. 3 shows the BER performances when different types of zero-forcing equalizers discussed in this paper are used to reduce the performance degradation of the OFDM system due to the time-varying channel. Three different cases where Doppler frequencies are set to 20 Hz, 100 Hz, and 200 Hz are considered for the multipath fading channel. Fig. 3 shows the BER comparison when the conventional zero-forcing equalizer, denoted by ZF-C, and the proposed zero-forcing equalizers, denoted by ZF-P, with different matrix sizes are applied to the channel. From Fig. 3(a), one can see that there is no big advantage of using the proposed equalizer when channel is slowly-varying, i.e., f_D = 20 Hz. However, as Doppler frequency increases, the gap between the conventional equalizer and the proposed equalizer becomes larger. Notice that the proposed equalizers with small matrix size (3 or 5) are effective in compensating the ICI and multiplicative distortion at self-subchannel. For the equalizer with matrix size of 3 (5), 2 (4), the adjacent ICI's in addition to the distortion at self-subchannel are compensated. In overall, the loss of orthogonality due to time-variation of multipath fading channel can be compensated to a certain extent by the proposed equalizer with small computational complexity.

5. CONCLUSION

In OFDM and MC-CDMA systems, time-varying fading effect of a mobile wireless channel is known to impair the orthogonality of the subchannel, resulting in an increase of error floor. In this paper, a simple frequency-domain equalization technique which can effectively compensate the ICI with a low computational burden was proposed. By assuming that the CIR varies in a linear fashion during a block period, a simple estimation technique for ICI and distortion at self-subchannel, and a simple equalization technique for their compensation were described. Finally, it was confirmed by simulation that the performance of a time-varying fading channel can be significantly improved by the proposed equalizer that compensates only a few neighboring ICI's and distortion at self-subchannel.

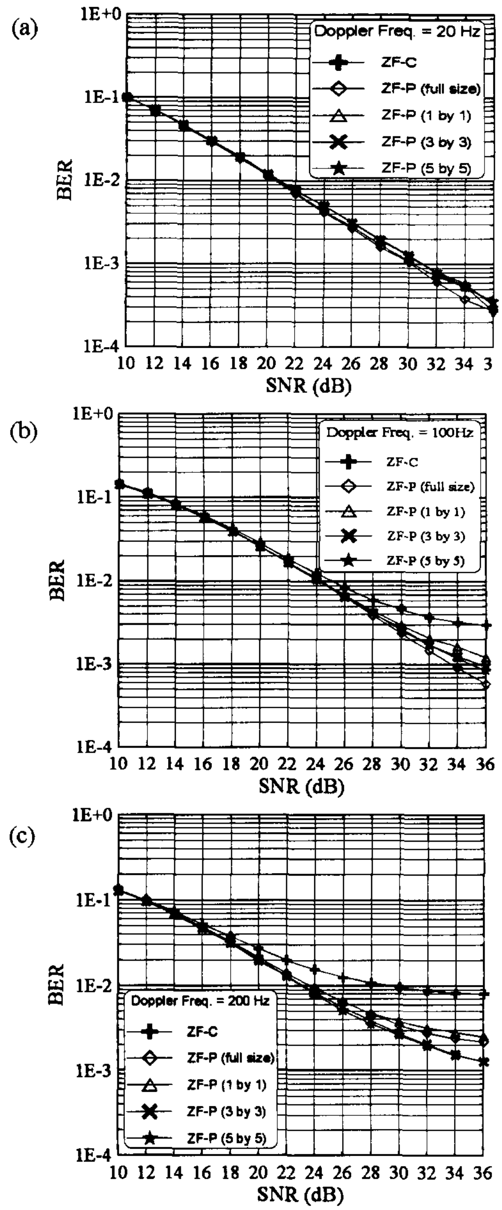

Fig. 3. BER comparisons when the conventional ZF equalizer and proposed ZF equalizers are applied to the time-varying channels with three different Doppler frequencies.

REFERENCES

[1] L. C. Cimini, Jr., "Analysis and simulation of a digital mobile channel using orthogonal frequency-division multiplexing," *IEEE Trans. Commun.*, vol. 33, no. 7, pp. 665-675, July 1985.

[2] M. Alard and R. Lassale, "Principles of modulation and channel coding for digital broadcasting for mobile receivers," *EBU Tech. Review*, no. 224, pp. 3-25, Aug. 1987.

[3] J. A. C. Bingham, "Multicarrier modulation for data transmission: an idea whose time has come," *IEEE Commun. Magazine*, vol. 28, no. 5, pp. 5-14, May 1990.

[4] H. Sari, G. Karam, and I. Jeanclaude, "Transmission techniques for digital terrestrial TV broadcasting," *IEEE Commun. Magazine*, vol. 33, pp. 100-109, Feb. 1995.

[5] N. Yee, J. Linnartz, and G. Fettweis, "Multi-carrier CDMA in indoor wireless radio networks," *Proc. PIMRC*, pp. 109-113, Sep. 1993.

[6] S. Kaiser, "OFDM-CDMA versus DS-CDMA: performance evaluation for fading channels," *Proc. ICC*, pp. 1722-1726, June 1995.

[7] M. Russel and G. L. Stüber, "Interchannel interference analysis of OFDM in a mobile environment," *Proc. VTC*, pp. 820-824, July 1995.

[8] E. A. Lee and D. G. Messerschmitt, *Digital Communication*, KAP, second ed., 1994.