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PAPER

# Joint Use of Frequency-Domain Equalization and Transmit/Receive Antenna Diversity for Single-Carrier Transmissions

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**SUMMARY** The joint use of frequency-domain equalization and antenna diversity is presented for single-carrier (SC) transmission in a frequency-selective fading channel. Frequency-domain equalization techniques using minimum mean square error (MMSE), orthogonal restoration combining (ORC) and maximum ratio combining (MRC), those used in multi-carrier code division multiple access (MC-CDMA), are considered. As antenna diversity techniques, receive diversity and delay transmit diversity (DTD) are considered. Bit error rate (BER) performance achievable with the joint use of frequency-domain equalization and antenna diversity is evaluated by computer simulation.

***key words:*** *single-carrier transmission, frequency-domain equalization, delay transmit diversity, frequency-selective fading*

## 1. Introduction

Wireless channel is composed of many propagation paths with different time delays, producing frequency-selective multipath fading [1]. In a frequency-selective fading channel, since the performance of single-carrier (SC) transmission significantly degrades due to severe inter-symbol-interference (ISI), some adaptive equalization techniques (e.g., decision feedback equalization (DFE) or maximum likelihood sequence estimation (MLSE)) must be employed [2]. Although MLSE gives better performance than DFE, its computational complexity grows exponentially as the number of propagation paths increases, i.e., the channel frequency-selectivity becomes stronger (note that the MLSE can be implemented using Viterbi algorithm and there have been studies on reducing its computational complexity [3], [4]). To exploit the channel frequency-selectivity for improving the transmission performance, a coherent rake combiner can be employed as the channel matched filter in direct sequence code division multiple access (DS-CDMA) [2]. Wideband DS-CDMA has been adopted in the 3rd generation mobile communications systems, known as IMT-2000 systems, for data transmissions of up to a few Mbps [5]. However, for transmissions of more than a few Mbps in DS-CDMA, too many rake fingers (or correlators) are required (this increases the receiver complexity) and furthermore, the transmission performance may significantly degrade due to large inter-path interference (IPI) even if coherent rake combining is used.

Recently, instead of DS-CDMA, multi-carrier (MC) transmission using orthogonal subcarriers [6], [7] (i.e., orthogonal frequency division multiplexing (OFDM) and MC-CDMA, which is a combination of OFDM and CDMA) has been attracting much attention for high speed data transmissions in a severe frequency-selective channel. However, the MC signals have large peak-to-average power ratio (PAPR) and thus, a linear transmit power amplifier with large peak power is required. More recently, SC transmission using one-tap frequency-domain equalization has been gaining an increasing popularity [8]. SC transmission has advantages that the problem of high PAPR can be alleviated and the computational complexity of frequency-domain equalization does not depend on the degree of channel frequency-selectivity.

As mentioned earlier, adaptive equalization techniques can be used to improve the SC transmission performance in a frequency-selective fading. However, in a frequency-nonselective fading channel, adaptive equalization does not give any advantage. Transmit/receive antenna diversity is a well-known effective technique to improve the bit error rate (BER) performance [1]. Recently, transmit antenna diversity has been attracting much attention [9]. Recent studies have shown that the combination of delay transmit diversity (DTD) at a transmitter and adaptive equalization, e.g., MLSE, at a receiver offers improvements in the BER performance when the channel exhibits frequency-nonselective or weak frequency-selective fading [10]–[13]. With DTD, the same signal is transmitted from different antennas after adding different time delays so that the frequency-nonselective fading channel can be transformed into a frequency-selective fading channel which can be fully exploited by adaptive equalization at the receiver. A delay of more than a symbol period between the transmit antennas increases the number of states in MLSE and therefore, relative transmit time delay of a symbol period is used [13]. So far, only the combination of DTD and time-domain equalization has been considered as in [10]–[13].

Objective of this paper is to show that instead of time-domain equalization, frequency-domain equalization can be used jointly with DTD. The remainder of this paper is organized as follows. In Sect. 2, the BER performance of SC transmission achievable by the joint use of one-tap frequency-domain equalization and receive antenna diversity is discussed. Frequency-domain equalization techniques employing minimum mean square error (MMSE), orthogonal restoration combining (ORC) and maximum ratio combining (MRC), those used in MC-CDMA [14], are considered. Performance achieved with frequency-

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domain equalization is compared with that of MLSE time-domain equalization to show that MMSE frequency-domain equalization can also exploit the frequency-selectivity of the channel and achieve similar performance improvement (with some degradations) to MLSE time-domain equalization. This suggests that MMSE frequency-domain equalization can be used jointly with DTD. In Sect. 3, we discuss the joint use of MMSE frequency-domain equalization and DTD combined with receive antenna diversity. Section 4 offers some conclusions and future work.

## 2. Joint Use of Frequency-Domain Equalization and Receive Antenna Diversity

### 2.1 System Model

Figure 1 illustrates the transmitter and the receiver structure for SC transmission with joint use of frequency-domain equalization and receive antenna diversity. The transmit data symbol sequence is divided into frames of $N_c$ data-modulated symbols each. The last $N_g$ symbols in each frame is copied and inserted as the cyclic prefix into the guard interval (GI) placed at the beginning of each frame. Without loss of generality, we consider the transmission of one frame. Symbol-spaced discrete time representation is used throughout the paper. Data symbol sequence of $N_c$ symbols is denoted by $\{d(t); t = 0 \sim N_c-1\}$. The resultant GI-inserted symbol sequence of $(N_c + N_g)$-symbol length becomes

$$\tilde{d}(t) = d(t \bmod N_c) \tag{1}$$

for $t = -N_g \sim N_c - 1$. The SC signal sequence $\{s(t); t = -N_g \sim N_c - 1\}$ to be transmitted is expressed using the equivalent baseband representation as

$$s(t) = \sqrt{2E_s/T}\,\tilde{d}(t), \tag{2}$$

where $E_s$ is the transmit signal energy per symbol and $T$ is the symbol length.

The SC signal sequence $\{s(t)\}$ is transmitted over a frequency-selective fading channel and is received by $N_r$ antennas at the receiver. The channel is assumed to be a symbol-spaced $L$-path frequency-selective fading channel, each discrete path being subjected to independent fading. Time delay of the $l$-th path, $l = 0 \sim L-1$, is assumed to be $l$ symbols. After removal of GI from each received frame, $N_c$-point fast Fourier transform (FFT) is applied to obtain $N_c$ subcarrier components (although SC transmission does not use subcarriers for modulation, the terminology "subcarrier" is used for explanation purpose only), followed by one-tap frequency-domain equalization and receive antenna diversity combining. Then, $N_c$-point inverse FFT (IFFT) is applied to the $N_c$ diversity-combined subcarrier components to transform back into the time-domain signal. Finally, data demodulation is carried out.

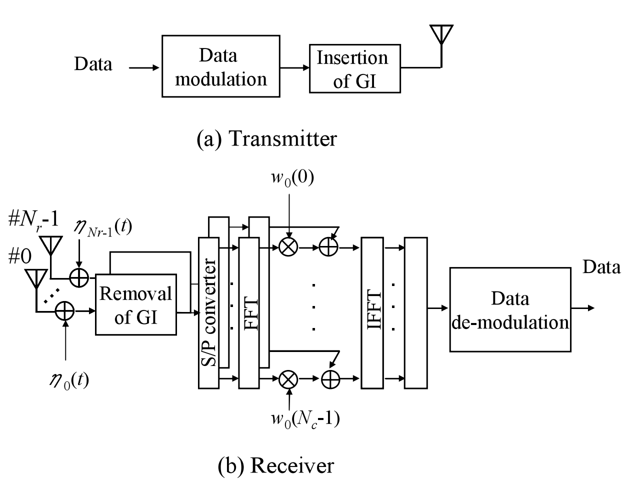



**Fig. 1** Transmitter and receiver with frequency-domain equalization and receive antenna diversity.

### 2.2 Frequency-Domain Equalization and Receive Antenna Diversity

The received signal sample $r_m(t)$ at time $t$ on the $m$-th antenna, $m = 0 \sim N_r-1$, can be expressed using the equivalent lowpass representation as

$$r_m(t) = \sum_{l=0}^{L-1} \xi_{m,l}\, s(t-l) + \eta_m(t), \tag{3}$$

where $\xi_{m,l}$ represents the complex path gain of the $l$-th path observed at the $m$-th receive antenna and $\eta_m(t)$ is the noise process characterized by a zero-mean complex Gaussian process with a variance $2N_0/T$; $N_0$ is the one-sided power spectrum density of additive white Gaussian noise (AWGN). Block fading, where the path gains stay constant over one data frame, has been assumed for simplicity.

At the receiver, after removal of GI, the received signal sample sequence $\{r_m(t);\ t = 0 \sim N_c - 1\}$ is decomposed into $N_c$ subcarrier components $\{R_m(n);\ n = 0 \sim N_c - 1\}$ by applying FFT. $R_m(n)$ is given by

$$\begin{aligned} R_m(n) &= \sum_{t=0}^{N_c-1} r_m(t) \exp(-j2\pi tn/N_c) \\ &= \sqrt{2E_s/T}\, H_m(n) D(n) + N_m(n), \end{aligned} \tag{4}$$

where $\{H_m(n)\}$ and $\{D(n)\}$ are the Fourier transforms of the channel impulse response and the transmitted symbol sequence of $N_c$ symbols, respectively, given by

$$\left\{ \begin{aligned} H_m(n) &= \sum_{l=0}^{L-1} \xi_{m,l} \exp\left(-j2\pi l \frac{n}{N_c}\right) \\ D(n) &= \sum_{t=0}^{N_c-1} d(t) \exp\left(-j2\pi t \frac{n}{N_c}\right) \end{aligned} \right. , \tag{5}$$

and $N_m(n)$ is the noise component due to the AWGN at the $n$-th subcarrier. Then, one-tap frequency-domain equalization and receive antenna diversity combining are carried out simultaneously. The $n$-th subcarrier component $\tilde{R}(n)$ can be written as

$$\begin{aligned}\tilde{R}(n) &= \sum_{m=0}^{N_r-1} R_m(n)w_m(n)\\ &= \sqrt{2E_s/T}\left(\sum_{m=0}^{N_r-1} w_m(n)H_m(n)\right)D(n)\\ &\quad+\sum_{m=0}^{N_r-1} w_m(n)N_m(n), \end{aligned}\tag{6}$$

where $w_m(n)$ is the weight for the joint frequency-domain equalization and receive antenna diversity combining. The first term of Eq. (6) is the signal component and the second is the noise component. Comparison of Eqs. (4) and (6) shows that $\sum_{m=0}^{N_r-1} w_m(n)H_m(n)$ and $\sum_{m=0}^{N_r-1} w_m(n)N_m(n)$ represent the equivalent channel gain and noise after frequency-domain equalization and receive antenna diversity combining, respectively. The following weights obtained for MC-CDMA [15] are used in this paper:

$$w_m(n) = \begin{cases} \dfrac{H_m^*(n)}{\sum_{m=0}^{N_r-1} |H_m(n)|^2 + (E_s/N_0)^{-1}} & \text{for MMSE}\\ \dfrac{H_m^*(n)}{\sum_{m=0}^{N_r-1} |H_m(n)|^2} & \text{for ORC}\\ H_m^*(n) & \text{for MRC,}\end{cases}\tag{7}$$

where $E_s/N_0$ is the average received signal energy per symbol-to-AWGN power spectrum density ratio. $N_c$-point IFFT is applied to $N_c$ subcarrier components $\{\tilde{R}(n); n = 0 \sim N_c - 1\}$ to obtain the soft decision sample sequence $\{\hat{r}(t); t = 0 \sim N_c - 1\}$ for data demodulation with respect to $\{d(t); t = 0 \sim N_c - 1\}$:

$$\hat{r}(t) = (1/N_c)\sum_{n=0}^{N_c-1} \tilde{R}(n)\exp(j2\pi tn/N_c)\tag{8}$$

for $t = 0 \sim N_c - 1$.

ORC equalization perfectly restores frequency-nonselective channel, but produces the noise enhancement. MRC maximizes signal-to-noise ratio (SNR) of the time-domain signal sample sequence after IFFT operation, but enhances the frequency-selectivity of the channel and thus, produces a larger ISI. On the other hand, MMSE gives up the perfect restoration of frequency-nonselective channel to prevent the noise enhancement.

### 2.3 Computer Simulation

The average BER performance of SC transmission with joint frequency-domain equalization and receive antenna diversity combining is evaluated by computer simulation. The simulation parameters are given in Table 1. Binary phase shift keying (BPSK) data modulation, $N_c$=256, $N_g$=32, and a symbol-spaced $L$-path frequency-selective block Rayleigh fading channel (i.e., the largest time delay difference is $L-1$ symbols) are assumed. For the power delay profile model for wideband propagation channels, we consider an exponential power delay profile $\Omega(\tau)$ [16] with a decay factor of $\alpha$:

**Table 1** Simulation parameters.

| | | |
|---|---|---|
| Transmitter | Modulation | BPSK |
| | Number of FFT points | $N_c$=256 |
| | Guard interval length | $N_g$= 32 (symbol) |
| Channel | Fading | Frequency-selective block Rayleigh fading |
| | Power delay profile | $L$ path exponential power delay profile |
| | | Decay factor $\alpha$=0, 8 dB |
| Receiver | Number of received antennas | $N_r$=1, 2, 4 |
| | Frequency-domain Equalization | MMSE, MRC, ORC |
| | Channel estimation | ideal |

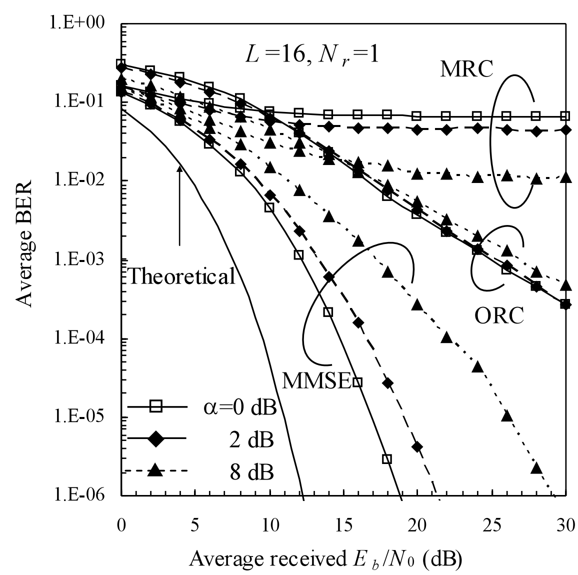



**Fig. 2** Performance comparison of MMSE, ORC, and MRC frequency-domain equalizations for no antenna diversity ($N_r$ = 1) and $L$ = 16.

$$\Omega(\tau) = \sum_{l=0}^{L-1} \Omega_l\delta(\tau - l) = \Omega_0\sum_{l=0}^{L-1} \alpha^{-l}\delta(\tau - l),\tag{9}$$

where $\Omega_l = E\left[\left|\xi_{m,l}\right|^2\right]$ for all $m$ ($E[.]$ denotes the ensemble average operation) and $\sum_{l=0}^{L-1}\Omega_l = 1$ (this gives $\Omega_0 = [1 - \alpha^{-1}]/[1 - \alpha^{-L}]$). Ideal sampling timing and ideal channel estimation at the receiver are also assumed.

First, we assume no diversity ($N_r = 1$) and $L = 16$. Figure 2 compares the average BER performances achievable with MMSE, ORC, and MRC frequency-domain equalizations, as a function of the average received signal energy per information bit-to-AWGN power spectrum density ratio $E_b/N_0$ with GI insertion, which is given by

$$\frac{E_b}{N_0} = \frac{E_s}{N_0}(1 + N_g/N_c) \tag{10}$$

for BPSK modulation. For comparison, the theoretical BER performance is also plotted in Fig. 2. In this paper, a single user is assumed for SC transmission. For the single user transmission in MC-CDMA, the best frequency-domain equalization scheme is MRC [6]. However, performance comparison for SC transmission in Fig. 2 has shown that MMSE frequency-domain equalization gives the best performance. The reason for this is that data symbol energy is spread over the entire signal bandwidth and hence, MRC produces larger ISI due to the enhancement of the frequency-selectivity (this is similar to the case of MC-CDMA in a multi-user environment). How the ORC, MRC, and MMSE frequency-domain equalization schemes equalize the transmission channel differently is discussed in Appendix. Since the ORC perfectly restores the frequency-nonselective channel, the BER performance using ORC is insensitive to the channel frequency-selectivity (which gets weaker as the decay factor $\alpha$ increases) and is close to that in the frequency-nonselective channel. It should be pointed out that the BER performance using MMSE frequency-domain equalization is sensitive to $\alpha$ and improves as $\alpha$ reduces. This is due to the increasing frequency diversity effect (i.e., the probability of the received signal powers dropping simultaneously at many subcarriers becomes less as $\alpha$ reduces). Hence, MMSE frequency-domain equalization is assumed in the following simulations.

The improvement in the BER performance with the joint use of MMSE frequency-domain equalization and receive antenna diversity combining is shown in Fig. 3, which plots the average BER performance as a function of the average $E_b/N_0$ per antenna with the number $L$ of paths and the number $N_r$ of receive antennas as parameters. For comparison, the BER performance using MLSE time-domain equalization, implemented by Viterbi algorithm having $2^{L-1}$ states, is also plotted. The branch metric $\lambda$ for state transition from state $S(t-1) = \{d(t-L+1), \ldots, d(t-1)\}$ to state $S(t) = \{d(t-L+2), \ldots, d(t)\}$ is computed from

$$\lambda\{S(t-1) \to S(t)\} = \sum_{m=0}^{N_r-1} \left| r_m(t) - \sqrt{2E_s/T} \sum_{l=0}^{L-1} \xi_{l,m}(t) d(t-l) \right|^2. \tag{11}$$

It can be seen from Fig. 3 that as $L$ increases, the BER performance improves. Although MLSE time-domain equalization gives better BER performance than MMSE frequency-domain equalization, the performance difference becomes smaller as $N_r$ increases. The computational complexity of MMSE frequency-domain equalization does not depend on the value of $L$, while that of MLSE time-domain equalization grows exponentially as $L$ increases. Therefore,

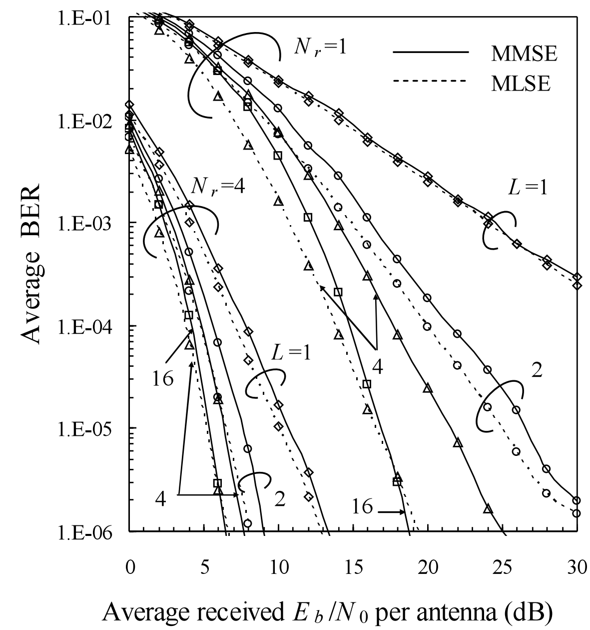



**Fig. 3** Joint effect of MMSE frequency-domain equalization and receive antenna diversity combining.

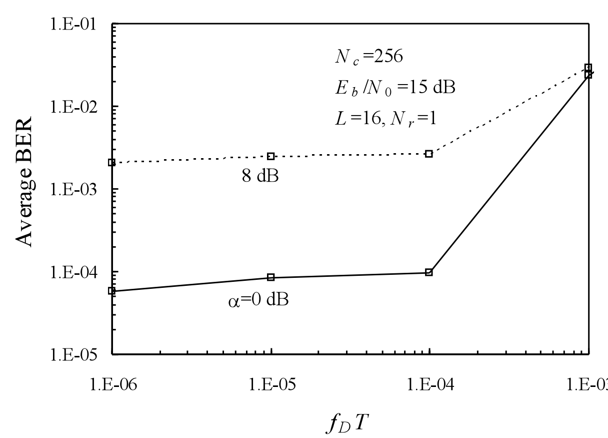



**Fig. 4** Dependency of the BER on the maximum Doppler frequency $f_D T$ at the average $E_b/N_0$=15 dB.

it can be said that the MMSE frequency-domain equalization is an attractive technique for broadband SC transmission.

So far, we have assumed block fading, where the path gains stay constant over one data frame (the frame length in time equals $N_c T$). However, in practice, path gains may vary during one frame if the mobile station travels fast. It is interesting to see how the fading maximum Doppler frequency $f_D$ impacts the achievable BER performance, where $f_D$ is given by the traveling speed/carrier wavelength [1]. The BER dependency on $f_D T$ at the average $E_b/N_0$=15 dB is plotted in Fig. 4 for the single receive antenna case. It can be seen that the achievable BER is almost insensitive to $f_D T$ if $f_D T < 0.0001$ when $N_c$=256 (this corresponds to the traveling speed of 200 km/h for the bit rate $(1/T)$ of 10 Mbps and 5 GHz carrier frequency). Hence, block fading is assumed in the following simulations.

## 3. Joint Use of MMSE Frequency-Domain Equalization and Delay Transmit/Receive Diversity

As understood from Fig. 3, the BER performance with frequency-domain equalization improves as the frequency-selectivity of channel becomes stronger (or as the number $L$ of paths increases). To artificially increase the frequency-selectivity of the channel, DTD is used where the same signal is transmitted from multiple antennas after giving different time delays [10]–[13]. DTD is particularly useful when frequency-selectivity of the channel is weak.

### 3.1 Application of DTD

Figure 5 illustrates the SC transmitter structure employing DTD. The receiver structure is the same as in Fig. 1. Different time delays $\{\tau_n;\ n = 0 \sim N_t - 1\}$ are inserted into the GI-inserted signal sequence and transmitted simultaneously from $N_t$ transmit antennas.

The signal $r_m(t)$ received on the $m$-th receive antenna at time $t$ can be represented as

$$r_m(t)=\sqrt{2\frac{E_s/N_t}{T}}\sum_{n=0}^{N_t-1}\sum_{l=0}^{L-1}\xi_{n,m,l}\tilde{d}(t-\tau_n-l)+\eta_m(t), \tag{12}$$

where $\xi_{n,m,l}$ is the $l$-th path gain between the $n$-th transmit antenna and the $m$-th receive antenna. Since the transmit power from each antenna is $1/N_t$ times the single transmit antenna case, the total transmit power is kept the same. The equivalent power delay profile $\tilde{\Omega}(\tau)$ observed at the receiver can be expressed as

$$\tilde{\Omega}(\tau) = \frac{1}{N_t}\sum_{n=0}^{N_t-1}\Omega(\tau-\tau_n). \tag{13}$$

For the case of the equal time delay difference (i.e., $\tau_n = n\Delta\tau$), $\tilde{\Omega}(\tau)$ is illustrated in Fig. 6 for $N_t$=4 and $\Delta\tau$ = 5 symbols when $L$=16 and $\alpha$=4 dB.

It can be clearly understood from Fig. 6 that DTD increases the frequency-selectivity of the channel, thereby improving the BER performance achievable with frequency-domain equalization.

### 3.2 Computer Simulation

Figure 7 plots the dependency of the BER on the time delay insertion $\Delta\tau$ at the average $E_b/N_0$=15 dB when $N_t$=2 and 4. As $\Delta\tau$ increases, the BER reduces and stays constant, but starts to increase when the maximum time delay difference resulting from the delay insertion and the propagation delay becomes larger than GI. Therefore, in the following simulation, $\Delta\tau$ is set as

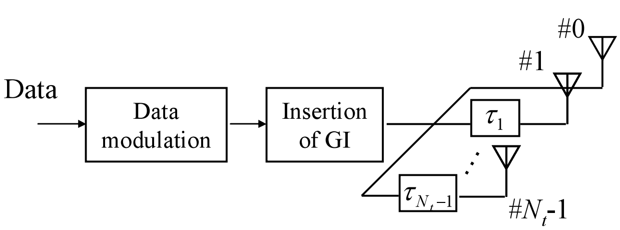



**Fig. 5** SC transmitter employing DTD.

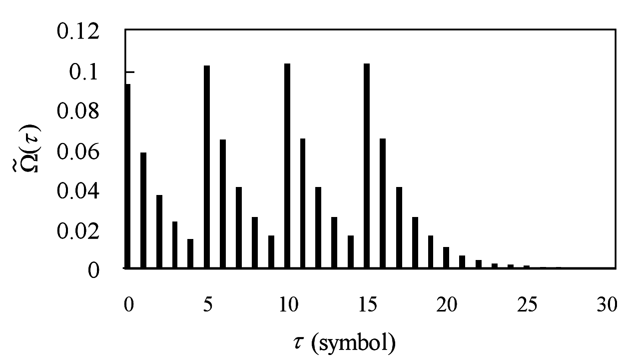
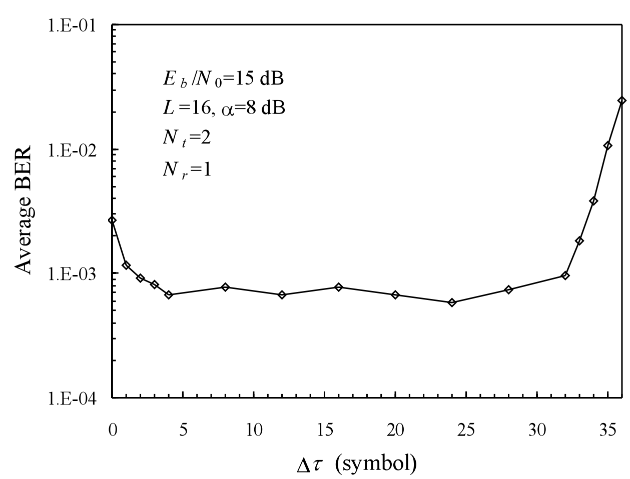
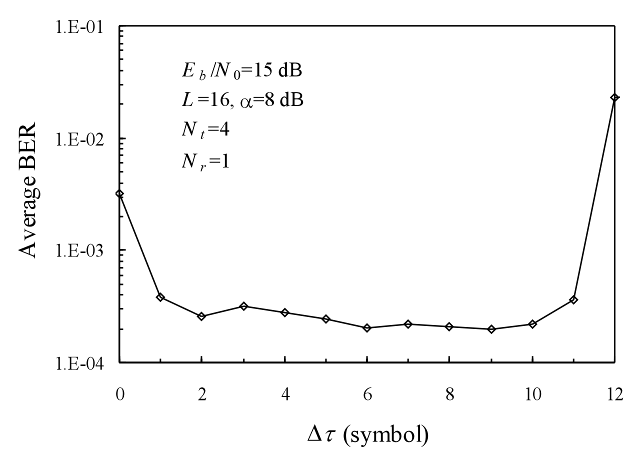



**Fig. 6** Equivalent power delay profile $\tilde{\Omega}(\tau)$ observed at the receiver for $N_t$=4 and $\Delta\tau$ = 5 symbols when $L$=16 and $\alpha$ = 4 dB.




(a) $N_t$ = 2.




(b) $N_t$ = 4.

**Fig. 7** BER dependency on $\Delta\tau$ at the average $E_b/N_0$ = 15 dB.

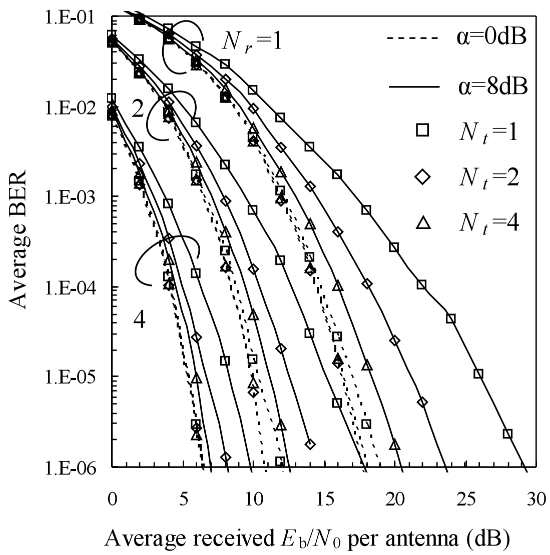



**Fig. 8** Joint effect of MMSE frequency-domain equalization and DTD/receive diversity.

$$\Delta\tau = \left\lfloor \frac{N_g - L}{N_t - 1} \right\rfloor \quad \text{symbols,} \tag{14}$$

so that the maximum time delay difference is within the GI, where $\lfloor x \rfloor$ represents the largest integer less than or equal to $x$.

Figure 8 shows how the joint use of MMSE frequency-domain equalization and DTD/receive diversity improves the average BER performance. For a channel with weak frequency-selectivity (e.g., when $\alpha$=8 dB), as $N_t$ increases, the frequency-selectivity of the channel becomes stronger and hence, the BER performance improves. When $\alpha$=0 dB (i.e., uniform power delay profile), however, the performance improvement obtainable by DTD is less because the channel frequency-selectivity is already strong enough. It can be found from Fig. 8 that the additional use of receive antenna diversity is always beneficial irrespective of the degree of channel frequency-selectivity.

## 4. Conclusion

In this paper, joint use of frequency-domain equalization and transmit/receive antenna diversity was presented for SC transmission and the BER performance was evaluated by computer simulation. The results obtained in this paper can be summarized as follow.

(a) In this paper, a single user was assumed since SC transmission was considered. For the single user transmission in MC-CDMA, the best frequency-domain equalization scheme is MRC [6]. However, performance comparison for the SC transmission has shown that MMSE frequency-domain equalization is the best. The reason for this is that each data symbol energy is spread over the entire signal bandwidth and hence, MRC produces larger ISI due to enhancement of the frequency-selectivity than MMSE.

(b) It was found that although MLSE time-domain equalization gives better BER performances than MMSE frequency-domain equalization, the performance difference between them tends to diminish as the number of receive antennas increases. As the number of path increases, the computational complexity of MLSE time-domain equalization grows exponentially, while that of MMSE frequency-domain equalization remains the same. Hence, MMSE frequency-domain equalization is considered to be attractive for SC transmission.

(c) When the channel frequency-selectivity is weak, joint use of frequency-domain equalization and DTD is useful since DTD can increase the equivalent number of propagation paths. The additional use of receive antenna diversity is always beneficial irrespective of the degree of channel frequency-selectivity.

In this paper, ideal channel estimation was assumed. The BER performance using practical channel estimation in a frequency-selective fading environment is left for future study.

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## Appendix

How the ORC, MRC, and MMSE frequency-domain equalizations equalize the transmission channel is discussed for the case of single transmit antenna and single receive antenna. Figure A· 1 illustrates the one-shot observation of the equivalent channel gain $\tilde{H}(n) = w(n)H(n)$ and the noise $\tilde{N}(n) = w(n)N(n)$ after frequency-domain equalization for the given instantaneous channel gains $\{H(n);\ n = 0 \sim N_c - 1\}$ when $L$=8, $N_t = N_r$=1 and $N_c$=256. Note that the noise power $N_0/T$ has been set to unity. The equalization weight of ORC is in inverse proportion to $H(n)$ and thus, a large noise enhancement is observed at the subcarrier where $|H(n)|$ drops, while the frequency-nonselective channel is perfectly restored, i.e., $\tilde{H}(n) = 1$. It can be clearly seen that the MRC can suppress the noise enhancement, but in turn, enhances the channel frequency-selectivity. On the other hand, MMSE suppresses the noise enhancement while weakening the channel frequency-selectivity. This suggests that MMSE frequency-domain equalization can provide the best performance.

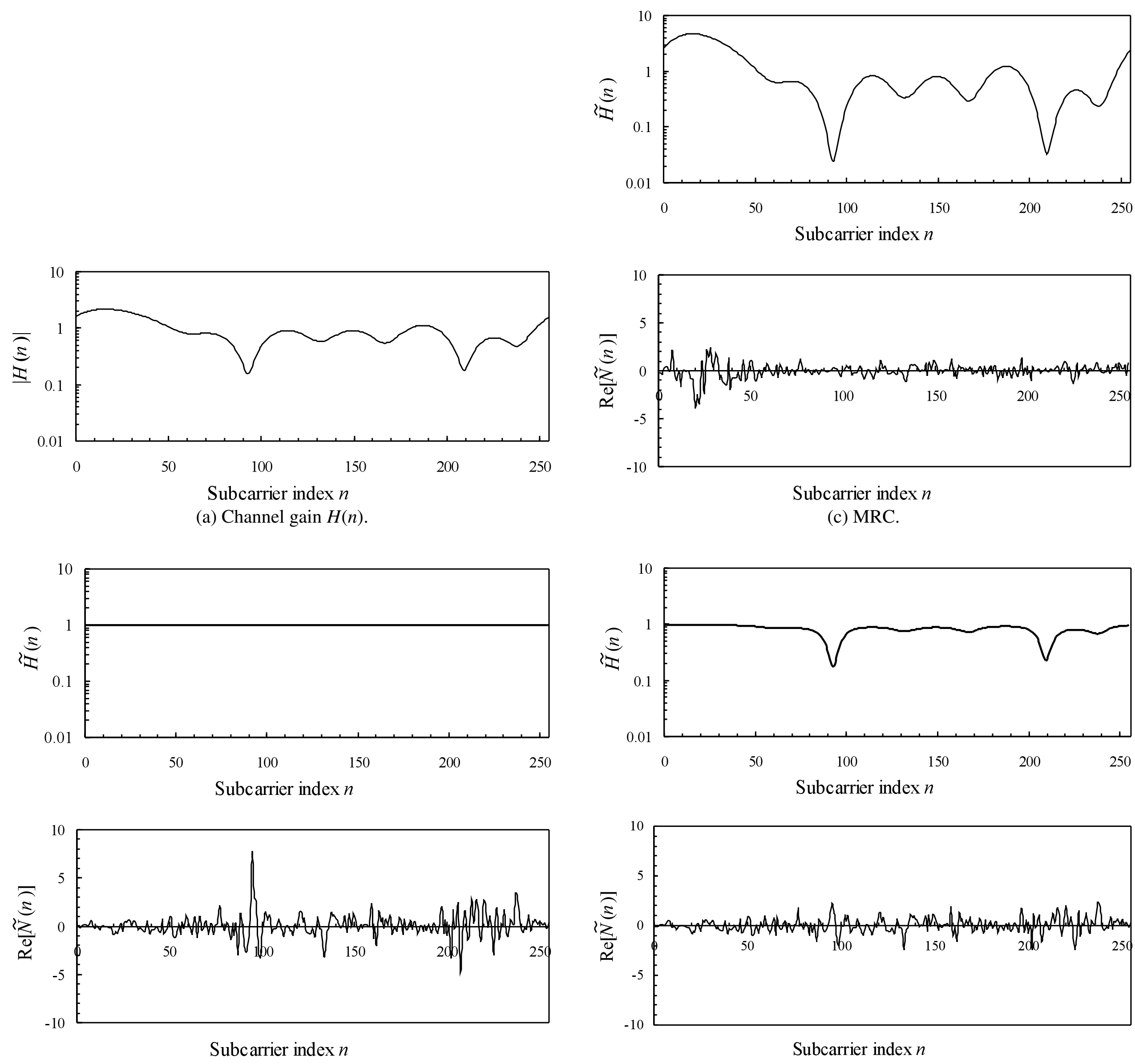


**Fig. A· 1** Equivalent channel gain $\tilde{H}(n)$ and noise $\tilde{N}(n)$ for the given instantaneous channel gain $H(n)$ when $L$=8, $N_t = N_r$=1 and $N_c$=256.

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