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OFDM/TDM における STTD とアンテナダイバーシチの併用効果

ガチャニンハリス* 高岡辰輔* 安達文幸**

東北大学大学部工学研究科　電気・通信工学 〒980-8579 宮城県仙台市青葉区荒巻字青葉 05

E-mail: *(haris, takaoka)@mobile.ecei.tohoku.ac.jp, **adachi@ mobile.ecei.tohoku.ac.jp

あらまし　直交周波数多重(OFDM)と時分割多重(TDM)を組み合わせた OFDM/TDM は最小,平均２乗誤差(MMSE)周波数領域等化を用いることで OFDM とシングルキャリア（SC）伝送の橋渡しできるフレキシブルな伝送方式である。厳しい周波数選択性フェージング環境下において，MMSE 周波数領域等化を用いる OFDM/TDM は周波数ダイバーシチ効果を得ることができ，ピーク対平均電力比(PAPR)を抑えつつ OFDM より良好なビット誤り率(BER)特性を得ることができる。周波数領域等化と送受信アンテナダイバーシチを併用することにより，更なる BER の改善が可能である。本論文は，OFDM/TDM における STTD とアンテナダイバーシチの併用効果について検討している。

Joint use of STTD and Antenna Diversity for OFDM/TDM

Haris GACANIN* Shinsuke TAKAOKA* and Fumiyuki ADACHI**

Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University

05 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan

E-mail: *(haris, takaoka)@mobile.ecei.tohoku.ac.jp, **adachi@ecei.tohoku.ac.jp

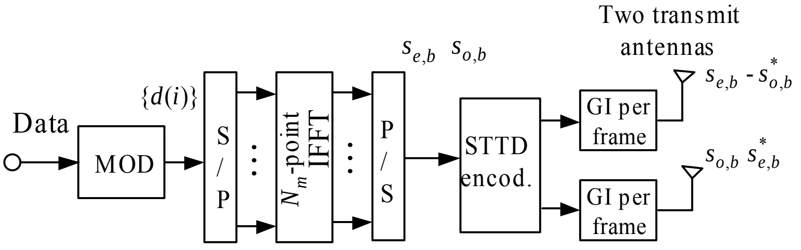
Abstract: Orthogonal frequency division multiplexing (OFDM) combined with time division multiplexing (TDM) can bridge the conventional OFDM and single carrier (SC) transmission by using minimum mean square error (MMSE) frequency-domain equalization (FDE). The channel frequency-selectivity can be exploited by MMSE-FDE to improve the bit error rate (BER) performance. A much better BER performance is achieved in comparison to conventional OFDM while reducing the peak-to-average power ratio (PAPR). Further performance improvement can be achieved by transmit/receive antenna diversity technique. In this paper, the joint use of space-time transmit diversity (STTD) and receive antenna diversity is discussed.

Keyword: OFDM, frequency-domain equalization, frequency-selective Rayleigh fading channel

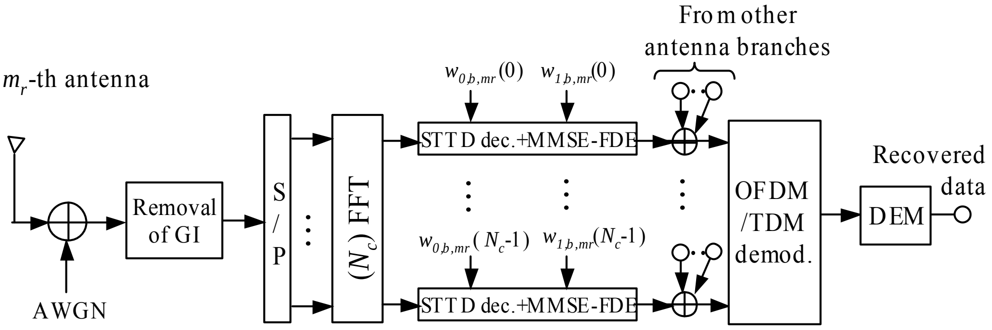
1. Introduction

In wireless channel, the presence of many propagation paths with different time delays produces frequency-selective multipath fading, which gives rise to inter-symbol interference (ISI) and severely degrades the transmission performance [1]; therefore, ISI limits achievable data rate. To improve the single-carrier (SC) transmission performance in such a frequency-selective multipath channel, some sophisticated adaptive equalization techniques (e.g., maximum likelihood sequence estimation (MLSE) [1], [2]) must be employed. Recently, orthogonal frequency division multiplexing (OFDM) has been attracting considerable attention, mainly because of its robustness against frequency-selective fading and simple one-tap frequency domain equalization (FDE). OFDM has recently been adopted in some wireless communications systems [3]-[5]. OFDM signal has high peak-to-average-power ratio (PAPR). Recently we proposed OFDM combined with time division multiplexing (TDM), called OFDM/TDM, to reduce the PAPR [6], [7]. It has been shown that OFDM/TDM with FDE based on minimum mean square error (MMSE) criterion outperforms OFDM while reducing the PAPR. In OFDM/TDM, the inverse fast Fourier transform (IFFT) time window (called OFDM/TDM frame) of N_c samples is divided into K slots; during each slot one OFDM signal with $N_m=N_c/K$ subcarriers is transmitted and no GI is inserted between them (N_c is the number of subcarriers of the conventional OFDM). The BER performance of OFDM/TDM is significantly improved when MMSE-FDE is used. OFDM/TDM can bridge the conventional OFDM and SC transmissions by controlling the value of K.

For achieving further performance improvement, the use of multiple transmit and receive antennas is very effective. Receive antenna diversity has already been used in some practical systems. Recently, space-time transmit diversity (STTD) has been gaining much attention since its use at a base station alleviates the complexity problem of mobile receivers [8]. STTD and receive diversity can be jointly applied to OFDM/TDM. In this paper we apply the joint use of FDE and transmit/receive antenna diversity to OFDM/TDM. The BER performance of OFDM/TDM with



(a) Transmitter



(b) Receiver

Figure 1. OFDM/TDM transmission model with joint use of FDE, STTD and antenna diversity reception.

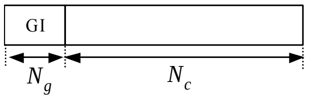
MMSE-FDE in a frequency-selective Rayleigh fading channel is evaluated by computer simulation.

Remainder of this paper is organized as follows. Section 2 briefly overviews an OFDM/TDM transmission model. In Sect. 3, OFDM/TDM signal representation, STTD encoding, channel model, and joint STTD decoding and MMSE-FDE are presented. Sect. 4 evaluates, by computer simulations, the BER performance of the OFDM/TDM in a frequency-selective Rayleigh fading channel and then, compares it with conventional OFDM and SC. Sect. 5 provides some conclusions and future works.

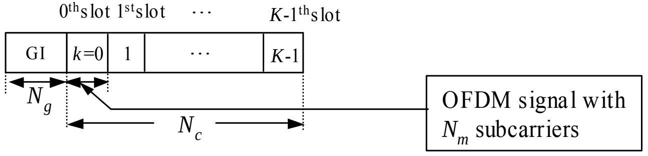
2. OFDM/TDM Transmission Model [6], [7]

The OFDM/TDM transmission model and frame structure are shown in Fig. 1 and 2, respectively. We assume 2 transmit antennas and N_r receive antennas. The inverse fast Fourier transform (IFFT) time window for the conventional OFDM is divided into K slots (which constitutes the OFDM/TDM frame) as illustrated in Fig. 2(b); an OFDM signal with reduced number of subcarriers ($N_m=N_c/K$) is transmitted during each time slot without inserting GI between consecutive OFDM signals. Note that OFDM/TDM becomes SC when $K=N_c$ while becomes conventional OFDM when K=1. N_g-sample GI with the length same as in conventional OFDM is inserted only at the beginning of each OFDM/TDM frame. Hence, the transmission data rate is kept the same as conventional OFDM, while the number of subcarriers is reduced by a factor of K, thus reducing the PAPR by the same factor.

FDE is applied to exploit the channel frequency-selectivity and improve the BER performance of OFDM/TDM. We consider MMSE-FDE used for equalization in SC transmission [9], multicarrier code division multiple access (MC-CDMA) [10], [11] and direct sequence CDMA (DS-CDMA) [12].



(a) Conventional OFDM with N_c subcarriers



(b) OFDM/TDM signal

Figure 2. OFDM/TDM frame structure.

3. OFDM/TDM Signal Representation

Data-modulated sequence $\{d(i)\}$ is divided into K blocks of N_m symbols each. N_c data symbols are transmitted over one OFDM/TDM frame. The k-th block symbol sequence in the qth frame is denoted as $\{d^{q,k}(i);\ i=0\sim N_m\text{-}1;\ q=0,\ 1\ldots\}$, where $d^{q,k}(i)=d(qN_c+kN_m+i)$. N_m-point IFFT is applied to each data block to generate a sequence of K OFDM signals with $N_m=N_c/K$ subcarriers as shown in Fig.2(b).

3.1. Transmit OFDM/TDM signal

The q-th frame OFDM/TDM signal before STTD encoding can be expressed using equivalent lowpass representation as

$$s^q(t) = s^{q,k}(t - qN_c - kN_m) \tag{1}$$

for $t=qN_c\sim(q+1)N_c-1$, where $k=\lfloor t-qN_c/N_m \rfloor$ with $\lfloor x \rfloor$ representing the largest integer smaller than or equal to x and $s^{q,k}(t)$ is the k-th OFDM signal with N_m subcarriers in a qth frame, given by

$$s^{q,k}(t) = \sqrt{\frac{2E_s}{T_c}} \sum_{i=0}^{N_m-1} d^k(i) \exp\left[j2\pi t \frac{i}{N_m} \right] \tag{2}$$

for $t=0\sim N_m-1$, where E_s and T_c represent the symbol energy and the sampling period, respectively.

3.2. STTD encoding

Alamouti's STTD encoding [8] is applied to each subcarrier of the OFDM/TDM signal. Pairs of even and odd OFDM/TDM frames ($q=2n$ and $2n+1$), for $n=0, 1\ldots$, are grouped for STTD encoding into a sequence of blocks, where each block contains even and odd pair of OFDM/TDM frames (see Fig. 3). In Fig. 1, $s^{2n}(2nN_c+t)$ and $s^{2n+1}((2n+1)N_c+t)$ are denoted as $s_{e,b}(t)$ (even frame) and $s_{o,b}(t)$ (odd frame) for the bth block, respectively. Fig. 3 illustrates STTD encoded signals in the bth block for transmission over the two antennas during the two frame intervals $2n\leq t\leq(2n+1)N_c-1$ (i.e., even and odd), are given as $s_{e,b}(t)$ and $s_{o,b}(t)$. The STTD encoding in time domain is performed subcarrier-by-subcarrier [14]. In the even time interval of $2n\leq t\leq 2nN_c-1$, the STTD encoded OFDM/TDM signal to be transmitted from the first antenna is $s_{e,b}(t)$ and the signal on the second antenna is $s_{o,b}(t)$. In the odd time interval of $2nN_c\leq t\leq(2n+1)N_c-1$, the STTD encoded signal to be transmitted from the first antenna is $-s^*_{o,b}(N_c-t)$ and that to be transmitted from the second antenna is $s^*_{e,b}(N_c-t)$ where * denotes complex conjugate operation.

Before transmission, the last N_g samples of the STTD encoded OFDM/TDM signal are copied as a cyclic prefix (CP) and inserted into GI of each frame. The GI-inserted OFDM/TDM signal is transmitted over a frequency-selective fading channel.

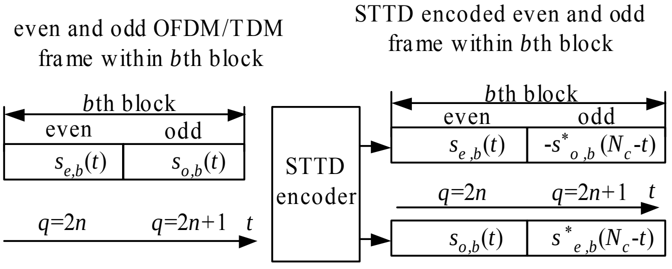


Figure 3. STTD encoding in time domain.

3.3. Channel model

The fading channel is assumed to be composed of L discrete propagation paths having sample-spaced time delays. We assume a block fading, where the path gains remain constant during the period of two frame intervals. The channel impulse response between the m_t-th (m_t=0, 1) transmit antenna and m_r-th ($m_r=0\sim N_r-1$) receive antenna $h_{m_t,m_r,b}(l)$ for the bth block can be expressed as

$$h_{m_t,m_r,b}(\tau) = \sum_{l=0}^{L-1} h^l_{m_t,m_r,b} \delta(\tau - \tau_l) , \tag{3}$$

where $E\left[\sum_{l=0}^{L-1} |h_l|^2 \right] = 1$ and $\delta(t)$ is the delta function. The channel gain at the kth subcarrier is given by

$$H_{m_t,m_r,b}(k) = \sum_{l=0}^{L-1} h^l_{m_t,m_r,b} \exp(-j2\pi k \tau_l / N_c) \tag{4}$$

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

3.4. Received OFDM/TDM signal

STTD encoded OFDM/TDM signals transmitted from two antennas are received by N_r antennas and the GI is removed from them. The even and odd frame signals in the bth block $r_{e,b,m_r}(t)$ and $r_{o,b,m_r}(t)$ received on the m_r-th antenna, respectively, can be expressed as

$$\begin{cases} r_{e,b,m_r}(t) = \sum_{l=0}^{L-1} \left(h^l_{0,b,m_r} s_{e,b}(t-\tau_l) + h^l_{1,b,m_r} s_{o,b}(t-\tau_l) \right) \\ \qquad + n_{e,b,m_r}(t) \\ r_{o,b,m_r}(t) = \sum_{l=0}^{L-1} \begin{pmatrix} -h^l_{0,b,m_r} s^*_{o,b}(N_c - t - \tau_l) \\ + h^l_{1,b,m_r} s^*_{e,b}(N_c - t - \tau_l) \end{pmatrix} + n_{o,b,m_r}(t) \end{cases} , \tag{5}$$

where $n_{e,b,mr}(t)$ and $n_{o,b,mr}(t)$ represent the independent additive white Gaussian noise (AWGN) processes for the even and odd time interval in the bth block having zero mean and variance $2N_0/T_c$ with N_0 representing single sided noise power spectrum density and $*$ denotes the complex conjugate operation.

3.5. Joint STTD decoding and Frequency-domain equalization

In OFDM/TDM, the GI is not inserted between consecutive slots but only at the beginning of the each OFDM/TDM frame (Fig. 2(b)). Therefore, the ISI may arise due to multipath fading and degrade the BER performance. To reduce the ISI, one-tap MMSE-FDE is carried out jointly with STTD decoding and N_r-branch receive antenna diversity combining.

The time-domain received signals $r_{e,m_r}(t)$ and $r_{o,m_r}(t)$ are decomposed into N_c frequency components by applying N_c-point FFT as

$$\begin{cases} R_{e,b,m_r}(k) = H_{0,b,m_r}(k)S_{e,b,m_r}(k) + H_{1,b,m_r}(k)S_{o,b,m_r}(k) \\ \qquad\qquad + N_{e,b,m_r}(k) \\ R_{o,b,m_r}(k) = -H_{0,b,m_r}(k)S^*_{o,b,m_r}(k) + H_{1,b,m_r}(k)S^*_{e,b,m_r}(k) \\ \qquad\qquad + N_{o,b,m_r}(k) \end{cases}, \tag{6}$$

where $H_{0(\mathrm{or}1),b,m_r}(k)$ and $N_{e(\mathrm{or}o),b,m_r}(k)$ represent the channel gain and noise at the *k*th subcarrier on the m_r-th receive antenna in the *b*th block, respectively. Joint STTD decoding and diversity combining based on MMSE-FDE is carried out as follows:

$$\begin{cases} \hat{R}_{e,b}(k) = \sum_{m_r=0}^{N_r-1}\left(w^*_{0,m_r}(k)R_{e,b,m_r}(k) + w_{1,m_r}R^*_{o,b,m_r}(k)\right) \\ \hat{R}_{o,b}(k) = \sum_{m_r=0}^{N_r-1}\left(-w_{0,m_r}(k)R^*_{o,b,m_r}(k) + w^*_{1,m_r}R_{e,b,m_r}(k)\right) \end{cases}, \tag{8}$$

where $w_{m_t,m_r}(k)$ is given by [14]

$$\begin{cases} w_{0,b,m_r}(k) = \dfrac{H_{0,b,m_r}(k)}{\sum_{m_t=0}^{1}\sum_{m_r=0}^{N_r-1}\left|H_{0,b,m_r}(k)\right|^2 + \left(\dfrac{E_c}{N_0}\right)^{-1}} \\ w_{1,b,m_r}(k) = \dfrac{H_{1,b,m_r}(k)}{\sum_{m_t=0}^{1}\sum_{m_r=0}^{N_r-1}\left|H_{1,b,m_r}(k)\right|^2 + \left(\dfrac{E_c}{N_0}\right)^{-1}} \end{cases}. \tag{9}$$

3.6. OFDM/TDM signal demodulation

By applying N_c-point IFFT to $\{\hat{R}_{e(\mathrm{oro}),b}(k)\}$, we recover the time-domain OFDM/TDM signal $\hat{r}_{e(\mathrm{oro}),b}(t)$:

$$\hat{r}_{e(\mathrm{oro}),b}(t) = \frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{R}_{e(\mathrm{oro}),b}(k)\exp\left[j2\pi t\frac{n}{N_c}\right] \tag{10}$$

for $t=qN_c\sim(q+1)N_c-1$. Then, N_m-point FFT is applied to $\hat{r}_{e(\mathrm{oro}),b}(t)$ to obtain

$$\begin{aligned} \hat{d}^k_{e,b}(i) &= \frac{1}{N_m}\sum_{t=2nN_c+kN_m}^{2nN_c+(k+1)N_m-1}\hat{r}_{e,b}(t-2nN_c-kN_m) \\ &\quad\times\exp\left[-j2\pi i\frac{t}{N_m}\right] \\ \hat{d}^k_{o,b}(i) &= \frac{1}{N_m}\sum_{t=(2n+1)N_c+kN_m}^{(2n+1)N_c+(k+1)N_m-1}\hat{r}_{o,b}(t-(2n+1)N_c-kN_m) \\ &\quad\times\exp\left[-j2\pi i\frac{t}{N_m}\right] \end{aligned} \tag{11}$$

for $i=0\sim N_m-1$ and $k=0\sim K-1$, which is the soft decision variable for data demodulation of the 2*n*th and (2*n*+1)th frames in the *b*th block.

4. Simulation results

In the simulation, we assume $K=1\sim256$, frame length of $N_c=256$ samples and GI of $N_g=32$ samples (this condition corresponds to the conventional OFDM with $N_c=256$ subcarriers and $N_g=32$ GI). QPSK data-modulation is assumed. OFDM/TDM parameters, are shown in Table 1. The propagation channel considered for the computer simulation is an $L=16$-path frequency-selective block Rayleigh fading channel having exponential power delay profile with decay factor β (Fig. 4) and a time-delay spacing of 2 samples (i.e., $\tau_l=2l$). Ideal channel estimation is assumed.

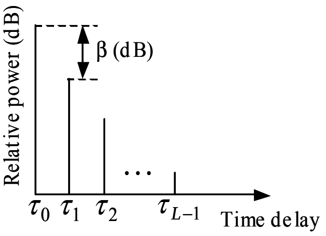


Figure 4. Channel power delay profile.

Table 1. Simulation conditions

Transmitter	Data modulation	QPSK
	Number of IFFT points	N_m=256/*K*
	Number of slots per frame	*K*=1~256
	Frame length	N_c = 256
	GI	N_g = 32
Channel	Frequency -selective	Rayleigh fading
	Number of paths	*L* = 16
	Channel decay factor	β=0 and 8 dB
Receiver	Number of FFT points	N_c = 256 N_m =256/*K*
	Frequency-domain equalization	MMSE
	Channel estimation	Ideal

Fig. 5 plots the average BER performance of OFDM/TDM using MMSE-FDE as a function of the average received E_b/N_0, where $E_b/N_0=0.5(E_s/N_0)\times(1+N_g/N_c)$, with K as a parameter when 2-antenna STTD and N_r=2-antenna receive diversity are used separately. Note that OFDM/TDM represents OFDM and SC system when K=1 and K=256, respectively. When K=1 (256), a STTD gain of about 15 (22.5) dB is obtained for an average BER=10^{-4} while 18 (25.5) dB for 2 antenna receive diversity (N_r=2) compared to no diversity case. As was expected, the STTD achieves the performance of 2-antenna receive diversity but with 3 dB penalty. However, MMSE-FDE takes advantage of channel frequency-selectivity and improves the BER performance of the OFDM/TDM due to enhanced frequency diversity effect as K increases. The worst BER performance is provided when K=1 (OFDM), while the best BER performance is achieved when K=256 (SC). For the average BER=10^{-4}, a STTD gain of about 3, 6 and 8.2 dB is achieved when K=4, 16 and 256, respectively, in comparison to OFDM (K=1).

Until now, we have treated STTD and receive antenna diversity separately. Fig. 6 shows the joint effect of STTD and N_r-branch receive antenna diversity on the BER performance for K=32 with N_r as a parameter. Joint STTD and N_r=2-branch receive antenna diversity achieves an E_b/N_0 gain of approximately 11 dB for BER=10^{-4} over the no diversity and 5.5 (2.7) dB compared to the case of STTD only (N_r=2-branch receive antenna diversity). Joint STTD and N_r=4-branch receive antenna diversity achieves an E_b/N_0 gain of approximately 1 dB for a BER=10^{-4} over N_r=4-branch receive antenna diversity.

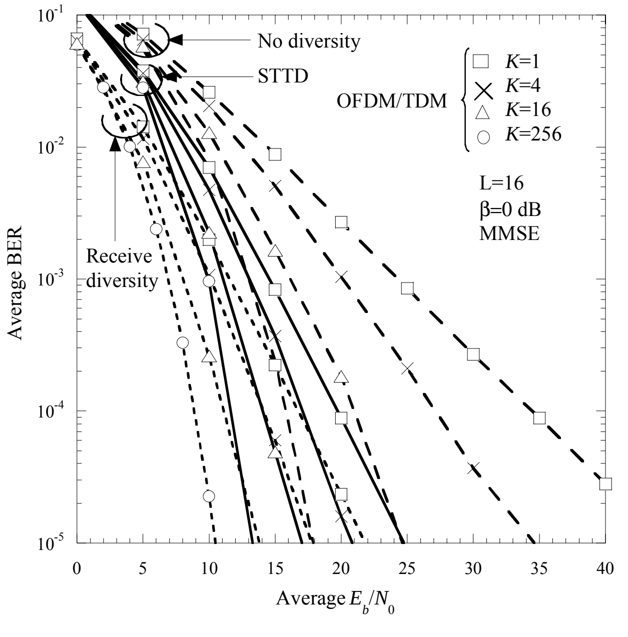


Figure 5 Simulated BER performance with K as parameter for 2-antenna STTD and N_r=2-antenna receive diversity.

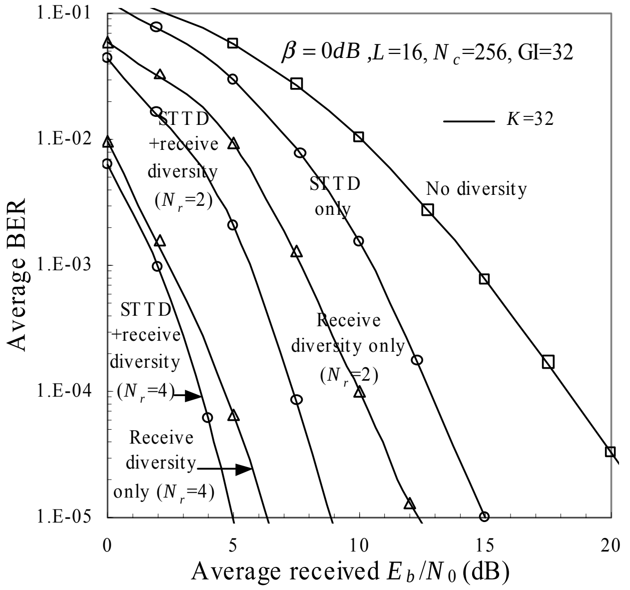


Figure 6 Joint use of STTD and N_r=2, 4-branch antenna diversity for OFDM/TDM.

The channel frequency-selectivity depends on the decay factor β. As β increases, the channel frequency-selectivity gets weaker and the BER performance of OFDM/TDM changes with β. The BER performance is better when the channel is more frequency-selective (i.e., better BER performance is obtained with β=0 dB than β=8 dB). The impact of channel frequency-selectivity on the BER performance of OFDM/TDM (K=32) with joint STTD and N_r-branch receive antenna is shown in Fig. 7. Joint STTD and N_r=1, 2 and 4-branch receive antenna diversity for the case of β=0 dB achieves an E_b/N_0 gain of approximately 5, 2.7, 1.1 dB for BER=10^{-4} compared to the case β=8 dB. Due to larger channel frequency-selectivity, the larger frequency diversity effect is obtained, resulting in the improved BER performance.

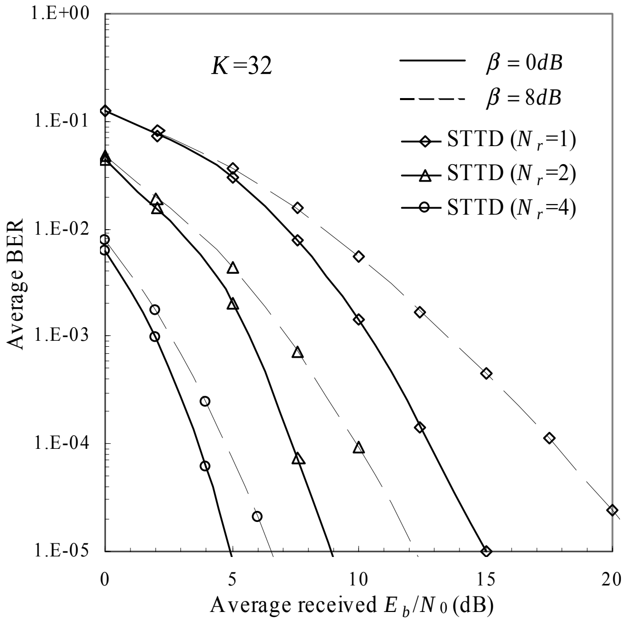


Figure 7. Impact of channel decay factor β.

5. Conclusions

In this paper, we presented joint STTD and N_r-branch receive antenna diversity for OFDM/TDM with MMSE-FDE. The BER performance of the OFDM/TDM in a frequency-selective block Rayleigh fading channel was evaluated by computer simulation. It was shown that use of STTD decoding and N_r-antenna receive diversity for OFDM/TDM with MMSE-FDE provides an additional E_b/N_0 gain and it is always better than that with receive diversity or STTD only. This is because STTD in addition to receive diversity increases the number of paths and therefore increases the degree of channel frequency-selectivity. Due to this and MMSE-FDE larger frequency diversity effect is achieved. We assumed ideal channel estimation and ideal timing synchronization, which are left as interesting future works.

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