Joint Tx/Rx FDE & Spectrum Combining for SC-ANC Bi-Directional Relay in Presence of Timing Offset

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Abstract— **Recently, we proposed a joint transmit/receive frequency-domain equalization (FDE) for single-carrier (SC) analog network coded (ANC) bi-directional relay and showed that the proposed joint transmit/receive FDE achieves better BER performance than the use of either transmit FDE or receive FDE only. However, our previous study for SC-ANC bi-directional relay assumed no arrival timing offset. However, the signals transmitted from base station (BS) and mobile terminal (MT) may not necessarily arrive at the relay station (RS) at the same time. The arrival timing offset causes the inter-symbol interference and accordingly, BER performance degradation. In this paper, we propose a joint transmit/receive FDE and spectrum combining for SC-ANC bi-directional relay in the presence of timing offset. RS performs oversampling and transmit FDE while both MT and BS receivers perform oversampling, receive FDE and spectrum combining. Transmit and receive FDE weights when using the spectrum combining are jointly optimized based on minimum mean square error (MMSE) criterion. Computer simulation confirms that the proposed joint transmit/receive FDE & spectrum combining obtains both spatial and frequency diversity gain and achieves a good BER performance even in the presence of timing offset.**

Keywords-component; Analog network coding, frequency-domain equalization, single-carrier transmission

I. INTRODUCTION

In broadband transmission, bit error rate (BER) performance severely degrades due to propagation path loss, shadowing loss and frequency-selective fading [1]. Cooperative relay [2] is a promising technique to overcome the impact of propagation path loss and shadowing loss. Furthermore, application of analog network coding (ANC) [3,4] to bi-directional relay can reduce the number of time-slots required for bi-directional relay and as a consequence, it achieves higher achievable throughput than cooperative relay. To overcome frequency-selective fading, single-carrier transmission with frequency-domain equalization (SC-FDE) [5,6] is attractive. SC transmission has lower peak-to-average power ratio (PAPR) property than orthogonal frequency division multiplexing (OFDM) transmission. The use of minimum mean square error (MMSE) based frequency-domain equalization (FDE) takes an advantage of channel frequency-selectivity and obtains large frequency diversity gain [5,6]. The use of joint transmit/receive MMSE-FDE [7] can suppress the residual inter-symbol interference (ISI) after FDE and accordingly, it achieves better BER performance than the use of either transmit FDE or receive FDE only.

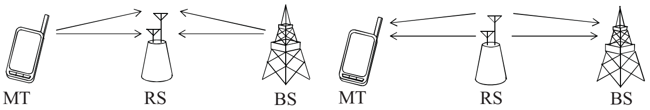
Recently, we proposed a joint transmit/receive MMSE-FDE for SC-ANC bi-directional relay [8,9]. The relay station (RS) having multiple antennas performs transmit FDE and both the mobile terminal (MT) and the base station (BS) receivers perform receive FDE. Transmit and receive FDE weights are jointly optimized based on MMSE criterion. However, the signals transmitted from BS and MT may not necessarily arrive at RS at the same time because the distance between MT and RS and that between BS and RS are different. Therefore, the timing offset will be caused in uplink and/or downlink and as a consequence, BER performance degrades due to ISI [10].

In this paper, we introduce spectrum combining [11] to joint transmit/receive FDE (called joint transmit/receive FDE & spectrum combining) for SC-ANC bi-directional relay in order to suppress ISI caused by both timing offset and frequency-selective fading. In SC-ANC bi-directional relay with joint transmit/receive FDE & spectrum combining, RS performs oversampling and transmit FDE while both MT and BS receivers perform oversampling, receive FDE and spectrum combining. Transmit and receive FDE weights when using the spectrum combining are jointly optimized based on MMSE criterion. Computer simulation confirms that the proposed joint transmit/receive FDE & spectrum combining obtains both spatial and frequency diversity gains and achieves a good BER performance for both uplink and downlink even in the presence of timing offset.

The remainder of this paper is organized as follows. Joint transmit/receive FDE & spectrum combining for SC-ANC bi-directional relay is presented in Sect. II. Sect. III presents the joint optimization of transmit and receive MMSE-FDE weight when using the spectrum combining. Sect. IV discusses the computer simulation results, and Sect. V offers some conclusions.

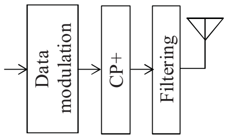
II. SC-ANC BI-DIRECTIONAL RELAY

In this paper, SC-ANC bi-directional relay with the joint transmit/receive FDE & spectrum combining is considered. It is considered that RS equips with N_R antennas and MT and BS has single antenna, respectively. For simplicity, propagation path loss and shadowing loss are not considered in this paper.

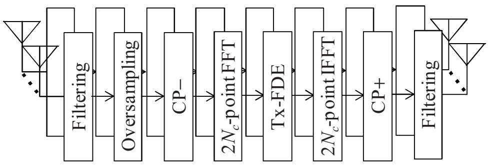


(a) First time-slot (b) Second time-slot

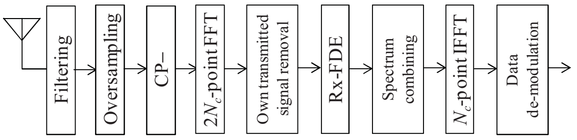
Fig. 1. Behavior of SC-ANC bi-directional relay.



(a) MT/BS transmitter



(b) RS



(c) MT/BS receiver

Fig. 2. Transmitter/receiver structures.

A. Transmitter/receiver structures

Fig. 1 describes the behavior of MT, RS and BS in each time-slot and Fig. 2 shows transmitter/receiver structures. In the first time-slot, MT and BS transmit their signals to RS simultaneously. At RS, double oversampling is applied to the received signal to avoid ISI caused by timing offset. Then, RS computes the transmit FDE weights and carries out the transmit FDE on the received signal. In the second time-slot, RS broadcasts the transmit signal to MT and BS. At both MT and BS receivers, double oversampling is applied to the received signal. After removing own transmitted signal from the received signal, MT and BS receivers compute their own receive FDE weights, respectively, carry out the receive FDE and spectrum combining, and finally, perform data de-modulation.

B. Signal reprensentation

Below, symbol-spaced discrete time signal representation is used.

(a) First time-slot

At BS and MT transmitters, the modulated symbol sequence is divided into some blocks of N_c-symbols each. After CP insertion and Nyquist filtering, BS and MT simultaneously transmit their signals to RS. At RS, Nyquist filtering and double oversampling are carried out. After CP removal, the received signal is transformed into the frequency-domain signal by $2N_c$-point FFT. The frequency-domain received signal, $\{R_R(n_R,k);k=-N_c,\ldots,N_c-1\}$ at the n_Rth RS antenna can be expressed as

$$\begin{aligned}R_R(n_R,k)=&\sqrt{2P_M}H_{M-R}(n_R,k)\exp(j2\pi k\Delta_{M-R}/N_c)S_M(k)\\&+\sqrt{2P_B}H_{B-R}(n_R,k)\exp(j2\pi k\Delta_{B-R}/N_c)S_B(k)\\&+\mathrm{N}_R(n_R,k)+\Pi_R(n_R,k)\end{aligned}\quad, (1)$$

where P_M and P_B denote the transmit power of MT and BS, respectively. $H_{M\text{-}R}(n_R,k)$ ($H_{B\text{-}R}(n_R,k)$) is total channel transfer function, which is a concatenation of transfer function of the channel and that of transmit/receive filters, between MT (BS) and the n_Rth RS antenna. $\Delta_{M\text{-}R}$ ($\Delta_{B\text{-}R}$) denotes timing offset for uplink (downlink) signal normalized by symbol duration T_s. $S_M(k)$ and $S_B(k)$ are the frequency-domain transmit signal of MT and BS, respectively. $\mathrm{N}_R(n_R,k)$ is the contribution of inter-block interference (IBI) caused by timing offset. $\Pi_R(n_R,k)$ denotes zero-mean additive white Gaussian noise (AWGN) having variance $2\sigma^2$.

(b) Second time-slot

RS performs the transmit FDE to the frequency-domain received signal. The frequency-domain received signal, $\{S_R(n_R,k);k=-N_c,\ldots,N_c-1\}$ after the transmit FDE is given as $S_R(n_R,k)=V(n_R,k)R_R(n_R,k)$, where $V(n_R,k)$ denotes the transmit FDE weight at the n_Rth RS antenna. The transmit FDE weight has a constraint in order to keep the average transmit power of RS constant as

$$\sum_{k=-N_c}^{N_c-1}\sum_{n_R=0}^{N_R-1}\left|V(n_R,k)\right|^2=\sum_{k=-N_c/2}^{N_c/2-1}\sum_{n_R=0}^{N_R-1}\sum_{q=-1}^{1}\left|V(n_R,k-qN_c)\right|^2=N_c\,. \quad (2)$$

The frequency-domain transmit signal after the transmit FDE is transformed back to the time-domain signal by $2N_c$-point IFFT. After CP insertion and Nyquist filtering, RS broadcasts the signal to BS and MT in the second time-slot. At BS and MT receiver, Nyquist filtering and double oversampling are carried out. After CP removal, the received signal is transformed into the frequency-domain received signal by $2N_c$-point FFT. The frequency-domain received signals, $\{R_M(k);k=-N_c,\ldots,N_c-1\}$ and $\{R_B(k);k=-N_c,\ldots,N_c-1\}$, at MT and BS can be expressed as

$$\begin{cases}R_M(k)=\displaystyle\sum_{n_R=0}^{N_R-1}G(n_R)H_{M-R}(n_R,k)\exp(j2\pi k\Delta_M/N_c)S_R(n_R,k)\\ \qquad+\mathrm{N}_M(k)+\Pi_M(k)\\ R_B(k)=\displaystyle\sum_{n_R=0}^{N_R-1}G(n_R)H_{B-R}(n_R,k)\exp(j2\pi k\Delta_B/N_c)S_R(n_R,k)\\ \qquad+\mathrm{N}_B(k)+\Pi_B(k)\end{cases}, \quad (3)$$

where $G(n_R)$ denotes the amplifying factor at the n_Rth RS antenna. It is set so as to keep the block average transmit power of RS constant as

$$G(n_R)=\sqrt{\frac{P_R}{\dfrac{1}{2N_c}\left\{P_M\displaystyle\sum_{k=-N_c}^{N_c}\left|H_{M-R}(n_R,k)\right|^2+P_B\sum_{k=-N_c}^{N_c}\left|H_{B-R}(n_R,k)\right|^2\right\}+\sigma^2}}\quad, (4)$$

where P_R is the transmit power of RS. Δ_M and Δ_B are normalized timing offset at MT and BS, respectively. $\mathrm{N}_M(k)$ and $\mathrm{N}_B(k)$ are the contributions of IBI caused by timing offset at MT and BS, respectively. $\Pi_M(k)$ and $\Pi_B(k)$ are zero-mean AWGNs having variance $2\sigma^2$. From (1), (3) can be rewritten as

$$\begin{cases} R_M(k)=\sqrt{2P_B}H_{B-M}(k)S_B(k)+\sqrt{2P_M}H_{M-M}(k)S_M(k) \\ \quad +\sum_{n_R=0}^{N_R-1}G(n_R)H_{M-R}(n_R,k)V(n_R,k)\exp\left(j\frac{2\pi k\Delta_M}{N_c}\right)\cdot\begin{pmatrix}\mathrm{N}_R(n_R,k)\\+\Pi_R(n_R,k)\end{pmatrix} \\ \quad +\mathrm{N}_M(k)+\Pi_M(k) \\ R_B(k)=\sqrt{2P_M}H_{M-B}(k)S_M(k)+\sqrt{2P_B}H_{B-B}(k)S_B(k) \\ \quad +\sum_{n_R=0}^{N_R-1}G(n_R)H_{B-R}(n_R,k)V(n_R,k)\exp\left(j\frac{2\pi k\Delta_B}{N_c}\right)\cdot\begin{pmatrix}\mathrm{N}_R(n_R,k)\\+\Pi_R(n_R,k)\end{pmatrix} \\ \quad +\mathrm{N}_B(k)+\Pi_B(k) \end{cases}, \tag{5}$$

where $H_{B\text{-}M}(k)$, $H_{M\text{-}M}(k)$, $H_{M\text{-}B}(k)$ and $H_{B\text{-}B}(k)$ are equivalent channel gains of BS-to-RS-to-MT link , MT-to-RS-to-MT link, MT-to-RS-to-BS link and BS-to-RS-to-BS link, respectively. They are given as

$$\begin{cases} H_{B-M}(k)=\sum_{n_R=0}^{N_R-1}\begin{bmatrix}G(n_R)H_{B-R}(n_R,k)H_{M-R}(n_R,k)\\ \times V(n_R,k)\exp\left(j\frac{2\pi k(\Delta_{B-R}+\Delta_M)}{N_c}\right)\end{bmatrix} \\ H_{M-M}(k)=\sum_{n_R=0}^{N_R-1}\begin{bmatrix}G(n_R)H_{M-R}(n_R,k)H_{M-R}(n_R,k)\\ \times V(n_R,k)\exp\left(j\frac{2\pi k(\Delta_{M-R}+\Delta_M)}{N_c}\right)\end{bmatrix} \\ H_{M-B}(k)=\sum_{n_R=0}^{N_R-1}\begin{bmatrix}G(n_R)H_{B-R}(n_R,k)H_{M-R}(n_R,k)\\ \times V(n_R,k)\exp\left(j\frac{2\pi k(\Delta_{M-R}+\Delta_B)}{N_c}\right)\end{bmatrix} \\ H_{B-B}(k)=\sum_{n_R=0}^{N_R-1}\begin{bmatrix}G(n_R)H_{B-R}(n_R,k)H_{B-R}(n_R,k)\\ \times V(n_R,k)\exp\left(j\frac{2\pi k(\Delta_{B-R}+\Delta_B)}{N_c}\right)\end{bmatrix} \end{cases}. \tag{6}$$

In (5), the first term is the desired signal and the second term is the own transmitted signal. Therefore, the own transmitted signal is removed from the received signal as

$$\begin{cases} \tilde{R}_M(k)=R_M(k)-\sqrt{2P_M}H_{M-M}(k)S_M(k) \\ \tilde{R}_B(k)=R_B(k)-\sqrt{2P_B}H_{B-B}(k)S_B(k) \end{cases}. \tag{7}$$

After the own transmitted signal removal, the receive FDE and spectrum combining are performed in order to compensate both the phase rotation due to timing offset and the spectrum distortion caused by frequency-selective fading. The frequency-domain received signal, {$\hat{R}_M(k)$;k=$-N_c/2,\ldots,N_c/2-1$} and {$\hat{R}_B(k)$;k=$-N_c/2,\ldots,N_c/2-1$}, after the receive FDE and spectrum combining at BS and MT are given as

$$\begin{cases} \hat{R}_M(k)=\sum_{q=-1}^{1}W_M(k-qN_c)\tilde{R}_M(k-qN_c) \\ \hat{R}_B(k)=\sum_{q=-1}^{1}W_B(k-qN_c)\tilde{R}_B(k-qN_c) \end{cases}, \tag{8}$$

where $W_M(k)$ and $W_B(k)$ are the receive FDE weights at MT and BS, respectively. The received signal after the receive FDE and spectrum combining is transformed back to the time-domain signal and finally, data demodulation is carried out.

III. JOINT TX/RX FDE & SPECTRUM COMBINING

In this paper, the transmit and receive FDE weights are jointly optimized so as to minimize mean square error (MSE) between the transmit signal and the received signal after the receive FDE and spectrum combining. The MSE, e_U and e_D, for uplink and downlink are given as

$$\begin{cases} e_U=\sum_{k=-N_c/2}^{N_c/2-1}E\left[\left|S_M(k)-\hat{R}_B(k)/\sqrt{2P_M}\right|^2\right] \\ e_D=\sum_{k=-N_c/2}^{N_c/2-1}E\left[\left|S_B(k)-\hat{R}_M(k)/\sqrt{2P_B}\right|^2\right] \end{cases}. \tag{9}$$

From (5), (7) and (8), (9) can be rewritten as

$$\begin{cases} e_U=\sum_{k=-N_c/2}^{N_c/2-1}\begin{bmatrix}\left|\sum_{q=-1}^{1}H_{M-B}(k-qN_c)W_B(k-qN_c)-1\right|^2\\ +\sum_{q=-1}^{1}\left|W_B(k-qN_c)\right|^2\Gamma_U(k-qN_c)\end{bmatrix} \\ e_D=\sum_{k=-N_c/2}^{N_c/2-1}\begin{bmatrix}\left|\sum_{q=-1}^{1}H_{B-M}(k-qN_c)W_M(k-qN_c)-1\right|^2\\ +\sum_{q=-1}^{1}\left|W_M(k-qN_c)\right|^2\Gamma_D(k-qN_c)\end{bmatrix} \end{cases}, \tag{10}$$

where

$$\begin{cases} \Gamma_U(k)=\sum_{n_R=0}^{N_R}\left|G(n_R)H_{B-R}(n_R,k)V(n_R,k)\right|^2\left(\frac{P_M}{\sigma_R^2(n_R)}\right)^{-1}+\left(\frac{P_M}{\sigma_B^2}\right)^{-1} \\ \Gamma_D(k)=\sum_{n_R=0}^{N_R}\left|G(n_R)H_{M-R}(n_R,k)V(n_R,k)\right|^2\left(\frac{P_B}{\sigma_R^2(n_R)}\right)^{-1}+\left(\frac{P_B}{\sigma_M^2}\right)^{-1} \end{cases}, \tag{11}$$

and $\sigma_R^2(n_R)$, σ_M^2 and σ_B^2 are the (IBI+noise) powers at the n_Rth RS antenna, MT and BS, respectively.

In this paper, the transmit/receive MMSE-FDE weights are derived as follows. At first, the receive FDE weights are derived viewing the concatenation of the transmit FDE and the channel as an equivalent channel. Then, the transmit FDE weights optimized for either uplink or downlink are derived.

A. *Receive FDE*

The receive FDE weights are derived viewing the concatenation of the transmit FDE and the channel as an equivalent channel. By solving $\partial e_U/\partial W_B(k)=0$ and $\partial e_D/\partial W_M(k)=0$, the receive MMSE-FDE weights are obtained as

$$\begin{cases} W_B(k-qN_c)=\dfrac{H_{M-B}^{*}(k-qN_c)}{\sum_{q=-1}^{1}\left|H_{M-B}(k-qN_c)\right|^2+\Gamma_U(k-qN_c)} \\ W_M(k-qN_c)=\dfrac{H_{B-M}^{*}(k-qN_c)}{\sum_{q=-1}^{1}\left|H_{B-M}(k-qN_c)\right|^2+\Gamma_D(k-qN_c)} \end{cases}. \tag{12}$$

$$\begin{cases} V(n_R, k-qN_c) = \dfrac{G(n_R)H^*_{M-R}(n_R, k-qN_c)H^*_{B-R}(n_R, k-qN_c)}{\sqrt{A(k-qN_c)}} \cdot \sqrt{\max\left[\dfrac{\sqrt{\dfrac{A(k-qN_c)(P_B/\sigma_B^2)^{-1}}{\lambda}} - (P_B/\sigma_B^2)^{-1}}{A(k-qN_c) + \dfrac{B_U(k-qN_c)}{A(k-qN_c)}}, 0\right]} & \text{if } q = \arg\max\limits_{q'=1,0,1} A(k-q'N_c) \\ V(n_R, k-qN_c) = 0 & \text{otherwise} \end{cases} \quad (16)$$

B. Transmit FDE

Substituting (12) to (10), we can obtain

$$\begin{cases} e_U = \sum\limits_{k=-N_c/2}^{N_c/2-1} \dfrac{\sum\limits_{q=-1}^{1}\Gamma_U(k-qN_c)}{\left|\sum\limits_{q=-1}^{1} H(k-qN_c)\right|^2 + \sum\limits_{q=-1}^{1}\Gamma_U(k-qN_c)} \\ e_D = \sum\limits_{k=-N_c/2}^{N_c/2-1} \dfrac{\sum\limits_{q=-1}^{1}\Gamma_D(k-qN_c)}{\left|\sum\limits_{q=-1}^{1} H(k-qN_c)\right|^2 + \sum\limits_{q=-1}^{1}\Gamma_D(k-qN_c)} \end{cases}, \quad (13)$$

where

$$H(k) = \sum_{n_R=0}^{N_R-1} G(n_R)H_{B-R}(n_R, k)H_{M-R}(n_R, k)V(n_R, k). \quad (14)$$

It is seen from (13) and (14) that the equivalent channel gains, $H_{M\text{-}B}(k)$ and $H_{B\text{-}M}(k)$, for uplink and downlink become equal to $H(k)$ and as a consequence, the equivalent channels for uplink and downlink become reciprocal. This is because phase rotation due to timing offset can be removed by the receive MMSE-FDE and spectrum combining. Therefore, the transmit FDE optimized for minimizing the uplink MSE can almost minimize the downlink MSE and vice versa [8,9]. This means that the transmit FDE optimized for uplink achieves almost the same BER performance as the transmit FDE optimized for downlink.

Below, the transmit FDE weight optimized for uplink is derived. The transmit FDE weight optimized for downlink can be derived similar to that for uplink, however, it is skipped due to page limitation.

From (2) and (13), the optimization problem for the transmit FDE can be expressed as

$$\begin{aligned} &\text{minimize} \quad e_U \\ &\text{s.t.} \quad \sum_{k=-N_c/2}^{N_c/2-1}\sum_{n_R=0}^{N_R-1}\sum_{q=-1}^{1}\left|V(n_R, k-qN_c)\right|^2 - N_c = 0 \,. \quad (15) \\ &\qquad\quad -\left|V(n_R, k-qN_c)\right|^2 \le 0 \end{aligned}$$

The optimization problem can be solved by using the Karuch-Kuhn-Tucker condition and the Cauchy-Schwarz inequality [12]. The transmit MMSE-FDE weight optimized for uplink is given as (16), where λ is chosen so as to satisfy (2) and

$$\begin{cases} A(k) = \sum\limits_{n_R=0}^{N_R-1}\left|G(n_R)H_{M-R}(n_R, k)H_{B-R}(n_R, k)\right|^2 \\ B_U(k) = \sum\limits_{n_R=0}^{N_R-1}\left|G(n_R)H_{B-R}(n_R, k)\right|^4\left|H_{M-R}(n_R, k)\right|^2\left(\dfrac{P_M}{\sigma_R^2(n_R)}\right)^{-1} \end{cases}. \quad (17)$$

IV. COMPUTER SIMULATION

We evaluate, by the computer simulation, the BER performance of SC-ANC bi-directional relay with the joint transmit/receive FDE & spectrum combining in the presence of timing error. We consider QPSK data modulation. FFT block size N_c and CP length N_g are set to N_c=128 symbols and N_g=16 samples, respectively. Square root raised cosine filter [13] with roll off factor α=1.0 is used as Nyquist filter. The timing offsets, $\Delta_{M\text{-}R}$, $\Delta_{B\text{-}R}$, Δ_M and Δ_B, normalized by symbol duration are assumed to be uniformly distributed over [–0.5, 0.5]. We assume the total transmit power for bi-directional relay is constant as $P_M+P_B+P_R=P_T$, where P_T is the total transmit power. In computer simulations, the power allocation of $P_R=P_T/2$, $P_B=P_M=P_T/4$ is assumed. The channel is assumed to be frequency-selective block Rayleigh fading having L=16 path uniform power delay profile. We assume that perfect channel state information can be available at RS, BS and MT.

A. Transmit/receive FDE weights

Fig. 3 shows the magnitudes of equivalent channel of MT-to-RS-to-BS link $|G(n_R)H_{M\text{-}R}(n_R,k)H_{B\text{-}R}(n_R,k)|$ and transmit/receive FDE weights. The total transmit power-to-noise power ratio (SNR) Γ is set to 15dB. It is seen from Fig. 3(a) and 3(b) that the most of transmit power is allocated to the antenna whose equivalent channel gain is high so as to maximize spatial diversity gain. Furthermore, the transmit FDE weight acts as reverse function of equivalent channel so as to suppress ISI caused by frequency-selective fading. It is noted that the transmit power for two frequency components which are combined by spectrum combining is allocated only to one frequency component whose channel gain is larger so as to maximize the received SNR after spectrum combining. Therefore, the proposed transmit/receive FDE & spectrum combining can obtain additional frequency diversity gain by frequency selection diversity and spectrum combining.

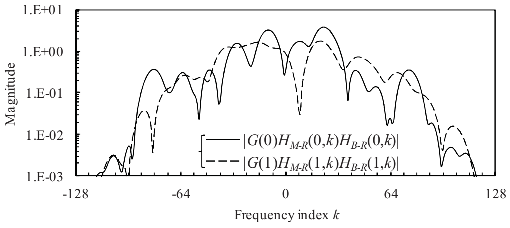
B. BER performance

Fig. 4 shows the BER performance when using the proposed joint transmit/receive FDE & spectrum combining (Proposed) as a function of the total transmit SNR Γ. For comparison, the performance when using the joint transmit/receive FDE (Conventional) [8,9] and that in no timing offset case are also shown in Fig. 4. It is seen from Fig. 4 that the performance of the joint transmit/receive FDE degrades from that in no timing offset case due to ISI caused by timing offset. On the other hand, the proposed joint transmit/receive FDE & spectrum combining achieves almost the same BER performance as that in no timing offset case. Only when the number

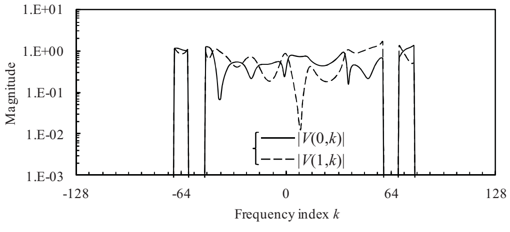
N_R of RS antenna is N_R=1, the BER performance of the proposed joint transmit/receive FDE & spectrum combining has error floor and it slightly degrades compared to that of the joint transmit/receive FDE in high SNR region. This is because the impact of IBI caused by timing offset becomes larger by performing oversampling. However, by setting the number N_R of RS antenna to $N_R \geq 2$, the impact of IBI can be mitigated by spatial diversity gain and accordingly, the proposed scheme always achieve better BER performance than the conventional joint transmit/receive FDE. For example, when N_R=2, the proposed joint transmit/receive FDE & spectrum combining reduces the required transmit SNR for BER=10^{-5} by about 5dB compared to the joint transmit/receive FDE. It is seen from Fig. 4(a) and 4(b) that the proposed scheme can achieve almost the same BER performance as that in no timing offset case for both uplink and downlink.

V. CONCLUSIONS

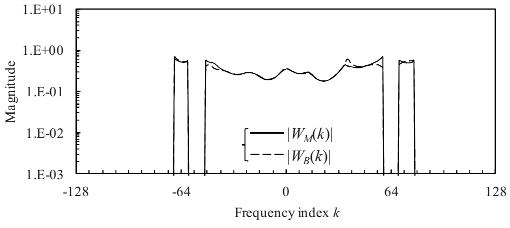
In this paper, we proposed a joint transmit/receive FDE & spectrum combining for SC-ANC bi-directional relay in the presence of timing offset. By performing oversampling and transmit FDE at RS while performing oversampling, simultaneous receive FDE and spectrum combining at both MT and BS receivers, the ISI caused by both timing offset and frequency-selective fading can be significantly suppressed. Joint optimization of transmit and receive FDE weights taking into account spectrum combining was presented. Computer simulation confirmed that the proposed joint transmit/receive FDE & spectrum combining obtains both spatial and frequency diversity gains and achieves a good BER performance for both uplink and downlink even in the presence of timing offset.



(a) MT-to-RS-to-BS equivalent channel

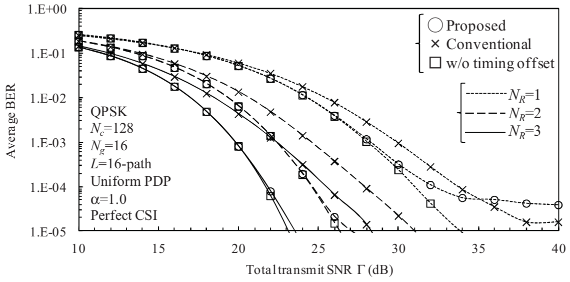


(b) Transmit FDE

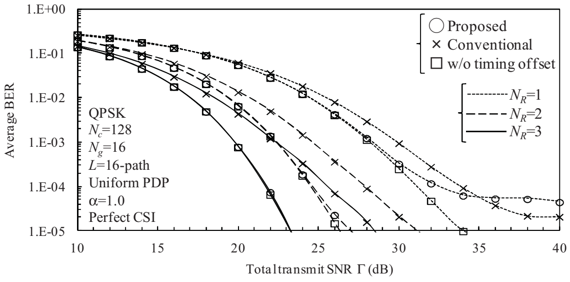


(c) Receive FDE

Fig. 3. Transmit/receive FDE weights.



(a) Uplink



(b) Downlink

Fig. 4. BER performance.

REFERENCES

[1] J. G. Proakis and M. Salehi, *Digital communications*, 5th ed., McGraw-Hill, 2008.

[2] J. G. Laneman, D. N. C. Tse, and G. W. worwell, “Cooperative diversity in wireless networks: efficient protocol and outage behavior,” IEEE Trans. Inf. Theory, vol. 50, no. 12, Dec. 2004.

[3] S.Katti, S. Gollakota, and D. Katabi, “Embracing wireless interference: analog network coding” Proc. ACM SIGCOMM, pp. 397-408, Aug. 2007.

[4] H. Gacanin, and F. Adachi, “Broadband analog network coding” IEEE Trans. Wireless Commun, vol.9, no.5, pp. 1577-1783, May 2010.

[5] D. Falconer, S. L. Ariyavistakul, A. Benyamin-Seeyar, and B. Edison, “Frequency domain equalization for single-carrier broadband wireless systems,” IEEE Commun.. Mag., vol. 40, no. 4, pp. 58-66, Apr. 2002.

[6] F. Adachi, T. Sao and T. Itagaki, “Performance of multicode DS-CDMA using frequency domain equalization in a frequency selective fading channel,” Electron. Lett., vol. 39, no. 2, pp. 239-241, Jan. 2003.

[7] K. Takeda and F. Adachi, “Joint transmit/receive one-tap minimum mean square error frequency-domain equalisation for broadband multicode direct-sequence code division multiple access,” IET Commun., vol. 4, no. 14, pp. 1752-1764, Sep. 2010.

[8] H. Miyazaki, T. Obara and F. Adachi, ”Joint transmit/receive MMSE-FDE for analog network coded single-carrier bi-directional multi-antenna relay,” IEICE Trans. Commun., vol. E96-B, no.12, pp. 3153-3162, Dec. 2013.

[9] H. Miyazaki, M. Nakada, T. Obara and F. Adachi, ”Joint transmit/receive MMSE-FDE for MIMO analog network coding in single-carrier bi-directional relay communications,” Proc. 2012 IEEE 76th Vehiqular Technology Conference (VTC2012-fall), Quebec, Canada, Sept. 2012.

[10] Y. Wang and X. Dong, “comparion of frequency offset and timing offset effects on the performance of SC-FDE and OFDM over UWB Channels,” IEEE Trans. Veh., vol. 58, no. 1, pp. 240-250, Jan. 2009.

[11] T. Obara, Kazuki Takeda, and F. Adachi, ”Joint MMSE-FDE & spectrum combining for a broadband single-carrier transmission in the presence of timing offset,” IEICE Trans. Commun., vol.E94-B, no.5, pp.1366-1375, May 2011.

[12] S. Boyd and L. Vandenberghe, *Convex Optimizations*, Cambridge, 2006.

[13] Y. Akaiwa, *Introduction to digital mobile communication*, Wiley, Newyork, 1997.