Adaptive Analog Network Coded Two-Way Relay

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***Abstract*—Previous studies on analog network-coded two-way relay (ANC-TWR) assumed the same modulation and coding both for the mobile terminal (MT)-relay station (RS) link and the base station (BS)-RS link. In this paper, we propose an adaptive ANC-TWR, where adaptive modulation and coding (AMC) is employed in order to maximize the uplink (MT-RS-BS) and downlink (BS-RS-MT) throughputs. The single-carrier transmission with frequency-domain equalization (SC-FDE) is utilized for the uplink and the orthogonal frequency division multiplexing (OFDM) is utilized for the downlink. We evaluate, by the computer simulation, the throughput performance of adaptive ANC-TWR. It is shown that the adaptive ANC-TWR achieves better throughput performance than the non-adaptive ANC-TWR with fixed modulation and coding.**

Keywords—component; Analog network coding, adaptive modulation and coding, single-carrier transmission

I. INTRODUCTION

In cellular mobile communications, the throughput of a user near the cell edge is degraded by the propagation path loss and the shadowing loss [1]. Recently, the cooperative relay [2] has been intensively studied; but, the maximum throughput is reduced since four time-slots are necessary for two-way relay (TWR). The number of time slots can be reduced by applying network coding to TWR. Network coding is typically divided into two types: XOR network coding (XOR-NC) [3] and analog network coding (ANC) [4-6]. In ANC-TWR, a relay station (RS) amplifies and broadcasts the superposition of uplink and downlink signals to base station (BS) and mobile terminal (MT) without demodulation and decoding unlike XOR-NC-TWR. ANC-TWR has been attracting much attention since it requires two time-slots for TWR, and hence, it achieves the same maximum throughput as the point-to-point communications.

It should be noted that the received signal-to-noise power ratios (SNRs) at BS and MT are different due to the transferred noise from RS (the noise received at RS is amplified and broadcasted by RS). Hence, an introduction of adaptive modulation and coding (AMC) [7-9] to ANC-TWR improves the throughput performance. However, the past studies for ANC-TWR [4-6] assumed the same modulation and coding.

In this paper, we propose an adaptive ANC-TWR in order to maximize the uplink (MT-RS-BS) and downlink (BS-RS-MT) throughputs. Single-carrier transmission with frequency-domain equalization (SC-FDE) [10] and orthogonal frequency division multiplexing (OFDM) [11] are respectively assumed for uplink and downlink. MT and BS independently perform AMC so as to maximize their respective throughputs. We evaluate, by the computer simulation, the throughput performance of adaptive ANC-TWR to show that the adaptive ANC-TWR achieves better throughput performance than the non-adaptive ANC-TWR with fixed modulation and coding.

II. ANC-TWR

A. Network model

Fig. 1 illustrates the relay network model of ANC-TWR considering in this paper. BS, RS and MT are linearly positioned. The distance between MT and RS and that between MT and BS are denoted by $D_{M\text{-}R}$, and $D_{M\text{-}B}$, respectively. In this paper, we define the normalized distance between MT and RS as $d_{M\text{-}R}=D_{M\text{-}R}/D_{M\text{-}B}$. For simplicity, shadowing loss is not considered in this paper. We assume that MT, RS and BS have single antenna each. Ideal channel estimation at BS and MT is assumed. Turbo coding [12] is also considered.

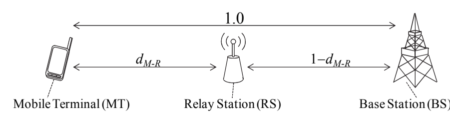


Fig. 1. Relay network model.

Fig. 2 and 3 show the transmitter/receiver structure of MT and BS, respectively. After estimating the receive signal-to-noise-power ratio (SNR) at BS (MT), MT (BS) selects modulation and coding scheme (MCS) so as to maximize the uplink (downlink) throughput. After that, BS and MT carry out the selected coding and data modulation.

In the first time-slot, BS generates OFDM signal by applying N_c-point inverse fast Fourier transform (IFFT) to N_c data symbol block. After insertion of N_g sample cyclic prefix (CP) into the beginning of each block, BS and MT transmit their signals to RS. In the second time-slot, RS amplifies and broadcasts the received signal to BS and MT. At MT and BS receiver, the removal of own transmitted signal and the receive FDE is applied. Finally, data demodulation and turbo decoding is carried out.

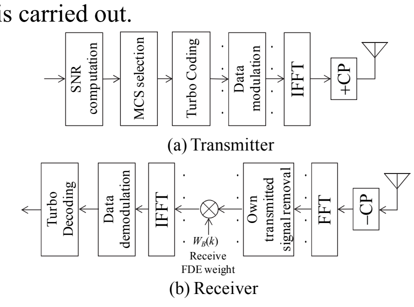


Fig. 2. Transmitter/receiver structure of BS.

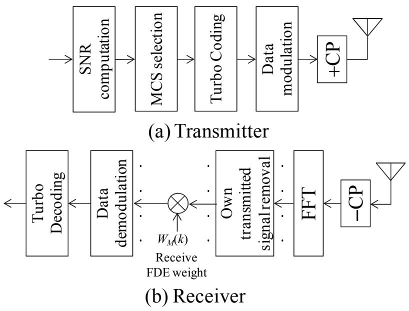


Fig. 3. Transmitter/receiver structure of MT.

B. Signal reprensentation

In this paper, symbol-spaced discrete time signal representation is used. The data symbol block of N_c symbols at BS and MT are denoted as $\{d_B(t) : t=0,\ldots,N_c-1\}$ and $\{d_M(t) : t=0,\ldots,N_c-1\}$, respectively. At BS transmitter, OFDM symbol block, $\{x_B(t) : t=0,\ldots,N_c-1\}$, is generated by applying N_c-point IFFT to the data symbol block as

$$x_B(t) = \frac{1}{\sqrt{N_c}} \sum_{m=0}^{N_c-1} d_B(m) \exp(j2\pi tm/N_c). \tag{1}$$

On the other hand, SC symbol block, $\{x_M(t) : t=0,\ldots,N_c-1\}$, at MT transmitter is given as $x_M(t)= d_M(t)$. After CP insertion, BS and MT simultaneously transmit their signal to RS in the first time-slot.

In the second time-slot, RS amplifies the received signal and broadcasts it to BS and MT. At BS and MT receiver, after CP removal, the time-domain receive signal is transformed into the frequency-domain signal by N_c-point FFT. The frequency-domain received signal, $\{Y_M(k) : t=0,\ldots,N_c-1\}$ and $\{Y_B(k) : t=0,\ldots,N_c-1\}$, at MT and BS can be expressed as

$$\begin{cases} Y_M(k) = \sqrt{2P_B}\, GH_{M-R}(k)H_{B-R}(k)X_B(k) \\ \qquad + \sqrt{2P_M}\, GH_{M-R}(k)H_{M-R}(k)X_M(k) \\ \qquad + GH_{M-R}(k)N_R(k) + N_M(k) \\ Y_B(k) = \sqrt{2P_M}\, GH_{M-R}(k)H_{B-R}(k)X_M(k) \\ \qquad + \sqrt{2P_B}\, GH_{B-R}(k)H_{B-R}(k)X_B(k) \\ \qquad + GH_{B-R}(k)N_R(k) + N_B(k) \end{cases}, \tag{2}$$

where P_M and P_B are the normalized transmit power of MT and BS, respectively. They are given as $P_M = \overline{P}_M D_{M-B}^{-\alpha}$ and $P_B = \overline{P}_B D_{M-B}^{-\alpha}$ with denoting $\overline{P}_M$ and $\overline{P}_B$ as the actual transmit powers of MT and BS, respectively. $X_M(k)$ and $X_B(k)$ are the kth frequency components of the transmitted signal of MT and BS, which are

$$\begin{cases} X_M(k) = \dfrac{1}{\sqrt{N_c}} \displaystyle\sum_{t=0}^{N_c-1} x_M(t) \exp(-j2\pi kt/N_c) \\ X_B(k) = \dfrac{1}{\sqrt{N_c}} \displaystyle\sum_{t=0}^{N_c-1} x_B(t) \exp(-j2\pi kt/N_c) \end{cases}. \tag{3}$$

$H_{M-R}(k)$ and $H_{B-R}(k)$ are the kth frequency complex-valued channel gains, including the impact of the propagation path loss of the MT-RS and BS-RS links, respectively. They are given as

$$\begin{cases} H_{M-R}(k) = \sqrt{d_{M-R}^{-\alpha}} \cdot \overline{H}_{M-R}(k) \\ H_{B-R}(k) = \sqrt{(1-d_{M-R})^{-\alpha}} \cdot \overline{H}_{B-R}(k) \end{cases}, \tag{4}$$

where α is the path loss exponent. $\overline{H}_{M-R}(k)$ and $\overline{H}_{B-R}(k)$ are the channel transfer functions of the MT-RS links and BS-RS links, respectively. $N_R(k)$, $N_M(k)$ and $N_B(k)$ are the independent zero-mean additive white Gaussian noises (AWGNs) having variance $2N_0/T_s$ where N_0 and T_s are the single-side noise power spectrum density and symbol duration, respectively. G is the amplification gain of RS, which is set to keep the RS transmit power constraint as

$$G = \sqrt{\frac{P_R}{\dfrac{P_M}{N_c} \displaystyle\sum_{k=0}^{N_c-1} |H_{M-R}(k)|^2 + \dfrac{P_B}{N_c} \displaystyle\sum_{k=0}^{N_c-1} |H_{B-R}(k)|^2 + N}}, \tag{5}$$

where $P_R = \overline{P}_R D_{M-B}^{-\alpha}$ with denoting $\overline{P}_R$ as the actual transmit powers of RS. $N=N_0/T_s$ is the noise power. In (2), the first term is the desired signal and the second term is the own transmitted signal. The third term is the noise which is amplified and broadcasted by RS.

The removal of own transmitted signal is done by

$$\begin{cases} \tilde{Y}_M(k) = Y_M(k) - \sqrt{2P_M}\, GH_{M-R}(k)H_{M-R}(k)X_M(k) \\ \tilde{Y}_B(k) = Y_B(k) - \sqrt{2P_B}\, GH_{B-R}(k)H_{B-R}(k)X_B(k) \end{cases}. \tag{6}$$

After that, one-tap receive FDE is done by

$$\begin{cases} \hat{Y}_M(k) = \tilde{Y}_M(k) W_M(k) \\ \hat{Y}_B(k) = \tilde{Y}_B(k) W_B(k) \end{cases}, \tag{7}$$

where, $W_M(k)$ and $W_B(k)$ are the FDE weights at MT and BS, respectively. In the proposed adaptive ANC-TWR, the uplink and downlink use SC and OFDM, respectively. Therefore, the FDE weights at MT are determined based on zero-forcing criterion, while the FDE weight at BS is derived so as to minimize mean square error (MSE) between $X_M(k)$ and $\hat{Y}_B(k)$. The FDE weights are expressed by

$$\begin{cases} W_M(k) = \dfrac{\{GH_{M-R}(k)H_{B-R}(k)\}^*}{|GH_{M-R}(k)H_{B-R}(k)|^2} \\ W_B(k) = \dfrac{\{GH_{M-R}(k)H_{B-R}(k)\}^*}{|GH_{M-R}(k)H_{B-R}(k)|^2 + \{|GH_{B-R}(k)|^2 + 1\}\left(\dfrac{P_M}{N}\right)^{-1}} \end{cases}. \tag{8}$$

At BS receiver, the received signal after FDE is data demodulated and decoded, while the received signal after FDE at MT is transformed back to the time-domain signal by N_c-point IFFT, prior to demodulation and turbo decoding.

III. Adaptive Modulation and Coding

MCS candidates considered in this paper are summarized in table 1. The MCS is selected so as to maximize the throughput while satisfying the required BER of 10^{-3}. However, it is quite difficult to derive the theoretical BER when the turbo coding is used. In this paper, we introduce the simple MCS selection by using a lookup table containing the SNR thresholds (i.e., SNRs necessary for achieving the required BER) determined from the computer simulation or transmission experiment [10].

TABLE I. MCS CANDIDATES

MCS1	MCS2	MCS3	MCS4	MCS5	MCS6
BPSK R=1/2	BPSK R=3/4	QPSK R=1/2	QPSK R=3/4	16QAM R=1/2	16QAM R=3/4

A. MCS selection at MT transmitter

The received SINR γ_B at BS after FDE is given as

$$\gamma_B = \frac{\frac{2P_M}{N}\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1}\widetilde{H}(k)\right|^2}{\left[\frac{P_M}{N}\left\{\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|\widetilde{H}(k)\right|^2-\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1}\widetilde{H}(k)\right|^2\right\}+\sum_{k=0}^{N_c-1}\left\{\left|GH_{B-R}(k)\right|^2+1\right\}\left|W_B(k)\right|^2\right]}, \quad (9)$$

where $\widetilde{H}(k)=GH_{M-R}(k)H_{B-R}(k)W_B(k)$. The first term in the denominator is the contribution of the residual ISI and the second term is the contribution of the noise. As understood from Eq. (9), SC transmission with MMSE-FDE still suffers from the residual inter-symbol interference (ISI) [10]. Therefore, the MCS at MT transmitter is selected based on signal-to-interference plus noise power ratio (SINR) at BS after FDE. It is understood from Eq. (9) that for MCS selection, MT needs the knowledge of the channel state information (CSI) of the MT-RS link and BS-RS link, the BS transmit power, and the noise power, in order to compute the received SINR γ_B.

B. MCS selection at BS transmitter

In the adaptive ANC-TWR, BS determines the coding rate and modulation level for each subcarrier as follows [8,9].

Step 1. The coding rate R and the total number of information bits per one block N_{bit} is determined based on the block average received SNR Γ_M.

Step 2. For the given coding rate R, modulation level for each subcarrier $M(k)$ is selected based on the received SNR on each subcarrier γ_M.

Step 3. Modulation level for each subcarrier is adjusted so as to make the number of information bits per one block equal to N_{bit}.

Step 1) The coding rate R and the total number of information bits per one block N_{bit} is determined based on the block-averaged received SNR at MT. The block-averaged received SNR Γ_M at MT is given as

$$\Gamma_M = \frac{1}{N_c}\sum_{k=0}^{N_c-1}\gamma_M(k), \quad (10)$$

where $\gamma_M(k)$ is the received SNR for the kth subcarrier, that is

$$\gamma_M(k) = \frac{P_B}{N}\frac{\left|GH_{M-R}(k)H_{B-R}(k)W_M(k)\right|^2}{\left\{\left|GH_{M-R}(k)\right|^2+1\right\}\left|W_M(k)\right|^2}. \quad (11)$$

After calculating the received SNR using Eq. (10), the coding rate and the total number of information bits is determined so as to maximize the throughput using the lookup table.

Step 2) After calculating the received SNR on each subcarrier, the modulation level for each subcarrier for the given coding rate R is selected based on the look-up tables.

Step 3) The modulation level for each subcarrier is adjusted in order to meet N_{bit}. The number of information bits per one block when using the modulation level selected in the second step can be expressed as

$$\widetilde{N}_{bit} = \sum_{k=0}^{N_c-1}\log_2 M(k), \quad (12)$$

where $M(k)$ denotes the modulation level for the kth subcarrier. If $\widetilde{N}_{bit}$ differs from N_{bit}, the modulation level is selected as follows [9].

(a) If $\widetilde{N}_{bit} < N_{bit}$.
The difference between the receive SNR and SNR threshold is calculated. Then the modulation level for the subcarrier which has the smallest SNR difference is changed to higher modulation level.

(b) If $\widetilde{N}_{bit} > N_{bit}$.
The difference between the receive SNR and SNR threshold is calculated. Then, the modulation level for the subcarrier which has the smallest SNR difference is changed to lower modulation level.

A series of Step 1, 2, and 3 is repeated until $\widetilde{N}_{bit} = N_{bit}$. It is understood from Eqs. (10) and (11) that for MCS selection, BS as well as MT needs the knowledge of the CSI of BS-RS link and MT-RS link, the MT transmit power, and the noise power, in order to compute the received SNR $\gamma_M(k)$.

IV. COMPUTER SIMULATION

We evaluate, by the computer simulation, the throughput performance of the proposed scheme. The information bit sequence to be transmitted is 1536 bits and is encoded by turbo coding with the original coding rate 1/3 using two (13,15) recursive systematic convolutional (RCS) encoders. The coding rate R is set to R=1/2, 3/4 by puncturing. Turbo decoding is performed by using Log-Map algorithm [13] with 6 iterations. FFT block size N_c and CP length N_g are set to N_c=128, and N_g=32. We assume a frequency-selective block Rayleigh fading having symbol-spaced L=16-path uniform power delay profile. The path loss exponent α is assumed to be α=3.5. We assume the total transmit power constraint ($P_T=P_M+P_B+P_R$) and the total transmit power allocation to RS, BS and MT is set as $P_R=P_T/2$ and $P_B=P_M=P_T/4$, where P_T is the normalized total transmit power. We assume that BS (MT) has the perfect knowledge of the CSI of MT-RS link and BS-RS link, the noise power, and the MT (BS) transmit power in this paper. The average throughput S is given as

$$S = \frac{1}{2}\frac{1}{\sum_{i=1}^{6}\frac{P_i}{\eta_i(1-PER_i)}}\frac{N_c}{N_c+N_g}, \quad (13)$$

where P_i is the probability which ith MCS is selected and η_i is the spectrum efficiency of ith MCS. PER_i is the packet error rate when ith MCS is selected.

We measured the average BER performance for the given MCS by the preliminary computer simulation to obtain the SNR threshold of each MCS. MCS selection at MT is shown in Table II. The MCS is selected so as to maximize the throughput as shown in Table II. For example, MCS4 (QPSK, R=3/4) is selected when $\gamma_B = 8.5$(dB) at MT. The SINR threshold for MCS2 is the same as for MCS3. Therefore, MCS3 is selected when $4.5(\text{dB}) \le \gamma_B \le 7.6(\text{dB})$ since MCS3 has higher spectrum efficiency than MCS2. The MCS selection at BS is shown in Tables III, IV and V.

TABLE II. MCS SELECTION AT MT

γ_B (dB)	~4.5	4.5 ~7.6	7.6 ~10.0	10.0 ~14.0	14.0~
MCS	MCS1	MCS2 MCS3	MCS4	MCS5	MCS6

TABLE III. SELECTION OF R AND N_{BIT} AT BS

Γ_M (dB)	~4.0	4.0~7.4	7.4~10.2	10.2~	15.4~
R	1/2	1/2	3/4	1/2	3/4
N_{bit}	N_c	$2N_c$	$2N_c$	$4N_c$	$4N_c$

TABLE IV. MODULATION SELECTION V.S. SNR (R=1/2)

γ_M (dB)	~1.8	1.8~4.0	4.0~10.2	10.2~
Modulation	Zero padding	BPSK	QPSK	16QAM

TABLE V. MODULATION SELECTION V.S. SNR (R=3/4)

γ_M (dB)	~4.3	4.3~7.4	7.4~13.6	13.6~
Modulation	Zero padding	BPSK	QPSK	16QAM

A. Throughput

Fig. 4 shows the average throughput as a function of the normalized distance, $d_{M\text{-}R}$. Fig. 5 shows probability of MCS as a function of the normalized distance, $d_{M\text{-}R}$. The normalized total transmit power-to-noise power ratio P_T/N is set to 18dB. For comparison, the throughput achievable with the non-adaptive ANC-TWR (using 16QAM and R=3/4) is also plotted in Fig. 4. It is seen from Fig. 5 that the downlink and uplink throughput of the non-adaptive ANC is degraded when $d_{M-R} \approx 0$ and $d_{M-R} \approx 1$. The reason for this is explained as follows. In ANC-TWR, the receive SNRs at BS and MT depend on the location of RS since the noise powers received from RS are different. When $d_{M-R} \approx 0$, the propagation path loss of the BS-RS link is larger than that of MT-RS link. Therefore, the received SNR at BS is smaller than the received SNR at MT and vice versa.

On the other hand, the proposed adaptive ANC-TWR selects MCS so as to maximize the throughput while satisfying BER=10^{-3}. Therefore, the proposed adaptive ANC-TWR can reduce the packet error and can always achieve the higher throughput than the non-adaptive ANC-TWR. For example, when $d_{M\text{-}R}$ = 0.2, the adaptive ANC-TWR can achieve about 10 times higher downlink throughput than the non-adaptive ANC-TWR.

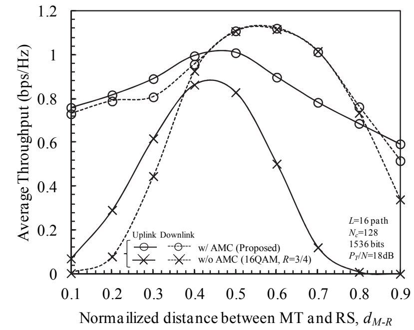
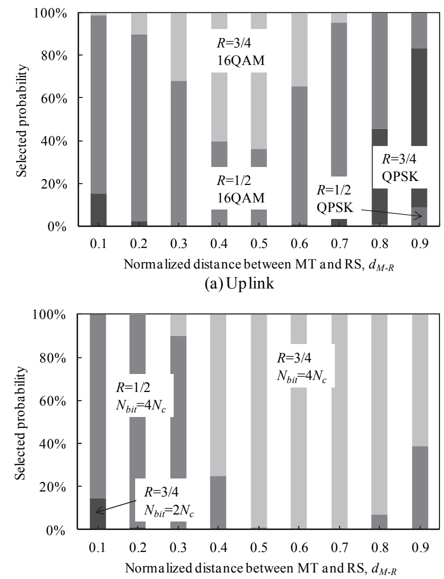


Fig. 4. Average throughput.



(a) Uplink

(b) Downlink

Fig. 5. Probability of MCS.

B. Conparison of SC/SC-, SC/OFDM-,OFDM/SC-, and OFDM/OFDM-ANC-TWR

Fig. 6 compares the average throughput among SC/SC-, SC/OFDM-, OFDM/SC-, and OFDM/OFDM-ANC-TWR (SC/OFDM indicates that SC and OFDM are selected for the uplink and downlink, respectively). It can be seen from Figs. 6(a) and 6(b) that for the uplink, SC/SC and SC/OFDM achieve almost the same throughput and OFDM/OFDM and OFDM/SC achieve almost the same throughput. On the other hand, for the downlink, SC/SC and OFDM/SC achieve almost the same throughput and OFDM/OFDM and SC/OFDM achieve almost the same throughput. It is seen from Fig. 6(c) that the best sum throughput (uplink+downlink) is obtained by selecting SC/OFDM when 0<$d_{M\text{-}R}$< 0.2, OFDM/OFDM when 0.2<$d_{M\text{-}R}$< 0.8, and OFDM/SC when 0.8<$d_{M\text{-}R}$< 1.

The reason for why the highest sum throughput is achieved by selecting SC/OFDM when 0<$d_{M\text{-}R}$<0.2 can be explained as follows. SC suffers from residual ISI after FDE but obtains the frequency diversity gain through FDE while OFDM avoids ISI and obtains the frequency diversity gain through turbo coding which is lower than that obtained in SC. When 0<$d_{M\text{-}R}$<0.2, the uplink received SNR at BS is lower than the downlink received SNR at MT. Because of low SNR, the predominant factor to degrade the throughput is the noise rather than the residual ISI. As a consequence, SC is chosen so as to obtain higher throughput, since SC obtains higher frequency diversity gain than OFDM. On the other hand, the downlink received SNR at MT is sufficiently high. Because of high SNR, the predominant factor to degrade the throughput is the residual ISI rather than the noise. As a consequence, OFDM is chosen so as to obtain higher throughput, since OFDM avoids ISI while SC suffers from the residual ISI.

When $0.8<d_{M\text{-}R}<1$, the downlink received SNR at MT is lower than the uplink received SNR at BS, and hence, OFDM/SC achieves the highest sum throughput among SC/SC-, SC/OFDM-, OFDM/SC-, and OFDM/OFDM for the same reason when $0<d_{M\text{-}R}<0.2$. The above discussion suggests using the adaptive switching between SC and OFDM.

V. Conclusion

In this paper, we proposed an adaptive ANC-TWR, where AMC is employed in order to maximize the uplink and downlink throughputs. It was shown by the computer simulation that the optimum transmission scheme depends on the RS location and the sum throughput is maximized by selecting SC/OFDM when $0<d_{M\text{-}R}<0.2$, OFDM/OFDM when $0.2<d_{M\text{-}R}< 0.8$, and OFDM/SC when $0.8<d_{M\text{-}R}< 1$. In this paper, we presented only computer simulation results. The theoretical analysis of the proposed adaptive ANC-TWR is left as our future work. We assumed that BS (MT) has the perfect knowledge of CSI of BS-RS link and MT-RS link, noise power, and MT (BS) transmit power in this paper. The channel estimation and how MT and BS share the CSI of MT-RS link and BT-RS link are also left as our future work.

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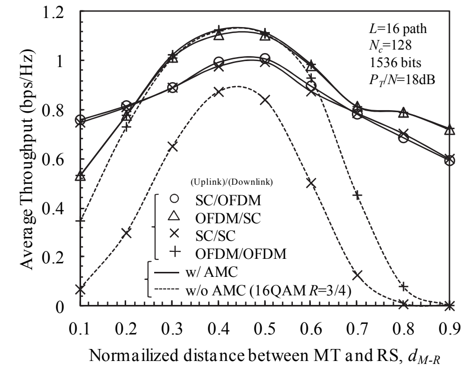
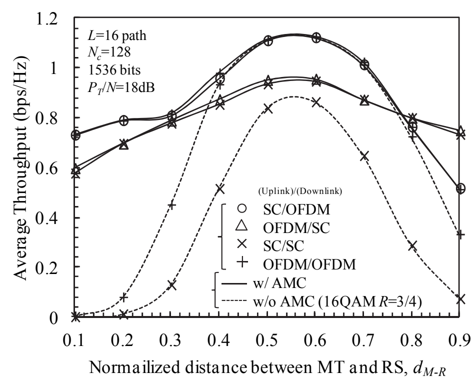
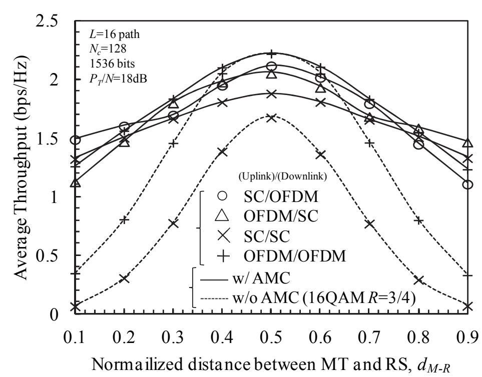


(a) Uplink throughput



(b) Downlink throughput



(c) Sum throughput

Fig. 6. Comparison of SC/SC-, SC/OFDM, OFDM/SC-, and OFDM/OFDM-ANC.