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*Research Article*

# ARQ Protocols for Two-Way Wireless Relay Systems: Design and Performance Analysis

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Two-way relay (TWR) communication, a new cooperation paradigm that allows two terminals to share one relay node to communicate with each other in two phases, has played an increasingly valuable role in wireless networks to meet the stringent throughput requirement. In this paper, we focus on the designing of automatic repeat-request (ARQ) protocols for the two-way wireless relay systems. According to different feedback schedules, we propose three basic ARQ protocols to improve the throughput of two-way relay systems, namely, relay-only ARQ (Ro-ARQ), terminal only ARQ (To-ARQ) and relay-terminal ARQ (RT-ARQ). Through analyzing the outage throughput of these three ARQ protocols, it is verified that all three protocols can improve the system performance. In addition, simulation results reveal that the RT-ARQ protocol has the closest performance to the theoretical throughput upperbound among all given methods without severe deterioration on system complexity.

## 1. Introduction

Wireless communication has experienced tremendous progress in the past two decades. The development of relative technologies, for example, coding schemes, multiple-input, multiple-output (MIMO), and orthogonal frequency-division multiplexing (OFDM), and so forth, has contributed on accelerating the transmission rate sharply from a few kilo-bits per second (e.g., AMPS) to more than 300 Mb/s (e.g., 3GPP LTE) accompanied with the appearance of high-rate-requiring services [1]. On the other hand, however, it can also be predicted that the challenge of transmission data rate would be more serious in the near future on considering such rate-demanding applications and the limited radio resources. To cope with the insufficiency of rate caused by a variety of factors including fading, noise accumulation and interference, and so forth, the implementation of relay is introduced to assist the communication where the radio resources are not ideal, such as edge of cellular systems [2]. In this paper, two-way relay (TWR) channel, also known as physical-layer network coding (PNC) [3–6], is discussed for its improved spectral efficiency over the one-way relay or any other conventional relay strategies. The key idea of two-way relay is that two participating terminals can simultaneously transmit packets to the relay in the same phase, after which the relay processes the received signal and broadcasts it to each destination in the following phase. In other words, different from sequential data rate [7], both interacting terminals can exchange information via transmitting or receiving synchronously.

Recent works on two-way relay channels have gained great achievements on promoting its performance. These papers [3, 4] mainly demonstrated the application and designing of PNC. In [8], transmission protocols for TWR were proposed and verified of their contribution on the multiplexing as well as the diversity gain. Also, [9] designed a method of optimization on two-way relay transmission which raised the sumrate and utilize Karush Kuhn Tucker (KKT) condition to transform a nonconvex problem of power-minimization into a feasible one, reaching a tradeoff between multiplexing and diversity gain. To mitigate error propagation, error check at relay was introduced in the work of [10], by setting a threshold at relay.

Departing from most previous works in TWR [1–10], an alternative method to improve system performance is applying the automatic repeat-request (ARQ) protocols at the data link layer to guarantee the system throughput performance [11], where cyclical redundancy check (CRC) is used for checking error packets, and retransmissions are requested if packets are received in error. The tasks of ARQ protocol designing for two-way relay channels were also conducted in previous works lately. In [12], a set of ARQ protocols were presented and analyzed but under the assumption that the bit-error rate (BER) between the relay and each individual terminal is directly assigned instead of taking the influence of transmitting power and rate into account. A unique set of ARQ protocols for TWR were also proposed and analyzed in [13] and it can be viewed as a special case of this work. Since there are two terminals and one relay in the two-way relay system, different feedback schedules can be designed to meet various transmission conditions for ARQ protocol [14]. For this reason, the ARQ protocols in our work are classified into 3 types according to where retransmissions are requested for an erroneous packet:

(i) relay-only ARQ (RO-ARQ), where retransmissions are requested at relay and the link reliability from terminals to the relay is guaranteed only,

(ii) terminal-only ARQ (TO-ARQ), where only the terminals execute repeat-request, and the end-to-end link between the terminals via relay will affect the performance, and

(iii) relay-terminal ARQ (RT-ARQ), which combines the RO-ARQ and TO-ARQ protocol together.

In [15], we just proposed above three protocols and described the details but did not analyze the performances and performed complete simulations. In this journal paper, throughput performances are analyzed. Finite-state Markov chain is applied to decompose the procedure of ARQ protocol into discrete states like [16]. Computer simulations are performed to verify the performance analysis. It can be obtained that the proposed protocols promote the throughput, and RT-ARQ protocol has the best performance.

The paper is organized as follows. A brief description of the system model of two-way relay channels is introduced in Section 2, followed by the detailed procedures of all three ARQ protocols in Section 3. The method of finite-state Markov chain analysis of the given protocols is in Section 4. After that, in Section 5, Monte-Carlo simulations of all three protocols are conducted. Finally the work is concluded in Section 6.

## 2. System Model and Assumptions

This work considers a wireless network where two terminals, $T_1$ and $T_2$, exchange their information through the assistance of a third node $R$, which acts as a relay and lies geographically between both terminals (Figure 1). Generally, there are two processing strategies at relay: amplify and forward (AF) and decode and forward (DF) [17]. The achievable throughput of the AF-based two-way relay systems has already been studied in [18]. Furthermore, the noise amplification can severely degrade the performance, especially in very low and middle signal-to-noise-ratio (SNR) environments. Thus, the DF strategy is the only consideration in this work. In addition, the DF scheme dealing with the data packet is more suitable for protocols in link layer. It is assumed that the direct link between $T_1$ and $T_2$ is not available, and all nodes work in the half-duplex mode [3, 4, 17, 18]. The transmission consists of two phases: the multiple access (MA) phase and broadcast (BC) phase. Two terminals simultaneously transmit their packets to the relay in the first phase (MA phase). Then the relay straightly decodes the received signal to perform network coding and broadcasts the encoded information in the next phase (BC phase). Each terminal is able to eliminate the interference (generated by its own packet) from the received signal and recover the information from the other terminal.

In the MA phase, the symbols of $S_1$ and $S_2$ are simultaneously transmitted to $R$ from $T_1$ and $T_2$, respectively. Therefore, $R$ receives the following:

$$y_R = \sqrt{P_{T_1}} h_{T_1R} S_1 + \sqrt{P_{T_2}} h_{T_2R} S_2 + n_R, \tag{1}$$

where $h_{T_iR}$, $i \in \{1, 2\}$ is the channel coefficient between $T_i$ and $R$ assumed to be frequency flat and constant over the entire time slot and is characterized by Rayleigh fading, $h_{T_iR} \sim \mathrm{CN}(0,1)$. In this work, $h_{T_iR}$ is presumed to be correctly estimated through the use of training sequences. In other words, perfect channel knowledge is available at both transceiver sides. $P_{T_i}$ represents the average transmitting power of $T_i$ while $n_i$ ($n_R$) stands for the noise at $T_i(R)$ and is complex Gaussian random variable with $\mathrm{CN}(0, \sigma^2)$. The relay operates in the DF and adopts maximum likelihood principle to decode the received signal. To be specified, the relay will choose $\widehat{S}_1$ and $\widehat{S}_2$ from codebooks of each node as decoded symbols that satisfies the following:

$$\left(\widehat{S}_1, \widehat{S}_2\right) = \arg \min_{(\widehat{S}_1, \widehat{S}_2)} \left\{ \left\| y_R - \left( \sqrt{P_{T_1}} h_{T_1R} \widehat{S}_1 + \sqrt{P_{T_2}} h_{T_2R} \widehat{S}_2 \right) \right\|^2 \right\}. \tag{2}$$

Then the relay maps $(\widehat{S}_1, \widehat{S}_2)$ to $S_R$, $S_R = M(\widehat{S}_1, \widehat{S}_2)$ using the mapping principle $M(\cdot)$ like [4].

In the BC phase, the relay broadcasts $S_R$ to $T_1$ and $T_2$. Hence, the signal received by $T_i$ can be written as

$$y_i = \sqrt{P_R} h_{T_iR} S_R + n_i, \quad \text{for} \quad i = 1, 2, \tag{3}$$

where $P_R$ symbolizes the average transmitting power of the relay. Additionally, at each packet, besides CRC, extra information about original owner of this packet is also included like [19], and the feedback messages from $T_i(R)$ are presumed to be received without error or delay at the $R(T_i)$.

## 3. Protocol Descriptions

In this paper, we aim at improving the reliable transmission in the TWR systems; thus, we propose three basic ARQ

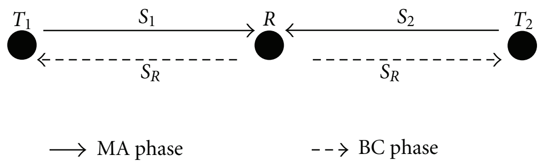



FIGURE 1: The two-way relay channel.

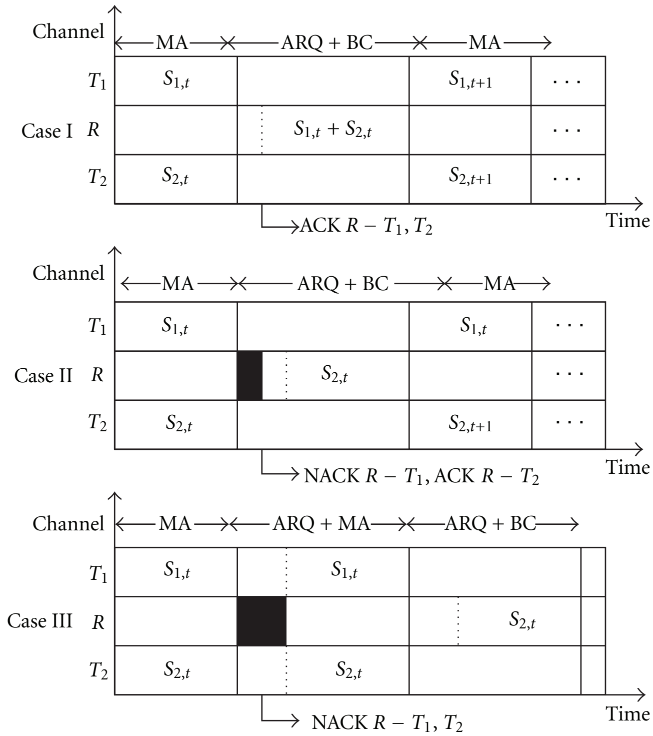



FIGURE 2: The RO-ARQ protocol.

protocols to fulfill this purpose: relay-only ARQ (RO-ARQ), terminal-only ARQ (TO-ARQ), and relay-terminal ARQ (RT-ARQ), which are named by where the retransmissions are requested and which link reliability is ensured. They are described in detail as follows. The analysis on their performance of throughput will be discussed in the next section.

*3.1. RO-ARQ.* Relay-only arq: only the relay feeds back the CRC, checking results of decoded packets $(\hat{S}_1, \hat{S}_2)$ in the MA phase, while the terminal does not feed back in the BC phase. In other words, the link reliability between $T_k$ and $R$ in the MA phase is guaranteed only. We classify three packet-error cases to describe the RO-ARQ protocol.

*Case 1.* No packets are in error at relay. The relay transmits two ACK messages, which inform $T_1$ and $T_2$ that their packets are intact in the MA phase and inserted in $S_R$ packet header. Then $T_1$ and $T_2$ start a new round transmission in the next packet slot.

*Case 2.* One packet is in error at relay. If $T_1$'s packet is in error only, the relay feeds back a NACK for $T_1$ and an ACK for $T_2$. Then retransmission will be performed by $T_1$ in the next packet slot while $T_2$ transmit its next packet in the same slot. Similarly, when only $T_2$'s packet is in error, a reciprocity ARQ process is executed. In this paper, $T_1$'s erroneous packet is taken as the example of Case 2 merely.

*Case 3.* Both the packets are in error at relay. The relay discards all the wrong packets and feeds back two NACK messages to inform the two terminals to retransmit copies of their packets. Retransmission will be started immediately on receiving the NACKs. In other words, BC phase is skipped, and MA phase will be executed again. Figure 2 depicts the RO-ARQ protocol in detail.

*3.2. TO-ARQ.* Terminal-only ARQ: only the terminal feeds back the CRC-checking results after the BC phase. The relay just decodes and forwards in the MA phase and feedback duration; thus, the whole end-to-end link between $T_1$ and $T_2$ will have an effect on the throughput performance. Note that the retransmission requirement is made at the end of BC phase so that the procedure will not skip any phase comparing with that of RO-ARQ. The TO-ARQ protocol can also be classified into three individual packet-error cases as illustrated in Figure 3.

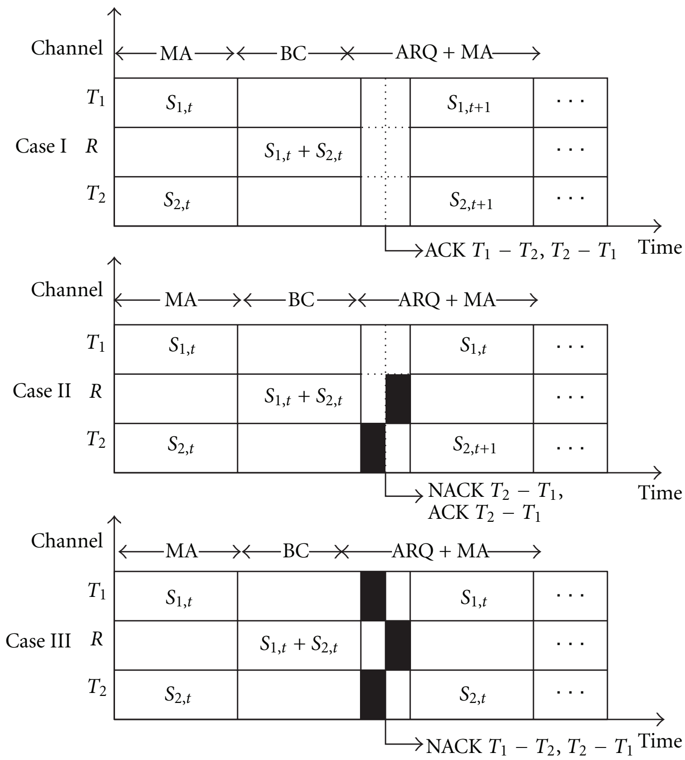



Figure 3: The TO-ARQ protocol.

*Case 1.* No packets are in error at terminal. Each terminal transmits an ACK message to the other one via the relay, informing that the packet was received correctly. Then the next packet slot is started.

*Case 2.* One packet is in error at terminal. If the packet received by $T_2$ is erroneous only, $T_2$ feeds back a NACK for $T_1$ and $T_1$ feeds back an ACK for $T_2$. Retransmission will be performed by $T_1$ in the next packet slot, during which $T_2$ will transmit its next packet and vice versa.

*Case 3.* Both the packets are in error at terminal. Each terminal will feed back a NACK message to inform the other one to retransmit the packet in next packet slot.

*3.3. RT-ARQ.* Relay-terminal ARQ: both the relay and terminals feed back the CRC-checking results, which combine the RO-ARQ and TO-ARQ protocol together. The relay will retransmit the packet only if packets are received at relay correctly in the MA phase yet corrupted at terminals during the BC phase. Similarly, when the relay detects error packets, NACKs will be sent to terminals and retransmission will be executed correspondingly. Note that whenever a packet fails to transmit correctly, only the related phase (i.e., MA when error at relay, BC when error at terminals) will be re-executed instead of the whole packet slot. Six packet error cases are classified to describe the RT-ARQ protocol as shown in Figure 4.

*Case 1.* No packets are in error at relay and terminals. The relay sends ACK messages to both terminals. The terminals send their ACK messages back in the feedback duration.

*Case 2.* No packets are in error at relay, while only one terminal's packet corrupted at terminal. The terminal who received the failed packet sends a NACK back in the feedback duration, and the BC phase will be executed again in which the relay retransmits the copy.

*Case 3.* No packets are in error at relay, while both the packets corrupted at terminal. Each terminal sends a NACK back, and the relay carries out the same operation as Case 2.

*Case 4.* Only one terminal's packet is in error at relay while no errors at terminal. The relay sends a NACK back for $T_1$ in the MA phase, and $T_1$ sends an ACK back in the feedback duration.

*Case 5.* Only one terminal's packet in error at relay, while the other's corrupted at the terminal. The relay sends a NACK back for $T_1$ in the MA phase, and $T_1$ sends a NACK back for $T_2$.

*Case 6.* Both the packets in error at relay. The relay feeds back two NACK messages to inform the terminals to retransmit their incorrect packet again in next packet slot.

## 4. Throughput Analysis

Data reliability in this work is more considered rather than the transmitting latency, forasmuch the relay and terminals will discard all failed copies of packets and their decoding are based only on the most recent copies, which have the highest

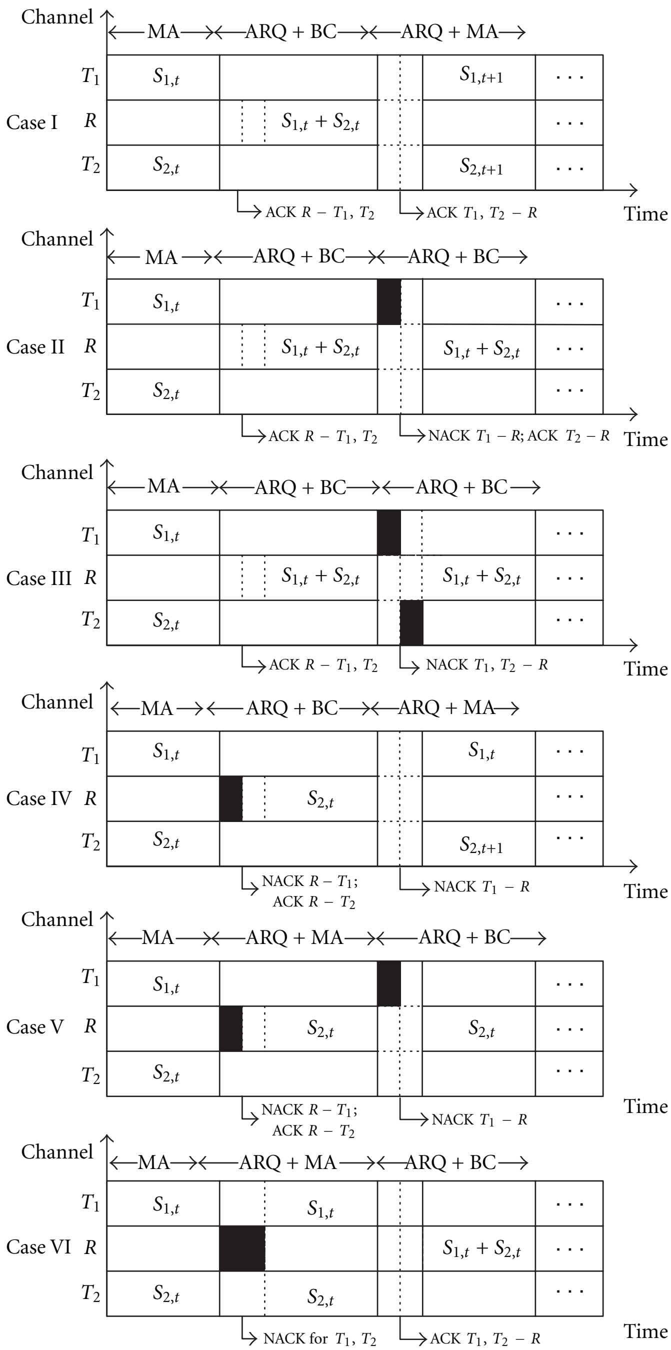



Figure 4: The RT-ARQ protocol.

probability of transmitting successfully [13]. By taking this issue into considerations, the system long-term throughput could be defined as:

$$\eta = \lim_{M\to\infty} \frac{1}{M} \sum_{m=1}^{M} (R_1 I_1[m] + R_2 I_2[m]), \tag{4}$$

where $R_i$, for $i \in \{1,2\}$, is the transmission rate (bps/Hz) of each terminal and $I_i[m]$ is an indicator function of a successful decoding event, in which a packet from node $i$ is decoded by another terminal node in time slot $m$.

In this section, the procedures of all three types of ARQ protocol would be described and analyzed under the models of finite state Markov chains. Consequently, the proposed ARQ protocols satisfy appropriate assumptions of stationary and ergodicity. Thence, the long-term throughput can be re-written as

$$\eta = R_1 \bar{I}_1 + R_2 \bar{I}_2, \tag{5}$$

where $\bar{I}_i = E[I_i[m]]$ denotes the expectation of $I_i[m]$ over fading.

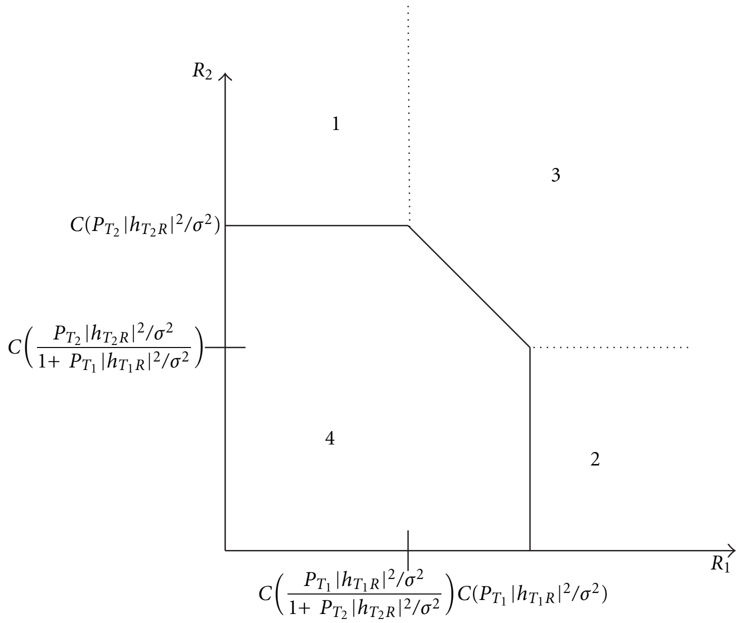



Figure 5: Achievable region conditioned on channel state for two-user MAC. Note that $C(x) = \log_2(1+x)$.

Before the analysis of proposed ARQ protocols is provided, several variables will be employed helping describe the outage probabilities of each model. In the MA phase, the outage probabilities could be depicted in Figure 5 [20].

Each region represents an individual event when two packets arrive at relay in the MA phase.

(i) Region 1: packet from $T_1$ arrives at relay successfully while packet from $T_2$ fails;

(ii) Region 2: packet from $T_2$ arrives at relay successfully while packet from $T_1$ fails;

(iii) Region 3: both packets fail;

(iv) Region 4: both packets arrive successfully.

Variables $\{P_1, P_2, P_3, P_4\}$ are defined as the probability of each corresponding region in the figure as follows:

$$\begin{aligned}
P_1 &= \frac{1}{2^{R_2}}\left[\exp\left(-\frac{2^{R_2}-1}{P_T}\right) - \exp\left(-\frac{2^{R_1+R_2}-1}{P_T}\right)\right],\\
P_2 &= \frac{1}{2^{R_1}}\left[\exp\left(-\frac{2^{R_1}-1}{P_T}\right) - \exp\left(-\frac{2^{R_1+R_2}-1}{P_T}\right)\right],\\
P_3 &= 1 - \frac{1}{2^{R_1}}\exp\left(-\frac{2^{R_1}-1}{P_T}\right) - \frac{1}{2^{R_2}}\exp\left(-\frac{2^{R_2}-1}{P_T}\right)\\
&\quad - \exp\left(-\frac{2^{R_1+R_2}-1}{P_T}\right)\\
&\quad \times\left[1 - \frac{1}{2^{R_1}} - \frac{1}{2^{R_2}} + \frac{(2^{R_1}-1)(2^{R_2}-1)}{P_T}\right],\\
P_4 &= 1 - P_1 - P_2 - P_3,
\end{aligned} \tag{6}$$

where $P_T$ is the value of transmitting power of both terminals since in the current work they are assumed equal (i.e., $P_{T_1} = P_{T_2} = P_T$). Note that the value of $\sigma$ is normalized in this work, the effect of SNR at each node is therefore directly reflected by their transmit power (i.e., $P_T/\sigma^2 = P_T$).

In the BC phase, the link between the relay and two terminals can be viewed as peer-to-peer links [13], and the outage probabilities on each link are defined as $P_{\text{out},RT_1}$ and $P_{\text{out},RT_2}$ and in the current work as follows:

$$P_{\text{out},RT_1} = P_{\text{out},RT_2} = 1 - \exp\left(-\frac{2^{R_R}-1}{P_R}\right), \tag{7}$$

where $R_R$ and $P_R$ symbolize the transmitting rate and power of the relay node, respectively. Similarly, SNR at relay is represented by its transmit power (i.e., $P_R/\sigma^2 = P_R$).

In order to represent the expressions in the rest of the paper less complicated, the complements of $P_{\text{out},RT_1}$ and $P_{\text{out},RT_2}$ are introduced as follows:

$$\begin{aligned}
P_{r1} &= 1 - P_{\text{out},RT_1},\\
P_{r2} &= 1 - P_{\text{out},RT_2}.
\end{aligned} \tag{8}$$

*4.1. Upper Bound.* The upper bound of the transmission can be obtained by assuming that two terminals can transmit without interfering each other. Thus, the maximum throughput of any terminal (e.g., $T_1$) can be calculated as

$$\tilde{\eta}_1 = R_1\frac{(1-P_{\text{out},T_1R})(1-P_{\text{out},RT_2})}{(2-P_{\text{out},T_1R}-P_{\text{out},RT_2})}, \tag{9}$$

in which $P_{\text{out},T_1R}$ ($P_{\text{out},T_2R}$), similar to $P_{\text{out},RT_1}$ ($P_{\text{out},RT_2}$), symbolizes the outage probability of the peer-to-peer link between $T_1(T_2)$ and the relay.

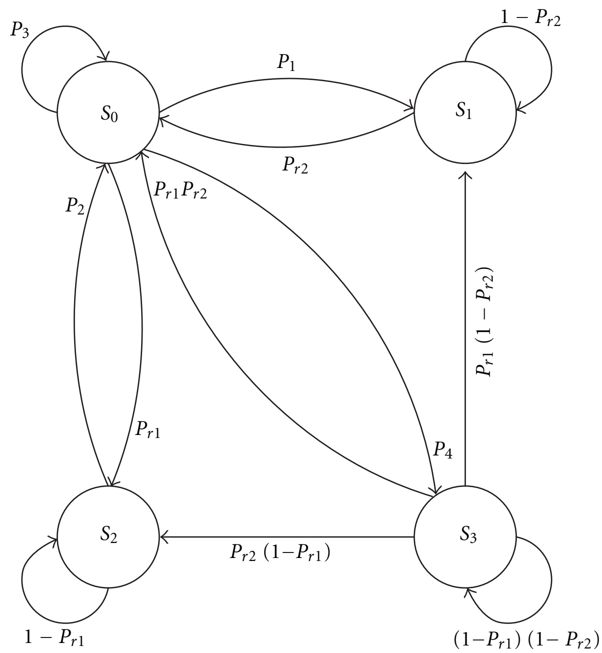



Figure 6: The state-transition diagram of RO-ARQ protocol.

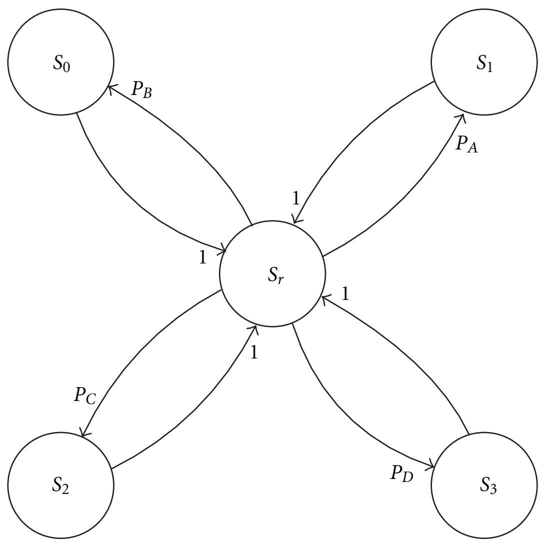



Figure 7: The state-transition diagram of TO-ARQ protocol.

Analogously, the maximum throughput $\tilde{\eta}_2$ can be given for $T_2$. Consequently, the upper bound for throughput can be obtained as $\eta \leq \eta_{\text{UB}} = \tilde{\eta}_1 + \tilde{\eta}_2$.

*4.2. RO-ARQ.* Under the protocol of RO-ARQ, the repeat request is only made at the relay node; therefore the model can be studied as a Markov chain with states of relay's buffer.

(i) $S_0$: no packets are cached in the relay's buffer and the relay is expecting the next transmission;

(ii) $S_1$: packet from $T_1$ successfully arrives at relay while packet from $T_2$ fails, Corresponding to Case 2 of RO-ARQ in the previous section;

(iii) $S_2$: reciprocity of state $S_1$ substituting $T_1$ with $T_2$ and vice versa;

(iv) $S_3$: packets from both terminals arrive at relay with no error, corresponding to Case 1 of RO-ARQ in the previous section.

The states above can be depicted in Figure 6. As can be seen from the diagram, a successful transmission from $T_i$ to $T_j$ ($i, j \in \{1, 2\}, i \neq j$) is determined when the system is at state $S_3$, $S_2$, or $S_1$, and packets are sent forward with probability $P_{r1}$ or $P_{r2}$. Consequently, the indicator variable $\bar{I}_i$ can be written as

$$\bar{I}_i = \left(P_{si}^{\text{RO}} + P_{s3}^{\text{RO}}\right) P_{RT_j}, \quad i, j \in \{1, 2\}, \ i \neq j, \tag{10}$$

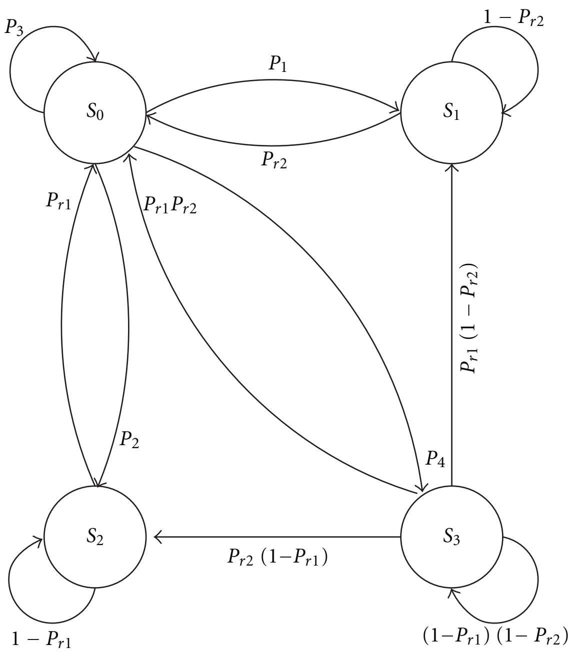



FIGURE 8: The state-transition diagram of RT-ARQ protocol.

where $P_{RT_j}$ is defined as the probability of a successful packet transmission from $R$ to $T_j$, and $P_{si}^{\mathrm{RO}}$ stands for the steady probability of relay being at state $S_i$ within RO-ARQ protocol. By solving the state transition equations listed below:

$$\begin{aligned} P_{s0}^{\mathrm{RO}} P_1 &= P_{s1}^{\mathrm{RO}}, \\ P_{s1}^{\mathrm{RO}} P_2 &= P_{s2}^{\mathrm{RO}}, \\ P_{s2}^{\mathrm{RO}} P_4 &= P_{s3}^{\mathrm{RO}}, \\ \sum_{i=0}^{3} P_{si}^{\mathrm{RO}} &= 1, \end{aligned} \tag{11}$$

the steady state probability is:

$$\begin{aligned} P_{s0}^{\mathrm{RO}} &= (1 + P_1 + P_2 + P_4)^{-1}, \\ P_{s1}^{\mathrm{RO}} &= P_1(1 + P_1 + P_2 + P_4)^{-1}, \\ P_{s2}^{\mathrm{RO}} &= P_2(1 + P_1 + P_2 + P_4)^{-1}, \\ P_{s3}^{\mathrm{RO}} &= P_4(1 + P_1 + P_2 + P_4)^{-1}. \end{aligned} \tag{12}$$

The steady distribution of the Markov chain is acquired and thereby the throughput can be obtained as follows:

$$\eta_{\mathrm{RO}} = R_1\left[P_{r2}\left(P_{s3}^{\mathrm{RO}} + P_{s2}^{\mathrm{RO}}\right)\right] + R_2\left[P_{r1}\left(P_{s3}^{\mathrm{RO}} + P_{s1}^{\mathrm{RO}}\right)\right]. \tag{13}$$

*4.3. TO-ARQ.* In TO-ARQ model, the signals received at relay do not reveal whether the transmission is successful or not. Due to this reason, the analysis of TO-ARQ model adopts the combination of the relay's buffer together with terminals' rather than the relay's alone as the state variable. Under such circumstance, the state variable also has five possibilities:

(i) $S_0$: none of packets from both terminals transmitted correctly, and NACKs are sent to both terminals, corresponding to Case 3 of TO-ARQ in the previous section;

(ii) $S_1$: packet from $T_1$ successfully arrives at $T_2$ while packet from $T_2$ fails. Correspond to Case 2 of TO-ARQ in the previous section;

(iii) $S_2$: reciprocity of state $S_1$ substituting $T_1$ with $T_2$ and vice versa;

(iv) $S_3$: packets from both terminals arrive with no error, corresponding to Case 1 of TO-ARQ in the previous section;

(v) $S_r$: packets arrive at the relay and will be sent to both terminals in the next phase.

The states above can be depicted in Figure 7. Here the state-transition probabilities are coded for the convenience of representation as follows:

$$\begin{aligned} P_A &= P_1 P_{r2} + P_4 P_{r2}(1 - P_{r1}), \\ P_B &= P_3 + P_1(1 - P_{r2}) + P_2(1 - P_{r1}) + P_4(1 - P_{r1})(1 - P_{r2}), \\ P_C &= P_2 P_{r1} + P_4 P_{r1}(1 - P_{r2}), \\ P_D &= P_4 P_{r2} P_{r1}, \end{aligned} \tag{14}$$

and easily the sum of all four probabilities is solved as follows: $P_A + P_B + P_C + P_D = 1$.

The state-transition equations of this Markov chain are the following:

$$\begin{aligned} P_{sr}^{\mathrm{TO}} P_B &= P_{s0}^{\mathrm{TO}}, \\ P_{sr}^{\mathrm{TO}} P_A &= P_{s1}^{\mathrm{TO}}, \\ P_{sr}^{\mathrm{TO}} P_C &= P_{s2}^{\mathrm{TO}}, \\ P_{sr}^{\mathrm{TO}} P_D &= P_{s3}^{\mathrm{TO}}, \\ P_{sr}^{\mathrm{TO}} + \sum_{i=0}^{3} P_{si}^{\mathrm{TO}} &= 1, \end{aligned} \tag{15}$$

where $P_{si}^{\mathrm{TO}}$, $i \in \{0,1,2,3,r\}$ is defined as the steady probability of each state $S_i$ within TO-ARQ protocol. The steady-state probabilities to each state in the diagram can be solved as follows:

$$\begin{aligned} P_{sr}^{\mathrm{TO}} &= 0.5, \\ P_{s0}^{\mathrm{TO}} &= 0.5P_B, \\ P_{s1}^{\mathrm{TO}} &= 0.5P_A, \\ P_{s2}^{\mathrm{TO}} &= 0.5P_C, \\ P_{s3}^{\mathrm{TO}} &= 0.5P_D. \end{aligned} \tag{16}$$

According to the description of the protocol given above, the correct transmission of a packet from terminal $i$ occurs only when the system is at state $S_i$ or $S_3$. Therefore the throughput of TO-ARQ model is calculated as follows:

$$\eta_{\mathrm{TO}} = 0.5R_1\left(P_{s1}^{\mathrm{TO}} + P_{s3}^{\mathrm{TO}}\right) + 0.5R_2\left(P_{s2}^{\mathrm{TO}} + P_{s3}^{\mathrm{TO}}\right). \tag{17}$$

*4.4. RT-ARQ.* In RT-ARQ model, the relay shares the same functions as in RO-ARQ while it executes the retransmission requested by terminals. Hence, the state variable can be similar with that of RO-ARQ yet it is not the representation of the relay's buffer alone, but also, the operations the relay going to take in the next phase. Therefore, the diagram of the state transition needs modification as well to suit the current protocol, which is shown in Figure 8. The definitions of RT-ARQ's state $S_0$, $S_1$, $S_2$, and $S_3$ are given by

(i) $S_0$: no packets are stored in the relay's buffer, and the relay is expecting the next transmission;

(ii) $S_1$: the packet from $T_1$ is cached in the relay's buffer and will be transmitted to $T_2$ in the next phase. The transmission of packet from $T_2$ is ignored due to a failed transition $S_0 \rightarrow S_1$ or a accomplished one $S_3 \rightarrow S_1$;

(iii) $S_2$: reciprocity of state $S_1$ substituting $T_1$ with $T_2$ and vice versa;

(iv) $S_3$: packets from both terminals arrive at relay with no error. State may shift to $S_0$, $S_1$, or $S_2$ depending on whether the corresponding transmission of packet is successful or not. It is specified in Figure 8.

The state-transition equations of this Markov chain are the following:

$$\begin{aligned} P_{s1}^{\mathrm{RT}}(1-P_{r2}) + P_{s0}^{\mathrm{RT}}P_1 + P_{s3}^{\mathrm{RT}}P_{r1}(1-P_{r2}) &= P_{s1}^{\mathrm{RT}}, \\ P_{s2}^{\mathrm{RT}}(1-P_{r1}) + P_{s0}^{\mathrm{RT}}P_2 + P_{s3}^{\mathrm{RT}}P_{r2}(1-P_{r1}) &= P_{s2}^{\mathrm{RT}}, \\ P_{s3}^{\mathrm{RT}}(1-P_{r1})(1-P_{r2}) + P_{s0}^{\mathrm{RT}}P_4 &= P_{s3}^{\mathrm{RT}}, \\ \sum_{i=0}^{3} P_{si}^{\mathrm{RT}} &= 1, \end{aligned} \tag{18}$$

where $P_{si}^{\mathrm{RT}}$, $i \in \{0,1,2,3\}$ represents the steady probability of each state $S_i$ within RT-ARQ protocol. The steady probabilities to each state in the diagram can be solved as follows:

$$\begin{aligned} P_{s0}^{\mathrm{RT}} &= \left(\frac{P_1}{P_{r2}} + \frac{P_{r1}}{P_{r2}}\frac{(1-P_{r2})P_4}{P_{r1}+P_{r2}-P_{r1}P_{r2}} + \frac{P_2}{P_{r1}} + \frac{P_{r2}}{P_{r1}} \times \frac{(1-P_{r1})P_4}{P_{r1}+P_{r2}-P_{r1}P_{r2}} + \frac{P_4}{P_{r1}+P_{r2}-P_{r1}P_{r2}} + 1\right)^{-1}, \\ P_{s1}^{\mathrm{RT}} &= \left(\frac{P_1}{P_{r2}} + \frac{P_{r1}}{P_{r2}}\frac{(1-P_{r2})P_4}{P_{r1}+P_{r2}-P_{r1}P_{r2}}\right)P_{s0}^{\mathrm{RT}}, \\ P_{s2}^{\mathrm{RT}} &= \left(\frac{P_2}{P_{r1}} + \frac{P_{r2}}{P_{r1}}\frac{(1-P_{r1})P_4}{P_{r1}+P_{r2}-P_{r1}P_{r2}}\right)P_{s0}^{\mathrm{RT}}, \\ P_{s3}^{\mathrm{RT}} &= \frac{P_4}{P_{r1}+P_{r2}-P_{r1}P_{r2}}P_{s0}^{\mathrm{RT}}. \end{aligned} \tag{19}$$

A successful transmission from $T_i$ to $T_j$ $(i,j \in \{1,2\}, i \neq j)$ is determined when the following state transitions take place:

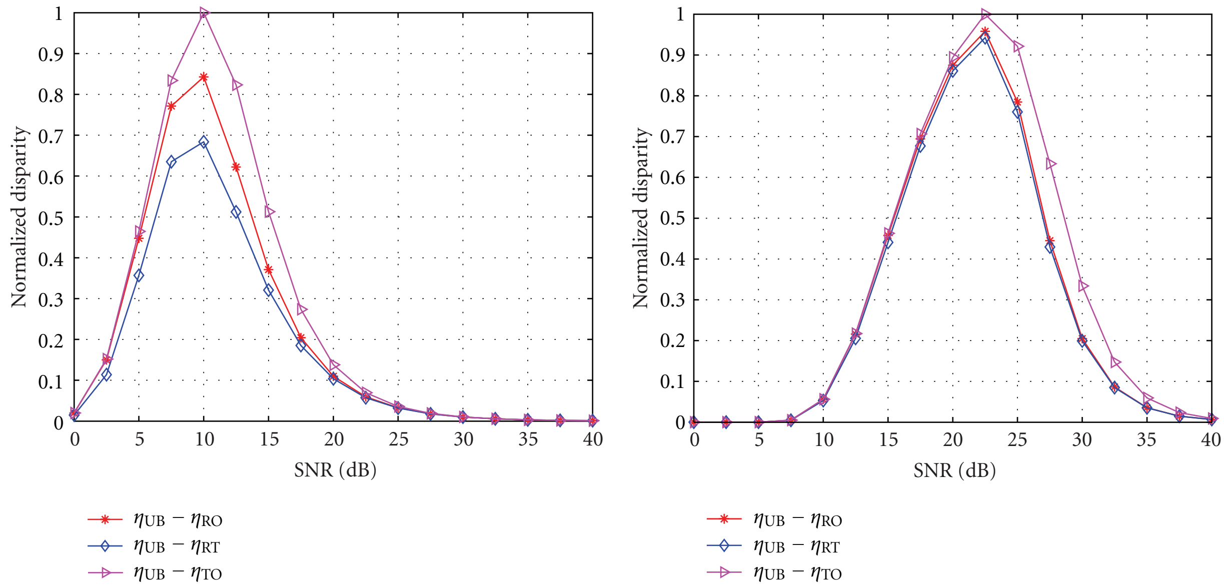
$$\begin{aligned} S_3 &\longrightarrow S_0, S_1, \text{ or } S_2, \\ S_2 &\longrightarrow S_0, \\ S_1 &\longrightarrow S_0, \end{aligned} \tag{20}$$

thence the throughput of RT-ARQ model is given by:

$$\eta_{\mathrm{RT}} = R_1\left[P_{r2}\left(P_{s3}^{\mathrm{RT}} + P_{s2}^{\mathrm{RT}}\right)\right] + R_2\left[P_{r1}\left(P_{s3}^{\mathrm{RT}} + P_{s1}^{\mathrm{RT}}\right)\right]. \tag{21}$$

*4.5. Throughput Comparisons of Different ARQ.* By calculating the difference between each of $\{\eta_{\mathrm{RT}}, \eta_{\mathrm{RO}}, \eta_{\mathrm{TO}}, \eta_{\mathrm{UB}}\}$, their relationship can thus be obtained as $\eta_{\mathrm{UB}} \geq \eta_{\mathrm{RT}} \geq \eta_{\mathrm{RO}} \geq \eta_{\mathrm{TO}}$ which is depicted in Figure 9. The acceleration (deceleration) of transmission will shrink (broaden) all gaps, yet leaving the sequence of quantity unchanged.

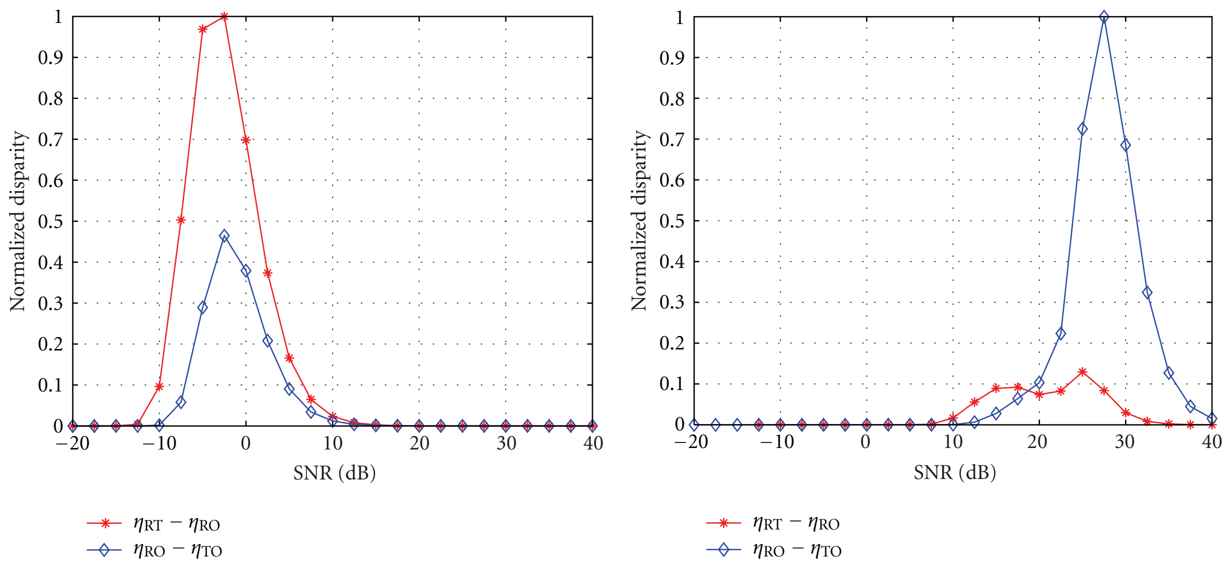
Thereby the mutual gap between each protocol's throughput performances can be predicted from each of their differences with the upper bound. The gap between the RT-ARQ and TO-ARQ is omitted because the combination of RT-RO gap and RO-TO gap can indirectly reflect the RT-TO gap which is shown in Figure 10. When the rate




(a) $R = 2.5$ bps/Hz

(b) $R = 5.0$ bps/Hz

Figure 9: Throughput difference between the upper bound and each of the proposed ARQ protocols under the transmitting rate of $R = 2.5$ and 5.0 bps/Hz, respectively.




(a) $R = 0.5$ bps/Hz

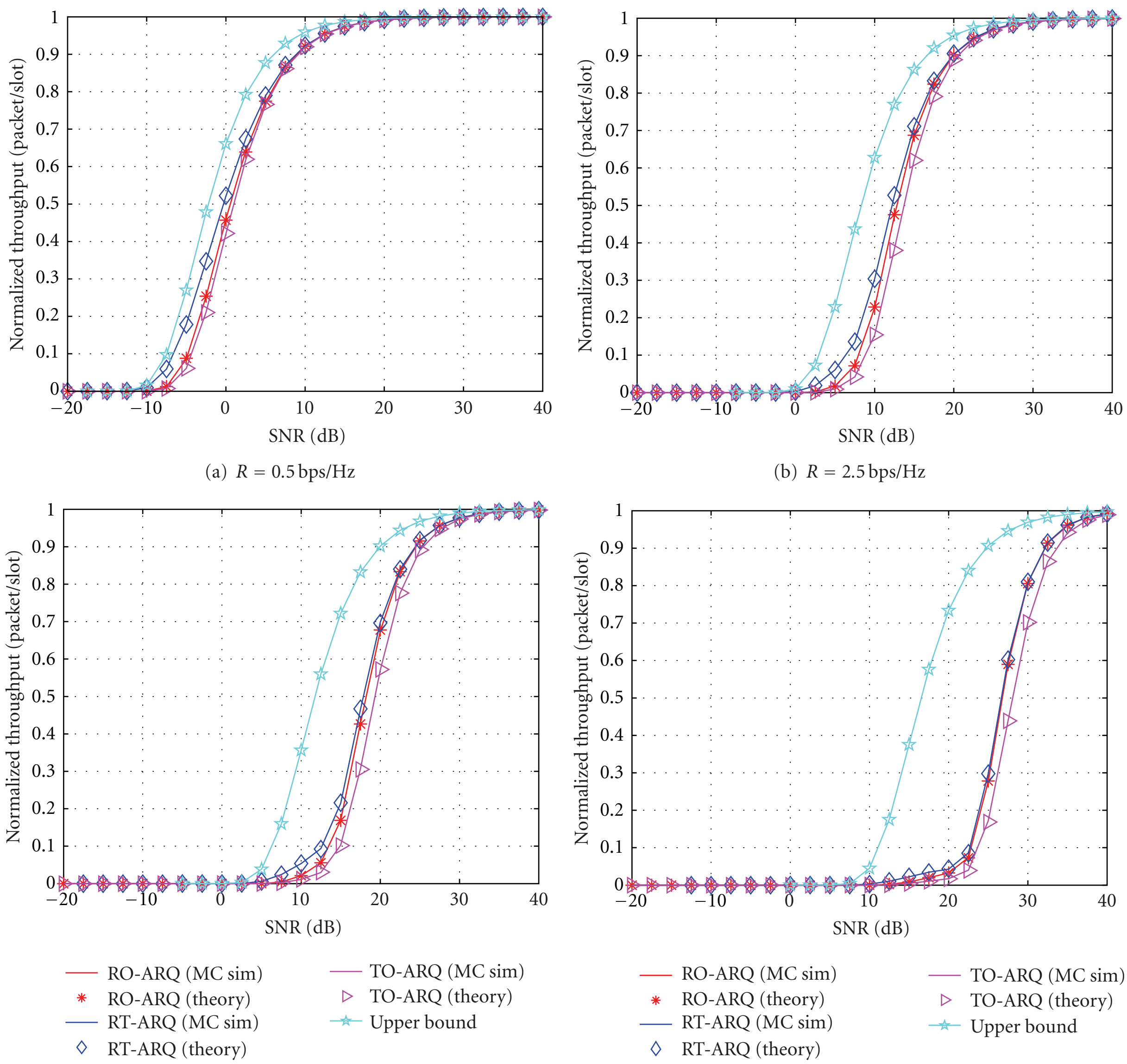
(b) $R = 0.5$ bps/Hz

Figure 10: Throughput difference of RT-RO and RO-TO, under the transmitting rate of $R = 0.5$ and 5.0 bps/Hz, respectively.

is relatively low, the performance of RO-ARQ is quite close to that of the TO-ARQ's. And when it rises, on the contrary, RO-ARQ's throughput performance will approach RT-ARQ's. Therefore, it will be much saving to choose RO-ARQ over RT-ARQ under high transmitting rate since they perform similarly while reducing the number of execution of ARQ by half. However, RT-ARQ is more preferable when the rate is low for the throughput performance can be guaranteed.

## 5. Numerical Results

In this section, computer simulation results are presented to reveal the end-to-end throughput performance of proposed ARQ protocols. For the sake of comparison, the evaluation of the transmission's upper bound is also taken into the simulation. The simulation focused on symmetric case in which $R_1 = R_2 = R_R$ and $P_T = P_R$ and is executed on four different rates, namely, $R = 0.5, 2.5, 3.5, 5$ bps/Hz




(a) $R = 0.5$ bps/Hz

(b) $R = 2.5$ bps/Hz

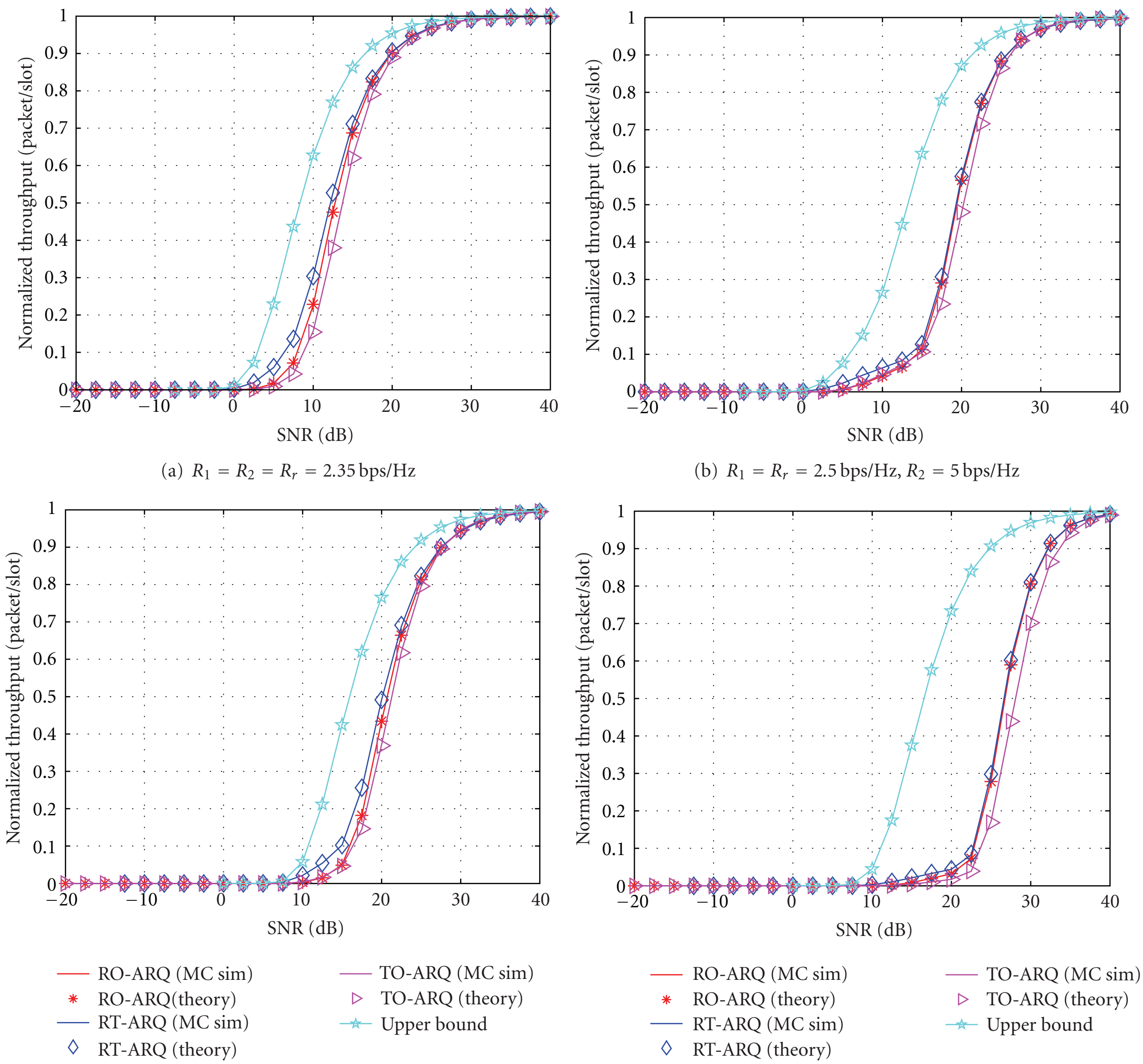
(c) $R = 3.5$ bps/Hz

(d) $R = 5.0$ bps/Hz

FIGURE 11: Normalized throughput $\eta/R$ versus SNR for a symmetric TWR with transmission rate $R = 0.5, 2.5, 3.5, 5$ bps/Hz, respectively.

[13]. The range of SNR is from −20 dB to 40 dB [8, 17]; thus, the whole trend of curves can be observed while, on the other hand, both links ($T_1 \leftrightarrow R, T_2 \leftrightarrow R$) share the same SNR. The results are shown in Figure 11. Additionally, same scale of throughput can be convenient for observation and comparison; hence, all figures of computer simulations have been normalized. The Monte-Carlo simulation is implemented in this work to verify the consistency of the algorithm applied in the previous section with the actual scenarios, and, judging from the observation of Figure 11, both outcomes can be perfectly matched.

As can be seen, for any given transmission rate, RT-ARQ protocol has the best throughput performance among all the proposed schemes, and RO-ARQ has better throughput efficiency than TO-ARQ under any circumstances. This is due to the reason that RT-ARQ has the most flexible slot procedure. To be specified, whenever an erroneous transmission occurs, the retransmission requirement can be sent immediately in the next phase under RT-ARQ protocol: consequently, the MA or BC phase can be reexecuted and need not have to wait for any idle phase. In other words, the retransmission of RT-ARQ takes half the period of a slot on average. RO-ARQ protocol has the ability to reexecute the MA phase when packets arrive at relay unsuccessfully; yet, links of the second hop are not guaranteed forasmuch the successful transmission of a packet will require the retransmission to take more than one phase while less than a whole slot. As for TO-ARQ protocol, the retransmission takes a whole slot to carry out in the long run, and the MA phase will be seen as an idle phase when mistakes appear. For




(a) $R_1 = R_2 = R_r = 2.35$ bps/Hz

(b) $R_1 = R_r = 2.5$ bps/Hz, $R_2 = 5$ bps/Hz

(c) $R_1 = R_r = 5.0$ bps/Hz, $R_2 = 2.5$ bps/Hz

(d) $R_1 = R_2 = R_r = 5$ bps/Hz

Figure 12: Normalized throughput $\eta/R$ versus SNR for a symmetric TWR with different transmission rate on each terminal.

example, if a packet arrives at relay with mistake, it will take RT-ARQ and RO-ARQ protocol one phase to accomplish the retransmission comparing that TO-ARQ will take a full slot.

When SNR is at low region, all protocols' curves including the upper bound are near zero and when SNR transcends a threshold value, throughput values rise dramatically and approach one. This is attributed to the fact that when SNR is abysmal, high-outage probability will stuck all the protocol at retransmitting states, causing decode-recode at relay unreliable. On the contrary, TWR system runs between the state of ready-to-send and the state of receiving successfully when SNR is very high. The rising range, observed from the figures, is approximately 20 dB, and the threshold floats with the transmission rate. However, comparing with the upper bound, the threshold of proposed protocols is rather more sensitive to the rate; thus, their curves move toward right side faster than the upper bound's curve as the rate increases.

Another set of curves are presented to demonstrate the performance of unequal transmission rate (i.e., $R_1 \neq R_2$). The trend of curves, as can be seen from Figure 12, follows that of equal-rate condition. Curves of three proposed protocols cluster and depart from the upper-bound as any of the rate increases. As for the influence of the relay, the ascension of the relay's transmitting rate also push all curves toward right judging from the observation of Figures 12(b) and 12(c). This can be concluded from the peer-to-peer outage probability (7) which is an increasing function of $R_R$ and directly affects the evaluation of system's throughput. Yet RT-ARQ still outperforms RO-ARQ and TO-ARQ under all circumstances executed in the simulation.

## 6. Conclusion

In this paper, three ARQ protocols are investigated which designed for two-way relay systems with physical-layer network coding according to different feedback schedules at the relay and terminals. Work mainly focuses on the link reliability improvement in terms of end-to-end throughput of TWR system over slow fading wireless channels. Through performance evaluations, we confirmed that the proposed protocols can offer a smoother increase of the throughput curve, and it can significantly improve the end-to-end throughput performance in two-way relay systems. It can be observed that the RT-ARQ protocol has a better performance than the other protocols and can best approach the upper bound under low transmission rate among all proposed schemes.

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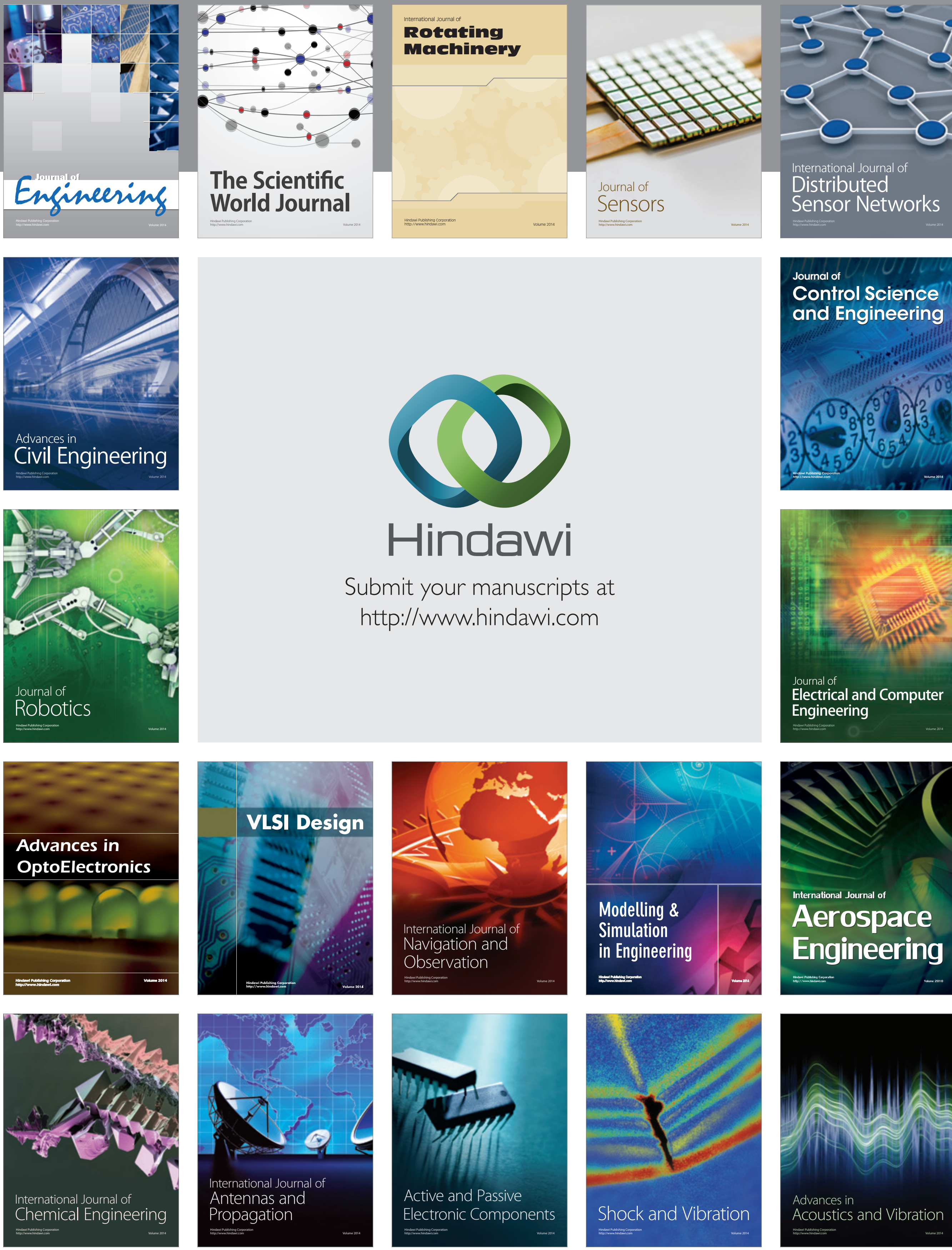
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