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An Efficient Automatic Repeat Request Mechanism for Wireless Multihop Relay Networks

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***Abstract*—Recently, relay technology has been adopted to enhance the coverage and performance of wireless networks such as Worldwide Interoperability for Microwave Access and Long-Term Evolution Advanced (LTE-A). However, using relays to forward packets may induce more packet losses than traditional single-hop wireless networks because transmissions are conducted through multiple radio links. When there are lost packets, relay stations (RSs) decide whether to retransmit these packets with automatic repeat request (ARQ) strategies. We observe that an improper ARQ strategy increases latency, blocked packets, and workloads on the multihop relay network. This paper proposes a new relay ARQ (RARQ) scheme, providing efficient acknowledgement to reduce packet latency and the number of blocked packets with small workloads. We also propose an analytic model to evaluate the performance of the proposed mechanism. Simulation results have validated the proposed model and demonstrated that our ARQ scheme outperforms conventional approaches.**

***Index Terms*—Automatic Repeat-reQuest (ARQ), relays, wireless communication.**

I. Introduction

Industrial interest in wireless relay networks has increased in recent years. IEEE 802.16j specifies a relay system based on the IEEE 802.16e wireless network; the Third-Generation Partnership Project Long-Term Evaluation Advance (3GPP LTE-A) also uses relay functionalities [1]. Soldani and Dixit [2] showed that relay stations (RSs) with packet decoding and buffering functions can improve the coverage, throughput, and capacity of a relay system, although this design may introduce implementation complexity to an RS. The recent release of 3GPP LTE-A uses the network architecture with RSs [3], and the relay network can avoid complex routing problems and manage packet losses with low complexity [4]. From an operator perspective, Bhat *et al.* [5] indicated that relays are crucial enablers for dense small-cell deployment and can improve user experience. Hoymann *et al.* [6] identified the backhaul link as the performance bottleneck of future networks and suggested further investigation of relay backhaul links to assess the tradeoff among performance, standardization, and implementation complexity for multihop relay transmission. In the relay network, the base station (BS) administrates network radio resources and can use RSs to retransmit directly corrupted packets.

Compared with conventional single-hop wireless networks, a relay network may suffer more packet losses, thus increasing the overhead for handling packet losses. A conventional way to manage packet losses is to use the automatic repeat request (ARQ) mechanisms [7]. However, ARQ designs cannot be applied to relay networks directly because of the high packet error rate caused by multiple radio links.

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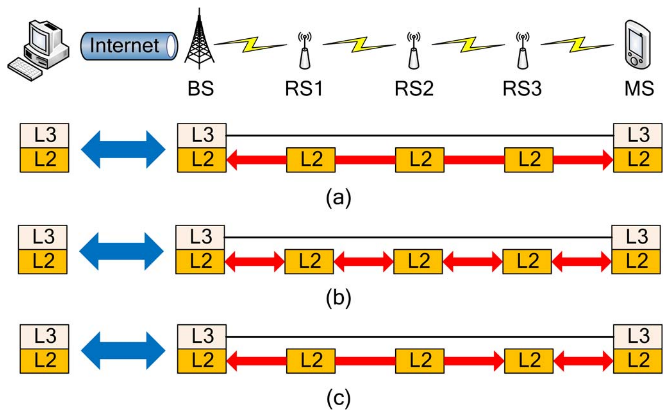

Fig. 1. RARQ overview.

Fig. 1 shows three conventional relay ARQ (RARQ) schemes that may be applied in the relay network. The first scheme is the end-to-end (E2E) RARQ, in which all RSs simply relay packets, and the error control is delegated to packet senders and receivers. The second scheme is the hop-by-hop (HbH) RARQ, in which RSs are responsible for detecting errors, sending acknowledgements, and retransmitting packets. More specifically, each RS must guarantee the correct transmissions with its preceding RS before it can continue relaying the packets. The third scheme is the two-link (TL) RARQ scheme, which divides an E2E path into a multihop relay link and a single-hop access link, and a specific RS has to recover packet losses for both links. The red arrows in Fig. 1 indicate the RARQ controls among a BS, RSs, and a mobile station (MS). See Appendix A for detailed description and analysis of the three existing RARQ mechanisms.

The conventional RARQ schemes utilize the concept of relay acknowledgment (RACK) [8] and relay negative acknowledgment (RNACK) [9] to confirm successful and failed receptions between RSs, respectively. We recognize potential drawbacks of applying RACK and RNACK in a multihop relay network. First, RNACK may cause an ambiguous error report to the BS and trigger redundant retransmissions. This is because an RNACK packet cannot explicitly indicate which RS loses a data packet. Second, RSs may transmit a number of RACKs for a successful reception, thus increasing transmission overhead and ARQ workload. Third, a packet may be retransmitted several times between RSs if the packet is lost during the relay transmission, and the retransmissions among relays may prolong E2E latency. If the BS cannot know the retransmissions between relays, then the delay may significantly grow from a BS's perspective, and the BS is unable to manage the buffer resources for transmitted packets and to handle new incoming packets.

This paper proposes an enhanced RARQ mechanism, called the local E2E (LE) RARQ, inheriting the assumptions made in [2] that RSs are able to buffer ARQ blocks, to decode packets, and to confirm the correctness of ARQ blocks for better coverage and performance of a relay system. The basic idea behind our scheme is to facilitate RSs with relay error control by appending RACKs or RNACKs to acknowledgement packets so that ARQ states on each RS can be known by the BS and the MS. In our scheme, an RS locally decides whether to append its RACK or RNACK in E2E feedback (i.e., E2E ACKs or NACKs) to the BS. The BS can know the overall transmission states along a relay path according to the explicit RACK and RNACK information. The BS can trigger retransmissions from a designated RS, thus avoiding the redundant retransmissions of a packet through the entire relay path. Moreover, the proposed RARQ appends error control information only when error packets are present so that the RARQ workload can be considerably reduced.

To evaluate the performance of the proposed scheme, this paper presents a novel analytic model to investigate the delay, packet blocking, and workload in multihop relay networks. Sunny *et al.* [10] developed the delay model of wireless single-hop networks based on the M/M/1 model. To evaluate the performance of multihop wireless networks, Issariyakul *et al.* [11] applied the discrete-time Markov chain (DTMC) model to analyze the latency, reliability, and throughput of a multihop HbH ARQ. Using the DTMC model, Jeon *et al.* [12] analyzed the RARQ behaviors of a wireless relay system for two-hop cases. However, their model may not be directly extended to a multihop case. Fu *et al.* [13] explored RARQ characteristics, evaluated E2E latency for a multihop relay network, and discussed RARQ workload issues. The tradeoff of time, delay, and reliability was investigated in [14], and the optimal number of retransmissions was derived using an exact expression for multihop wireless ad hoc networks. Saleh *et al.* [15] showed the requirement for relay site planning when deploying relays, and obtained closed-form expressions for the link signal-to-interference ratio, link rate, and E2E user rate distribution. This paper consider limited buffers on a BS, which is a more practical assumption in actual applications, and propose a novel M/M/1/K model to analyze the performance of transmission delay, packet blocking, and RARQ workload in relay networks.

The remainder of this paper is organized as follows. Section II presents the proposed enhanced RARQ mechanism. The proposed M/M/1/K model is described in Section III. Section IV compares simulation and analytical results. Finally, the paper is concluded in Section V.

II. Local End-to-End Relay Automatic Repeat Request

Here, we present the proposed LE RARQ scheme. We describe the procedure for the downlink transmission of a packet from the BS via RSs to an MS and its acknowledgement as follows:

1) When an RS_i receives a data packet from the BS or its preceding RS and successfully decodes it, RS_i triggers a timer for receiving a feedback message and forwards the packet to the next hop. If RS_i fails to decode the received packet, the timer is also triggered, and RS_i waits for a feedback message from the MS. Go to Step 2 if RS_i does not receive the feedback message from the MS, or go to Step 3 if it receives a feedback message before the timer expires.
2) If the data packet is successfully decoded, RS_i sends a stand-alone RACK message to the BS; otherwise, RS_i transmits a stand-alone RNACK message to the BS.
3) When RS_i receives an E2E ACK from its preceding node, RS_i forwards it to the BS directly. However, if an E2E NACK, a stand-alone RACK, or a RNACK is received, RS_i attaches its local RARQ state (e.g., $RACK_i$ or $RNACK_i$) to the feedback message and forwards it to the BS.
4) After sending a data packet, the BS waits feedback messages from the RSs and the MS. When the BS receives an E2E ACK from the MS, the transmission is complete. The BS can release the buffer space that temporarily keeps the packet. If the BS receives an E2E NACK from the MS, or a stand-alone RACK or RNACK from RSs, the BS can determine the intermediate RS RS_j in which the packet was lost. RS_j is identified by examining the feedback message in which RS_j attaches a RACK, whereas RS_{j+1} appends a RNACK.
5) The BS then arranges radio resources and triggers the retransmission from RS_j.

Note that each RS appends a local ARQ state to an E2E NACK in Step 3. The BS that receives an E2E NACK can know the

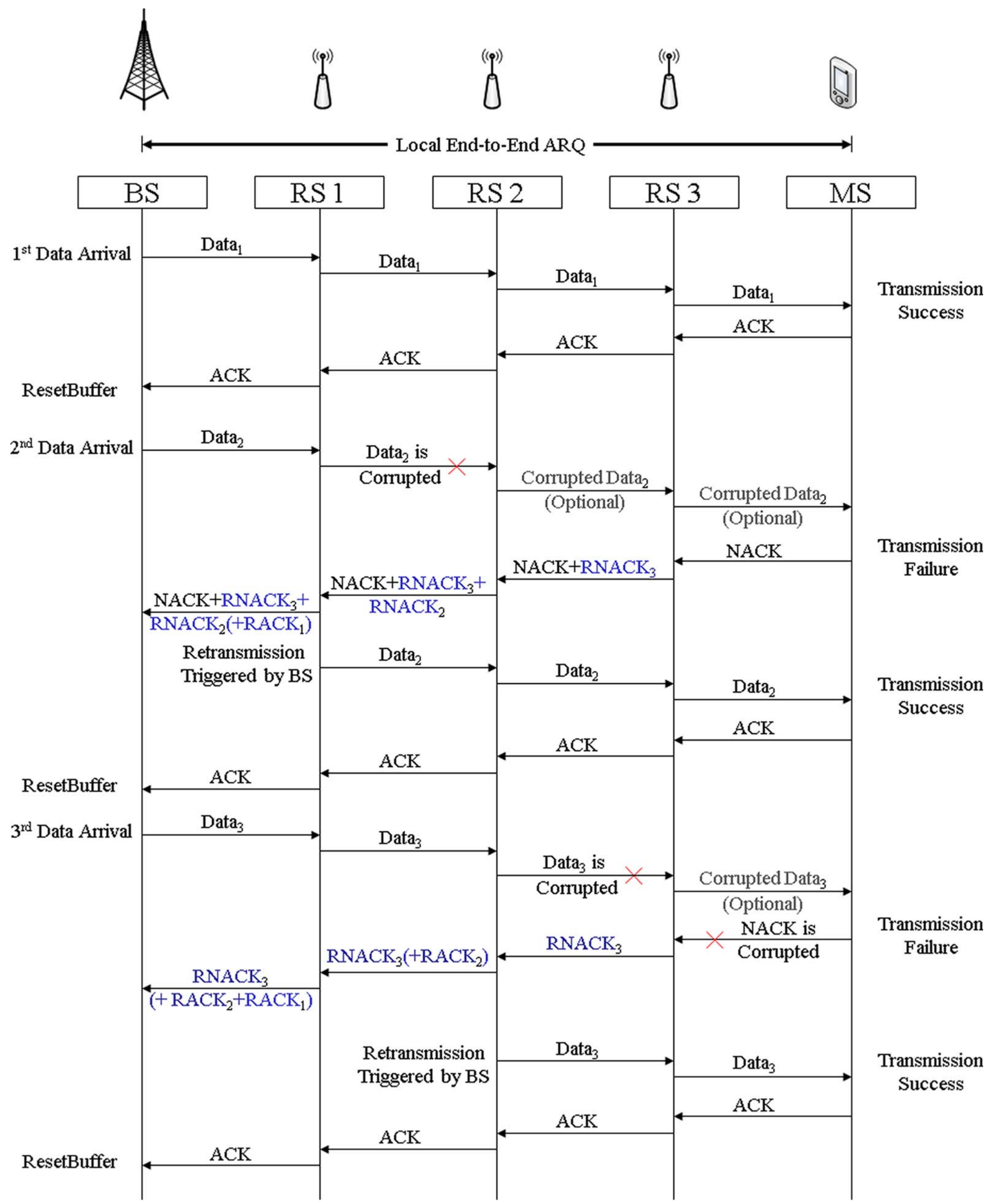

Fig. 2. Message flow for the LE RARQ.

transmission states of RSs and initiate a retransmission at a proper RS if necessary, and redundant retransmissions can be avoided. The proposed RARQ can be further improved, and the RARQ workload can be reduced by eliminating RACK feedback if the acknowledgement errors rarely happen. In addition, the workload is minimized because RARQ states are attached only in E2E NACKs for packet corruption cases.

Fig. 2 gives examples to illustrate the proposed scheme. In the first case, RS_1 relays $Data_1$ to RS_2 if RS_1 receives the packet correctly. RS_2 and RS_3 also relay the packet to the MS, which replies with an E2E ACK that is forwarded by RS_3, RS_2, and RS_1 to the BS. In the second case, $Data_2$ is corrupted in the second hop. When RS_3 receives a NACK from the MS, RS_3 appends $RNACK_3$ to the NACK message because it does not receive the packet. RS_2 also indicates the failure of relaying the transmission by appending $RNACK_2$ to the NACK message. RS_1 appends the message with $RACK_1$ that indicates successful reception of the packet. By checking the received NACK message, the BS triggers the retransmission at RS_1. In the third case, a packet error occurs in the third hop. Moreover, the feedback message is also corrupted in the last hop, causing the E2E NACK missing in RS_3. Triggered by its timer, RS_3 generates a stand-alone $RNACK_3$. RS_2 and RS_1 provide local ARQ states by appending, respectively, a $RACK_2$ and a $RACK_1$ to $RNACK_3$. Upon receiving the $RNACK_3$, the BS triggers retransmission of $Data_3$ at RS_2.

Compared with the three conventional RARQ schemes, the proposed scheme causes no ambiguous error report problem because all RSs along a relay path indicate their ARQ states using RACKs and RNACKs. The BS triggers retransmissions at the RS nearest to the MS that has the packet, thus avoiding redundant retransmissions and reduce E2E transmission time. Moreover, the proposed LE RARQ avoids sending redundant RACKs by appending RARQ indicators only in the cases of packet corruption. Finally, the RSs trigger no additional retransmissions in LE RARQ because the BS completely controls the transmission/retransmission process.

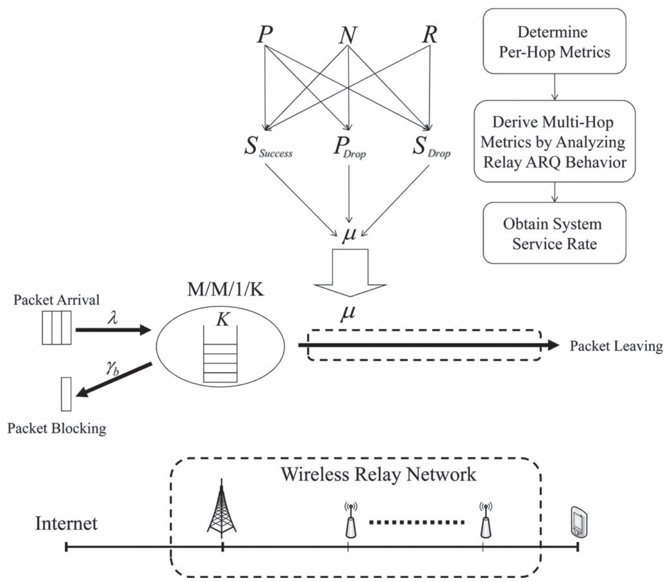

Fig. 3. Proposed analytic model.

III. Analytic Model

We assume that the relay network uses the same architecture as that of the IEEE 802.16j and LTE-A systems. Therefore, we generalize the proposed models and schemes for both the Worldwide Interoperability for Microwave Access and LTE-A systems. Without loss of generality, we use the terms from LTE-A to describe the models and methods in this paper. In an actual wireless system, the BS has a limited buffer. We propose an analytic model (see Fig. 3) that models the entire system as an M/M/1/K queuing system. This paper analyze the ARQ behavior for static multihop backhaul links and use deterministic metrics, namely, per-hop transmission rate R, per-hop packet error probability P, and hop count N to calculate the expected packet service time S_{system}. We assume that the distribution of the time for the system to serve each multihop transmission is identical and independent. It is reasonable to expect that the packet service time approaches an exponential distribution. In this paper, we regard S_{system} as exponentially distributed and model the relay system as an M/M/1/K queue to analyze the packet-blocking rate and the RARQ workload. With the proposed model, we can analyze the RARQ behaviors with reduced computation complexity since only the expected value of system service time is used in calculation.

In this system, the BS and RSs serve each incoming packet with relay transmissions destined to an MS. The packets arrive in this system with rate λ and depart if they are received by the MS or dropped after retrying $\mathrm{Retry}_{\mathrm{MS}}$ times. To simplify the modeling, we assume that all radio links are stable with constant and identical R and P. Let R be the number of transmitted packets per second. The transmission time between two RSs (including the queuing and processing delay at each RS) is $1/R$. The transmission latency through N hops is N/R.

Because a packet departs from the relay system in a received or dropped case, the packet service time S_{system} can be formulated as the following equation:

$$S_{\mathrm{system}} = (1 - P_{\mathrm{Drop}}) \times S_{\mathrm{Success}} + P_{\mathrm{Drop}} \times S_{\mathrm{Drop}} \tag{1}$$

where P_{Drop} is the packet-dropping probability, S_{Success} is the service time for a successful transmission, and S_{Drop} represents the service time of a dropped packet. In the following, we provide detailed derivations of the service times of S_{Success} and S_{Drop} and the probability of packet loss P_{Drop} for the proposed LE RARQ (see Fig. 4). Due to page limitations, see Appendix B for the analytic results of E2E, HbH, and TL RARQs.

1) Service Time for Successful Relay Transmissions: The service time for a successful multihop transmission is composed of the transmission time for an N-hop successful relay and the time for retransmissions. The service time can be further divided into T_{Tx} and T_{Wait} times, which denote the time for transmitting a packet and the waiting time for the MS to reply an ACK or NACK, respectively. Since the MS will wait for N-hop relay transmission time to receive a packet, the summation of T_{Tx} and T_{Wait} can be considered to be N/R because that MS cannot determine whether the packet is successfully received or dropped in an RS before the time of N/R. Fig. 4(a) and (b) shows these scenarios. The service time for a successful case can be derived as follows:

$$S_{\mathrm{Success}} = \frac{N}{R} + \sum_{i=0}^{\mathrm{Retry}_{\mathrm{MS}}-1} \mathrm{Total\_}T_{\mathrm{Wait}} \times P_{\mathrm{Complete\_before\_(Retry_{MS}-1)\_Retries}} \tag{2}$$

where i is the count of retransmissions, $\mathrm{Total\_}T_{\mathrm{Wait}}$ shows the summation of T_{Wait}, and $P_{\mathrm{Complete\_before\_(Retry_{MS}-1)\_Retries}}$ is the probability that the relay service is completed before retrying $\mathrm{Retry}_{\mathrm{MS}} - 1$ times. This model considers all the successful cases before retrying $\mathrm{Retry}_{\mathrm{MS}} - 1$ times and use the summation of the probability for retrying i retransmission times in (2), in which $i = 0$ to $\mathrm{Retry}_{\mathrm{MS}} - 1$. Since T_{Wait} is the waiting time for MS to reply an acknowledgement and associates with the remaining transmitting hops, it can be represented as $(N - n)/R$, in which n is the hop count for the completed relay transmission. Therefore, $\mathrm{Total\_}T_{\mathrm{Wait}}$ and $P_{\mathrm{Complete\_before\_(Retry_{MS}-1)\_Retries}}$ can be expressed as $\sum_{n=1}^{N}(1 - P)^{n-1} \times P \times (N - n/R)$ and $(1 - P)^N \times P^i$, respectively.

2) Service Time for Dropped Packets: In the proposed LE scheme, we assume that packets may be corrupted at any hop with equal probability during relaying. For each retry, the expected retransmission length is half of the remaining hops. By considering the first transmission length of N hops, the first retransmission path length is $N/2$, and the length for second retransmission is $N/2^2$. Therefore, S_{Drop} can be derived as follows:

$$S_{\mathrm{Drop}} = \frac{\sum_{i=0}^{\mathrm{Retry}_{\mathrm{MS}}} \frac{N}{2^i}}{R}. \tag{3}$$

3) Packet-Dropping Probability: Fig. 4 also shows the error cases for LE RARQ. Because each packet error may occur in any hop along the relaying path, the probability of one error is $P^1 \times C_1^N$. Moreover, multiple errors may occur for a packet to be relayed in each hop. This model uses simple mathematical combination and permutation to derive the probability; the probability of two errors is $P^2 \times C_2^{N+1}$, and that of $(\mathrm{Retry}_{\mathrm{MS}} - 1)$ errors is $P^{\mathrm{Retry}_{\mathrm{MS}}-1} \times C_{\mathrm{Retry}_{\mathrm{MS}}-1}^{N+\mathrm{Retry}_{\mathrm{MS}}-2}$. Consequently, the success probability P_{Success} can be obtained as follows:

$$\begin{aligned} P_{\mathrm{Success}} &= (1 - P)^N \sum_{i=0}^{\mathrm{Retry}_{\mathrm{MS}}-1} \times P^i \times C_i^{N+i-1} \\ &= (1 - P)^N \sum_{i=0}^{\mathrm{Retry}_{\mathrm{MS}}-1} \times P^i \times \frac{(N+i-1)!}{i! \times (N-1)!}. \end{aligned} \tag{4}$$

Therefore, the overall packet-dropping probability is $P_{\mathrm{Drop}} = 1 - P_{\mathrm{Success}}$.

4) Packet-Blocking Rate: In this relay system, the BS blocks incoming packets when the buffer overflows, and the packet-blocking rate γ_b is derived by considering the whole system as an M/M/1/K queue, as discussed earlier. The blocking probability P_b is obtained

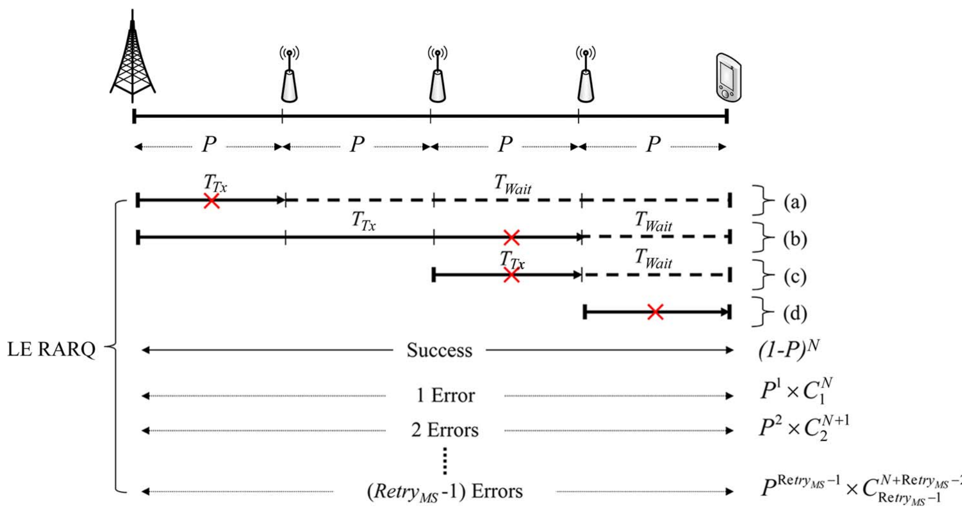

Fig. 4. Packet error and retransmission probabilities.

according to [16], and we use $1/S_{\text{system}}$ as the service rate μ in the derivation

$$P_b = \frac{\left(1-\frac{\lambda}{\mu}\right)\left(\frac{\lambda}{\mu}\right)^k}{1-\left(\frac{\lambda}{\mu}\right)^{k+1}}. \quad (5)$$

Therefore, the blocking rate γ_b is $\lambda \times P_b$.

5) RARQ Workload: We define the ARQ feedback rate (AFR) as the number of feedback messages per second and use the AFR to represent the RARQ workload. The workload of RARQ indicates the number of ARQ feedback messages, including RACKs and RNACKs that the BS and RSs process for error control per second. Because only one ARQ feedback message is replied for each relay transmission in the proposal, we use the packet service rate μ to approach the AFR. The following equation shows the feedback rate as μ if the system is fully loaded and as λ in light-load cases:

$$\text{AFR}_{\text{LE}} = \min(\lambda, \mu). \quad (6)$$

IV. Performance Evaluation and Model Validation

Here, we presents numerical simulations to verify the analytic model and evaluates the RARQ mechanisms with four metrics: service time for completing a relay transmission S_{Success}, packet-dropping rate R_{Drop}, packet-blocking rate γ_b, and AFR. Since our goal is to investigate the RARQ behavior in error control, the study considers static parameter of packet error probability in each hop P, the number of hops N, transmission rates R, and buffer size K as static for each evaluation case. The simulation was conducted using CSIM simulator [17] for a multihop relay network. The simulations assume stable radio links with the same P for all hops. Furthermore, the MS and RSs set a timer with the timeout limit for replying feedback. After the timer expires, retransmission counter is accumulated until reaching the retry limits, Retry_{MS}, which is set to 3 throughout all evaluations. Compared with the size of data packets, the size of one-bit ARQ indicator is ignored. This paper analyzes the relay ARQ workload issue by considering the ARQ feedback rate and does not consider the transmission latency of ARQ feedbacks. Therefore, this paper does not consider the hops that an ARQ feedback needs to be transmitted while evaluating the performance.

A. Transmission Service Time

Fig. 5 shows the transmission service time, which represents the duration for completing an E2E relay transmission. In the figures, the curves with prefix "M_" indicate the results produced by the proposed analytic model, whereas the others show the simulation results. This figure suggests that the path extension by multiple RSs not only increases the first transmission delay but the latency caused by retransmissions as well. HbH RARQ shows the lowest service time among all mechanisms, and it shows that HbH relaying can reduce the delay. According to the simulation results in the ten-hop cases, the LE solution outperforms the E2E and TL schemes, respectively, by 15.7% and 37.9% in packet service time, indicating the benefit of local retransmissions of our proposed scheme. E2E RARQ does not have favorable outcome because of the high retransmission probability and ambiguous report problem. As stated in Appendix A, TL RARQ also inherits the ambiguous error reporting from E2E RARQ, and the unexpected retransmissions lead to the least favorable results. Furthermore, Fig. 5 also shows that the analytic result is quite close to the simulation result.

B. Packet Block and Drop Rate

Fig. 6 shows the outcomes of packet blocking and dropping. The results indicate that the length of a relay path dramatically affects the packet-blocking rate because a long relay path increases the transmission time and causes more packets to be blocked by the BS. Similar to the results of packet service time in the previous experiments, the E2E and TL RARQ schemes also perform poorly in packet blocking. Regarding packet dropping, the ratio of dropped packets to transmitted packets is less than 5% for all the RARQ methods. According to the results, the low packet-dropping rate comes from the help of multiple retransmissions, but more packets are blocked due to the extended transmission time. Numerical results show that the HbH and LE RARQ schemes outperform the other two schemes in packet dropping and blocking. According to the simulation result, the proposed LE RARQ can reduce 5.9% and 7.9% of packet blocking for E2E and TL RARQs in the ten-hop case, respectively.

C. RARQ Workload

Fig. 7 shows the RARQ workload regarding AFR, confirming that the analytic results are close to those of simulation. In the two-hop case, the workloads by HbH and TL methods almost double those of E2E and our LE schemes. This is because the HbH and TL RARQs transmit one more feedback message than the E2E and LE RARQs. Moreover, the AFR of the HbH RARQ depends on the hops of a relay path, and it cannot effectively perform because all RSs excessively launch feedback messages, despite most of them being redundant.

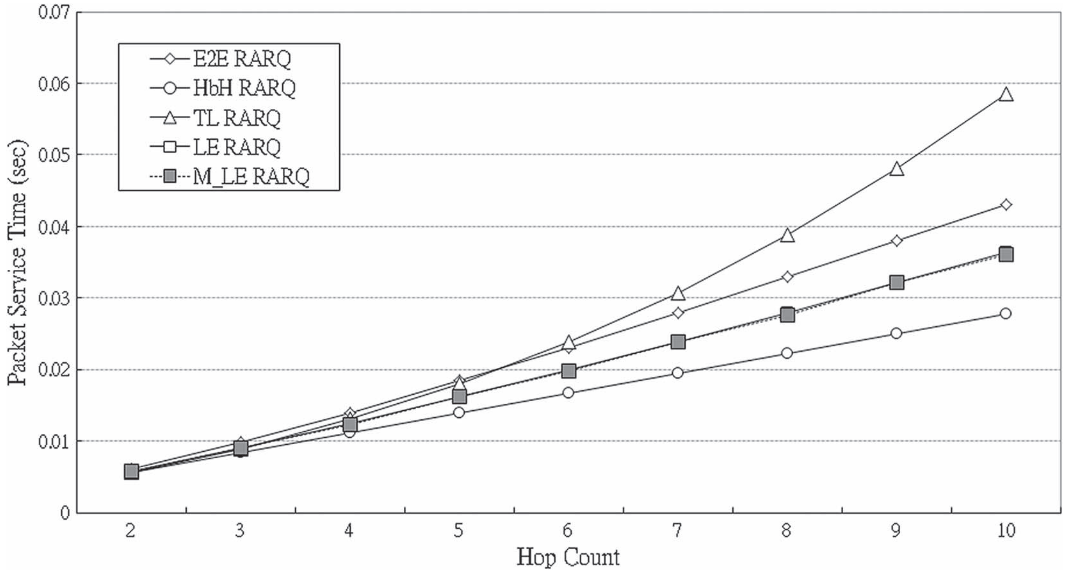

Fig. 5. Packet service time $(K = 20,\ P = 0.1,\ R = 400$ packet/s). Change the vertical caption.

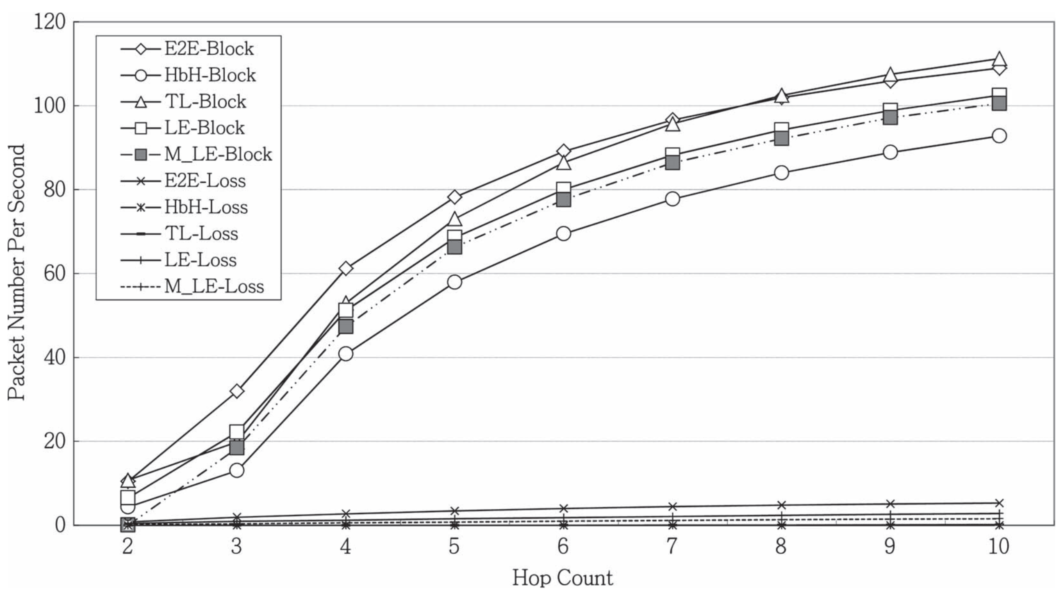

Fig. 6. Packet blocking and loss rate $(K = 20,\ P = 0.1,\ R = 400$ packet/s).

Results for E2E, TL, and LE RARQs decrease with the relay path extension because the rate of E2E transmissions also decreases. Note that the LE RARQ shows the smallest AFR among all simulations and requires only 5.7% of the workload of the HbH RARQ.

V. Conclusion

This paper has investigated the RARQ problems created by multihop transmissions and proposed a new RARQ mechanism with efficient feedback to overcome the problems of transmission delay, packet blocking, and RARQ workload. The proposed mechanism attaches RSs' ARQ states with RACKs and RNACKs in E2E feedback so that the BS knows the overall transmission states along the relaying path to minimize retransmissions. Moreover, the proposed RARQ appends the states only when error packets are present. With the efficient RARQ acknowledgement design, the proposed mechanism can alleviate the packet-blocking problem with adequate E2E transmission latency in a low RARQ workload. An analytic model is also presented to evaluate the performance. According to the simulation results, the proposed RARQ reduces the packet delay by 15.7% and 37.9%, respectively, as compared with E2E and TL RARQs. The simulation results also confirm the performance improvement over these two traditional RARQ schemes in packet blocking. Furthermore, the proposed LE RARQ requires significantly lower the workload than that of the HbH RARQ to obtain superior RARQ performance. The simulation results confirm the proposed analytic models of RARQ mechanisms and demonstrate that the new RARQ scheme outperforms conventional approaches.

Appendix A
Relay ARQ Overview

Here, we review three RARQ schemes for both uplink and downlink data flows in the relay networks in [1].

1) E2E RARQ: The E2E RARQ recovers packet errors from an E2E perspective, and all of the RSs simply relay packets and leave the error control for the packet sender and the receiver. In this scheme, the BS and the MS behave in a manner similar to a single-hop legacy wireless network. The retransmission for a lost

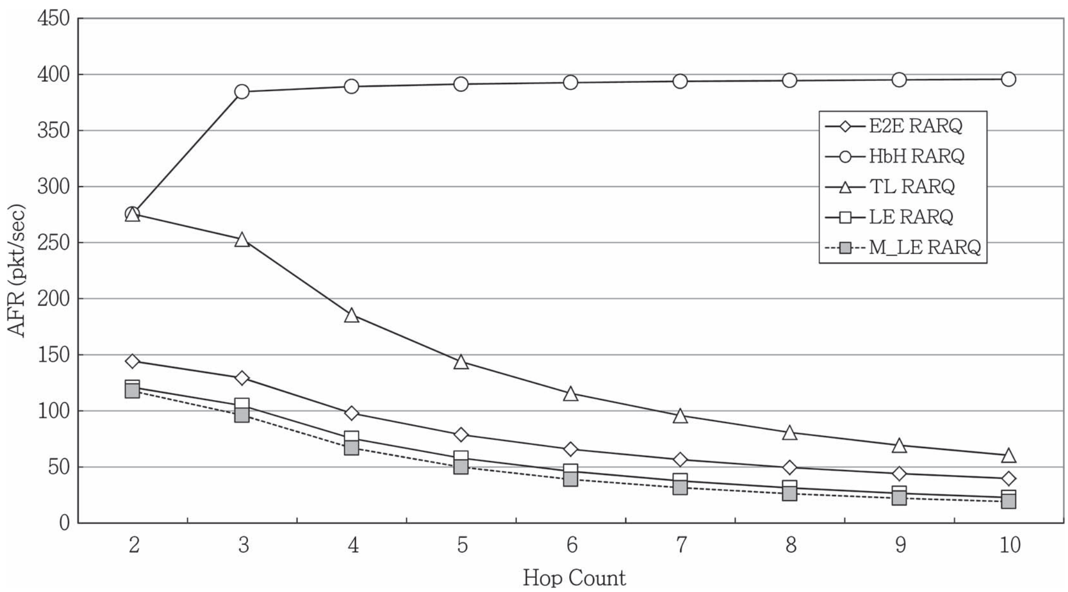

Fig. 7. RARQ workload.

packet must undergo all hops from the BS to the MS, thus increasing packet latency. In addition, the E2E feedback indicates only the error of packet transmission and does not provide additional information for retransmitting the packet. This ambiguous error report results in retransmission beginning from the BS to an MS, regardless of whether the RSs have already received the packet. For example, as shown in Fig. 8, the E2E NACK results in a redundant retransmission between BS and RS_1 and increases the latency.

2) HbH RARQ: This RARQ mechanism requires every RS to be involved in the error control process, and every RS is responsible for detecting errors, sending acknowledgements, and retransmitting packets. Fig. 8 shows that each RS must acknowledge its preceding node when receiving a packet in the HbH RARQ method. In the first hop, RS_1 sends a RACK to indicate successful reception of a packet and forwards the packet to the next hop. If the transmission in the second hop fails, RS_2 sends an RNACK to RS_1 to trigger a retransmission. Each RS needs to repeat packet forwarding until its succeeding RS replies with an RACK. With the additional error control on RSs, the HbH RARQ can manage packet error and loss, thus avoiding the redundant transmission problem. Nevertheless, the HbH RARQ requires RSs to report excessive reception states, creating ARQ workloads.

3) TL RARQ: The TL RARQ separates an E2E relay service into a relay transmission and an access transmission and applies two different ARQ processes to these two transmissions. An access RS, to which an MS attaches, manages two ARQ processes for both transmissions (see Fig. 8). A BS and an access RS (i.e., RS_3) exchange data with the assistance of RS_1 and RS_2. The access RS replies with an RNACK when detecting a packet error and sends a RACK back to the BS when the packet is successfully received. If the transmission in the access link fails, RS_3 retransmits the packet after receiving a NACK from the MS. Although the TL RARQ provides more opportunities for retransmitting packets at a specific RS when compared with the E2E RARQ, the retransmission might prolong the transmission and induces packet blocking in the BS. Moreover, the feedback message reduction incurs the ambiguous error reporting problem in relay links. In addition, serving packets with two ARQ processes prolongs transmission delay and incurs the workload problem.

APPENDIX B
ANALYTIC MODEL FOR RARQS

Here, we provide the analysis of service times, packet-dropping probability, and RARQ workload, for the three conventional RARQs: E2E, HbH, and TL RARQs.

1) Service Time for Successful Relay Transmission: In the E2E RARQ, a complete transmission over a relay path consists of one E2E relay with N-hop transmissions and possibly zero or more retransmissions. The serving time for an E2E relay transmission is N/R, where N denotes the hop count, and R is the rate for per-hop transmission (i.e., packets per second). Because a served packet may be retransmitted during the relay transmission, the service rate μ is smaller than the transmission rate R in most cases.

In the example of case (e) in Fig. 9, $T_{\rm Tx}$ and $T_{\rm Wait}$ denote the time for transmitting a packet and for waiting for MS feedback, respectively. The service time for each successful relay transmission $S_{\rm Success}$ can be derived as follows:

$$S_{\rm Success} = \sum_{i=0}^{{\rm Retry}_{\rm MS}-1} \frac{N\times(i+1)}{R}(1-P_{\rm RP})\times(P_{\rm RP})^i \qquad \text{(A-1)}$$

where ${\rm Retry}_{\rm MS}$ denotes the retry limit, i represents the retransmission count, and $P_{\rm RP}$ is the packet error probability of an E2E relay service. $P_{\rm RP} = 1-(1-P)^N$, where P is the per-hop packet error probability.

In the HbH RARQ, every RS playing a sender role attempts ${\rm Retry}_{\rm RS} - 1$ times to forward a packet before dropping it, where ${\rm Retry}_{\rm RS}$ is the limit of RS attempts. The serving time for a one-hop transmission $S_{\rm One-Hop}$ can be derived as follows:

$$S_{\rm One-Hop} = \sum_{j=0}^{{\rm Retry}_{\rm RS}-1} \frac{1}{R}\times\left((1-P)\times P^j\right) \qquad \text{(A-2)}$$

where j denotes the number of RS attempts. For case (f) in Fig. 4, the time for the HbH RARQ to finish an N-hop transmission is obtained by the following equation:

$$S_{\rm Success} = \sum_{i=0}^{{\rm Retry}_{\rm MS}-1} \left(N\times S_{\rm One-Hop} + \frac{i\times {\rm Retry}_{\rm RS}}{R}\right) \times P_{\rm ith\_Retransmission} \qquad \text{(A-3)}$$

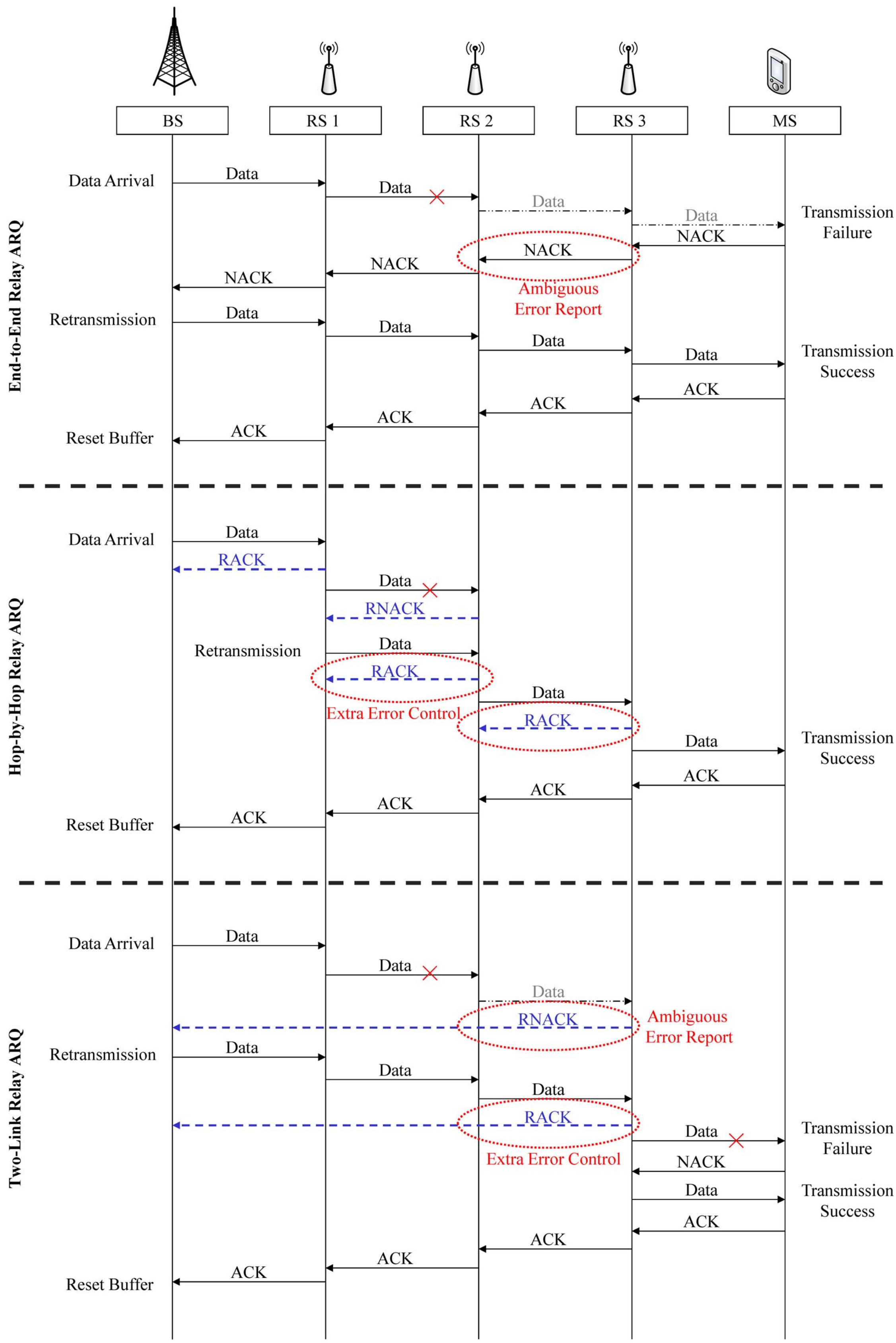

Fig. 8. RARQ overview.

where Retry_{MS} is the E2E retry opportunities, and the MS completes the relay service at the ith retransmission with the probability $P_{i\text{th\_Retransmission}}$. The first term in parentheses of equation (A-3) is the expected time to accomplish N one-hop transmissions, whereas the second term is the total time spent in retransmitting damaged packets.

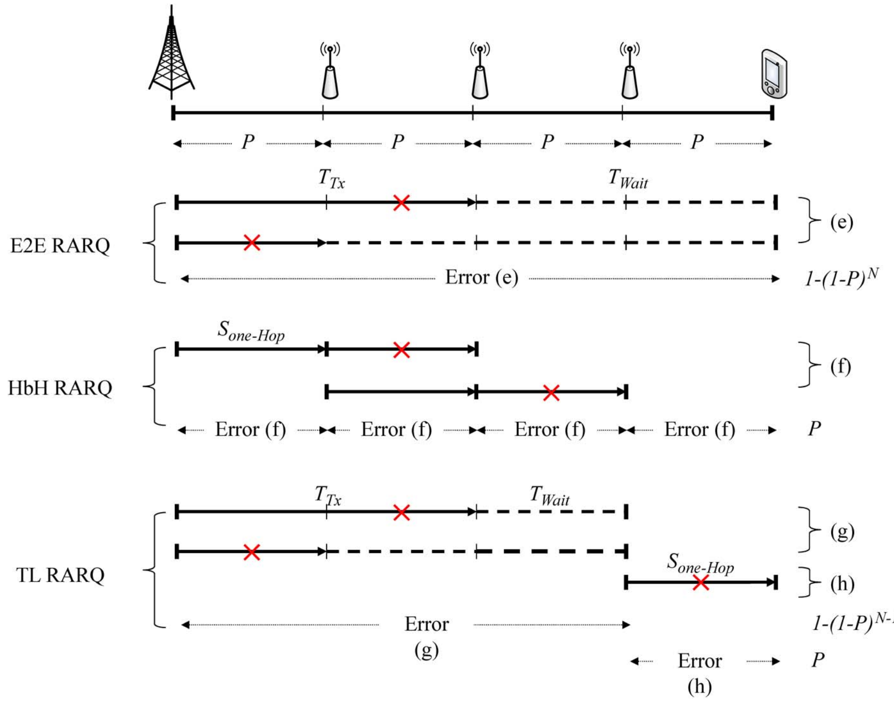

Fig. 9. Packet error and retransmission probabilities for E2E, TL, and HbH RARQs.

Examples (g) and (h) in Fig. 9 show that the TL RARQ operates in a manner similar to the E2E RARQ in the relay link and behaves as the HbH RARQ in the access link. The time for the TL RARQ to complete a relay service is

$$S_{\text{Success}} = \sum_{i=0,j=0}^{i+j<(\text{Retry}_{\text{MS}}-1)} \Big[S_{\text{RL}}(1-P_{\text{RL}}) \times P_{\text{RL}}^{i} + S_{\text{AL}}(1-P_{\text{AL}}) \times P_{\text{AL}}^{j} \Big] \quad \text{(A-4)}$$

where S_{RL} and S_{AL} are the times for completing a transmission in the relay link and the access link, respectively, and P_{RL} and P_{AL} are respective success probabilities. S_{RL} can be obtained by (A-1) with $N = N_{\text{RL}} = N_{\text{RP}} - 1$, and S_{AL} can be derived. (A-3) with $N = 1$; P_{RL} and P_{AL} are respectively $1-(1-P)^{N-1}$ and P.

2) Service Time for Dropped Packets: In the E2E RARQ, a packet is not dropped until it has been retransmitted Retry_{MS} times. The service time for each dropped packet S_{Drop} is obtained by the following equation:

$$S_{\text{Drop}} = \frac{N}{R} \times \text{Retry}_{\text{MS}}. \quad \text{(A-5)}$$

S_{Drop} in the HbH RARQ can be divided into two parts: the time for relaying a packet to the ith RS and the time for the RS to retransmit the packet after retrying Retry_{RS} times. In the first part, (A-2) can be used to derive the outcome

$$S_{\text{Relay\_to\_}i\text{th\_RS}} = (i-1) \times \sum_{j=0}^{\text{Retry}_{\text{RS}}-1} \frac{1}{R} \times \left((1-P) \times P^{j}\right). \quad \text{(A-6)}$$

In the second part, the multiplication of Retry_{MS} and Retry_{RS} shows the total number of failed retransmissions at the ith hop. Therefore, the derivation for S_{Drop} is

$$S_{\text{Drop}} = \sum_{i=1}^{N} (S_{\text{Relay\_to\_}i\text{th\_RS}} \times P_{\text{Failure\_at\_}i\text{th\_RS}}) + \frac{\text{Retry}_{\text{MS}} \times \text{Retry}_{\text{RS}}}{R} \quad \text{(A-7)}$$

where $P_{\text{Failure\_at\_}i\text{th\_RS}}$ denotes the probability of the relay service failure at the ith RS.

The relay service may fail at either the relay link or the access link in the TL RARQ, and S_{Drop} can be obtained as in (A-8), shown at the bottom of the page. where $P_{\text{Retry\_}i\text{\_in\_RL}}$ and $P_{\text{Retry\_}j\text{\_in\_}AL}$ represent the probabilities that the BS and access RS perform i and j retransmissions in the relay and access links, respectively.

3) Packet Drop Probability: In the case (e) of Fig. 9, $1-(1-P)^N$ is the packet error probability for each E2E transmission. The packet-dropping probability P_{Drop} for the E2E RARQ is as follows:

$$P_{\text{Drop}} = \left(1-(1-P)^{N}\right)^{\text{Retry}_{\text{MS}}}. \quad \text{(A-9)}$$

For the HbH RARQ, the BS drops the packet in a hop with the probability of $(P^{\text{Retry}_{\text{RS}}})^{\text{Retry}_{\text{MS}}}$. Because there may be multiple failures for relaying a packet in a single hop, P_{Drop} can be derived as follows:

$$P_{\text{Drop}} = C_{\text{Retry}_{\text{MS}}}^{N+\text{Retry}_{\text{MS}}-1} \times (P^{\text{Retry}_{\text{RS}}})^{\text{Retry}_{\text{MS}}}. \quad \text{(A-10)}$$

$$S_{\text{Drop}} = \sum_{i=0,j=0}^{i+j=\text{Retry}_{\text{MS}}} \frac{((N-1) \times i \times P_{\text{Retry\_}i\text{\_in\_RL}} + j \times P_{\text{Retry\_}j\text{\_in\_AL}})}{R} \quad \text{(A-8)}$$

Because a packet may be either dropped in the relay link or access link for the TL RARQ, P_{Drop} is derived as follows:

$$\begin{aligned} P_{\text{Drop}} &= P_{\text{Drop}(\text{Retry}_{\text{MS}},0)} + P_{\text{Drop}(\text{Retry}_{\text{MS}}-1,1)} \\ &\quad + P_{\text{Drop}(\text{Retry}_{\text{MS}}-2,2)} + \cdots + P_{\text{Drop}(0,\text{Retry}_{\text{MS}})} \\ &= \sum_{i=0}^{\text{Retry}_{\text{MS}}} P_{\text{Drop}(\text{Retry}_{\text{MS}}-i,i)} \end{aligned} \quad \text{(A-11)}$$

where $P_{\text{Drop}(X,Y)}$ denotes the probability that there are X and Y transmission failures in the relay and access links throughout all relay service.

4) RARQ Workload: The RARQ workload depends on the number of processed feedback messages. In the E2E RARQ, the message feedback rate is identical to the E2E transmission rate R/N. If the radio resource is not fully occupied, the MS could transmit feedback messages at arrivals of all packets. In other words, the AFR is the same as the packet arrival rate λ. The AFR of E2E RARQ can be obtained as

$$\text{AFR}_{\text{E2E}} = \min\left(\lambda, \frac{R}{N}\right). \quad \text{(A-12)}$$

Because the HbH RARQ sends packets on a per-hop basis, N feedback messages are associated with a relay transmission. Considering light load cases, the workload for the HbH RARQ is given by the following:

$$\text{AFR}_{\text{HbH}} = \min\left(\lambda, \frac{R}{N}\right) \times N. \quad \text{(A-13)}$$

The TL RARQ employs an access RS to report ARQ states, and introduces an additional feedback message. AFR_{TL} is derived in the following:

$$\text{AFR}_{\text{TL}} = \min\left(\lambda, \frac{R}{N}\right) \times 2. \quad \text{(A-14)}$$

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Comments on "Distributed Space–Time–Frequency Coding for Broadband Wireless Relay Network"

Meilu Lin, Jianhua Ge, and Ye Yang

***Abstract*—The achievable diversity order analyzed by Yang *et al.* for a class of distributed space–time–frequency codes (DSTFCs) is erroneous in general. Therefore, this commentary corrects their analysis and shows the true diversity order achieved by the DSTFCs.**

***Index Terms*—Distributed space–time–frequency coding (DSTFC), multipath diversity, spatial diversity.**

I. INTRODUCTION

In [1], Yang *et al.* proposed a class of distributed space–time–frequency codes (DSTFCs) for broadband wireless relay networks. The proposed DSTFCs were shown to be capable of achieving the diversity order of $\min\{\sum_{i=1}^{M} L_{SR_i}, \sum_{i=1}^{M} L_{R_iD}\}$, where L_{SR_i} and L_{R_iD} are the number of taps of multipath fading channels from source S to relay R_i and from relay R_i to destination D, respectively. While this diversity result is reasonable for symmetric multipath channels

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