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Error Control Strategies for WiMAX Multi-hop Relay Networks

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***Abstract*—Next generation wireless system such as advanced WiMAX (i.e., IEEE802.16m) and LTE advanced will fully embrace multi-hop relay architecture. The conventional Automatic Repeat reQuest (ARQ) and the more recent Hybrid ARQ (HARQ) are two simple yet highly effective error control techniques designed for single hop system. Nevertheless, extending them in a synergistic manner to support multi-hop relay networks is by no means a trivial undertaking. This paper explores a variety of multi-hop error control techniques such as hop-by-hop ARQ, 2-link ARQ and end-to-end ARQ, and various possible combinations with HARQ. We further establish an analytical framework for each of these key techniques and evaluate the performance. Based on the analysis and comparison, we propose a low complexity error control mechanism tailored for the multi-hop transmission features. Extensive simulation results compare the performance and validate our analytical framework.**

I. Introduction

In order to extend coverage and/or improve cell throughput, next generation cellular system (e.g., IEEE802.16j[1], IEEE802.16m[2] and LTE advanced) will fully embrace a multi-hop relay network architecture. Different from wired communication system, wireless channel is an error-prone environment. Due to various fading and interference, data transmissions are highly prone to be corrupted. The error can be further propagated and even amplified, as data packets are forwarded across multiple hops. In addition, data packets can be dropped at the intermediate relay stations (RSs) due to buffer overflow. Meanwhile, it has been shown in [3] that throughput would experience dismal degradation as the number of hops increases, even in an error-free multi-hop environment. Therefore, in order to meet the performance and reliability requirement of next generation mobile systems, an efficient error control mechanism for multi-hop transmission is indispensable.

Automatic Repeat reQuest (ARQ) is a classic error detection and recovery mechanism widely used in contemporary communications system. If data packet is lost or corrupted, transmitter can do a retransmission if it receives a negative acknowledgement (ACK) from the intended receiver or its local ARQ transmission timer expires. Hybrid ARQ (HARQ) is an advanced cross-layer technique that has been recently adopted by many wireless systems to leverage coding gain and improve the reliability. There are two main flavors of HARQ, namely chase combining (CC) and incremental redundancy (IR). HARQ can be used either independently, or in conjunction with ARQ to provide robust data transmission. The performance of ARQ mechanism in a single hop system has already been thoroughly studied [4][5][6][7]. HARQ in single hop network is also a well-researched topic. Interested readers are encouraged to refer to [8][9] for more details. In contrast, however, the architecture and performance of both ARQ and HARQ in multi-hop wireless network have yet to be carefully examined.

This paper investigates the error control problem in multi-hop transmission from serving BS to MS through multiple RSs. We develop analytical framework for comparing the performance of ARQ, HARQ, and their combinations in multi-hop transmission. The analytical and simulation studies shed valuable glimpse on how error control mechanism shall be designed for a multi-hop wireless system. Based on the insights gained, we propose a low-complexity error control mechanism exploring various key features of multi-hop relay transmission.

The remainder of this paper is organized as follows: Related work regarding ARQ, HARQ, and their interactions are provided in Section II. Various error control architectures including our proposed scheme are explained and explored in Section III. Proposed analytical framework for multi-hop wireless system is described in Section IV. Section V provides performance evaluation results obtained by both analysis and simulation. Finally, the paper is concluded in Section VI.

II. Related Work

The performance of single hop ARQ has been discussed in [7][10] for various wireless channel condition impacts. Modulation and coding of HARQ for single hop transmission are well investigated in [11][12][13] as well. However, end-to-end error control has only been investigated for wired networks in the literature. End-to-end error control in wired networks was considered in [14][15][16]. As indicated in these papers, the performance difference between end-to-end and link-by-link error control is dominated by the buffer size, propagation delay, transmission error probability, acknowledge message feedback delay and so on. The analytical model of [14] is

Weihuang Fu worked on this study while visiting Mitsubishi Electric Research Lab, Cambridge, MA.

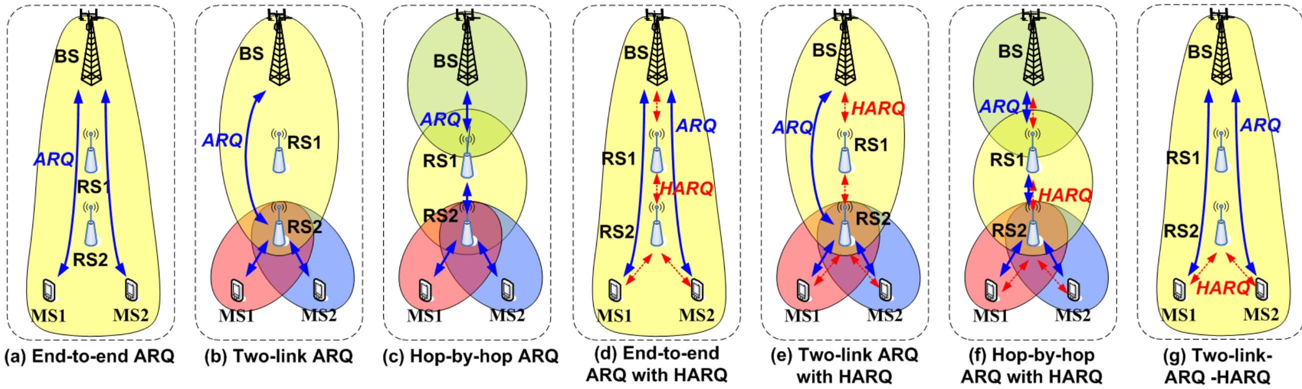

Fig. 1: Error Control for Multi-hop Relay Networks

primarily affected by the buffer size. Propagation delay and transmission errors are ignored since the wired channel is assumed to be reliable. The retransmission is triggered by the packet drop at intermediate RS. The results in [15] indicates that link-by-link approach has better performance since it can retransmit packets in shorter time as compared to that of end-to-end approach. However, the results in [16] is completely different. This is because, [16] primarily considers the effect of high speed transmission and long propagation delay in optical fiber where multiple packets can be present on a link. So, the conclusion in [16] is that end-to-end approach has at least equivalent or a better performance. These indicate that different values of these factors lead to completely different conclusions. Although extensive research has been conducted in wired network, comparison and evaluation for error control in multi-hop relay networks have not been investigated.

III. Error Control Architectures

In our analytical frame work, we investigate the error control problem in a h-hop transmission. Without loss generality, we assume the connection is from a BS to an MS through multiple RSs. The whole h-hop transmission can be divided into several segments for multihop ARQ implementation. In an m-hop ($m \leq h$) segment, ARQ sends the data frame at the first node and the acknowledge message is sent back from the mth hop node. Obviously, $m = 1$ is corresponding to hop-by-hop ARQ case and $m = h$ is corresponding to end-to-end ARQ case.

Two kinds of RSs may be present in the network. The first one is able to decode, buffer and forward ARQ blocks, called decode and forward RS (DF-RS). Corrupted ARQ burst received by DF-RS will be dropped. The other one just performs the functions to receive, amplify and forward the physical (PHY) layer frame, called amplify and forward RS (AF-RS). It does not exam received ARQ bursts, neither at the MAC layer nor at the PHY layer. Corrupted ARQ bursts will be continuously transmitted until reaching the destination node. In this paper, we consider DF-RS which is a part of major standards. HARQ is used based on per-hop basis by this type of RS. Different from end-to-end and link-by-link error control in wired networks, error control in multi-hop wireless networks involves more usage alternatives [17]. Following are six usage cases of ARQ, HARQ, and their combinations in relay networks.

1) End-to-end ARQ: As shown in the example of Fig. 1(a), ARQ is performed between the BS and the MSs. For the connection from BS to MS, the ARQ state machine is initiated at the BS. RS1 and RS2 relay the ARQ burst, but do not check if error introduced during the transmission. MS1 and MS2 will check if the ARQ burst is dropped or has error. MS1 and MS2 send the feedback acknowledge information to the BS for retransmission or confirmation of receipt.

2) 2-link ARQ: The h-hop transmission is divided into two segment. The first segment has $h-1$ hops and perform ARQ for the transmission from the BS to the last hop RS. The last hop transmission from the RS to the MS is the other segment having an ARQ control. As the example shown in Fig. 1(b), when a connection is built between the BS and the MSs, the end-to-end connection is divided into two segments. ARQ will be created between the BS and the last hop RS. The other one is created between the last hop RS and the MS. For data frame from the BS to the MS, RS1 takes responsibility for forwarding ARQ bursts. RS2 will check the ARQ burst: If there is an error or drop event, RS2 sends the feedback to the BS for retransmission. At RS2, the received data will be arranged for ARQ bursts and have the transmission between RS1 and MSs. If there is an error or drop event happening between RS1 and MS1, RS1 is in charge for retransmission. So, in this scheme, the last hop RS needs to store the data for retransmission purpose, which requires more memory resource as compared to end-to-end ARQ.

3) Hop-by-hop ARQ: It has only one ARQ segment from BS to MS. As shown in Fig. 1(c), the ARQ is initiated for every hop on the connection from BS to MS. It is obvious that if the error occurs at any hop, it will be detected by the receiver immediately and the receiver will require the sender to retransmit the ARQ burst.

4) End-to-end ARQ with HARQ: It has per-hop HARQ under end-to-end ARQ, as shown in Fig. 1(d).

5) 2-link ARQ with HARQ: It has per-hop HARQ under 2-link ARQ. As shown in Fig. 1(e), HARQ is used for every hop. ARQ is used on 2-link basis. For data frame from the BS to the MS, if RS1 cannot decode the HARQ sub-burst from BS, it will require the BS to retransmit HARQ sub-burst. However, if the error already incurs in the ARQ burst and HARQ sub-burst is received correctly, RS1 would not find the error and will forward the ARQ burst.

6) Hop-by-hop ARQ with HARQ: Besides hop-by-hop ARQ, HARQ is used for every hop, as shown in Fig. 1(f). End-to-end control may be required for the connection between BS and MS to eliminate error or any lost packets during multi-hop transmission.

7) 2-link-ARQ-HARQ: We propose this error control mechanism that uses ARQ for end-to-end error control and HARQ for the access link error control. It is a hybrid way of taking advantages of both ARQ and HARQ. According to our observed and simulation results presented in later sections, relay link has much lower block error rate (BLER) as compared to that of the access link. This is because RSs are statically deployed and the locations are pre-planed. RSs may also have high antenna gains. So, per-hop HARQ is not necessary for the relay links. However, MSs may have various mobility that access link may have much higher BLER. The usage of HARQ for access link could bring significant difference to the performance. The complexity of this scheme is much lower than that of end-to-end ARQ with per-hop HARQ. Its complexity may be little higher than that of end-to-end ARQ. But the performance will be much improved. This scheme is shown in Fig. 1(g). HARQ is only used for the access links between RS2 and MS1 and between RS2 and MS2, while ARQ is between BS and MS1 and between BS and MS2 for end-to-end error control.

Generally, we consider HARQ at the lower MAC layer that is transparent to the ARQ at the upper MAC layer. In pure ARQ case, the receiver may send ARQ NACK immediately after the detection of an error so as to reduce the average transmission time (including the retransmission time). While working with HARQ, such immediate response and retransmission may be invoked before the HARQ completes its retransmission, which lead to duplications at the link and impacts the system performance significantly. So, for the case of ARQ on the top of HARQ, the ARQ feedback needs some delay, so that the HARQ can have enough time to perform the retransmission. On the other side, when HARQ reaches the maximum times of retransmission, waiting of ARQ becomes meaningless. To reduce the delay, we assume existence of a following mechanism between ARQ and HARQ: When both ARQ and HARQ are applied for a connection, if the HARQ entity in the transmitter determines that the HARQ process is terminated with an unsuccessful outcome, the HARQ entity in the transmitter informs the ARQ entity in the transmitter about the failure of the HARQ sub-burst. The ARQ entity in the transmitter can then initiate retransmission and/or re-segmentation [2].

IV. Error Control Analysis

A. Multi-hop ARQ

We firstly have a look at the delay and the throughput of ARQ in multihop transmission. An m-hop ARQ segment can be modeled as a queueing network shown in Fig. 2. ARQ

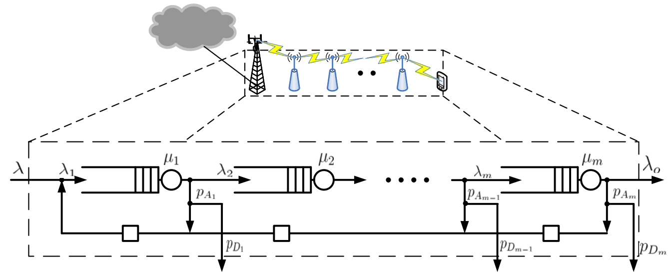

Fig. 2: Multi-hop Error Control

blocks are assembled in ARQ burst that enters the segment as Poisson arrival process with arrival rate λ. It is obvious that the arrival rate of the first queue is larger than λ due to the retransmission of ARQ bursts. The departure rate of the ith queue in m-hop segment is denoted by μ_i, which is the rate that MAC layer sends ARQ bursts to PHY layer.

The probability that ARQ burst can be correctly transmitted from the ith node to the $(i+1)$th node, is denoted by $1-p_{A_i}$, where p_{A_i} is the probability that the ARQ burst needs to be retransmitted due to error. The last hop node of the segment will send the feedback in the reverse order to the first node of the segment, no matter where the ARQ burst has an error or is dropped. The maximum number of transmission for ARQ burst is denoted by N_{tr}. We denote p_{D_i} as the ARQ burst drop probability of the ith hop relay link. The value is approximated by $p_{D_i} = p_{A_i}^{N_{tr}-1}$, which means the failures of the burst in $N_{tr}-1$ retransmissions.

To investigate the delay at each hop, we firstly compute the arrival rate at each queue. The ARQ burst arrival rate at RS i in the queueing network is expressed by:

$$\lambda_i = \lambda_{0i} + \sum_{j=1}^{m} \lambda_j p_{ji}, \tag{1}$$

where λ_{0i} denotes the traffic arrival rate from outside of the m-hop segment to RS i and p_{ji} denotes the transition probability from RS j to RS i. In the m-hop ARQ segment, the burst arrival rate at the ith hop node, denoted by λ_i, is the rate of the bursts that depart from the $(i-1)$th hop node and arrive at the ith hop node without error. The burst departure rate of the $(i-1)$th hop node is identical to the burst arrival rate of the $(i-1)$th hop node. So, the burst arrival rate at the ith hop node is computed by:

$$\lambda_i = \lambda_{i-1}(1 - p_{A_{i-1}}). \tag{2}$$

Looking at an m-hop segment, the departure rate of the segment, which is also the departure rate at the last hop node, is:

$$\lambda_o = \lambda_m(1 - p_{A_m}). \tag{3}$$

From Eq. (1), the burst arrival rate at the first node is the sum of the burst arrival rates from segment outside and those retransmission bursts. We have the expression:

$$\lambda_1 = \lambda + \sum_{j=1}^{m} \lambda_j p_{A_j}(1 - p_{D_j}). \tag{4}$$

Solving from the equations above, we can obtain the arrival rate at the ith hop node:

$$\lambda_i = \frac{\lambda P_l^{(i-1)}}{1 - \sum_{j=1}^{m} p_{A_j}(1-p_{D_j})P_l^{(j-1)}}, \quad (5)$$

where $P_l^{(i-1)} = \prod_{j=1}^{i-1}(1-p_{A_j}), i = 2, ..., m$. We know $P_l^0 = 1$. Based on Eq. (1), the rate of the ARQ burst visiting the ith hop node is defined by:

$$e_i = p_{0i} + \sum_{j=1}^{m} e_j p_{ji}, \quad (6)$$

where p_{0i} denotes the probability that ARQ burst comes from a segment outside the ith hop node.

The visit rate of ARQ burst at the ith hop node can be expressed by:

$$e_i = \frac{P_l^{(i-1)}}{1 - \sum_{j=1}^{m} p_{A_j}(1-p_{D_j})P_l^{(j-1)}}. \quad (7)$$

Let $\pi(k_1, k_2, ..., k_m)$ denote the probability of the numbers of ARQ bursts in queues $1, 2, ..., m$, respectively, where k_i denotes the number of ARQ bursts in queue i. In general, the arrival processes at the RSs will not be completely Poisson process due to retransmission and dropping of ARQ bursts. However, the ARQ bursts arriving at the RS queues can be assumed to behave like independent Poisson processes with Jackson's theorem [18]. Then, we have:

$$\pi(k_1, k_2, ..., k_m) = \pi_1(k_1)\pi_2(k_2)...\pi_m(k_m). \quad (8)$$

For an M/M/1 queue, the average number of ARQ bursts in the RS can be computed by:

$$E[n_i] = \frac{\rho_i}{1-\rho_i}, \quad (9)$$

where utility of RS i, ρ_i denotes the utility of the ith node and is computed by $\rho_i = \frac{\lambda_i}{\mu_i}$.

When queue i is ergodicity, the mean response time is computed by:

$$\overline{T}_Q(i) = \frac{E[n_i]}{\lambda_i} + T_c(i), \quad (10)$$

where $T_c(i)$ denotes the time interval from an ARQ burst leaving ARQ control unit at the sender to reach the corresponding ARQ unit at the receiver.

The time length for an acknowledge message back to the source is the accumulation of transmission delay from the destination to the source of the segment, which is:

$$T_{ACK} = \sum_{i=1}^{m} \frac{1}{\mu_i} + mT_p + T_A, \quad (11)$$

where T_A denotes the delay between receiving the burst and sending the acknowledge message and T_p denotes the propagation delay. When HARQ is implemented beneath ARQ, the time interval, T_A, should be enough for HARQ to perform retransmission.

Considering Eq. (7), Eq. (10) and Eq. (11), the average delay for ARQ burst transmission in an m-hop segment can be computed by:

$$\overline{T}(m, \mathbf{p}_A) = \sum_{i=1}^{m} e_i \overline{T}_Q(i) + (e_1 - 1)T_{ACK}, \quad (12)$$

where $\mathbf{p}_A = \{p_{A_1}, ..., p_{A_m}\}$.

We denote $\mathbf{p}_a = \{p_{a_1}, ..., p_{a_h}\}$ as the probability vector of burst error on total h hop links. The probability vector of burst error for the links of segment, $\mathbf{p}_A = \{p_{A_1}, ..., p_{A_m}\}$, is a subvector of $\mathbf{p}_a$. Given h hops from BS to MS in total and the average delay for ARQ transmission is:

$$\overline{D}(h) = \begin{cases} \sum_{i=1}^{h} \overline{T}(1, p_{a_i}), & \text{hop-by-hop} \\ \overline{T}(h-1, \mathbf{p}_a^{h-1}) + \overline{T}(1, p_{a_h}), & \text{2-link} \\ \overline{T}(h, \mathbf{p}_a), & \text{end-to-end,} \end{cases} \quad (13)$$

where $\mathbf{p}_a^{h-1} = \{p_{a_1}, \ldots, p_{a_{h-1}}\}$.

B. Per-hop HARQ

HARQ exploits the coding gain and is utilized per-hop basis by DF-RS. We denote the maximum number of transmission times of HARQ sub-burst by H_{tr} and use a state transit graph to model HARQ error control mechanism. Let $0, 1, 2, ..., H_{tr}$ represent send (state 0), retransmission (states $1, ..., H_{tr} - 1$), and discard (state H_{tr}), respectively. The probability that state i transits to next state is denoted by p_i, where $1 - p_i$ means the probability that the HARQ sub-burst can be corrected by the combination of previous received HARQ sub-bursts. So, p_i is the decode failure probability of HARQ sub-burst and it is related to the implemented coding scheme.

Due to this coding gain of forward error correction (FEC), HARQ is able to decode the sub-burst with limited error. The probability that ARQ sub-burst is successfully sent to next hop at the first transmissions, denoted by $p_s^{(k)}(1)$, can be expressed by:

$$p_s^{(k)}(1) = 1 - p_e^{(k)}(L) + p_e^{(k)}(L)(1-p_1) = 1 - p_e^{(k)}(L)p_1, \quad (14)$$

where L denotes the transmission time for sub-burst and $p_e^{(k)}(L)$ denotes the sub-burst error probability at the kth hop.

If the $(i-1)$th transmission to the same HARQ sub-burst fails, the conditional probability that the ith transmission is successful, can be computed by:

$$\begin{aligned} p_s^{(k)}(i|i-1) &= (1 - p_e^{(k)}(L_i)) + p_e^{(k)}(L_i)(1-p_i) \\ &= 1 - p_e^{(k)}(L_i)p_i, \end{aligned} \quad (15)$$

where L_i denotes the transmission time for the ith HARQ sub-burst. Due to coding of HARQ sub-packet, the sub-burst at different retransmission may not be the same. In CC scheme, $L_i = L$. In IR scheme, L_i varies with the the number of retransmission times. From the previous equation, we have the probability that HARQ sub-burst is successfully sent to next hop at the ith transmission:

$$p_s^{(k)}(i) = (1 - p_e^{(k)}(L_i)p_i) \prod_{j=1}^{i} p_e^{(k)}(L_j)p_j. \tag{16}$$

If the number of retransmission reaches H_{tr}, the HARQ sub-burst will be discarded. The probability that an ARQ block is discarded due to reach the maximum retransmission is:

$$p_{r_k} = \prod_{j=1}^{H_{tr}} p_e^{(k)}(L_j)p_j. \tag{17}$$

From the view of upper MAC, the probability of retransmission of an ARQ block is:

$$p_{a_k} = \begin{cases} p_e^{(k)}(L), & \text{without HARQ} \\ p_{r_k}, & \text{with HARQ.} \end{cases} \tag{18}$$

The average number of transmissions needed for successful HARQ sub-burst transmission, is:

$$N_t^{(k)} = \sum_{i=1}^{H_{tr}} i p_s^{(k)}(i) + H_{tr}p_r. \tag{19}$$

So, from the view of upper MAC, the effective departure rate of ARQ with HARQ, becomes:

$$\mu_k^H = \frac{\mu_0}{N_t^{(k)}}. \tag{20}$$

Equivalent delay at the kth hop from the view of ARQ if HARQ beneath:

$$T_c^H(k) = T_p + \sum_{i=1}^{H_{tr}} (i-1)(T_p + T_H)p_s^{(k)}(i), \tag{21}$$

where T_H denotes the feedback HARQ delay.

So, to compute the performance with HARQ, $T_c(i)$ in Eq. (10) is replaced by $T_c^H(i)$ obtained by Eq. (21). The delay with HARQ at the ith hop is:

$$\overline{T}_Q^H(i) = \frac{E[n_i]}{\lambda_i} + T_c^H(i). \tag{22}$$

With the implementation of HARQ beneath ARQ, the feedback time is also changed by considering the delay of HARQ retransmission. So, Eq. (11) is replaced by:

$$T_{ACK}^H = \sum_{i=1}^{m} \frac{1}{\mu_i^H} + mT_p + T_H, \tag{23}$$

The segment delay is now affected by new parameters with HARQ: $\overline{T}_Q^H(i)$ and T_{ACK}^H. The connection delay for various ARQ with HARQ is:

$$\overline{D}_H(h) = \begin{cases} \sum_{i=1}^{h} \overline{T}_H(1, p_{r_i}), & \text{hop-by-hop} \\ \overline{T}_H(h-1, \mathbf{p}_r^{h-1}) + \overline{T}_H(1, p_{r_h}), & \text{2-link} \\ \overline{T}_H(h, \mathbf{p}_r), & \text{end-to-end.} \end{cases} \tag{24}$$

C. 2-link-ARQ-HARQ

With per-hop HARQ, the connection will become complex. Every RS has to build state machine and allocate resource for the HARQ transmission. In addition, a large amount of HARQ state machine information has to be collected from all RSs on the connection path during handover procedure. We notice that the relay link is more stable because the RS is usually static and the configuration of antennas can be adjusted for optimization. So, the BLER is usually low for the RS link. However, the access link has high BLER because of the mobility of MS. MS also does not have high transmission power and gain as that of RS. It is hard to predict and adjust the access link BLER. Based on such situation, we propose to only use HARQ for the access link rather than per-hop basis. Besides the complexity and handover benefit, this method also reduces the ARQ feedback time, which now can be given by:

$$T_{ACK}^{AH} = \sum_{i=1}^{m-1} \frac{1}{\mu_i} + \frac{1}{\mu_h^H} + mT_p + T_H < T_{ACK}^H. \tag{25}$$

To ensure end-to-end error control, the whole connection between BS and MS uses end-to-end ARQ. The delay with this hybrid method can be computed by:

$$\overline{D}_{AH}(h) = \overline{T}_{AH}(h, \{\mathbf{p}_a^{h-1}, p_{r_h}\}). \tag{26}$$

V. Performance Evaluation

In this section, we investigate the performance of various error control schemes discussed in the previous section. Figures in this section will show the simulation curves and the analytical results. To display it clearly, simulation curves will be shown by dotted lines and analytical curves will be shown by lines. In addition, besides different notations, the curves of same scheme will be shown by the same color for color printing. In the simulation, the data frame is sent from BS to MS and relayed by RSs. An ARQ burst contains 10 ARQ blocks with Poisson arrival process. Departure rate is 200 ARQ burst per second, which means 2000 ARQ blocks can be processed by RS per second. Fig. 3, Fig. 4, and Fig. 5 show the throughput-delay curves and the simulation with the same relay link and access link channel configurations. The relay link BLER (RLK-BLER) is set to 10^{-3} and the access link BLER (ALK-BLER) is set to 0.01. The number of hops from BS to MS is $h = 4$.

Fig. 3 shows simulation and analytical results for ARQ only schemes. With the increase of offered load, the delay of all schemes increases. When those curves close to the transmission rate of node, the delay increases dramatically. In comparing three curves, the e2e-ARQ (end-to-end ARQ) always has the longest delay. The performance of hbh-ARQ (hop-by-hop ARQ) is similar to that of 2-link-ARQ. Hbh-ARQ always has the lowest delay with same throughput. This is because it has to do error correction for every hop transmission. However, 2-link-ARQ and hbh-ARQ cannot solve the error introduced in the node. Although hbh-ARQ has the lowest end to end delay, it has most complex error control process. Every hop has to implement ARQ mechanism. When an MS

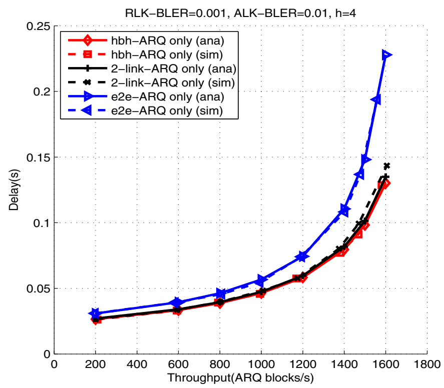

Fig. 3: ARQ Only

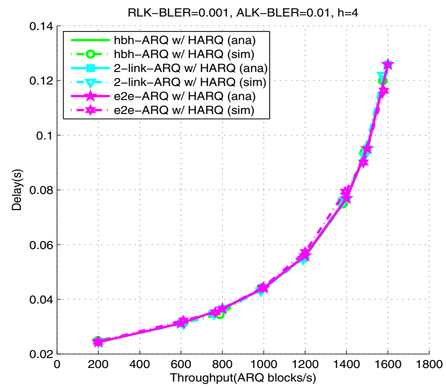

Fig. 4: ARQ w/ HARQ

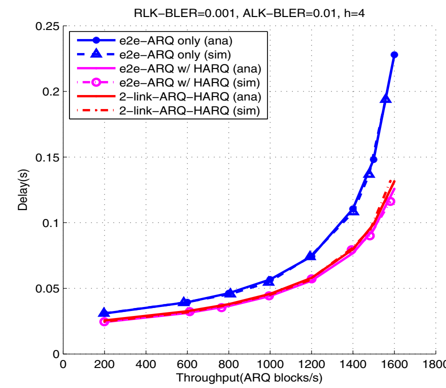

Fig. 5: ARQ-HARQ

performs handover from serving BS to another BS, all those ARQ state machine information of the RSs on the data delivery path has to be collected and provided to the target BS, which leads to a large overhead.

Fig. 4 shows three types of ARQ with HARQ. HARQ reduces the retransmission at the ARQ level. So, with the configuration, the three methods of multi-hop ARQ implementation have almost same performance. From the view of system complexity, the e2e-ARQ with HARQ is most simple. At 0.1s delay point, the throughput of e2e-ARQ without HARQ in Fig. 3 is about 1350 and the throughput with HARQ is about 1520, which increases about 12 percent throughput. Hbh-ARQ and 2-link-ARQ have very small improvement.

Fig. 5 shows the curve of proposed 2-link-ARQ-HARQ and compares the performance of e2e-ARQ with and without HARQ. 2-link-ARQ-HARQ has similar performance as that of e2e-ARQ with HARQ. However, the complexity of 2-link-ARQ-HARQ is much lower. It only uses HARQ at the last hop – access link of MS. The device and protocol complexity between RSs are very low.

VI. Conclusion

We analyze the error control for multi-hop wireless transmission in this paper. It is shown by the analytical work and simulation results that pure ARQ schemes do not perform well in multi-hop networks. When the number of hops increases, the initial value of the retransmission timer has to increase, which leads to a longer delay to retransmit a frame. HARQ can be used for single hop transmission. When the number of hops increases, the probability that error introduced at the intermediate RSs will increase, which cannot be solved by single hop HARQ. Different from a combination of HARQ and ARQ, we implement end-to-end ARQ plus access link HARQ. It exploits the factor that the relay link has much lower block error rate. The proposed scheme has much lower complexity as compared to the end-to-end ARQ with per-hop HARQ. Furthermore, it has much less information exchange during handover process. BS does not have to collect the HARQ state machine from every RS on the connection path for the handover.

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