NETWORK-ADAPTIVE ERROR CONTROL FOR VIDEO STREAMING OVER WIRELESS MULTI-HOP NETWORKS

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ABSTRACT

Multi-hop wireless mesh networks (WMNs) suffer from significant packet losses due to insufficient available bandwidth and high channel error probability. To conquer packet losses, *end-to-end* (E2E) error control schemes have been proposed. However, in WMNs, E2E error control schemes are not effective in adapting to the time-varying network condition due to large delay. Thus, in this paper, we propose a network-adaptive error control for video streaming over WMNs that flexibly operates E2E and *hop-by-hop* (HbH) error control according to network condition. Moreover, to provide lightweight support at intermediate nodes for HbH error control, we use *path-partition-based* adaptation. To verify the proposed scheme, we implement it and evaluate its transport performance through MPEG-2 video streaming over a real IEEE 802.11a-based WMN testbed.

Keywords: Multi-hop wireless network, end-to-end error control, hop-by-hop error control, wireless video streaming, and dynamic network adaptation.

1. Introduction

Recently, multi-hop wireless mesh networks (WMNs) have received much attention as a potential candidate for low-cost, self-configuring and flexible infrastructure. These features make WMNs an appealing solution to enable a variety of wireless services like video on demand service. However, we are still facing many challenges to realize high-quality video streaming service in WMNs. Typically residential wireless networks suffer from time-varying and insufficient bandwidth, high channel loss probability, large delay, and jitter variation. Especially, channel errors due to noise, fading, and interference lead to the degradation of video quality.

Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ) are methods widely used for error recovery in error-prone networks with unreliable links. When applying these error control schemes for video streaming, most existing schemes in WMNs still consider multiple hops from a sender to a receiver as one combined ink (i.e., does not differentiate individual hops), and then control the video streaming based on end-to-end (E2E) channel condition, namely, end-to-end error control [1-4]. Recent few studies [5-8] however show that E2E error controls are not effective over multi-hop-based WMNs. E2E FEC may require significant number of redundant packets to provide reasonable reliability. This lowers the channel-coding ratio, which in turns leads to lower source (e.g., video) rate. Under severe wireless channel condition, E2E ARQ induces too many retransmissions, which can waste scarce bandwidth and require short end-to-end delay for efficiency. It is well-known that E2E ARQ is not suitable for delay-unfriendly environment like multi-hop based WMNs. Thus, few recent studies apply hop-by-hop (HbH) error control approach. That is, based on the resource and network condition of each hop, active adaptations are made to improve packet loss recovery and throughput. In [5, 6], supported by powerful distributed nodes, the idea of multi-hop FEC for video streaming is explored. In [7], an algorithm was proposed to reduce end-to-end delay of video stream transmission in a multi-hop wireless environment. Also, in [8], an approach called SDRT (segmented data reliable transport), a hybrid approach of ARQ and FEC, is proposed for underwater sensor networks. It adopts efficient erasure codes and transfer encoded packets block-by-block and HbH. In these schemes, each sender node solves FEC adaptation based on its local (around it and nearby nodes) resource availability and channel reliability. Thus, to our understanding, they are limited in balancing the overall multi-hop network condition with local ones. In addition, additional considerations are still necessary for delay-constraint of underlying network/application environment and for the prioritized transmission of video data.

Thus, by noting these issues, this paper proposes a new hybrid network-adaptive error control for video streaming over WMNs. The proposed scheme flexibly operates between E2E and HbH error control according to network condition. Moreover, in order to provide lightweight support at intermediate nodes for HbH error control, we use path-partition-based adaptation. Based on the loss recovery capability of E2E error control and channel status, the network routing path is divided into partitions. So, packet recovery nodes among intermediate nodes are properly chosen. Then suitable error control scheme is selectively applied to each partition according to the application and channel status (hopefully local/global coordinated). To verify the proposed scheme, we implement it and evaluate its transport performance through MPEG-2 video streaming over a real IEEE 802.11a-based WMN testbed.

The remainder of this paper is organized as follows. In Section 2, we describe the motivation for hybrid E2E and HbH error control. We then present the proposed hybrid error control in Section 3, which is followed by experimental validation in Section 4. Finally, we conclude this paper in Section 5.

2. Motivation for Hybrid Error control

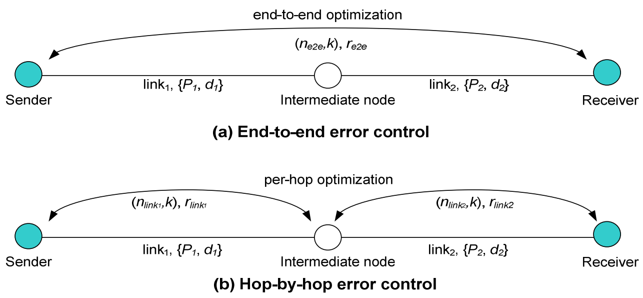

Fig. 1: Two approaches on network-adaptive error control over multi-hop wireless networks.

Fig.1 illustrates the respective scenarios of E2E and HbH error control over WMNs where a video sender sends video packets to a receiver through intermediate nodes over the multi-hop. In order to compare E2E and HbH error control over WMNs, we analyze the packet loss probability after recovery. When we use ARQ to control packet losses, it is important to select the number of retransmissions r for each packet because the number of retransmissions influences the error recovery performance and resulting delay. The optimal values, r_{e2e}, r_1, and r_2 are respectively chosen to minimize the packet loss probability under given delay constraints as in Eq. (1) and (2),

$$\begin{aligned}
&\min\ p_{ARQ}(r_{e2e}) \\
&\quad = p_{e2e}{}^{r_{e2e}} \\
&s.t.\ \frac{B_n}{R_T} + d_1 + d_2 + \left(\frac{B_n}{R_T} + 2\times(d_1+d_2)\right)\times r_{e2e} < T_0, \qquad (1)
\end{aligned}$$

and

$$\begin{aligned}
&\min\ p_{ARQ}(r_1, r_2) \\
&\quad = 1-(1-p_1{}^{r_1})\times(1-p_2{}^{r_2}) \\
&s.t.\ \frac{B_n}{R_T} + d_1 + d_2 + \left(\frac{B_n}{R_T} + 2\times d_1\right)\times r_1 + \left(\frac{B_n}{R_T} + 2\times d_2\right)\times r_2 < T_0, \quad (2)
\end{aligned}$$

where B_n is total averaged bits; R_T is the transmission rate; T_0 is the transmission delay constraint of each frame; p_{e2e} is E2E packet loss rate; p_1 and p_2 are packet loss rates on link$_1$ and link$_2$, respectively; d_1 and d_2 are delay on link$_1$ and link$_2$, respectively.

In FEC, generically, a FEC block of n packets contains k video packets and n-k FEC packets. The receiver can fully reconstruct the original k video data packets as long as it correctly receives at least k packets of the FEC block. Optimal values, n_{e2e}, n_1, and n_2 are selected to minimize the packet loss probability after error control P_{FEC} as in Eq. (3) and (4).

$$\begin{aligned}
&\min\ p_{FEC}(n_{e2e}) \\
&\quad = \left(1 - \sum_{i=0}^{n-1-k}\binom{n-1}{i} p^i (1-p)^{n-1-i}\right) \\
&\quad = \sum_{i=n-k+1}^{n} \frac{i}{n}\binom{n}{i} p^i (1-p)^{n-i} \\
&s.t.\ n_{e2e} > k,\ B_n > B_{available} \qquad (3)
\end{aligned}$$

and

$$\begin{aligned}
&\min\ 1-(1-p_{FEC_link_1}(n_{link_1}))\times(1-p_{FEC_link_2}(n_{link_2})) \\
&s.t.\ n_{link_1}, n_{link_2} \geq k, \left(\frac{B_{n_link_1} + B_{n_link_2}}{2}\right) < B_{available} \qquad (4)
\end{aligned}$$

where $B_{available}$ is end-to-end available bandwidth; $B_{n'}$ is total averaged bits used for FEC on E2E path; B_{n_link1} and B_{n_link2} are total averaged bits used for FEC on link$_1$ and link$_2$, respectively.

In order to find optimal values in Eq. (1) ~ (4), we use non-linear programming-based optimization schemes such as penalty method and Nelder and Mead method. The parameter values used are summarized in Table.1.

Table.1: Parameter setting.

Parameter	Value	Parameter	Value
B_n	1400Byte	k	18
R_T	5Mbps	T_0	15ms
d_1	2ms	$B_{available}$	3.5Mbps
d_2	1ms		

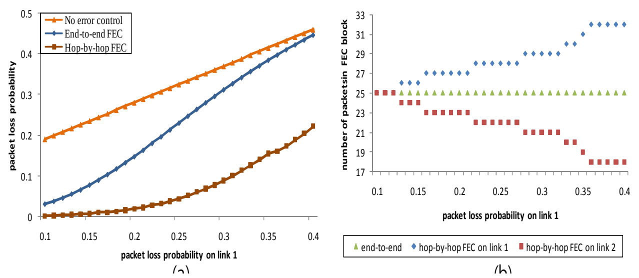

Fig. 2: Comparison of E2E and HbH ARQ: (a) packet loss probability and (b) number of retransmissions.

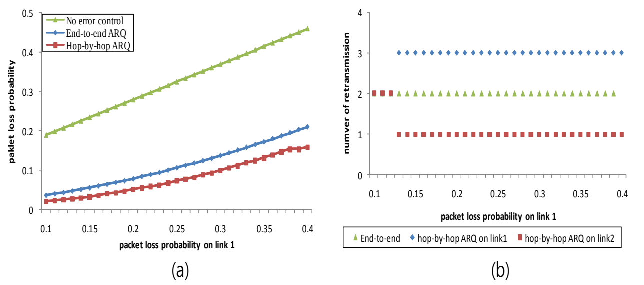

Fig. 3: Comparison of E2E and HbH FEC: (a) packet loss probability and (b) number of packets in a FEC block.

Fig. 2 and Fig. 3 compare three schemes (No error control, E2E error control, HbH error control) when link$_1$ and link$_2$ have different packet loss probability and delay. HbH ARQ can recover more packet losses than E2E ARQ because HbH ARQ can have different number of retransmissions for each packet at different hops (as shown in Fig. 2). Note that HbH FEC also can recover more packet losses when compared to E2E FEC (as shown in Fig. 3). Especially, while the packet loss probability is from 0.15 to 0.3, the performance of E2E and HbH FECs are different. HbH FEC is sufficiently capable of recovering the lost packets. Otherwise, packet losses are beyond the loss recovery capability in E2E FEC. Thus, when the underlying channel has low packet loss probability, E2E error control is appropriate because the loss recovery capability of E2E ARQ is similar to those of E2E ARQ. On the other hand, when the packet loss probability is high, H2H error control that has high reliability is suitable. But delay and complexity induced by error control at per-hop should be considered.

3. Proposed Hybrid E2E and HbH Error Control

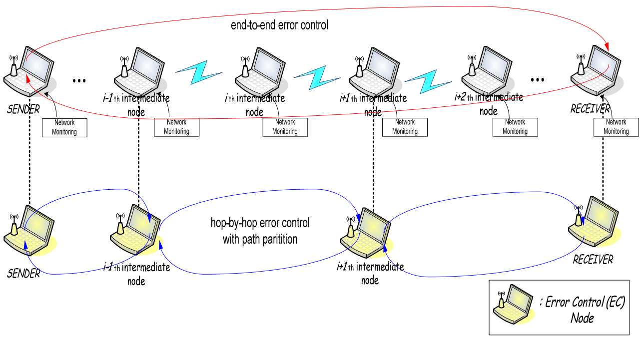

Fig. 4: Proposed hybrid E2E and HbH error control.

The proposed hybrid E2E and HbH error control scheme focuses on how to increase packet loss recovery under given network resources and target application status. For this goal, the proposed hybrid error control scheme uses intermediate nodes between the video sender and the video receiver. In this scheme, each intermediate node measures the wireless network condition (e.g., packet loss rate, network available bandwidth, and others) and recovers the dynamically occurring packet losses. As shown in Fig. 4, we flexibly adopt and adjust both E2E and HbH error controls. First, E2E error control is applied to recover packet losses. When the channel status is good or the channel has sufficient bandwidth, E2E error control alone may cope with packet losses. In this case, we use only E2E error control. However, the number of lost packets may exceed the recovery capability of E2E error control. In this case, the remaining lost packets after E2E error control can be additionally recovered by HbH error control. For example, FEC is applied for E2E error control[1] while FEC or ARQ is applied for HbH error control. Moreover, in order to provide lightweight support at intermediate nodes in HbH error control, the network routing path is divided into partitions. Then HbH error control is selectively applied to these partitions. With partitioning, only selected so-called EC (error control) intermediate nodes are responsible to control lost packets (e.g., recover packet losses). For monitoring, we use a simple packet-pair based tool to estimate E2E available bandwidth. MAC-layer monitoring is also used to measure the packet loss probability at each link.

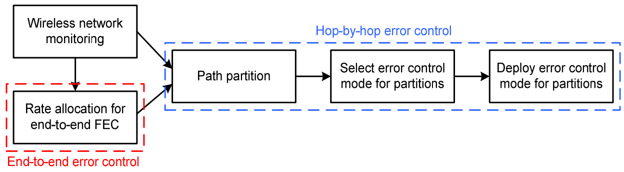

Fig. 5: Procedure of hybrid E2E and HbH error control.

As shown in Fig. 5, the proposed scheme passes through the procedures of hybrid E2E and HbH error controls. First, with the wireless network monitoring, the sender perceives E2E loss rate P_{e2e}, loss rates at hop i P_i's and estimated E2E available bandwidth B_{avail}. The sender allocates FEC rate for E2E FEC based on these information. When E2E loss probability and target loss probability[2] are given, if k is fixed, the lower bound of n can be determined. When the allocated video data bandwidth B_{data}[3] $_i$ given, the required minimum FEC bandwidth B_{req} to recover the lost packets at the receiver becomes:

$$B_{req} = \frac{n}{k} B_{data} - B_{data} = \frac{n-k}{k} B_{data}. \quad (6)$$

FEC needs additional bandwidth because it uses redundant packets for loss recovery. When the bandwidth is sufficient ($B_{req}<B_{avail}-B_{data}$), all packet losses can be recovered by only E2E error control. On the other hand, in case that there is not surplus bandwidth for FEC ($B_{req}>B_{avail}-B_{data}$), it is impossible to recover all the lost packets by only E2E error control as it means the number of lost packets may exceed the recovery capability of E2E error control. So, E2E error control recovers lost packets within its own capability and the remaining lost packets can be recovered HbH error control at each hop. So, the sender determines FEC rate as the minimum value between E2E available bandwidth and the required minimum FEC bandwidth as in Eq. (7).

$$B_{e2e\_FEC} = \min\{ B_{avail} - B_{data}, B_{req} \} \quad (7)$$

HbH error control can not only significantly reduce packet loss probability but also use the network resource of each hop more efficiently. But a heavyweight HBH error control induces more per-hop delay and uses more computational power of intermediate nodes than is necessary. FEC Therefore, to provide lightweight support in HbH error control, we only use few intermediate nodes that are selected for error control among intermediate nodes. Note also that, in order to maintain the best video quality, the expected video distortion of proposed scheme should be kept the same as that obtained by using hop-by-hop error control.

[1] In E2E control, we don't consider ARQ as ARQ is not suitable for multi-hop video streaming due to long delay.

[2] The viewing quality of video is acceptable at a loss rate of 10^{-4} and good at loss rate of 10^{-5}.

[3] We assume B_{data} is less than B_{avail} by source rate control.

Algorithm 1. Path partition algorithm

Start = 1, $N_{partition}$ = 1, n = the number of nodes

For (i=1;i<=n;i++){

/*Packet loss rate from Start link to ith link*/

Calculate accumulated PLR(start, i)

/* FEC bandwidth from Start node to ith node*/

Calculate $B_{req\_partition}$(start, i)

/*Find a boundary node to divided the path in partition*/

Calculate $B_{req\_partition}$(start, i+1)

If ($B_{req\_partition}$(start, i) > B_{e2e_FEC} **&&** $B_{req\_partition}$(start, i+1) < B_{e2e_FEC})

then {

Start node to (start+i)th node is divided as one partition.

Start node = Start node + i

$N_{partition}$++

}

}

For this purpose, we use path partition algorithm. Algorithm (1) shows the detailed procedures. First, a sender is the start node and we consider multiple partitions from the start node to the (start+i)th node. We can get the required minimum FEC bandwidth in partition, $B_{req\_partition}$(start, i) by Eq. (3) and (6). If $B_{req\_partition}$(start, i) > B_{e2e_FEC}, it means the packet loss probability in current partition within the loss recovery capability of E2E FEC. So, next node may join current partition. Otherwise, if $B_{req\_partition}$(start, i) < B_{e2e_FEC}, we add one more partition and node i becomes the new start node. Like this, the entire path is divided into several partitions until we reach the receiver. With this algorithm, the largest partition may include all nodes of path (E2E error control) while the smallest partition(s) may be only one hop (HbH error control). For each partition, suitable error control scheme is selected and applied. Also, for HbH error control, FEC or ARQ is selectively used based on the application and channel status.

In order to decide the error control mode, we use training-based approximation for the PDR (packet delivery rate) estimation of [1]. Error control mode is selected according to the packet loss rate of wireless channel as well as the buffer level. If FEC is selected as HbH error control at a partition, EC node attempts to recover packet losses with FEC decoding. It then re-encodes recovered data packets with B_{e2e_FEC}. After that, EC node forwards packets to the neighbor node. If ARQ is selected for a partition, EC node requests retransmission to backward EC node.

4. Experimental Results

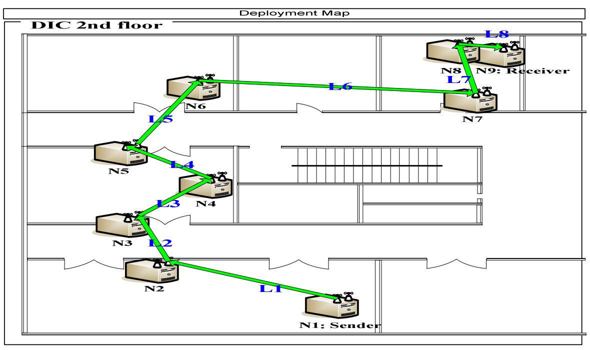

Fig. 6: Node deployment of testbed.

Our testbed consists of a video sender, 7 intermediate nodes, and a receiver as shown in Fig. 6. All the nodes have a single IEEE 802.11a wireless interface. We set a static routing path from N1 to N8 for single-path video streaming. Through this path, a video receiver (R) receives a video stream from N1. In the present implementation and experiments, we use a video stream source with a profile of 'MPEG-2 TS (transport stream) over RTP'. The detailed specification of experimental video is that spatial resolution, frame rate, bitrate, and GOP are 720x480, 29.97fps, 3Mbps, and '*IBBPBB*', respectively.

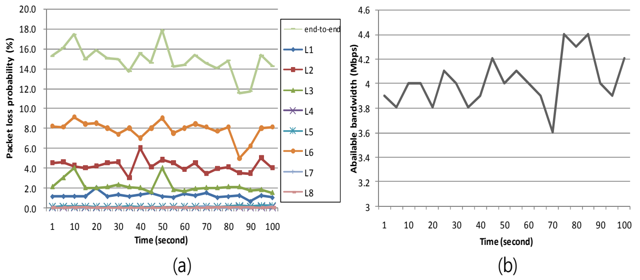

Fig. 7: (a) Packet loss probability on each hop and (b) E2E available bandwidth.

As the basic test, Fig. 7 shows packet loss probability on each hop and E2E available bandwidth. In order to measure packet loss rate at each hop, MAC-layer monitoring is used[4]. We use a simple packet-pair based tool[5] to estimate E2E available bandwidth.

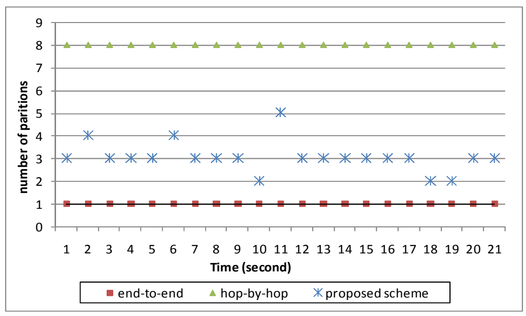

Fig. 8: The number of partitions.

Fig. 8 compares the number of partitions in E2E error control, HBH error control, and proposed scheme. The number of partition E2E error control and HbH error control always are 1 and 8, respectively. But, in the proposed scheme, the number of partitions is dynamically changed according to network condition. When the channel condition is poor, the network routing path is divided into multiple partitions. However, when the channel condition improves, the network path is divided into fewer partitions.

Table.2: The comparison of three schemes.

4 The loss rate is defined as the ratio of the number of discarded video packets at MAC-layer interface queue over the number of total video packets arrived at the queue, for a given monitoring interval.

5 We use AdHoc Probe [11].

E2E packet loss rate (%)	*Packet loss rate (E2E)*	*Packet loss rate (HBH)*	*Packet loss rate (Proposed)*	*The average number of partitions*
1.61	0	0	0	1.22
5.2	2.1	0	0	2.34
12.3	8.1	3.42	3.41	3.43
18.1	16.28	7.55	7.64	5.13

Table 2 compares three schemes. The results show that the proposed scheme can reduce more packet losses than E2E error control. On the other hand, it uses fewer intermediate nodes than HbH error control because the proposed scheme divides the network routing path into several partitions. Thus, the proposed scheme can reduce per-hop delay and computational complexity caused by error control at intermediate nodes but with nearly the similar loss recovery performance to those of HbH error control.

5. Conclusion

In this paper, we propose network-adaptive error control for video streaming over WMNs, which flexibly operates E2E and HbH error control according to network condition. We use path-partition-based adaptation to provide lightweight support at intermediate nodes in HbH error control. The proposed schemes can improve the recovery of packet losses compared to E2E error recovery and use fewer intermediate nodes while still maintain the recovery capability in hop-by-hop error control. In future works, we will develop control mechanism that combines with rate control.

ACKNOWLEDGEMENT

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