Regenerating Nodes for Real-Time Transmissions in Multi-Hop Wireless Networks

Rui Ma
McGill University
Dept. of Electrical and Computer Eng.
Montreal, Quebec, H3A 2A7, Canada
rui.ma@ieee.org

Jacek Ilow
Dalhousie University
Dept. of Electrical and Computer Eng.
Halifax, NS, B3J 2X4, Canada
j.ilow@dal.ca

Abstract

This paper extends the analysis of a novel data link layer mechanism introduced in our previous work for real-time service provisioning in multi-hop wireless networks. To combat packet loss along unreliable paths connecting the source with the destination (i) packet transmissions are distributed along the multiple paths connecting joint nodes and (ii) the redundancy packets are utilized to recover the lost packets on these intermediate connections. The regenerating nodes (RNs), where the actual packet loss recovery is performed in the network, minimize the accumulated number of lost packets at the destination. This joint application of packet level Forward Error Control (FEC) and multiple path routing allows to meet the requirements of real-time transmissions, such as fixed delays and guaranteed Packet Loss Rate (PLR). The proposed scheme achieves load balancing along the multiple paths which are chosen for packet forwarding based on their PLR. The scheme is flexible sufficiently to accommodate various constraints for delay and reliability that can be tailored to the specific applications. Monte Carlo simulations are provided to demonstrate the robust performance of the proposed scheme in different topology and PLR scenarios with special attention given to the choice of the RN positions in the network.

1. Introduction

In the multi-hop wireless networks, because of the possible nodal mobility and unpredictable radio propagation, the link reliability is low, and, in order to improve it, multiple path transmissions are usually exploited. In these networks, in addition to performing the store and forwarding functions, every node is also a powerful computing device. It can implement complicated and intelligent tasks over all protocol layers, including active routing [8] and quality-of-service (QoS) provisioning. In this paper, the objective of the packet processing nodes is to reduce the end-to-end delay and to enhance the transmission reliability.

Packet level Forward Error Control (FEC) and Automatic Repeat Request (ARQ) are two methods widely used to recover the lost packets in networks with unreliable links. Either of these methods introduces overhead and delay with its unique characteristics. In real-time services, where the predictable and fixed delays are expected, packet level FEC is especially a promising technique, though, on the surface, its overhead seems prohibitively high. This drawback is mitigated in this paper by exploiting multiple path transmissions with the objective to guarantee fixed end-to-end delay.

The idea of redundant paths to compensate for the limited bandwidth and volatile topologies in the mobile ad-hoc networks (MANET) was explored in [12] and [2], while in [3], the authors designed a QoS-aware multipath dynamic source routing (MP-DSR) protocol. In [7], a multipath routing algorithm, called *Disjoint Pathset Selection Protocol* (DPSP), was proposed for selecting a set of paths to maximize network reliability. Instead of considering the reliability criterion alone in exploring routes, in this paper, both the end-to-end delay and the reliability are main factors while determining routes.

To accommodate the real-time multimedia transport in multi-hop wireless networks, two different implementations of packet loss protection combined with multipath routing techniques could be employed. In [6], ARQ over multiple paths was used to guarantee reliable transmissions of video over MANET. However, retransmissions may not be acceptable in networks with (i) high topology volatility and (ii) unpredictable link delays because of problems associated with (i) the availability of retransmission paths and (ii) time-outs, respectively. Multiple paths routing and packet level FEC between the source and the destination were combined for real-time transmissions in [9], [10], [11] based on *diversity coding* [1]. In this paper, we build on the latter method. We refer to this approach, which recovers the lost packets only

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at the destination using packet level FEC, as the end-to-end packet level FEC.

To satisfy the predetermined QoS requirements, multipath routing algorithms search for an acceptable number of disjoint paths. However, this is not an easy task, especially, for connections with a large number of hops. Moreover, when deploying the end-to-end packet level FEC, one has to watch for the packet loss recovery capability of the erasure code. On the way to the destination, the number of lost packets accumulates and may exceed the reconstruction capability of the FEC code. As the result, such an application of multipath routing and packet level FEC may not be effective, and this is a motivating factor for this paper.

Instead of avoiding the joint paths and nodes, which is a premise in the related work, we proposed in [5] a new mechanism that takes advantages of joint nodes to recover the lost packets. Our proposal uses hop-by-hop packet recovery with packet level FEC. On unreliable links, the hop-by-hop packet recovery is considered more effective than the end-to-end recovery as that described in [9]. In this paper, the joint nodes and packet level FEC are both exploited to alleviate the problems associated with the limited number of disjoint paths and accumulation of lost packets between the source and the destination. The selected joint nodes function as the regenerating nodes (RNs) [4]. They reconstruct the received data, add redundant packets into the forwarded packets, then distribute them among several paths. At last, when the destination receives the packets, the lost packets are mainly dropped in the last connection. The proposed scheme achieves Packet Loss Rate (PLR) performance improvements over the multipath end-to-end packet level FEC as demonstrated through the simulations. These improvements come at the expense of the additional processing in the RNs and the additional bandwidth requirements accommodated through multipath routing.

2. The Proposed Scheme

In our proposal, some of the joint nodes, at which several links overlap, are selected to function as the RNs. The redundant packets are added into the data stream so that the lost packets could be reconstructed at the RNs without need for retransmissions. The number of additional redundancy packets transmitted for a given number of the information packets is predetermined based on the FEC code so that the network resources could be allocated accordingly to achieve the fixed delay and prescribed end-to-end PLR. Furthermore, multiple paths are applied here to alleviate the average path vulnerability and decrease the overhead on each path. Integrated optimization of redundant packets and multiple paths can minimize the PLR at the destination and improve robustness to topological changes.

To simplify the discussion, the transmitted data are encapsulated into packets with the same size. PLR of each link is assumed to be known and is used as the metric to choose routes. The link PLR can be obtained through methods like ”keep-alive” packets. The packets are lost during transmission, or dropped by nodes for reasons such as overflow of buffers, misdelivery, FEC error at the lower layers, etc. All links in our discussion are “pure erasure”, i.e. the packets are either received correctly or lost completely. In the network model adopted, we assume that the mean time of packet transmission is much smaller than that between the variations of the network topology and the link PLR.

2.1. Details of the Scheme

In this section, we use Fig. 1 to illustrate the details of the proposed data link layer mechanism. According to the functions, the nodes in the network are classified into four types: (i) *the source* (Node S), which packetizes messages, constructs the FEC packets and manages packet transmissions through multiple links; (ii) *the forwarding nodes* (Nodes A, B, C, E, H, I, J, and K), which only forward the received packets; (iii) *the RNs* (Nodes F and G), which reconstruct the lost packets from the received ones according to the predetermined coding scheme; and (iv) *the destination* (Node D), which receives the packets and recovers the lost ones.

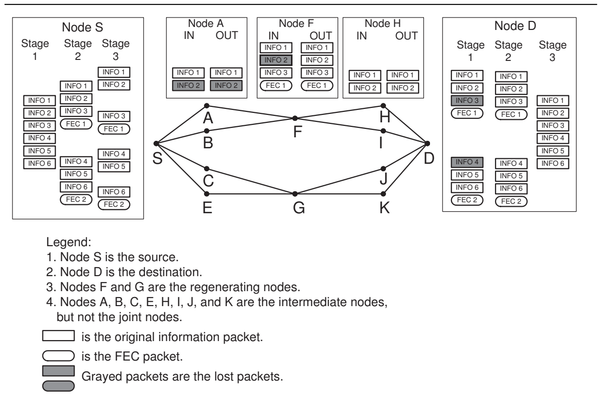

Figure 1. The example of the proposal.

At the beginning, the source S initiates the transmission and uses source routing to explore the multiple routes to the destination D. Based on the PLR reliability criterion, the source S selects paths and the RNs from the joint nodes, and then determines the coding scheme, e.g., even parity (4, 3, 1), which adds one FEC packet after each three information packets. Afterward, it notifies Nodes F, G and D about their packet loss recovery functions. Nodes F and G begin their functions as RNs for the transmission between Nodes S and D. Node D prepares for receiving the packets and recovering the lost ones.

During delivery, Node S (i) divides each six information packets into two 3-packet blocks at Stage 1, which will be sent along different paths, i.e. INFO 1, 2 and 3 along Path S-F-D, INFO 4, 5 and 6 along Path S-G-D; (ii) appends FEC packets (FEC 1 and 2) to the blocks and form coded packet blocks, respectively, at Stage 2; (iii) distributes the coded packet blocks over the selected paths at Stage 3, i.e., INFO 1, 2 over Path S-A-F-H-D, INFO 3, FEC 1 over Path S-B-F-I-D, INFO 4, 5 over Path S-C-G-J-D, and INFO 6, FEC 2 over Path S-E-G-K-D.

The forwarding Nodes A, B, C, E, H, I, J and K, only transmit the received packets. For example, at Node A, the packet INFO 2 is lost, so Node A sends only the packet INFO 1 to Node F.

The RNs F and G reconstruct the lost packets according to the coding scheme. For example, in Fig. 1 where the coding scheme is (4, 3, 1), after receiving INFO 1, 3 and FEC 1, Node F utilizes FEC 1 to recover the lost INFO 2. Later, Node F distributes packets INFO 1, 2 on Path F-H-D, and packets INFO 3, FEC 1 on Path F-I-D.

At last, the destination D receives packets INFO 1, 2, FEC 1 through Path S-F-D, and packets INFO 5, 6, FEC 2 through Path S-G-D at Stage 1. It recovers INFO 3 and INFO 4, respectively, at Stage 2; then throws away the redundant packets, re-sequences and gets the transmitted information packets, INFO 1, 2, 3, 4, 5, and 6, at Stage 3. As a result, despite three packets, INFO 2, 3 and 4, lost in the network, Node D recovers all the original information packets. Note that if the end-to-end packet level FEC recovery scheme was employed here with the same coding scheme, we would not be able to recover from three lost packets.

2.2. The Recovery Positions

In multi-hop wireless networks with high computing capability, each node can act as the RN to reconstruct the lost packets, but long delay will be introduced. A proper choice of the packet recovery nodes will not only reduce delay and power consumption associated with computational complexity, but also deliver sound performance. In general, there are two types of recovery positions:

1. *At the destination* (Coded Scheme): This is a conventional application of the packet level FEC where the reconstruction is only applied at the destination. In spite of easy implementation, the drawback of this scheme is the accumulation of lost packet along all links so that at the destination the number of the lost may exceed the recovery capability of the packet level FEC code.
2. *At the joint nodes* (Regenerated Scheme): Using source routing, the source can choose the stable intermediate nodes as the joint nodes, which have less failure possibility, furthermore, ask some of them to work as the RNs. The RNs recover the lost packets and relay the reconstructed packets. With proper number and positions, the RNs not only prevent spreading the effects of PLR on the incoming links beyond the point of no recovery at the destination, but also guarantee the required QoS for the real-time transmissions. This is a major novelty of our approach.

2.3. The Packet Level FEC Scheme

To implement packet level FEC, the original information packets are divided into a series of K-packet blocks. When constructing the redundant packets, we assume the use of an FEC code with parameters $(N,\ K,\ t)$, where (i) N is the number of transmitted packets in a coded block; (ii) K is the number of the information packets in this block; and (iii) t is the erasure recovery capability, i.e., the maximum number of lost packets within the coded block that can be reconstructed based on the received packets. In the case of Reed Solomon (RS) codes $t = N - K$ and the erasure recovery capability is twice of the error correction capability. With even parity codes $t = 1$. Each packet has a sequence number which (i) allows the detection of packets being lost or not delivered within the predetermined time interval dependent on delay constraints and (ii) triggers (if necessary) the packet erasure recovery.

In this paper, the efficiency of the code to recover from lost packets is measured by the normalized erasure recovery capability $R = \frac{t}{N}$ and its choice will depend on the average PLRs of all links utilized on a given hop:

$$R = \frac{1}{m}\sum_{i=1}^{m} p_i \tag{1}$$

where p_i is the raw PLR of each link.

2.4. Packet Level Interleaving

To combat bursts of lost packets (erasure bursts) caused by disconnections or nodal mobility, the packets can be interleaved in time or space when being transmitted from the source or the RNs.

First, for comparison purposes, we give an example of the transmission without interleaving, as illustrated in Fig. 2. By using the code (3, 2, 1), four information packets are grouped and encoded into two coded packet blocks, INFO 1, 2, FEC 1, and INFO 3, 4, FEC 2, respectively. Those two coded blocks are sent to the destination D in the sequence of INFO 1, 2, FEC 1, INFO 3, 4, FEC 2. During the transmission, two consecutive packets, INFO 2 and

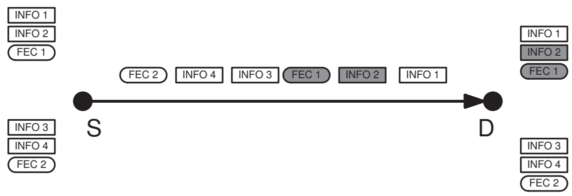

Figure 2. Example of the transmission without interleaving.

FEC 1, are lost. After receiving the packets at the destination D, because these two lost packets are in the same coded packet block, the number of the lost packets exceeds the erasure recovery capability of the code (3, 2, 1). So the destination cannot recover the lost packets and only receives three out of four, INFO 1, 3 and 4, transmitted information packets.

Now we use two examples, shown in Figs. 3 and 4, to explain temporal and spatial interleaving, respectively. In the example for temporal interleaving, except for the sequencing of packet transmission, the rest of network operation is the same as in the earlier example. The transmitted packet sequence is INFO 1, INFO 3, INFO 2, INFO 4, FEC 1, and FEC 2. Two consecutive packets, the second and the third, i.e., INFO 3, INFO 2, are lost during the transmission. However, those two packets are in the different coded packet blocks. In fact, in each coded block, only one packet is lost. So both lost packets can be recovered at the destination.

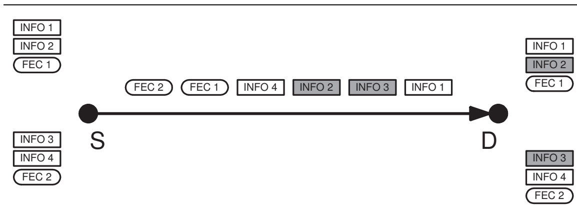

Figure 3. Example of the transmission with temporal interleaving.

The operations in temporal interleaving is to interleave the packets from different coded blocks, and transmit them along the same link. This method can effectively recover the burst erasure. Its disadvantage is the long delay caused by buffering the interleaved blocks. In the example considered, the destination begins decoding only after having received six packets, or equivalently after the time period corresponding to the transmissions of two interleaved coded

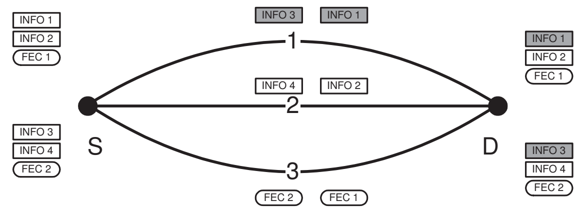

Figure 4. Example of the transmission with spatial interleaving.

packet blocks. In the example of the transmission without interleaving, the destination can begin decoding after having received only three packets, i.e., one coded packet block.

In the example of spatial interleaving as in Fig. 4, three links between the source S and the destination D are utilized. The six packets in the two coded blocks are distributed equally over the three links, INFO 1 and 3 on Link 1, INFO 2 and 4 on Link 2, FEC 1 and 2 on Link 3. During transmission, Link 1 fails so that both INFO 1 and 3 are lost. Nevertheless, since those two lost packets are located in two different blocks, the destination can recover both from the received information and FEC packets.

At the cost of more links being deployed, spatial interleaving offers such benefits as immunity to link failure and shorter delays over temporal interleaving of packets. From the example, we can see that even though a link fails, the destination still recovers all information packets. In addition, the destination can begin decoding after having received only one packet from each link.

In summary, temporal interleaving can achieve robust performance against burst erasure at the cost of longer delays; meanwhile, spatial interleaving involves higher number of parallel connections for immunity to link failure and shorter delay.

3. Simulation Models

In this section, we describe the topology models and the diversity coding scheme used in the simulation section to verify the performance of the scheme proposed.

3.1. Topology Models

Without loss of generality, the topologies are simplified first into two categories: (i) parallel (Fig. 5) and (ii) serial connection of links (Fig. 6). The hybrid topology illustrated in Fig. 7 is the combination of the above two, i.e. each link in the parallel topology could be a subnetwork without connectivity to other links (subnetworks).

For the purpose of this paper, the following definitions are in order: *Path:* The connectivity between the source and the destination. *Hop:* The connectivity between two neighboring RNs (including the source and the destination) is one hop. *Link:* The physical connection between two neighboring nodes. In characterizing the hybrid network, we assume three levels of link hierarchy. From the highest to the lowest level, the connectivity in the network as illustrated in Fig. 7 is: (I) *Path Level*, in which there are parallel connections of m paths from level 2; (II) *Hop Level*, in which there are serial connections of n hops from level 3 for the jth hop within the ith path. (III) *Link Level*, in which there are parallel connections of h links for the jth hop in the ith path on the kth link.

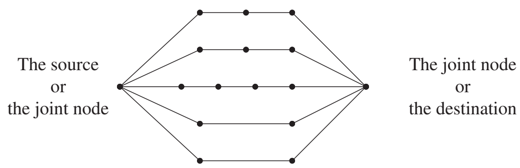

Figure 5. The topology model of parallel links.

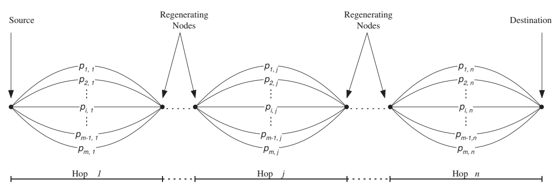

Figure 6. The topology model of serial links.

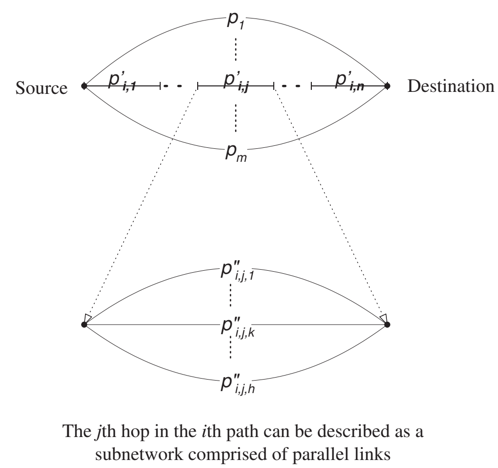

Figure 7. The topology model with three levels of link hierarchy.

Note that in the hybrid topologies considered, the links (at level 3) from different paths are disjoint i.e., there is no joint node in any of these links except for the cases of the source and the destination.

3.2. The Choice of Packet Level FEC

In this paper, to demonstrate the proposed mechanism, a simple, single parity, packet coding scheme is considered. In our simulations, the even parity packet is constructed to recover the single lost packet in a coded packet block. The original information packets are divided into a series of K-packet blocks, then one parity packet is appended. Afterward, the new packet series are one-by-one distributed equally over the forwarding paths/links. With this coding scheme, on a single hop, only one lost packet within each coded packet block can be reconstructed based on the received packets either at the RNs or the destination. Therefore, according to (1), the number of packets in a coded packet block $N \approx \left\lfloor \frac{1}{R} \right\rfloor + 1$, and $K = N - 1$.

4. Simulation Results and Discussion

To verify the performance of the scheme proposed, we simulate packet delivery over various topologies with high PLR along the links. The traditional applications of packet level FEC and the transmission without redundancy have been simulated for comparison purposes.

Fig. 8 and 9 show the end-to-end PLR with various link PLR. The topology for simulations in Fig. 8 is like that in Fig. 6 with 5 hops and 3 links per hop, in which the PLR of each link changes from 0.01 to 0.5. Meanwhile, the topology for simulations in Fig. 9 is illustrated in Fig. 10 with the link PLR from 0.01 to 0.3. The coding scheme is (4, 3, 1), i.e. the erasure recovery capability $R = 0.25$. In Fig. 8, when the raw end-to-end PLR, i.e. the PLR of the transmission without redundancy, is very low, for example, at 0.01, the performance of both Coded and Regenerated schemes is comparable. With the increase of the link PLR, the end-to-end PLR of Regenerated Scheme is lower than that of Coded Scheme. When the raw end-to-end PLR exceeds R, the end-to-end PLR of Coded Scheme is very close to the raw end-to-end PLR. In contrast, for the link PLR below 0.4, the end-to-end PLR of Regenerated Scheme is much lower than that of the other two schemes. The curves in Fig. 9 illustrate the similar results. Figure 11 demonstrates

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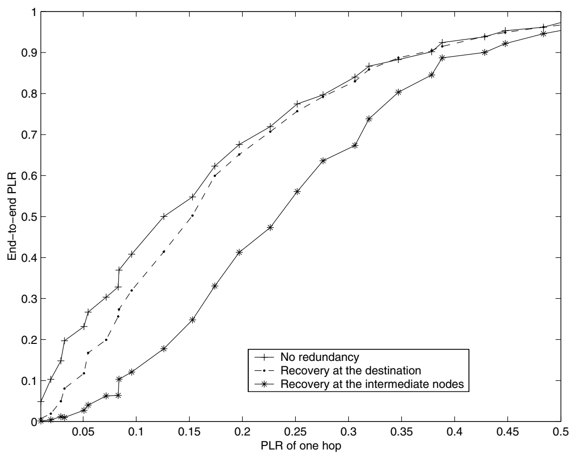

Figure 8. The end-to-end PLR vs. the PLR of each hop.

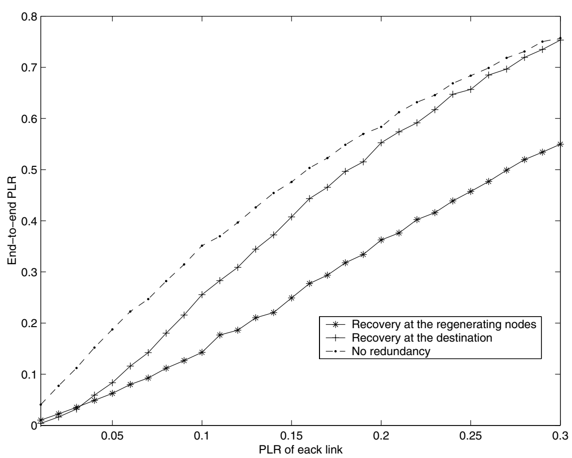

Figure 9. The end-to-end PLR vs. the PLR of each link.

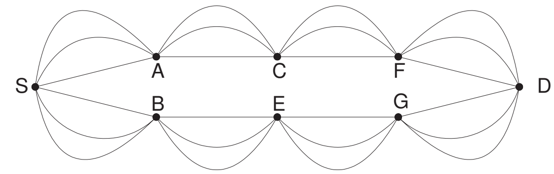

Figure 10. The topology model with 2 paths, 4 hops per path, 3 links per hop.

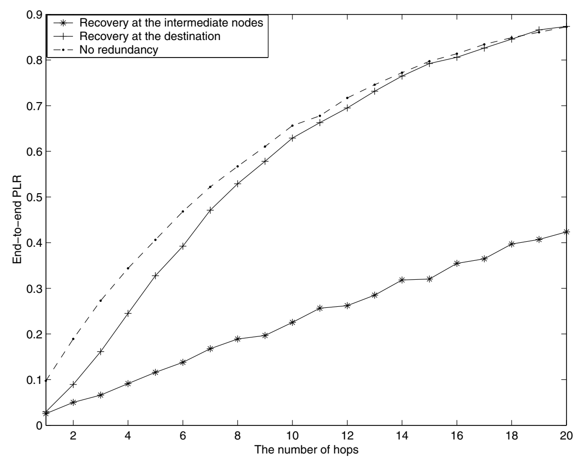

Figure 11. The end-to-end PLR vs. the number of hops.

the results in the network shown in Fig. 6 with a variable (1 to 20) number of hops and 3 links per hop. The coding scheme parameters are (4, 3, 1). The PLR of each link is 0.1. With the increased number of hops, the end-to-end PLR of Coded Scheme deteriorates from the similar performance to that of Regenerated Scheme to the raw end-to-end PLR. The above simulations verify that our proposal is more efficient than the conventional methods to prevent the adverse effects from packet loss accumulation. With proper erasure recovery capability, the destination can reconstruct the lost packets with predictable delay, which is beneficial in real-time services. In addition, since the packets are interleaved over several paths, proper coding schemes can help to combat burst erasure caused by disconnections or nodal mobility.

Figure 12 shows the relation between the end-to-end PLR performance using Regenerated Scheme and the positions of two RNs in the network of Fig. 13. As illustrated in Fig. 13, there are five intermediate joint nodes A, B, C, E, and F, which can be chosen as the RNs. The coding scheme is (4, 3, 1). Three possible locations of two RNs are considered. In Scheme 1, Nodes B and E are selected as the regenerating nodes. In Scheme 2 Nodes A and C work as the RNs. In Scheme 3, Nodes A and B are the RNs. Fig. 12 shows that Scheme 1 has the best performance and Scheme 3 has the worst. In general, it has been observed that the equally spaced regenerating nodes offer the lowest end-to-end PLR.

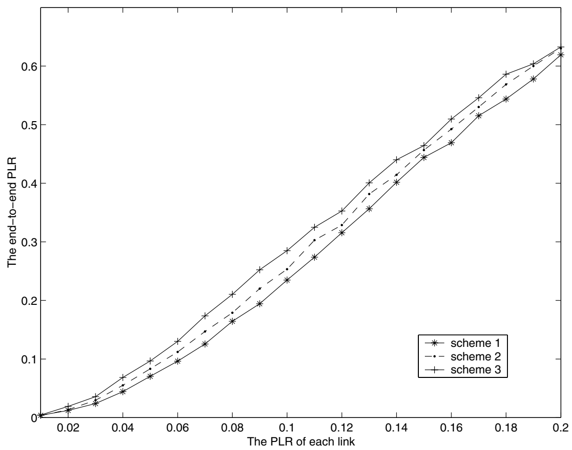

Figure 12. The end-to-end PLR with different positions of the RNs.

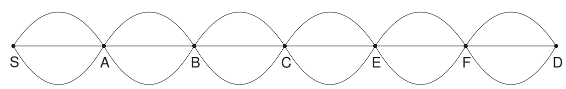

Figure 13. The network with different positions of the RNs.

5. Conclusions

This paper builds on the concept of RNs introduced in [5] for real-time transmissions in multi-hop wireless networks with the packet level FEC. By using parity packets, the RNs are able to reconstruct the lost packets along intermediate links, so that, the end-to-end PLR is limited to the PLR of the last hop. The RNs avoid accumulation of lost packets between the source and the destination as they combat the packet loss throughout the whole network. Packet level interleaving among diverse paths can improve the end-to-end reliability of the network further. The simulation results show the performance improvements of the proposed scheme over the end-to-end packet level FEC multipath schemes, and demonstrate the effects of the RN positions in the network.

The PLR improvements in the schemes proposed depend on (i) the network topology, (ii) link reliability, (iii) the number and positions of the RNs, (iv) packet distribution, and (v) packet level FEC recovery capability. In general, by introducing more RNs and more powerful codes, higher PLR performance improvements can be accomplished. These improvements are achieved at the cost of higher bandwidth overhead and computational complexity throughout the network. Even though the focus of this paper is on the PLR enhancements, through adaptive extensions, the proposed scheme can accommodate other QoS requirements for real-time transmissions in multi-hop wireless networks.

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