Reliable Multipath Routing with Fixed Delays in MANET Using Regenerating Nodes

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Abstract

This paper proposes a new framework in mobile ad hoc networks (MANET) for reliable multipath routing with fixed delays based on packet level Forward Error Control (FEC). The novelty of this work stems from the integrated optimization of the redundancy at the path and the FEC packet levels to arrive at the concept of the regenerating nodes. The regenerating nodes can reduce the packet loss rate (PLR) between the source and the intermediate nodes so that, eventually, the PLR between the source and the destination is minimized. In general, the residual PLR in the system is reduced to the PLR on the connection between the last regenerating node and the destination. Extensive Monte Carlo simulations are provided to demonstrate the robust performance of the proposed scheme in the network environments with frequently changing topologies and PLR scenarios. The scheme accommodates various constraints for delay and reliability in terms of PLR that can be tailored to the specific applications, such as real-time multimedia services in MANET.

1. Introduction

With recent advancements in computer and wireless communications technologies, mobile computing is gaining a wider acceptance on laptops and personal digital assistants (PDAs). The goal for advanced MANETs is to support multimedia traffic which require some quality of service (QoS) assurances. In this paper, the focus is (i) on ensuring data transfer with controllable reliability in terms of packet loss rate (PLR) and (ii) packet delivery with bounded delay. This two metrics define in broad sense the QoS aspects of the routing protocol proposed. The reason for the choice of these two parameters is that real-time streaming applications like video/audio conferencing require strict delay and/or jitter bounds, but they can tolerate a certain level of packet loss.

In current research on MANET, redundant paths and packets are introduced to combat the effects of unpredictable wireless propagation and nodal mobility. *Multipath Source Routing* (MSR) [10] introduced load distribution among several paths based on the measured round-trip time of every path. In [4], based on the end-to-end reliability, the authors designed a QoS-aware Multipath Dynamic Source Routing (MP-DSR) protocol. However, the availability of routes that satisfy the specific end-to-end reliability requirement is limited by the nature of the network.

Since failed joint links and nodes between paths can disable many or all of the paths used for forwarding, the existing work on multiple path transport in MANET concentrates on maximally disjoint paths, i.e., paths without link or node overlap. *Split Multipath Routing* (SMR) [2] uses a per-packet allocation scheme to distribute data packets into multiple maximally disjoint paths. In [7], a multipath routing algorithm, called *Disjoint Pathset Selection Protocol* (DPSP) is proposed for selecting a set of paths to maximize network reliability. Instead of the end-to-end delay, the reliability is considered as a main factor in exploring routes. Multiple paths routing [6] and Forward Error Control (FEC) are combined for real-time data transmission in [9] based on *diversity coding* [1].

In order to get the best performance, the previous work uses maximally disjoint paths and avoids joint paths and nodes. However, it is not easy to find and keep an acceptable number of disjoint paths to satisfy the predetermined QoS requirements. In particular, the longer the paths are, the more difficult it is to find the disjoint paths. Moreover, on their way to the destination the number of lost packets accumulates and may exceed the reconstruction capability of the FEC code deployed. As the result, this application of packet level FEC, with the reconstruction of lost packets at the destination only, may not be effective. We refer to this approach as end-to-end packet level FEC.

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In this paper, we propose a new framework for reliable multipath routing in MANET using a concept of hop-by-hop packet recovery with packet level FEC. This approach is similar to the X.25 protocol with ”lost” (erroneous) packets recovered at every node using ARQ except that in our case we use packet level FEC which improves packet delivery reliability with the fixed delay [5]. On unreliable links, the hop-by-hop packet recovery is considered more effective than the end-to-end recovery. In our work, the joint nodes and packet level FEC are both exploited to alleviate the problems associated with limited number of disjoint paths and accumulation of lost packets. The selected joint nodes function as the regenerating nodes. They reconstruct the received data, add redundant packets into the relayed packets series, and then distribute them among several paths. At last, when the destination receives the packets, the lost packets are mainly dropped in the last connection. In this paper, coding, distribution and reconstruction schemes are investigated to minimize the end-to-end PLR between the source and the destination in various topology and path PLR scenarios.

2. The Proposed Scheme

The objective of our scheme is to enhance the packet delivery reliability in MANET. Because of the nodal mobility and radio propagation characteristics, the reliability of links to deliver the packets is unpredictable and fluctuating. Redundant packets are added into the data stream so that the lost packets could be reconstructed at the regenerating nodes without need for retransmissions. Multiple paths are applied here to alleviate the fluctuation and reduce 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 is exploited as the metric to choose routes. 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.

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 regenerating nodes (including the source and the destination) is one hop. *Link:* The physical connection between two neighboring nodes.

2.1. Node Operation

In the network model adopted, the operation of the forwarding nodes are divided into: (i) the information transfer (InfoTx) and (ii) the administration (Admin) modes where (i) the nodes send the data packets and (ii) “learn” the network status, respectively. The Admin mode is deployed (i) during the network initialization; (ii) during the detected topological changes or (iii) at equally spaced time intervals to follow the variability in the PLR on the existing links. The forwarding nodes operate in the source routing manner as follows:

2.1.1. The Source Functions of the source are: In the InfoTx Mode: (i) encoding the information packets into packet groups and (ii) distributing these packets onto the outgoing interfaces according to the predetermined scheme by the Admin Mode. In the Admin Mode: (i) exploring the multiple routes to the destination; (ii) calculating distribution of transmitted packets on the forwarding links (packet distribution vector—PDV) based on the reliability (PLR) information along different links for the whole network; and (iii) determining the routes, regenerating nodes and the coding scheme. The source initiates the exploration of new routes for the upcoming communication. As the result, it knows the topology, possible routes and PLR of every path in the designated network. In terms of PLR, it selects routes, regenerating nodes, and determines the related schemes to minimize the PLR in the transmission. Afterward, it inserts the redundant packets into each original information packet group, then distributes them over the multiple paths.

2.1.2. The Regenerating Nodes Functions of the intermediate (regenerating) nodes are: In the InfoTx Mode: (i) decoding the received packet group and possibly recovering from lost packets (on the inlets) using packet level FEC; (ii) encoding and distributing the information packets on the outgoing interfaces. In the Admin Mode: (i) collecting reliability (PLR) information to its neighbors on the forward links; (ii) re-calculating the PDV; (iii) feeding the information about the current PLR back to the previous regenerating nodes and neighbors. Selected joint nodes are notified by the source to work as the regenerating nodes. They receive, re-sequence and reconstruct packet series from the upstream nodes, subsequently, re-encode and distribute the new packet series. The coding schemes are determined by the next hop’s PLR so as to maximize the capability of recovering the lost packets at the next regenerating nodes. This process is repeated by each regenerating node. Consequently, the received PLR at the destination is mainly caused by the last hop.

2.1.3. The Destination The destination decodes the received packet sequence, recovers the lost packets, calculates and feeds back the current end-to-end PLR.

Regenerating nodes prevent the adverse effects of packet loss accumulation along all links in the network, so that, at the destination, the number of lost packets has a better chance not to exceed the recovery capability of the packet level FEC codes. The packet level FEC routing schemes considered in this paper furnish a soft packet loss metric where the average PLR is below a given tolerable threshold. There could be, however, situations that the instantaneous PLR does not meet the specifications. The delay metric is always guaranteed. With proper erasure recovery capability, the destination can reconstruct the lost packets with predictable delay, i.e., the time required to receive the number of packets in a coded block, which is beneficial to real-time services. In this paper, the delay is determined in terms of number of packets in the coded group rather than the real time for the transmission of the group of packets to simplify our discussions.

2.2. Topology Model and PLR

Without loss of generality, the topologies are simplified first into two categories: (i) parallel and (ii) serial connection of links. In practical implementations, each link could be a subnetwork without connectivity to other links (subnetworks). In this paper, we actually consider the hybrid topologies as illustrated in Fig. 1.

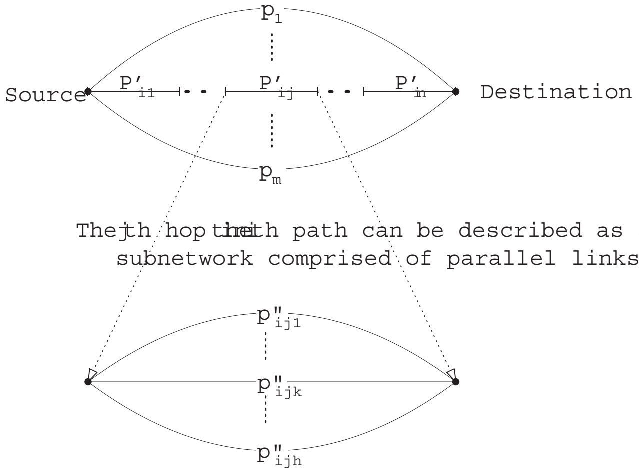

Figure 1. The topology model with three levels of link hierarchy.

In characterizing the PLR in the network, we assume a three-level link hierarchy. From the highest to the lowest level, the connectivity in the network as illustrated in Fig. 1 is:

I Path Level: parallel connections of m paths from the hop level with the PLR given by:

$$\begin{bmatrix} p_1 & p_2 & \cdots & p_i & \cdots & p_m \end{bmatrix}^T \tag{1}$$

II Hop Level: serial connection of n hops from the link level with the PLR $p'_{i\,j}$ for the jth hop within the ith path so that the PLR for the ith path is represented by:

$$\begin{bmatrix} p'_{i\,1} & p'_{i\,2} & \cdots & p'_{i\,j} & \cdots & p'_{i\,n} \end{bmatrix} \tag{2}$$

III Link Level: parallel connections of h links with the PLR p''_{ijk} for the jth hop in the ith path on the kth link so that the PLR for the hop level jth hop is represented by:

$$\begin{bmatrix} p''_{ij1} & p''_{ij2} & \cdots & p''_{ijk} & \cdots & p''_{ijh} \end{bmatrix}^T \tag{3}$$

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

Based on the PLR in the lower level links, the PLR in the higher level links can be calculated in the conventional systems without ARQ or packet level FEC as follows:

$$p_i = 1 - \prod_{j=1}^{n} \left(1 - p'_{ij}\right) \tag{4}$$

and

$$p'_{ij} = \frac{\sum\limits_{k=1}^{h} v_{ijk} p''_{ijk}}{\sum\limits_{k=1}^{h} v_{ijk}} \tag{5}$$

where v_{ijk} is a fraction of all packets transmitted on the kth link within the jth hop in the ith path.

3. Packet Level FEC and Packet Distribution

3.1. Coding Schemes: The Choice of Erasure Recovery Capability

To implement packet level FEC, the original information packets are divided into a series of K-packet groups. When constructing the redundancy 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 group; (ii) K is the number of the information packets in this group; and (iii) t is the erasure recovery capability, i.e., the maximum number of lost packets within the group 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 recovery (packet erasure correction).

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 PLRs in the network. At the path level, assuming we know a fraction of packets v_i transmitted on the ith path, we consider three methods to choose R:

1. **Mean-R Coding Scheme:** R is determined by the average reliability of all links.

$$R = \frac{1}{m}\sum_{i=1}^{m} p_i \tag{6}$$

2. **WeightedAvg-R Coding Scheme:** R is the weighted average reliability of all links.

$$R = \frac{\sum_{i=1}^{m} v_i p_i}{\sum_{i=1}^{m} v_i} \tag{7}$$

3. **Max-R Coding Scheme:** R is determined by the least reliable link.

$$R = max(p_i) \tag{8}$$

3.2. Packet Distribution Schemes

The packet distribution scheme determines what portion of packets is transmitted from the regenerating node (and the source) on its forwarding (parallel) links to the next regenerating node (or the destination). At the path level, the number of packets transmitted over the m paths is given through the packet distribution vector (PDV):

$$\vec{v} = \left[\begin{array}{ccccc} v_1 & \cdots & v_i & \cdots & v_m \end{array}\right] \;\; (i = 1, 2, \cdots, m)$$

There are different strategies to assign the number of packets transmitted on the forwarding links (paths) and these strategies should be dependent on the PLR table at a given regenerating node. It seems that the most reliable scheme is to transmit all packets always on the link with the smallest PLR. However, to balance (i) the traffic loads; (ii) risk with path failures and (iii) unpredictability in links PLRs, the following approaches are considered at the path level:

Equal Distribution Packets are equally distributed among all paths:

$$v_i = v_j = \lfloor \frac{N}{m} \rfloor \quad i, j = 1, \cdots, m \tag{9}$$

This scheme is easily implemented but its performance is decreased by the poorest links. It is suitable in networks with frequently changing topology.

Proportional distribution The more reliable the link is, the more packets are transmitted on it:

$$v_i = \frac{p_1}{p_i} v_1 + 1 \tag{10}$$

This scheme utilizes highly reliable paths more frequently and introduces bandwidth allocation problems. Thus, it is suitable for networks with less mobility.

k-Best Distribution Only k (two or more) of the m most reliable links are chosen for packet transmission:

$$\vec{v} = \left[\begin{array}{cccccccc} v_1 & \cdots & v_i & \cdots & v_k & 0 & \cdots & 0 \end{array}\right] \tag{11}$$

The number of packets transmitted on the k chosen paths can be distributed equally or proportionally.

The same distribution schemes can be applied at the regenerating node level with m paths being replayed by h links.

3.3. PLR Calculations

Without packet level FEC, the PLR for a group of m paths/links at the regenerating node/destination, called here the average erasure probability (p_{ave}), is [8]:

$$p_{ave} = \frac{1}{v}\sum_{j=1}^{m}\sum_{i=1}^{v_j} i\binom{v_j}{i} p_j^i (1 - p_j)^{v_j - i} \tag{12}$$

where $v = \sum_{j=1}^{m} v_j$ is the number of transmitted packets.

In the same situation, after applying packet level FEC to reconstruct the lost packets, the PLR, called here the recovered PLR (p_{rec}), is:

$$p_{rec} = \frac{1}{N}\sum_{i=t+1}^{n} i\binom{N}{i} p_{ave}^i (1 - p_{ave})^{N-i} \tag{13}$$

3.4. Reconstruction Schemes

The following are three reconstruction schemes according to the recovery location:

1. *At the destination* (Coded Scheme): This is a conventional application of packet level FEC where the reconstruction is only applied at the destination. In spite of easy implementation, the drawback of this scheme is that it accumulates packet loss along all links so that at the destination the number of lost packets may exceed the recovery capability of the packet level FEC code.
2. *At the regenerating nodes* (Regenerated Scheme): Intermediate joint nodes recover the lost packets and relay the reconstructed packets. With higher complexity,

in this scheme, joint nodes prevent spreading the effects of PLR on the incoming links beyond the point of no recovery at the destination.

3. *At the regenerating nodes and the destination* (*Combined Scheme*): The combination of the above two methods. First, the source adds redundant packets depending on PLR in the whole network, and then regenerating nodes and the source insert redundancy according to PLR of the next hop. This is equivalent to the concatenated coding. The packet recovery at the regenerating nodes reduces PLR along the paths to the level that the source-destination scheme can operates in favorable conditions so that even though we are adding the redundancy at two levels, to achieve acceptable performance, the overall redundancy is reduced from that of the individual schemes.

The last two schemes constitute the major novelty of this paper.

4. Performance Evaluation

To analyze the improvements achievable in the proposed forwarding schemes over conventional ones, we evaluate the end-to-end PLR based on (12) and (13) in networks with two general topologies: (i) serial connections of links (Level II) and (ii) parallel connection of paths (Level I). We assume that the mean time of packet transmissions is much smaller than that between the variations of the network topology and the link PLRs. Namely, the network is quasi-stationary during the transmissions of a group of packets.

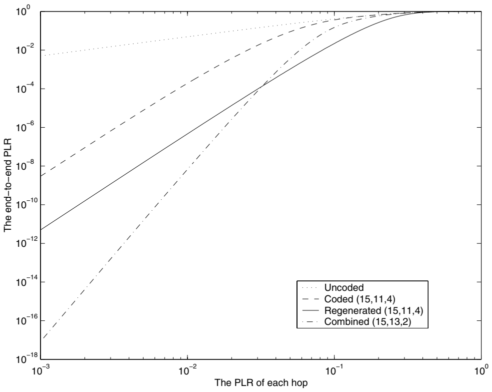

Figure 2. The end-to-end PLR in a serial network with 4 regenerating nodes as a function of the same PLR on each hop.

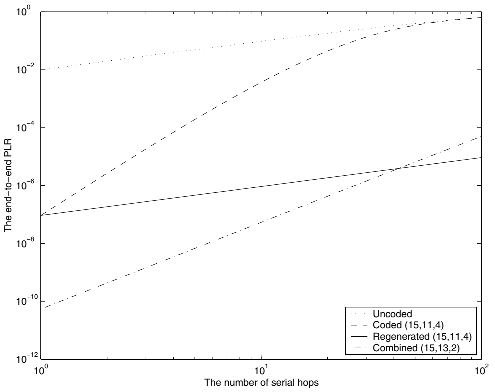

Figure 3. The end-to-end PLR vs. the number of serial hops n, each with $PLR = 0.01$.

In Fig. 2 and Fig. 3, we demonstrate the effects of the PLRs on individual links and the number of hops (regenerating nodes) in the networks with serial connections ($m = 1$), respectively. Fig. 2 shows the end-to-end PLR in the network where the PLR on each of $n = 5$ hops is the same and is varied between 10^{-3} and 1. The code rate R_{code} measuring the packet redundancy in three proposed schemes is comparable: (i) both, the coded and regenerated schemes use packet level FEC with $(15,\ 11,\ 4)$ ($R_{code} = 0.73$), while (ii) in the combined scheme, the codes with $(15,\ 13,\ 2)$ are applied at both the source and the regenerating nodes, so that $R_{code} = 0.75$. Figs 2 and 3 show that both proposed schemes, the regenerated and the combined, outperform the conventional schemes: the uncoded and the coded. In Fig. 2, when PLR on the individual links is higher, the regenerated scheme performs better than the combined one. The reason is that in the former scheme, the regenerating nodes isolate better most of the adverse effects from the previous hops. For serial networks with $PLR = 0.01$ on each hop, as illustrated in Fig. 3, the combined scheme exhibits better performance than the regenerated one for systems with lower number of regenerating nodes. In general, the regenerated scheme is showing more consistent performance, independent of n. The end-to-end PLR increases with the number of serial hops. This is why in spite of the same PLR on each link, the reliability of the coded scheme deteriorates rapidly with the number of serial links.

In Fig. 4, we plot the average end-to-end PLR as a function of m (number of parallel paths) in the parallel network ($n = 1$) where the PLR on each path is uniformly distributed between 10^{-8} and 10^{-1}. The figure shows that the mean of the PLR in the network is exponential function of the number of paths, m. The coding and the distribution schemes can significantly improve the reliability. Among various coding and the distribution schemes, 2-best Scheme is the most reliable. By analyzing the variance be-

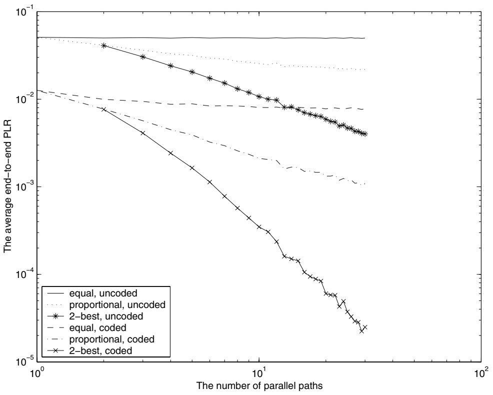

Figure 4. The average end-to-end PLR vs. the number of parallel paths m for different distribution schemes and the $(15,\ 13,\ 2)$ code.

havior of the PLR in the network, we also found that the proper packet distribution compensates the instability of paths. In Fig. 5 and Fig. 6, we plot the average end-to-end PLR and the corresponding average code redundancy $\frac{N-K}{N}$, respectively, with the bar representing the variance. In both figures, the results are presented as a function of m (number of parallel paths) at the path level ($n = 1$) where (i) the PLR on each path is uniformly distributed between 10^{-8} and 0.5; (ii) $N = 31$ and (iii) the proportional distribution scheme is applied. The results are shown for three schemes to determine the normalized erasure recovery capability as discussed in Section III.A. Fig. 5 demonstrates that network with *Max-R* coding scheme has the lowest average end-to-end PLR, while *WeightedAvg-R* coding scheme has the highest. Fig. 6 illustrates that the redundancy associated with *WeightedAvg-R* coding scheme is the lowest, while *Max-R* coding scheme is the highest. *Mean-R* coding scheme has almost constant redundancy and acceptable reliability.

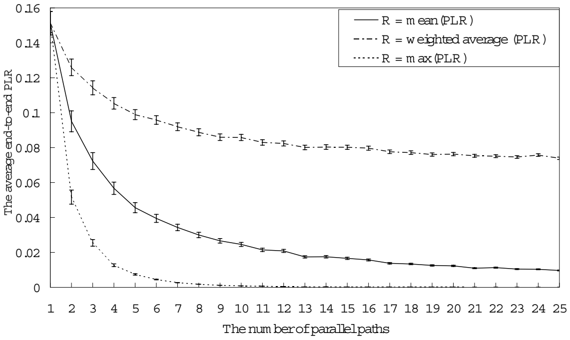

Figure 5. The average end-to-end PLR vs. the number of parallel paths, m, for different choice of erasure recovery capability R.

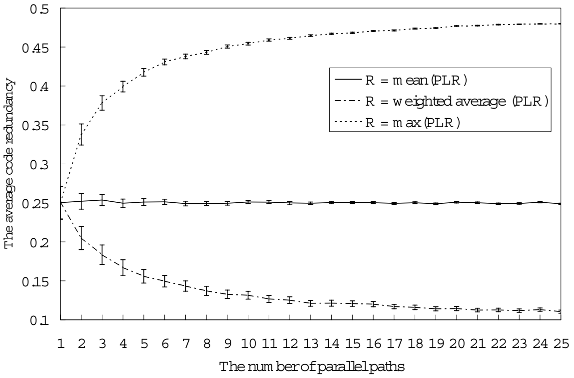

Figure 6. The average code redundancy vs. the number of parallel paths, m.

General observations from our simulations are: (1) Even though the PLR on individual links is fluctuating, the aggregate reliability of the set of paths keeps the network performance relatively stable. (2) Since the total overhead associated with packet level FEC is distributed and interleaved over multiple paths, the capability against packet loss bursts is enhanced. (3) In MANET, on average, the risk of congestion at regenerating nodes is not greater than that at the destination. (4) Proper coding, distribution and choice of reconstruction schemes can substantially compensate the unpredictability in ad hoc networks and make it easier to satisfy reliability and delay requirements.

5. Conclusions

This paper adopted packet level FEC in routing packets through multiple paths between the source and the destination. By introducing the regenerating nodes we were able to combat packet loss along intermediate links by using redundant packets to reconstruct the lost ones. Overall, by avoiding packet loss accumulation throughout the network, the PLR at the destination was limited to the PLR between the last regenerating node and the destination. In addition, the paper analyzed various packet distribution schemes among the multiple paths in order to (i) distribute traffic loads; (ii) increase reliability and (iii) stabilize the PLR performance at the destination for time-varying network environments.

The PLR improvements in the schemes proposed depend on (i) the network topology and (ii) PLR conditions.

In general, by introducing more regenerating nodes and using more powerful codes, as demonstrated in simulations, significant improvements can be achieved by using packet level FEC. This improvement is coming at the expense of more packets transmitted through the network. In addition to improved reliability, the proposed schemes are characterized with fixed delays and as such are suitable for real-time transmissions.

6. Future Directions

When discussing the proposed routing schemes, our focus was on MANET applications. However, our proposal is more general and can enhance the reliable real-time communications in any network with multiple paths and frequently changing topologies, not only in MANET. Our routing scheme constitute a framework for reliable multipath routing with soft PLR metrics that could be specialized to other networks such as the Internet and multicast networks with heterogeneous connectivity.

The validity for some of the assumptions in this paper requires further investigations. We concentrate here on three of them.

First, we assumed the raw link PLRs had been already obtained in some way and made available at the source. We used the actual PLR as the measure of reliability in our algorithms, but in practice we deal with their estimates. One way of obtaining PLR is to monitor the sequence numbers of the data packets passing along a certain link. The problem in this method is that if there is no ongoing transmission for a long time, the estimated PLR value would be outdated or even invalid. Another way is to count the “keep-alive” or “Heartbeat” packets. This method may result in too coarse estimates when we try to limit the frequency of management packets to save the bandwidth. Combination of those two approaches should result in an acceptable solution.

Second, our schemes are dependent on the assumption of the “quasi-stationary” topology. In MANET, high nodal mobility leads to frequent link failures. As a result, frequent routing information exchanges may be needed to maintain the up-to-date choice of parameters in our routing scheme. The effects of routing with imprecise roting information should be explored further.

Third, our discussions in the paper were disjoint from the packet length. Essentially, the point of reference was the raw link PLR and the delay was calculated in terms of number of packets in the coded group rather than the real time for the transmission of the group of packets. If the packet loss is a result of bits in error at the physical link layer, from the general relation between the raw PLR and the link BER, it is preferable to work with shorter frames to achieve lower PLRs. However, after incorporating the protocol header length into the effective throughput calculations, the choice for the optimum packet length is protocol and BER specific [3]. This is the reason why with high BER in the order of 5×10^{-4} in wireless networks, we usually work with shorter frames. With packet level FEC and multipath routing, the calculations for the optimum choice of packet length are much more complicated and they require further analysis.

In addition, our work in this paper concentrated on reliable transmissions in MANET under the assumption that the network topology and the link states were available at the source. In order to verify these schemes, a realistic routing information dissemination algorithms in MANET should be considered.

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