Improving Reliability of Packet Delivery in MANETs by a Holistic Routing Approach

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Abstract

In this report, we explore the problem of improving the reliability of packet transmissions in MANETs (Mobile Ad-hoc NETworks). Unlike existing solutions that address individual causes leading to packet losses in MANETs, the proposed routing protocol handles all causes - transmission failures, link failures, and network congestion - in a holistic way. Specifically it takes advantage of broadcasting nature of wireless communication and accommodates a sender-receiver joint-decision-making mechanism with a timer-triggered retransmission for opportunistic routing. Simulation results demonstrate that the new holistic routing protocol significantly improves the packet delivery ratio over AODV, DSDV, GeRaF, and ExOR in major MANET application scenarios. For example, by using the proposed holistic routing protocol, more than 90% of data packets can be successfully delivered in a 8-hop MANET when the maximum moving speed of nodes is 50 m/s and the loss rate for each link is 20%.

Keywords: Routing protocols, Reliability, Wireless ad-hoc network, Holistic approach

Date: May 7, 2006

I. INTRODUCTION

A. Motivations and Research Goals

The reliability of packet-delivery services provided by a network influences the behavior of networked applications, especially loss-sensitive ones. Thus it is important to improve the reliability of packet delivery for supporting such applications in different networking scenarios. In general, more packet losses may occur in Mobile Ad-hoc NETworks (MANETs) than in wired networks or other fine-tuned infrastructure-based wireless networks. Multiple reasons contribute to packet losses in MANETs. (i) Wireless channels in MANETs may have low quality since noise and external interference may be strong. Consequently, the Signal to Noise Ratio (SNR) of a signal in a MANET can be several magnitudes smaller than those in wired networks. Moreover, in MANETs, multiple wireless hops generally share the same medium, so intra-session interference contributes a non-negligible portion in the total interference. When the SNR is smaller than a threshold, *transmission failures* occur in the form of bit errors. If the bit errors cannot be corrected by the communication system's error-correction mechanism, the entire data packet must be discarded. (ii) Due to mobility and power limitations, links in MANETs are opportunistic. *Link failures* may happen at any time during the packet-transmission process, which may disrupt the transmission of a data packet.

If no mechanism is employed to discover and replace failed links, packet losses will occur. (iii) Packet losses may happen due to *network congestion*. When the input buffer in a node is full, either a newly received data packet or a stored data packet has to be discarded to avoid buffer overflow.

The goal of this research is to find a holistic solution to address the above-mentioned challenges in improving the reliability of packet-delivery services in MANETs. In this report, we use the Packet Delivery Ratio (PDR) to represent the reliability of packet transmissions in a network. It is defined as the percentage of data packets that can be successfully delivered from the source nodes to their destination nodes. In the rest of this report, we assume that every packet has a unique source node and a unique destination node.

Unlike existing solutions that address individual causes leading to packet losses in MANETs, our proposed routing protocol handles all causes - transmission failures, link failures, and network congestion - in a holistic way. Most existing solutions are designed to handle packet losses caused by one reason (refer to the next subsection for more details). When packet losses with multiple causes coexist, the system must distinguish packet loss causes in order to take advantages of these solutions. With limited information on the operational status of nodes and links, the reason for individual packet loss is not easy to be identified.

B. Related Work

Different approaches have been proposed in the research community to improve the reliability of packet-delivery systems in different application scenarios.

Forward Error Correction (FEC) approaches [6], [7] and multipath transmission approaches [8]–[11] are proposed to improve the reliability of packet-transmission services by adding redundant information into transmitted units of data. With the redundant information, some bit errors can be eliminated without retransmission. It has been observed that most transmission failures happen in bursts. To handle such errors, data-fusion mechanisms [12]–[14] can change the structure of data packets to distribute the errors across multiple packets. By using other error-correction approaches, the packets with these distributed errors can be corrected and the original message can be reassembled at the receiving nodes.

In order to recover lost packets that cannot be corrected by these approaches, lost packet recovery approaches are necessary. Some researchers uses explicit acknowledgments to detect the reception status of data packets and apply the Automatic Repeat reQuest (ARQ) approach to recover lost packets. This approach is simple yet efficient and is applied in multiple protocols in different layers. In the MAC layer [15], hop-by-hop ARQ can be used to recover frames lost to channel contention. In the transport layer [16], end-to-end ARQ can be used to recover packets lost to topology changes. In the protocol proposed in this research, we also apply the ARQ mechanism in the network layer to recover lost data packets and control messages.

Instead of handling lost packets, some researchers propose approaches to distinguish conditions in which packet losses are likely. Packet lost can be reduced if these conditions can be avoided. Geographical routing protocols [4] use nodes' location information to determine link status and avoid links between distant nodes. On-demand routing protocols [1], [17] check the status of links by exchanging a small control message before the transmission of any data packet. These approaches reduce the probability of transmitting a data packet through a link that has already failed. Extreme Opportunistic Routing (ExOR) [3], and MAC layer anycast [5] enable the competition among multiple forwarding candidates for the forwarding task. The candidate with optimal forwarding cost that has successfully received the data packet wins in the competition. Transmission failures through one link can be seamlessly recovered by opportunistically successful transmissions to neighboring links.

C. Originality

In this research, we propose a holistic routing protocol that recovers packets lost for different reasons. (i) At each hop, a data packet is pushed to the best-possible places according to the actual transmission conditions. Instead of unicasting the data packet to a preselected next-hop forwarder, a transmitter using the holistic routing protocol broadcasts the data packet to all its neighbors. After the broadcasting, successful receivers become forwarding candidates and compete to forward the data packet based on their forwarding costs. (ii) The selection of the next-hop forwarder among these forwarding candidates is made according to a joint decision-making mechanism. The joint decision-making mechanism takes advantage of opportunistic reception in unreliable wireless communications to improve the reliability of packet transmissions in unreliable networks. (iii) The holistic routing protocol also integrates next-hop forwarder discovery and link failure recovery approaches. This protocol has been demonstrated in simulations to outperform traditional ad-hoc routing protocols in MANETs with dynamic topologies in terms of reliability. (iv) In the holistic routing protocol, a timeout-triggered retransmission mechanism is applied at each hop to recover data packets and some control messages lost to transmission failures. Therefore, packet losses caused by transmission failures can be well controlled.

The rest of this report is organized as follows. We introduce the general assumptions in Section II. In Section III, the newly designed routing protocol is described. Routing components and design issues are discussed in detail in this Section. We compare the performance of the holistic protocol with AODV [1], DSDV [2], ExOR (Extremely Opportunistic Routing) [3], and GeRaF (Geographical Random Forwarding) [4] in Section IV. Section V concludes this report.

II. ASSUMPTIONS

A. Link Quality

In a multi-hop MANET, packets in transmission may be received with noise and interference. It is the physical layer and data link layer protocols' responsibility to decode individual bits from the interfered signals. All bits can be decoded correctly if the SNR is higher than a threshold. When the SNR is lower than the threshold, bit errors occur during the transmission, causing the receiver to drop some data packets. Using different types of physical- and data-link–layer protocols may change the probability of packet losses at each link among different systems. To compare the performance of different routing protocols in terms of the PDR, we assume that similar lower layer protocols are employed such that all peer routing protocols share an identical packet loss probability, P, in a connected link. In order to simplify the simulations, we also assume that the probability, P, is identical for all connected links. The only condition when this probability may change is when a link is disconnected due to node mobility.

B. Node Mobility

Nodes may move arbitrarily inside MANETs. This unbounded nature of nodes in MANETs makes MANETs flexible in deployment. However, it also makes links in MANETs instantaneous. The probability of successful packet transmissions between two nodes using wireless channels can be low when the distance between these two nodes is large. The link between these two nodes can be regarded as completely failed when their separation is larger than a threshold. Generally, the threshold is referred to as the communication range. In the rest of this report, we assume that a link between two nodes ceases to exist when the distance between these two nodes is larger than the communication range. Otherwise, all links have a constant quality, in which the probability of successful transmissions through this link is equal to P. To handle packet losses caused by node mobility or network congestion, the holistic routing protocol does not depend on any previous knowledge of its neighbors. Instead, it integrates the next-hop forwarder discovery function with the lost link recovery approach in its operation to dynamically replace failed links or links to congested nodes.

C. Network Density

The network density, which is represented by the average number of neighbors of a node, may change dramatically in different application scenarios. Some protocols control the density of wireless networks by putting nodes into sleep mode, thus saving energy and controlling channel conflicts. However, to keep the network fully connected, the average node's degree should not be too small. There may be more than one node that can receive a transmitted data packet. Due to the multicasting nature of wireless communications, it is possible that when a transmission failure happens at one link, other neighbors of the transmitter can overhear the data packet by opportunistic reception, improving the reliability of packet transmissions in a multicasting network. The holistic routing protocol takes advantage of this feature to improve the success rate of each packet-delivery hop. On the other hand, when a network becomes dense, the probability of channel contention increases. If no mechanism controls packet losses caused by the increased channel contention, the PDR may go down. The holistic routing protocol uses the joint decision-making mechanism to select the optimal forwarding candidate as its next-hop forwarder in every packet-transmission hop. Simulation results demonstrate that this can improve the reliability of packet transmissions in a network where multiple packet-loss types coexist.

III. THE HOLISTIC ROUTING PROTOCOL

A. Data-Packet Broadcasting

In a wireless network, all nodes share the same communication medium, i.e. the air. As a result, a packet transmitted between two nodes may be opportunistically received by their neighbors. This phenomenon is referred to as the multicasting advantage of wireless communications. Even when the packet transmission between the transmitter and the intended receiver fails for one reason or another, one or more neighbors may successfully receive the packet. In a network where several optimal paths exist, unicasting the data packet to a pre-selected next-hop forwarder ignores other neighboring nodes' successful opportunistic receptions, thus reducing the potential to address the reliability of packet transmission. Generally, one-to-many transmissions provide a better way to transmit data packets in these scenarios.

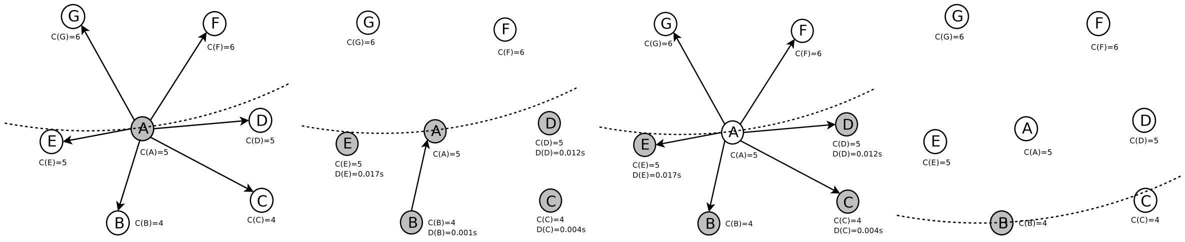
Some approaches, such as ExOR (Extreme Opportunistic Routing) [3], MAC layer anycast [5] and GeRaF (Geographical Random Forwarding) [4], multicast data packets to a group of forwarding candidates and neighbors' opportunistic receptions can improve the reliability of these protocols. However, a node depends on a well-maintained neighbor list to choose the receivers. When the information in the neighbor list becomes stale, the performance of these multicasting-based approaches degrades dramatically. Unfortunately, in MANETs, especially when nodes move quickly, maintaining an accurate neighbor list is a nontrivial task. To our knowledge, the problem is still not completely solved. Therefore, in the holistic routing protocol, we use broadcasts instead of multicasts to avoid the dependence on neighbor lists.

Moreover, the traffic overhead of using broadcasting instead of unicasting in a routing protocol for wireless networks is not necessarily high. If the protocol can guarantee that only one of the receivers replies, a unicasting transmission will hold the wireless channel longer than a broadcasting transmission since a broadcasting node pair does not need to exchange RTS/CTS messages before data frame exchanges happen. It is true that more neighbors need to receive and process the broadcast data packets, which may consume a significant amount of energy. However, in the case of using unicast, in order to increase the reliability of packet delivery, retransmissions are necessary, which also require additional energy supply. In broadcasting, more than one node may obtain the same data packet when the packet is transmitted once. Thus when forwarding candidate changing happens more frequently, broadcasting becomes more efficient.

B. Hop-by-Hop Store-and-Forwarding Approach

The proposed holistic routing protocol uses a hop-by-hop store-and-forwarding approach to transmit data packets from the source node to the destination node. At each hop of the holistic routing protocol, the data packet is pushed closer to the destination as shown in Fig. 1.

First, the transmitter (Node A) broadcasts the data packet to all its neighbors (Nodes B, C, D, E, F, and G) as depicted in Fig. 1(a). Node A piggybacks its forwarding cost, C_A, in the header of the broadcasted data packet. On receiving the data packet, all neighbors with forwarding costs not larger than the piggybacked one (Nodes B, C, D, and E) become forwarding candidates. The dotted line in Fig. 1 illustrates the points of the same distance to the destination as that from Node A. After receiving the broadcasted data packet, every forwarding candidate, X, calculates its responding delay, D_X, in a distributed manner according to the forwarding cost, C_X, stored in its routing table. A smaller C_X results in a smaller calculated D_X. (see Sections III-C, III-E, and III-D for details about forwarding-cost management and the formula to calculate the responding delay). A forwarding candidate waits for a period equal to the calculated responding delay before replying to the broadcasted data packet by unicasting a reply message to the transmitter (Node A) to nominate itself (e.g., Node B) as a possible next-hop forwarder. This reply



(a) Data Packet Broadcasting

(b) Self-nomination at 0.001s

(c) Explicit Notification

(d) Status After Notification

Fig. 1. A hop of packet transmissions in the holistic routing protocol

message is called as a *self-nomination message* in the rest of this report. On receiving the first self-nomination message, the transmitter chooses the responding candidate as the next-hop forwarder. Due to the deterministic relationship between the forwarding cost and the responding delay, optimal candidates have a better chance of replying earlier than non-optimal candidates. Of course in the event of packet loss between the transmitter and all optimal candidates, a non-optimal forwarding candidate may be selected to serve as the next-hop forwarder. We will explain more on this strategy in Section III-D. After the selection, the transmitter (Node A) explicitly declares its selection by broadcasting an explicit notification message. The notification message tells the selected forwarding candidate (Node B) to start the next-hop forwarding. It also informs the unselected forwarding candidates (Nodes C, D, and E) that the data packet has already been properly handled by other nodes. After receiving the notification message, the unselected forwarding candidates can stop any further operations for this data packet in this hop as shown in Fig. 1 (e). It is obvious that the data packet is pushed from the area where $C_X = 5$ in Fig. 1(a) to the area where $C_X = 4$ in Fig. 1(d).

C. QoS Metrics and Forwarding Cost

In the holistic routing protocol, the accumulated cost for forwarding a data packet from a node to its destination node is estimated by each node as a criteria to make routing decisions. Different types of QoS metrics can be taken into account in the estimation. The combination of all these QoS metrics is defined as the forwarding cost. Generally speaking, if the forwarding cost from Node A to the destination node is smaller than the forwarding cost from Node B to the destination, transmitting a data packet from Node A is preferable to transmitting the same data packet from Node B in terms of the QoS metrics in consideration. It is possible to combine the link quality, the successful delivery ratio, the network interference level, and the amount of remaining energy into a complex model of forwarding cost. The way to combine different types of QoS metrics is also flexible. Linear or nonlinear functions can be used to estimate the forwarding cost when multiple QoS metrics are considered. In the rest of this report, we take the hop count distance to the destination as an example of the forwarding cost to show how the holistic routing protocol works. This choice also enables direct comparisons among the holistic routing protocol and other ad-hoc routing protocols because they all use the same performance metrics.

The forwarding costs from a node to all possible destination nodes are stored in the node's routing table. By default, all nodes in the network are regarded as possible destinations. However, specific configurations can be set up to explicitly list only a few nodes as possible destinations. This reduces the storage space required for the routing table in a node and enables nodes with extremely limited memory resources to serve in large-scale networks. An entry in the routing table only contains the address of the possible destination node and the estimated forwarding cost. No next-hop forwarder information is stored in the routing table. A node rediscovers the next-hop forwarder for each data packet using the approach introduced in the following subsections.

D. Routing Table Operation

1) Initialization: By default, Node X joins a network in a two-step process. First, it obtains information about other nodes from its one-hop neighbors by broadcasting an initiation request. On receiving this request, its neighbors report their routing tables to this newly joined node. Based on these reports, Node X establishes its routing table. Next, if it is a possible destination node, it floods an initiation message containing its address and a space to store C, the forwarding cost, across the network to create a new entry in the routing table in any active node.

On receiving an initiation message, each node checks whether an entry corresponding to Node X is in its routing table. If an entry does not exist, the node creates a new entry and estimates the forwarding cost to Node X as $C_i = C + 1$ (This formula uses the hop-count distance as the forwarding cost) and it re-broadcasts the initiation message containing the address of Node X and C_i.

In contrast, if an entry for Node X already exists, the node compares C_i (from the routing table) with $C + 1$. If $C_i > C + 1$, it replaces C_i with $C + 1$ and re-broadcasts the initiation message containing the address of Node X and the new C_i. Otherwise, the node neither updates its routing table nor re-broadcasts the new initiation message. This process keeps going on until all nodes have the shortest hop-count distances to Node X stored in their routing tables. This process is similar to the initiation process of table-driven routing protocols, such as DSDV, although the content of routing tables is different.

2) Refreshment: Unlike table-driven routing protocols, which consume a significant amount of energy due to periodical updates of the information stored in routing tables, the holistic routing protocol updates routing tables in an on-demand manner. (i) If Node i discovers that neighbor Node j's hop count distance, C_j, to the destination is smaller than $C_i - 1$, it updates $C_i = C_j + 1$. (ii) If transmitter i broadcasts a packet and receives a self-nomination message from a new neighbor, l, and $C_i > C_l + 1$, it updates $C_i = C_l + 1$. (iii) If transmitter i broadcasts a packet and does not receive any self-nomination messages, it increases its own forwarding cost by 1. These three simple rules provide a distributed mechanism to maintain forwarding cost estimation in the routing tables.

When the shortest hop-count distances to the destination from some nodes are not accurate due to node mobility, the performance of the holistic routing protocol will be affected. If the estimated hop-count distance from Node A to the destination node is too small in Fig. 1, fewer nodes will respond to the broadcasted data packets. However, when there is no responder, the data packet will be retransmitted and the forwarding cost will be increased according to the rule (iii). Eventually some node(s) will reply. At this point, the packet transmission procedure can continue as described earlier.

If Node A's hop-count estimation is too large, all neighbors may obtain a responding delay that is smaller than τ. In the case of Fig. 1, Node F and Node G could win the competition. However, the probability of winning the competition is equal for all the neighbors. When Node B or Node C wins, the forwarding cost of Node A will be updated to the correct value, 5, which eliminates the possibility of transmitting additional packets from Node A to Node F or Node G. Therefore, in the long-run, the holistic routing protocol can correct the stale forwarding costs in the routing table to provide reliable packet-delivery services.

E. Cost Function

As shown in Fig. 1(b), the responding delay of a node is calculated using a cost function on its forwarding cost. Different cost functions can be applied for different applications and different design preferences. Generally, the cost function is a nondecreasing function over the forwarding cost. In the rest of this report, we use a simple formula as an example to demonstrate how the holistic routing protocol works. The application designer can define a different cost function to tune the performance of the holistic routing protocol. The cost function we use in this research is shown in Eq. 1.

$$D_i = \begin{cases} \tau \times (\max(C_i - C_0 + 1, 0) + r) & \text{if } C_i <= C_0 \\ \infty & \text{otherwise,} \end{cases} \tag{1}$$

in which τ is the scale parameter controlling the overall length of the average per-hop delay. C_i represents the estimated hop-count distance from Receiver i to the destination node and can be obtained in its routing table. C_0 is the hop-count distance from the transmitter of this hop to the destination node and is piggybacked in the data packet. r is a uniformly distributed random variable in the range of $[0, 1)$. The reason we add a random variable in this cost function is to reduce the probability of having more than one receiver transmitting self-nomination messages to the sender simultaneously when multiple receivers have the same hop-count distance to the destination node.

F. Next-Hop Forwarder Discovery

The holistic routing protocol discovers the next-hop forwarder for a packet at each hop using a joint decision-making mechanism. Different from the traditional transmitter decision-making mechanisms, in which the transmitter collects forwarding cost information in its neighborhood and selects a neighbor with the smallest forwarding cost estimation as the forwarder, the joint decision-making mechanism selects the forwarder according to the reply timing. Since neighboring nodes of failed links and congested neighboring nodes are not able to reply to a broadcasted data packet, only neighboring nodes of available links will be used in the holistic routing protocol. This is how failed links and links to congested nodes are eliminated from the competition in the holistic routing protocol.

Unlike traditional ad-hoc routing protocols, the holistic routing protocol broadcasts the data packet without any knowledge of its neighbors. This makes the procedure robust in MANETs' dynamic topologies. Neighbors that have successfully received the broadcasted data packet become the forwarding candidates if they have a lower forwarding cost than that of the transmitter. The forwarding candidates calculate their responding delays according the cost function shown in Eq. 1 in a distributed manner. Shorter-dealyed candidates reply earlier. The transmitter simply selects the earliest responder as the next-hop forwarder. The explicit notification message stops all unselected candidates from transmitting their self-nomination messages. In the ideal case, only one optimal candidate broadcasts a self-nomination message, while all other candidates keep silent during the entire procedure. By this means, energy and communication resources can be saved in the holistic routing protocol as compared to traditional ad-hoc routing protocols.

G. The Timeout-Triggered Retransmission Mechanism

The timeout-triggered retransmission mechanism applied in this research works as follows. For a protected data packet or control message, an acknowledgement message is expected by the transmitter after the transmission of the data packet or the control message. A lack of this acknowledgement message is interpreted as the loss of the data packet or control message. Under this interpretation, the transmitter retransmits to recover the lost data packet or control message. This interpretation is not always accurate since the transmitter may lose the acknowledgement message due to transmission failures. However, retransmitting an already-received data packet or control message does not harm the reliability of the packet-transmission system, although the system's energy efficiency may be affected.

1) Data Packets: When the data packet is transmitted, the transmitter expects to receive a self-nomination message in a certain period of time. When the cost function shown in Eq. 1 is used, the maximum time interval between the broadcasting of the data packet and the first arrived self-nomination message can be estimated as $t_1 \leq 2 \times \tau + RTT_{hop}$.

During every data-packet retransmission, a new next-hop forwarder discovery process is conducted. Therefore, the retransmission recovers not only packets lost due to transmission failures, as do most MAC-layer retransmission mechanisms, but also packets lost due to link failures and network congestion by switching to other available links or links to uncongested nodes. This retransmission mechanism is more efficient than MAC-layer retransmission mechanisms when packet losses caused by transmission failures, link failures, and network congestion coexist.

2) Control Messages: In the holistic routing protocol, the self-nomination messages are also protected by the retransmission mechanism. However, since self-nomination messages are transmitted in unicast, the retransmission mechanism cannot recover lost self-nomination messages due to link failures. It is reasonable to assume that network congestion will not affect the reception of this type of control message. However, it is possible that a link failure may cause the loss of a self-nomination message when it happens between the successful transmission of the data packet and the transmission of the self-nomination message. Under this condition, the forwarding candidate who successfully received the data packet withdraws from the competition silently, if the notification message is received. However, the PDR of the packet-delivery system is not harmed since other forwarding candidates can seamlessly replace the withdrawn node.

The PDR of a packet-delivery system can be harmed when the self-nomination message from a forwarding candidate (e.g., Node B in Fig. 1) is received by the transmitter yet the notification message from Node A is lost. Under this condition, Node B cannot determine whether it is selected as the next-hop forwarder. In the holistic routing protocol, the forwarding candidate retransmits its self-nomination message to request another notification message if it does not receive a notification message after time $t_2 \leq t_1$. Some lost notification messages due to transmission failures can be recovered by this approach.

IV. PERFORMANCE EVALUATION

A. *Configuration of the Proposed Routing Protocol*

We compare the performance of packet-delivery systems that use the holistic routing protocol under different configurations in a grid network. The simulation is conducted in a 5-by-5 grid network with the source node at one corner of the grid and the destination node at the diagonally opposite corner. The source node transmits an 800-byte packet to the destination node every 5 seconds. The communication range of every node is 100 m. The distance between two adjacent nodes is 80 m. Therefore, only adjacent nodes in the grid can communicate directly. Consequently, an 8-hop packet delivery is necessary in the network to transmit the packet from the source node to the destination node.

We use IEEE 802.11 as the MAC layer protocol in the following simulations. In order to fairly compare the proposed holistic routing protocol with other routing protocols, we enable a maximum number of five retransmissions for every packet when using other routing protocols and disable the retransmissions when simulating the proposed routing protocol. Although in IEEE 802.11, broadcast transmissions do not require RTS/CTS exchange which means such transmissions are more vulnerable to the hidden terminal problem, the proposed routing protocol outperforms other peer protocols even when most message exchanges in the proposed routing protocol are broadcast-based.

1) The Maximum Number of Retransmissions: In this section, we compare the PDR of packet-delivery systems that use the holistic routing protocol with different maximum retransmission values. We assume that the maximum number of data-packet retransmissions is equal to the maximum number of self-nomination message retransmissions. With this simulation, we demonstrate that the retransmission mechanism improves the reliability of packet-delivery systems, especially when channel-error probability is high. The results are shown in Fig. 2, in which Holistic-3, Holistic-5, and Holistic-10 represent the holistic routing protocol with configurations to retransmit data packets for at most 3, 5, and 10 times respectively. We use $\tau = 0.01$ s, $t_1 = 0.1$ s, and $t_2 = 0.02$ s to configure the holistic routing protocol in this simulation.

Fig. 2 shows that when channel-error probability is smaller than 20%, the maximum number of retransmissions does not affect the PDR significantly since the PDR of all three packet-delivery systems using the holistic routing protocol are 100%. However, as the channel-error probability increases, the PDR of the packet-delivery system that uses Holistic-3 begins to decrease faster than the other two packet-delivery systems. When the channel-error probability reaches 50%, only 25% of packets can be delivered in the packet-delivery system that uses Holistic-3. Meanwhile, the PDR for the other two packet-delivery systems are still higher than 60%. It is obvious that

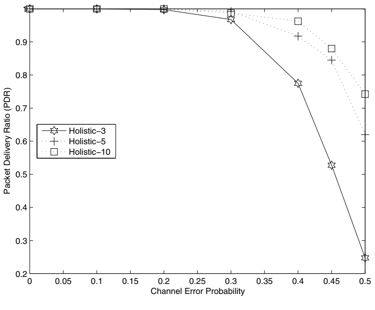


Fig. 2. A Comparison of the PDRs of packet-delivery systems using the holistic routing protocol with different maximum retransmission values

retransmission is helpful in improving the PDR of packet-delivery systems that uses the holistic routing protocol when channel-error probability is high. However, a larger maximum retransmission number implies that network nodes may have to cache packets for a longer period of time. In nodes with constrained buffer space, a large maximum retransmission number may cause more network congestion. In the rest of this report, we use Holistic-3 as an example to test the performance of the holistic routing protocol. In extreme conditions, where channel-error probability is high, to achieve a desired PDR, users may change the maximum number of retransmission configuration to improve results.

One thing needs to be noticed here is that enabling more retransmissions for a single packet does not cause the increase of traffic load under a reliable network condition. In an unreliable network, it is the system designers' task to determine the optimal tradeoff between the acceptable packet delivery ratio and the resource they want to contribute to achieve this target. The holistic protocol is proposed as a tool helping them to achieve this target in an efficient manner.

2) Scale Parameter τ in the Cost Function: In this section, we compare the PDR of packet-delivery systems that use the holistic routing protocol with different values of the scale parameter, τ, in the cost function. τ determines the average length between reception of a data packet and transmission of self-nomination messages. If τ is too short, MAC-layer back-offs may change the sequence of self-nomination messages with non-negligible probability. It may cause the holistic routing protocol to make suboptimal decisions, harming the PDR. On the other hand, if it is too long, the per-hop delay increases and nodes are more likely to be congested, which harms the PDR too. To demonstrate this phenomenon, we made an assumption here that a node in this network can only store one packet. During the following simulations, we keep using this assumption, which shows the holistic routing protocol's worst performance. Using a larger buffer would further improve the performance of the holistic routing protocol. The comparison result of the holistic routing protocol using different values of τ is shown in Fig. 3. In Fig. 3, we set $t_1 = 0.1$ s and $t_2 = 0.02$ s to configure the holistic routing protocol in this simulation.

It is obvious in Fig. 3 that when $\tau = 0.02$ and $\tau = 0.03$, the PDR performance of packet-delivery systems

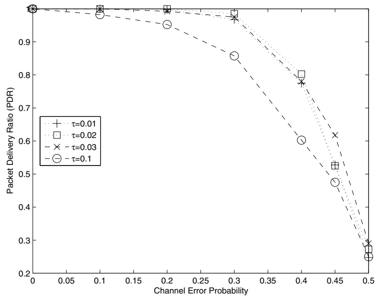


Fig. 3. A comparison of the PDR among packet-delivery systems that use the holistic routing protocol with different cost-function scale parameters

that use the holistic routing protocol is slightly better than that of the one that uses the holistic routing protocol when $\tau = 0.01$. When $\tau = 0.1$, the performance degradation is quite obvious due to the congestion problem. This simulation demonstrates that τ affects the PDR performance of the holistic routing protocol since the holistic routing protocol is quite sensitive to delay in the system.

Selecting proper τ can be regarded as choosing a trade-off point for the average per-hop delay and the possibility of conflicts among self-nomination messages. Conflicts among self-nomination messages happen when more than one self-nomination message is sent during one hop of packet forwarding in the holistic routing protocol. For a sender with m optimal forwarding candidates, the expected length of the per-hop delay is $\frac{\tau}{m+1}$ with no packet loss. If the sender always transmits the notification message right after it receives the first self-nomination message and the transmissions of a self-nomination message and a notification message need $2 \times T_m$ second, then the probability of a self-nomination message conflict is $\frac{1}{2} \times (1 + (\frac{2 \times T_m}{\tau})^k - (1 - \frac{2 \times T_m}{\tau})^k)$ when $\tau \gg 2 \times T_m$ and no packet loss happens. It is obvious that a larger τ can reduce the probability of self-nomination message conflicts while increasing the per-hop delay and vice versa.

3) Retransmission Delay t_1 and t_2: In this section, we discuss the impact of the length of retransmission delay. After a sender transmits a data packet, it waits for self-nomination messages from forwarding candidates for t_1. The sender interprets the condition in which no self-nomination message is received during t_1 as data-packet loss and retransmits the data packet. Meanwhile, another parameter, t_2, is used to control the retransmission of self-nomination messages. Generally, $t_2 \leq \frac{t_1}{5}$, so that lost self-nomination messages can be retransmitted before the data-packet retransmission. Another constraint is that $t_1 = 2 \times \tau + RTT_{hop}$, so that forwarding candidates have a chance to deliver self-nomination messages before the retransmission of the data packet. In this research, we require that if $\tau = 0.01$ s, $t_1 > 0.02$ s. In this simulation, we set $t_1 = 5 \times t_2$, and change the value of t_2 to observe the impact on the performance in terms of the PDR. The result is shown in Fig. 4.

It is shown in Fig. 4 that the PDR increases with the increment of t_2. When t_2 is larger than 0.02 s, the speed of increasing is almost negligible. The PDR converges to a value determined by τ and the maximum number of

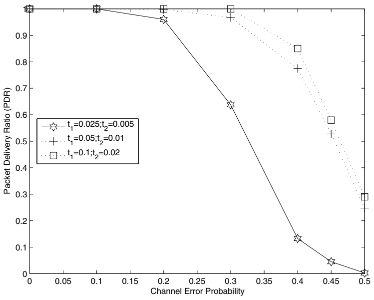


Fig. 4. A comparison of the PDR among packet-delivery systems that use the holistic routing protocol with different timeout parameters

retransmissions. Therefore, in the rest of this report, we use $t_2 = 0.02$ s and $t_1 = 0.1$ s.

Selecting a larger waiting delay, t_1, may increase the per-hop delay when packet losses happen. In a link through which β retransmissions are required in average to transmit a data packet through a link, the per-hop delay can be roughly estimated as $\beta \times t_1 + T_d + 2 \times T_m$, in which T_m is the transmission time for a message and T_d is the transmission time for a data packet. Meanwhile, since $t_1 > \tau$, reducing t_1 may decrease τ, thus increasing self-nomination message conflicts. Therefore, an acceptable per-hop delay and the additional energy consumption caused by self-nomination conflicts need to be considered during the process of selecting a proper t_1.

With a given t_1, selecting t_2 according to the maximum number of self-nomination message retransmissions can optimize the PDR. If t_2 is too large, lost self-nomination messages are not retransmitted in a sufficient number of times when a data-packet retransmission is triggered by t_1. Therefore, some self-nomination message loss may be wrongly interpreted as data-packet loss, resulting a certain number of data-packet retransmissions. Since the maximum number of data-packet retransmissions is limited, this reduces the effectiveness of data-packet retransmission. On the other hand, since the maximum number of self-nomination message retransmission is limited, a small t_2 will never benefit a packet-delivery system using the holistic routing protocol. We generally assign $t_1 = (R_s + \alpha) \times t_2$, in which R_s is the maximum number of self-nomination message retransmission and α is a constant to cover other time-consuming issues, such as transmission delay, processing delay and MAC-layer back-offs.

4) Varying Mobility in Reliable Ad-hoc Networks: In this section, we compare the packet-transmission reliability of packet-transmission systems using different routing protocols in a MANET with reliable links. The network is composed of 50 mobile nodes that are uniformly distributed in a $1,000 \times 1,000$ square meter area. The communication range of each node is a circular area with a 100-m radius. The carrier sense range is a circular area with a 250-m radius.

Fig. 5 shows that in stationary conditions, traditional ad-hoc routing protocols, such as AODV and DSDV, perform well. However, when the maximum moving speed of nodes in the network increases, the reliability of these protocols

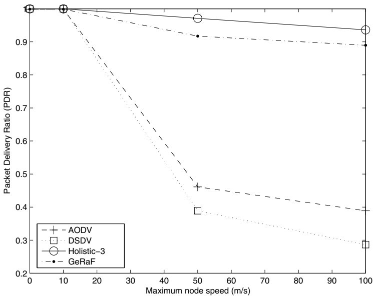


Fig. 5. Performance comparison among packet-delivery systems in MANETs with perfect channels and different maximum moving speeds

decreases due to the packet losses caused by link failures. The performance of ExOR degrades when the moving speed of nodes increases due to its dependency on a properly maintained neighbor list at each node. In a MANET with quickly moving nodes, maintaining the neighbor lists is difficult, if not impossible. Geographical routing protocols, such as GeRaF, still perform well in moving conditions, since the routing decisions are made according to the physical positions of nodes. However, GeRaf needs the node position information via additional GPS-like devices or services. The holistic routing protocol performs as well as GeRaF in mobile conditions because it replaces failed links and links to congested nodes with existing links and never depends on neighbor lists. In contrast with geographical routing protocols, the holistic routing protocol depends on neither positioning nor assumptions about the destination position. Therefore, the holistic routing protocol provides a satisfying packet-delivery ratio in mobile scenarios. In a large-scale network, using the holistic routing protocol can significantly reduce the cost of implementation as compared with geographical routing protocols.

5) Varying Link Quality in Stationary Ad-hoc Networks: In this section, we compare the reliability of packet-transmission systems using different routing protocols in stationary ad-hoc networks with different link qualities. The 5-by-5 grid stationary network is used again in this simulation.

Fig. 6 shows that since traditional routing protocols, such as AODV and DSDV, do not use any mechanisms to recover lost packets, their reliability decreases when the packet-loss rate in any link drops. ExOR considers using other alternative links as replacements when transmission failure or link failure happens. Therefore, it performs more reliably than AODV and DSDV in stationary conditions. Since the proposed ExOR in its original paper targets at increasing the throughput of the network instead of increasing the reliability, the author assumes that the retransmission will be conducted for an infinite number of times. However, to simulate the ExOR here, we use the idea of ExOR with a maximum of 3 retransmissions so that it can be compared with the holistic routing protocol in a fair manner. We observe that when using the same number of retransmissions, the proposed holistic routing protocol performs slightly better than ExOR-3. Since all forwarding candidates that can not overhear other candidates' ACK messages will forward the broadcasted data packets in ExOR, ExOR is less energy efficient than

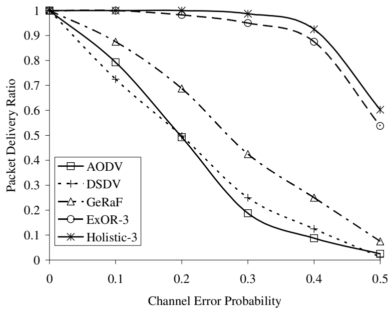


Fig. 6. Performance comparison among packet-delivery systems in stationary ad-hoc networks with different probabilities of packet losses caused by channel errors

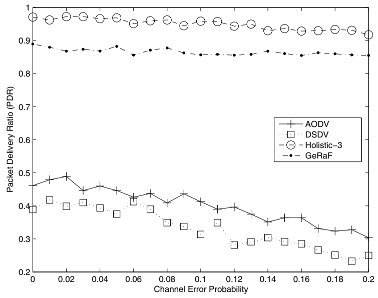


Fig. 7. Performance comparison among packet-delivery systems in MANETs with different probabilities of channel errors

the proposed holistic routing protocol.

6) Varying Link Quality in Mobile Ad-hoc Networks: When node mobility and link-quality degradation happen together, the holistic routing protocol outperforms all protocols in comparison. In this simulation, in the $1,000 \times 1,000$ square meter area, 50 nodes are uniformly deployed and move with a maximum speed of 20 m/s. We change the probability of packet losses at each link to study the performance of different routing protocols in MANETs with low-quality links.

We did not compare ExOR in mobile conditions because ExOR does not have a proper neighbor-list management approach proposed for mobile networks. To keep our comparison fair, we only compare ExOR in the stationary application scenarios per [3].

Fig. 7 shows that due to node mobility, the reliability of such traditional ad-hoc routing protocols as AODV and DSDV is less than 100% even when links are reliable. When the channel-error reliability decreases, AODV's and DSDV's PDR decreases almost linearly. It is shown that both node mobility and link quality may affect the reliability of packet delivery in ad-hoc networks that use traditional routing protocols. GeRaF outperforms AODV and DSDV due toits consideration of real-time position information during the routing decision-making procedure.

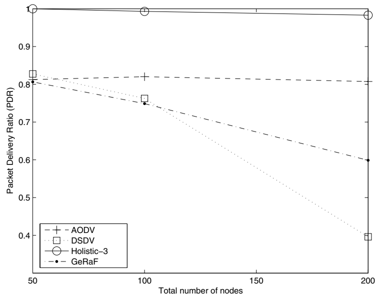


Fig. 8. Performance comparison among packet-delivery systems in MANETs with different network densities

The PDR of the holistic routing protocol is the highest among the four routing protocols because of the effects of the timeout-triggered retransmission scheme, the joint decision-making mechanism, the integrated next-hop forwarder discovery, and the lost-packet recovery approach.

7) Varying Network Density: As we have discussed, the multicasting advantage of wireless communications can be used to improve the reliability of data-packet transmissions. In addition, in networks with different densities, the efficiency of routing protocols in terms of delay and energy consumption can be different. In this section, we compare the performance of packet-transmission systems using different routing protocols in a MANET with a 10% packet loss rate and a 20-m/s maximum node speed to demonstrate the pros and cons of using these routing protocols in networks with different densities.

Fig. 8 shows that the PDR of AODV, DSDV, and GeRaF decreases when the network density increases due to the increased number of channel contentions. The holistic routing protocol performs almost identically in networks with different density settings because it takes advantage of the node density.

8) Reliability of TCP Traffic: In some application scenarios, MANETs must support TCP traffic. However, it is observed in [18] that ad-hoc routing protocols cannot support TCP in some unreliable conditions since routing protocols are not capable of distinguishing packet losses caused by network congestion from those lost for other reasons. The congestion control algorithm of TCP reduces the congestion window size when packet losses happen. As a result, in MANETs with transmission or link failures, the PDR of TCP traffic will be harmed in unreliable MANETs. In this section, we compare the reliability of TCP traffic for packet-delivery systems that use the holistic routing protocol, AODV, DSDV, and GeRaF.

Fig. 9 shows that while throughputs of TCP traffic transmitted in AODV, DSDV, and GeRaF packet-delivery systems is reduced significantly, TCP traffic transmitted in a packet-delivery system that uses the holistic routing protocol still has good throughput. Thus, we can conclude that although unreliable channels and unstable topologies can harm TCP throughput transmitted in packet-delivery systems that use the holistic routing protocol, it enlarges the range in which TCP traffic can be transmitted with the higher throughput performance.

This result is reasonable since the holistic routing protocol can improve the PDR of packet-delivery systems for

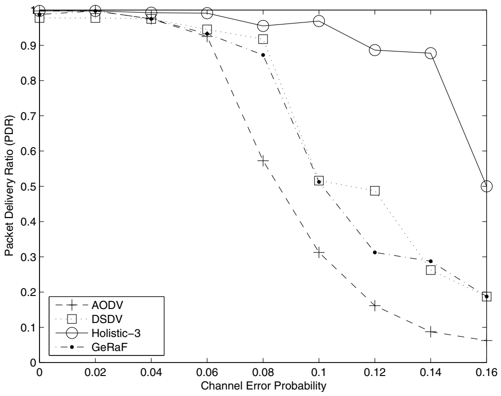


Fig. 9. The PDR of TCP traffic in a stationary ad-hoc network

UDP traffic. When TCP traffic is transmitted from the source node to the destination node in a network with high channel-error probability, more data packets can be received by the destination nodes by using the holistic routing protocol than using AODV, DSDV, or GeRaF. Therefore, more ACK messages are transmitted by destination nodes to source nodes. Meanwhile, the ACK messages can be regarded as small data packets transmitted in the reverse direction. As a result, the holistic routing protocol can also improve the reliability of ACK transmissions. For this reason, more ACK messages are received by the source nodes using the holistic routing protocol than using AODV, DSDV, and GeRaF when packet losses exist. With more ACKs the congestion control algorithm of TCP throttles the throughput less.

The proposed holistic routing protocol significantly increases the PDR of a packet delivery system at the cost of using more broadcasting and increasing the average per-hop delay. Our previous simulations have demonstrated that even when broadcasting traffic is not effectively protected from hidden terminal effects, the packet delivery ratio of the holistic routing protocol is still higher than those of general routing protocols in comparison. On the other hand, overall delays of packets in delivery may increase as the result of additional polling delay and time consumed for retransmissions, which have the potential to cause quality drops for certain delay sensitive applications. This simulation shows that for transport-layer protocol like TCP, which is delay sensitive, the packet delivery performance can still be improved by applying the proposed routing protocol. This simulation result shows that the proposed routing protocol can even be applied to improve PDRs for delay sensitive applications under certain conditions.

V. CONCLUSIONS

In this research, we propose a holistic routing protocol to handle packet losses caused by different mechanisms in MANETs. Unlike traditional solutions that focus more on solving a single cause of packet loss, the holistic routing protocol can efficiently recover lost packets due to transmission failures, link failures, and network congestion.

This routing protocol takes advantage of the multicasting nature of wireless communications to improve the effectiveness of individual transmissions. Approaches for next-hop forwarder discovery and lost-packet recovery are integrated in the routing protocol. Data packets are pushed towards the destination node at each hop, although the transmission paths for data packets may be different.

The holistic routing protocol is independent to neighbor lists, which are hard to maintain in MANETs with dynamic topologies. Thus, the holistic routing protocol is easier to implement in MANETs than some existing solutions, such as ExOR, MAC layer anycast, and GeRaF, which also try to use the multicasting nature of wireless communications to improve the reliability of packet transmissions.

In order to handle packet losses caused by link failures and network congestion, the holistic routing protocol applies the joint decision-making mechanism, which allows for competition among all forwarding candidates who receive a broadcasted data packet. The packet-transmission reliability is improved by applying the holistic routing protocol as compared to using such traditional ad-hoc routing protocols as AODV and DSDV. This phenomenon has been demonstrated in stationary ad-hoc networks with unreliable links, MANETs with reliable links, as well as MANETs with unreliable links.

The timeout-triggered retransmission mechanism is also applied in the holistic routing protocol to recover data packets and some control messages lost to transmission failures. In addition, by using the timeout-triggered retransmission mechanism, the reliability of the holistic routing protocol is compatible with MAC-layer ARQ mechanisms to handle packet losses caused by transmission failures. Simultaneously it can handle packet losses caused by link failures and network congestion, which is impossible for MAC-layer ARQ mechanisms. The improvements of using the timeout-triggered retransmission mechanism in terms of the PDR have been demonstrated in simulation results.

VI. ACKNOWLEDGMENT

This research was financed in part by a grant from the Commonwealth of Pennsylvania, Department of Community and Economic Development, through the Pennsylvania Infrastructure Technology Alliance (PITA).

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