Fuzzy Routing in Ad Hoc Networks

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Abstract

Routing and related resource allocation issues present special challenges in ad hoc networks. Typically, every node in an ad hoc network serves as a router for other nodes, and paths from source to destination often require multiple hops. Compared to wired networks, wireless ad hoc networks have less bandwidth, longer paths, and less stable connectivity, all of which render routing protocols from wired networks less suitable for the wireless world.

This paper presents a novel routing scheme for ad hoc networks that applies fuzzy logic to differentiated resource allocation, considering traffic importance and network state. Messages are routed over zero or more maximally disjoint paths to the destination: important packets may be forwarded redundantly over multiple disjoint paths for increased reliability, while less important traffic may be suppressed at the source. The performance of fuzzy routing is evaluated using simulation, and is compared to DSR and SMR wireless routing protocols.

1. Introduction

Mobility, constrained bandwidth, and (in some cases) limited power present difficult challenges to the architects of a routing strategy in wireless ad hoc networks. A good routing protocol must balance quality of service (e.g., delay and reliability of packet delivery) with consumption of network bandwidth and computing resources. In mobile ad hoc networks (MANETs), routing is further complicated by the need to construct and maintain multihop routes in the presence of dynamic connectivity.

An ad hoc mobile network is an autonomous collection of mobile hosts connected by wireless links with no fixed infrastructure. Mobile hosts are free to move randomly and organize themselves arbitrarily, which can cause the network's topology to change dramatically and unpredictably. The rate of topology change, and thus the rate and volume of routing protocol reaction, may be quite dramatic in some ad hoc networks.

Routing may be considered as two distinct processes: route discovery and packet forwarding. In wired networks, bandwidth is high and network topology is relatively static, compared to MANETs; as a result, wired networks typically employ proactive protocols such as OSPF [1] that strive to maintain a consistent picture of network connectivity throughout the routers in the network so that the next hop for an arriving packet can be computed quickly at each router.

The lower bandwidth and more dynamic connectivity in MANETs, by contrast, favors on-demand route discovery protocols [2, 3, 4], in which paths are found reactively, often by flooding a route request. Routes found in this way are then reported back to the packet source, which appends the route (an ordered list of intermediate nodes) to each packet as a source route. This can eliminate the need for routing tables at the intermediate nodes.

When a path from source to destination is known, packet forwarding is a straightforward task: a packet arriving at a router is simply forwarded to the next-hop node along that path. “Multipath” routing algorithms in ad hoc networks have been proposed in several research studies [5, 6, 7, 8, 9, 10]. The meaning of *multipath routing* in this context is the discovery and use of multiple paths from source to destination, which can increase robustness to mobility and fading. Most of these protocols send each packet via a single primary route to its destination; if that route is later determined to be unusable, the packet will be re-routed via an alternate path without the need for a new route discovery phase.

The existing MANET multipath routing algorithms do not address a broader sense of the term *multipath routing*: the possibility of sending some packets via multiple paths simultaneously when the cost in bandwidth and power is justified by the importance of those packets. As a further generalization of packet forwarding, we also consider the option of forwarding packets via neither one nor many paths, but via no paths: i.e., discarding some packets. Packets are dropped as needed in the Internet today when router queues overflow. We are interested in the benefits of preemptively discarding lower-precedence traffic before it enters the network, thereby reducing congestion and making deliberate decisions about which traffic to drop when discards are necessary.

It is intuitive that when a network is operating well below its capacity there will be little need for redundancy in sending important packets or for preemptively dropping less-important packets. These special measures are needed only when the network is becoming congested. Thus, a mechanism for sensing network status and a robust control scheme will be required if we are to make effective use of the new options of sending packets via zero or many paths.

In the research reported here, fuzzy control is applied to the dynamic allocation of network bandwidth based on message precedence and network status, with a goal of increasing the precedence-weighted performance of MANETs carrying multiple-precedence traffic.

2. On-demand MANET routing protocols

On-demand routing protocols determine routing for each new message. Route maintenance is invoked if this routing fails before the end of the message. Two of the key on-demand, source-routing protocols are described here: Dynamic Source Routing (DSR), proposed by Johnson and Maltz [4], and Split Multipath Routing (SMR) proposed by Lee and Gerla [9].

The DSR route discovery process is initiated when a host cannot find a route to the destination in its route cache. The source node broadcasts a route-request packet that names the traffic destination. Intermediate nodes may reply if they have a cached route to the destination; otherwise, each node rebroadcasts the request, appending its address to the recorded route in the header. This flood continues until either the destination or an intermediate node with a cached route is reached, whereupon a route reply is returned to the source.

SMR is somewhat similar to DSR in its route discovery protocol, in that it floods a route-request packet throughout the network. However, replies from cache are not used in SMR; only the destination is permitted to reply to route-requests, and the destination identifies not one but two *maximally disjoint* paths from the source node. When the destination receives the first SMR route-request packet from a source, it sends a route-reply packet through that shortest delay path. It then waits a specified time to receive more route-requests to learn all possible routes; and selects a second path that is maximally disjoint from the first. In SMR, the destination sends each route back to the source through the first-discovered route. The source splits data traffic over the two paths for load balancing, and can fall back to using only a single path (without re-starting route discovery) if one path fails.

3. Fuzzy logic wireless multipath routing

The fuzzy routing protocols presented here find a *maximal* set of disjoint paths from source to destination, and then employ a fuzzy logic controller to determine how to use those paths to carry the traffic. Two fuzzy routing approaches are introduced here: Fuzzy Logic Wireless Multipath Routing (FLWMR, pronounced “floomer”), which uses the number of hops in a path as its metric, and Fuzzy Logic Wireless Load Aware Multipath Routing (FLWLAMR), which uses aggregate packet backlog along the path as its metric.

As an example route discovery mechanism for fuzzy routing, we generalize SMR to find *all* available disjoint paths. In principle, fuzzy routing could employ either proactive or on-demand route discovery mechanisms.

3.1 Route discovery for FLWMR

In fuzzy logic wireless multipath routing (FLWMR), when a source host wants to send a message to a destination, FLWMR first calls upon the local fuzzy logic controller to determine whether to drop the message (see 3.4).

If the decision is to send the traffic, FLWMR uses a variant of the SMR route discovery process. It floods the network with route request packets (RREQ) to explore multiple paths to the destination. When an intermediate node receives a RREQ, it appends its ID and rebroadcasts the packet. The intermediate nodes forward any duplicate RREQ packets that arrived from a different node than the node from which the first RREQ was received and whose hop count is not larger than the first received RREQ. As in SMR, intermediate nodes are not allowed to send RREPs back to the source, to ensure that the destination receives all RREQ packets.

When the destination receives the first request packet, it records the entire path and returns a route reply (RREP) packet to the source via that path. The destination then waits for a programmable time to receive other RREQ messages in order to discover additional routes that are disjoint from the first one. As the destination identifies new maximally disjoint routes it sends each route’s information to the source via that route. Note that the selected maximally disjoint paths are not required to be of equal length.

Figure 1 depicts the route discovery flood from the source node S to the destination node D, and the resulting paths computed by the destination. Note that all four paths that are available are maximally disjoint.

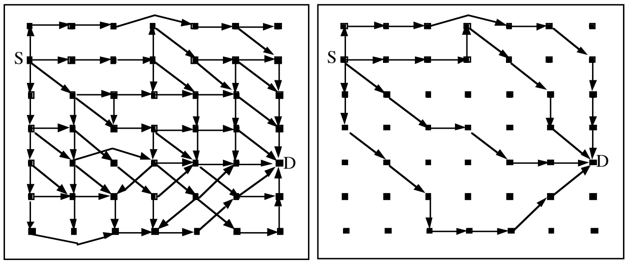

Figure 1: Route discovery

When the source receives the first RREP from the destination, it immediately sends buffered data packets via that path. As additional paths are received they are added to the path pool for use by the fuzzy router.

3.2 Route maintenance for FLWMR

When a node detects a link break, it considers this link as disconnected and it sends a route error (RERR) packet to the upstream direction of the route. The RERR packet contains the route to the source and the immediate upstream and downstream nodes of the broken link. When the source receives a RERR packet, it removes all entries in its route table that use the broken link. Since FLWMR stores multiple routes to the destination, it is not necessary to do route discovery again unless the only remaining route has been broken or the priority of the message needs more routes than the remaining path pool contains.

3.3 Network status

Fuzzy routing protocols consider network status as one factor in making routing decisions. (FLWLAMR [11] also considers the load at relay hosts in selecting routes.) Network status ranges from Excellent (low traffic, less mobility, no congestion) to Poor (high traffic, high mobility, and congested queues). The Fuzzy Routing algorithm monitors the congestion status of active routes and feeds the network status to the FLC in order to make the best routing decision.

The network status is measured as the load at each node's interface, i.e., the number of packets buffered at the interface. Intermediate nodes attached their load information (the number of packets buffered in their interface) to the RREQ packet before forwarding it to their neighbors. When a RREQ is received at a destination, the destination updates its information about the network status by measuring the number of packets buffered in each intermediate node in the network.

The destination calculates the network status using the formula below and sends the network status to the source with each RREP. In the formula, q_i is the most recent queue length at node i and b_i is the buffer capacity at that node.

$$Status = 1 - \left(\frac{\sum q_i}{\sum b_i} \right)$$

3.4 Fuzzy logic controller

Fuzzy logic has been applied in control systems either to improve performance or to avoid difficult mathematical problems. Researchers have recently considered fuzzy logic for bandwidth allocation in broadband networks [12, 13]. We here apply fuzzy control to MANET routing.

Fuzzy logic rules are used in FLWMR to determine whether to route messages through zero, one, multiple, or all available paths in a network. These rules depend on the priority of the messages and the traffic congestion in the network. For example, if we wish to discard low-importance messages when the network is congested, we would include a rule: **If** message precedence is **Routine** AND network status is **Poor** THEN **Discard** the message.

The Fuzzy Logic Controller (FLC) has two inputs: message precedence and network status, and one output: the routing decision.

The rules are expressed in Mamdani form:

$$R_i\text{: IF } \mathbf{x} \text{ is } A_i \text{ and } \mathbf{y} \text{ is } B_j \text{ THEN } \mathbf{z} \text{ is } C_k$$

where **x**, **y** and **z** are linguistic variables representing two process state variables and one control variable (two inputs and one output); A_i, B_j, and C_k are linguistic values (with fuzzy sets specifying their meaning) of the linguistic variables x, y, and z in the universes of discourse U, V, and W, respectively.

A fuzzy logic rule as given above is called a fuzzy association. A fuzzy associative memory (FAM) is formed by partitioning the universe of discourse of each condition variable (A_i and B_i in the above example) according to the level of fuzzy resolution chosen for these antecedents, thereby generating a grid of FAM elements. An example FAM for FLWMR, using four-element fuzzy sets for each input, is shown in Table 1.

Table 1: FLWMR FAM table

Network status	Routine	Priority	Immediate	Flash
Poor	Discard	Multiple	Multiple	Flood
Moderate	Discard	Single	Multiple	Flood
Good	Single	Single	Multiple	Multiple
Excellent	Single	Single	Single	Multiple

The entry at each grid element in the FAM corresponds to a fuzzy action (C_k in the example rule above). A fuzzy associative memory may be interpreted as a tabular representation of a fuzzy logic rule base. When the FAM is presented with input fuzzy sets, max-min compositions are carried out individually for each active element in the FAM, and the corresponding outputs are combined to form the final output fuzzy set. A crisp control output is computed from the output fuzzy set (for details and an example computation, see [11]).

4. Simulation

Simulations of the fuzzy routing protocols were performed using the QualNet simulator [14], a successor to GloMoSim. FLWMR and FLWLAMR, as well as DSR and SMR, were implemented in QualNet for evaluation.

Two scenarios were simulated: (1) the usual "flat" MANET scenario, with all nodes and routers on the ground, resulting in mostly multi-hop paths, and (2) a scenario with airborne routers and mobile hosts, resulting in mostly two-hop paths. Space does not permit further discussion of the second scenario here; for details see [11]. The "flat" scenario, used previously in comparing DSR and SMR [9], has the following characteristics:

- 50 mobile nodes are randomly placed on the ground within a 1000 meter X 1000 meter area.
- Each node has a radio propagation range of 250 meters and channel capacity of 2 Mb/s. A free space propagation model with a threshold cutoff was used. The radio model includes radio capture by the stronger signal.
- The IEEE 802.11 Distributed Coordination Function was used as the medium access control protocol.
- A random waypoint mobility model was used: each node randomly selects a position, and moves toward that location with a speed ranging from just above 0 m/s to 10 m/s. When the node reaches that position, it becomes stationary for a programmable pause time; then it selects another position and repeats the process.
- A traffic generator was developed to simulate a bit rate source. There are 20 data sessions, with randomly selected sources and the destinations. The size of link-layer data payload was 512 bytes.
- Message precedences were randomly assigned according to two profiles: In profile 1, 80% of messages are Routine and 20% Flash. In profile 2, we have Routine 50%, Priority 25%, Immediate 20%, and Flash 5%.

Each run executed for 300 seconds of simulation time.

5. Results and discussion

We compare our simulation results to published results for DSR and SMR in the same scenarios. The metrics used were suggested by the Internet Engineering Task Force (IETF) Mobile Ad hoc Network (MANET) working group for routing protocol evaluation [2]:

- *Packet delivery fraction*: the ratio of data packets delivered to the destination to those sent by the source
- *Average end-to-end delay of data packets*, including buffering during route discovery, queuing delay at the interface, retransmission delay at the MAC, propagation and processing time
- *Normalized routing load*: the average number of routing overhead packets transmitted for each delivered data packet

Two experimental factors (in addition to the choice of routing protocol) were varied in these experiments. Increasing the mobility of the nodes (decreasing the pause time) stresses the route discovery and maintenance functions because routes break more often. Increasing the traffic load, on the other hand, stresses the packet forwarding function and congests the network.

5.1 Packet delivery fraction

Effect of Mobility. Figure 2 illustrates the throughput of each protocol (with 95% confidence intervals) in terms of packet delivery ratio. The message load is constant at 4 packets/sec. Overall, FLWMR and FLWLAMR outperform both SMR and DSR at the 95% confidence level. For high mobility (short pause times), we see that FLWMR outperforms SMR, DSR, and FLWLAMR.

Many data packets are dropped during the DSR route discovery and route recovery. In DSR, only one route is used for each session, and that may be a stale, cached route. As mobility increases, cached connectivity data is of less value, and DSR performance drops.

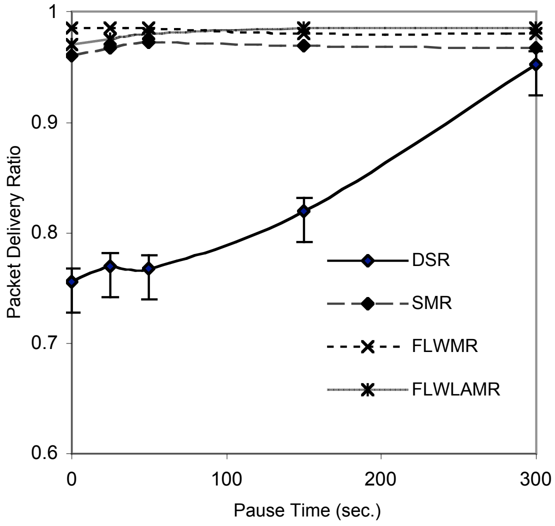

Figure 2: Packet delivery ratio versus mobility

Effect of Traffic Load. When the traffic increases in a network, the network gets congested, more packets are dropped, and the delivery ratio falls. Figure 3 shows the packet delivery ratio of each protocol as a function of load (and priority for FLWMR). Pause time is held constant at 10 seconds. Here, FLWMR outperforms SMR and DSR for Flash traffic at all loads, and for routine traffic except at the highest loading.

FLWMR and FLWLAMR dynamically allocate network bandwidth depending on the priority of the messages and the status of the network. If the decision is to send the message over more than one path, FLWMR and FLWLAMR send the whole message simultaneously over the computed number of paths. However, if the message has less priority and the network status is good (no heavy congestion), the source uses all available paths to balance the load by splitting the traffic into these routes. Many data packets are dropped during the DSR and SMR route discovery and route recovery. On the other hand, FLWMR and FLWLAMR showed better reliability in delivering the high priority messages.

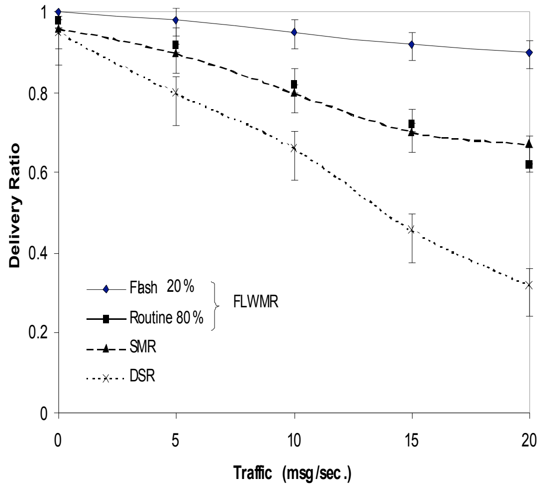

Figure 3: Delivery ratio versus load and priority

The results in Figure 3 illustrate that high priority (Flash) messages have a high delivery ratio that is relatively insensitive to load; thus, important messages are delivered more reliably using FLWMR despite high network loading. The same high priority messages have a lower delivery ratio when using SMR and DSR protocols because these protocols make no special provision for them.

FLWMR provides a lower delivery ratio for routine data packets than SMR at high loads because the fuzzy routing algorithms discard some routine data packets when the network is congested. Nevertheless, the combined delivery ratio (Flash and Routine) for FLWMR is slightly higher than the ratio for SMR.

5.2 Delay

Effect of Mobility. Figure 4 shows the average end-to-end delay for the four protocols (with 95% confidence intervals), which includes time to find and recover routes, in addition to packet transit time. Delay is measured from the time a message is generated until the message first arrives at the destination.

In general, the more routes known to a protocol, the lower its average delay will be, due to increased time between route reconstruction. DSR has the longest average delay in mobile scenarios because it uses the first route reported back, which may be longer than optimal due to caching. In addition, DSR suffers more frequent delays for reconstructing routes and the period of time the data packets are buffered at the source during route recovery results in larger end-to-end delays. FLWMR and FLWLAMR on the other hand, used all passable routes (more than one) while SMR uses only two routes.

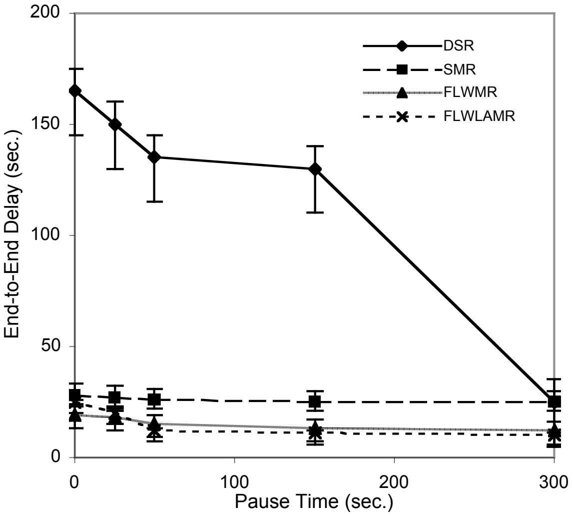

Figure 4: Delay versus mobility

Effect of Traffic Load. Figure 5 illustrates the performance of FLWMR in a scenario with all priorities of traffic present, (Traffic Profile 2). Note both the excellent performance provided for the most important traffic and the smooth degradation of performance for all classes of traffic as the load increases.

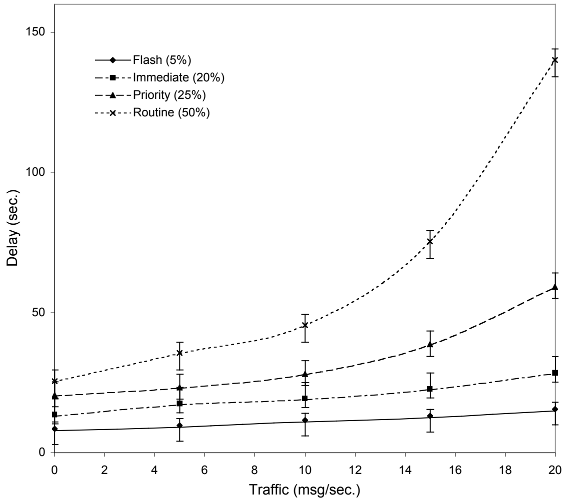

Figure 5: Delay versus load and priority