Adaptive Multi-path On-Demand Routing in Mobile Ad Hoc Networks

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Abstract

We present AMOR, a new scheme for on-demand routing in wireless ad hoc networks. In ad hoc networks, mobile nodes are connected to each other such that the connection pattern changes dynamically with the mobility of nodes. Therefore, classical table driven routing algorithms [1–6] necessitate updated network state information to be periodically disseminated, and incur significant costs in terms of network utilization, memory, and associated update-processing [7]. In contrast, on-demand routing algorithms do not maintain pre-computed routes and real time route discovery ensues when data traffic needs to be transmitted between a source-destination pair.

AMOR employs a modified version of the Dynamic Source Routing protocol [8] to discover multiple node-disjoint paths between a source-destination pair. A key feature of AMOR is that instead of computing minimum-hop paths, it computes paths such that a measure of the 'transmission reliability', namely ETX, between the source-destination pair is optimized. Furthermore, AMOR employs a real time loading algorithm that optimally load balances traffic across multiple paths. The control traffic overhead in AMOR is comparable to that of single-path on-demand protocols. We present analytical throughput results in a simplified AMOR model of a network of multi-radio nodes. We also conduct simulation experiments to study the throughput performance of the AMOR scheme in a network of single-radio nodes. Our results show that AMOR outperforms the traditional Dynamic Source Routing algorithm.

1 Introduction

Wireless ad hoc networks are characterized by the absence of a fixed topology and lack of a centralized control. The absence of an infrastructure implies that the network must configure and organize itself, in real time, while supporting of individual node mobility. Ad hoc networks are important in the context of areas where cost or logistical issues preempt the deployment of a communication infrastructure. Such networks are attractive for tactical communication with military and law enforcement applications [4] as well as situational awareness in difficult terrain, and search and rescue operations [9]. Possible commercial applications include delegates communicating at convention centers, etc. Not all pairs of mobile nodes are in direct transmission range of each other. Therefore, ad hoc networks employ a store and forward mechanism, whereby network nodes also act as routers and relay traffic between communicating pairs not within direct wireless transmission range of each other.

'Multi-hop' paths are discovered when network nodes participate in an ad hoc routing protocol. Thus, such participating nodes form their own network 'on the fly'. Issues that surround the choice of the ad hoc routing protocol include the control traffic overhead, storage requirements, optimality of computed routes, energy efficiency and fault tolerance [10]. Traditional routing protocols are proactive as they rely on link-state or distance vector algorithms, and entail that each node maintains routes to all other network nodes irrespective of the existence of traffic between the communicating pair. Topology change information must be propagated across the network to ensure the validity of the routes maintained at each node. Node mobility in ad hoc networks implies that classical table driven routing protocols [1–6] necessitate updated network state information to be periodically disseminated, and incur significant costs in terms of network utilization, memory, and associated update-processing [7]. Therefore, table driven protocols do not scale well to large networks. In contrast, on-demand routing algorithms do not maintain pre-computed routes and real time route discovery ensues when traffic needs to be transmitted between a source-destination pair. This results in scalable control traffic overhead [7].

We present an Adaptive Multi-path On-demand Routing scheme, AMOR, which employs a modified version of the Dynamic Source Routing (DSR) protocol [8] to discover multiple node-disjoint paths between a source-destination pair. A key feature of AMOR is that instead of computing minimum-hop paths, it computes paths such that a measure of the 'transmission reliability', namely ETX, between the source-destination pair is optimized. Precisely, we minimize the cumulative average transmissions (including retransmissions) required for a packet to travel from a source to a destination. Furthermore, AMOR employs a real time loading algorithm that load balances traffic across multiple paths. The control traffic overhead in AMOR is comparable to that of single-path on-demand protocols. We present analytical results for throughput in a simplified AMOR model of a network of multi-radio nodes. We also conduct simulation experiments to study the throughput performance of the AMOR scheme in a network of single-radio nodes. Our results show that the revised path selection metric and multi-path extensions embodied in AMOR outperform the traditional Dynamic Source Routing algorithm.

The rest of the paper is organized as follows: In Section 2 we explore the traditionally employed 'minimum-hop' metric and discuss how the ETX metric [11, 12] results in the discovery of high throughput paths. Section 3 details multipath routing and its associated advantages. In Section 4, we present AMOR, which includes a description of the multipath and ETX metric extensions to DSR. Section 5 gives the details of our adaptive loading algorithm along with the analysis and results for both the multi-radio and single-radio cases. Finally, our conclusions follow in Section 6.

2 Path Selection Metric

Traditionally, both reactive and proactive routing algorithms tend to minimize the number of hops between a source-destination pair. Prior research has indicated the shortcomings of such minimum-hop routing [11–15]. The following discussion enumerates some of the deficiencies of minimum-hop routing in wireless ad hoc networks.

Protocols that use minimum-hop routing assume that the probability of transmission errors on links between two adjacent nodes only takes extreme values, i.e., either the link is working with a negligible transmission error probability or it is completely absent. Although this assumption holds for wired networks, it is not necessarily true for wireless networks. In a wireless network, the link loss ratios vary significantly across different links. Traditional minimum-hop routing algorithms ignore this variation. A link is part of a route between a source-destination pair if it can successfully carry control traffic, even though its link loss ratio may be inadequate for data traffic. This phenomenon is particularly observed in quasi-static multi-hop wireless networks where minimum-hop protocols can include wireless links between distant nodes. Minimizing hop count results in maximizing the loss ratio as the effective distance between nodes increases resulting in a decrease in the average signal strength. De Couto et al. [11] quantified this hypothesis and demonstrated that on-demand routing finds paths with significantly lower throughput than the best available. High link loss ratios across intermediate links require packet retransmissions at the data link layer and, therefore, reduce overall path throughput and have the added disadvantage of interfering with other network traffic.

A specific performance disadvantage of minimum-hop routing transpires when network nodes have multiple radios. Draves et al. [12] detail two scenarios to illustrate this phenomenon. Consider a network where each node is equipped with a 802.11a and 802.11b radio. Since, the transmission range of 802.11b is greater, minimum-hop routing entails that data will be transmitted over the slower 802.11b links increasing latency and lowering throughput. Furthermore, consider a network with radios tuned to different channels. A two-hop path, chosen by the minimum-hop routing algorithm, with both links traversing the same channel may have significantly lower throughput than a three-hop path that traverses different channels.

De Couto et al. [11] suggest the use of the ETX metric, with the objective of selecting routes with high end-to-end throughput. The ETX metric is designed to account for [12]

a) a wide range of link loss ratios,

b) existence of links with asymmetric loss ratios, and

c) interference between successive hops of multi-hop paths

The ETX metric quantifies the loss rate of a packet across a wireless link. It measures the expected number of transmissions required for a packet to travel across a single hop. The ETX for a multi-hop route is the cumulative ETX of all the hops that constitute the route. ETX assumes the probability of packet loss to be independent of its size. Moreover, it assumes that packet loss events are independent and identically distributed, such that the number of actual transmissions made to send a given number of packets follows a negative binomial distribution [11, 13].

3 Multi-Path Routing

On-demand protocols in ad hoc networks typically involve routing data over a single path. Single-path routing implies that, at any given time, all data traffic between a source-destination pair traverses a unique path, discovered during the *route discovery* process of the routing algorithm. The selected path is optimized with respect to the specific path selection metric employed by the routing algorithm. However, there is a case for splitting the data traffic between a source-destination pair across multiple routes. Such load balancing has been extensively deployed in both circuit-switched and packet-switched networks. The use of multipath routing in ad hoc networks has been limited [16]. A major inhibiting factor is the control traffic overhead that is incurred as a result of the discovery and subsequent maintenance of multiple routes. However, multi-path extensions to on-demand routing protocols exist that keep the control overhead low. The next section details such an extension to the popular DSR algorithm.

Multi-path routing provides a significant advantage in improving the overall throughput between a source-destination pair. Where more than one equal cost multi-paths are discovered, the traffic between a source-destination pair may be load balanced across the entire set of routes. Such load balancing is also desirable when costs of the discovered paths vary. The challenge of a load balancing algorithm is to arbitrate the fraction of traffic that traverses each path, such that the overall throughput is maximized.

Furthermore, multi-path routing represents an enhanced level of fault tolerance in comparison to its single-path counterpart. Mobility of network nodes and poor wireless link quality often result in disconnection of routes. The multiple routes employed in multi-path routing make it robust to route disconnections. Secondly, single-path routing schemes rely on propagation of a route error message back to the source upon link or node failure, which in turn causes the source to initiate route discovery once again. This results in significant switch-over latency upon link and node failure in case of single-path routing. In multi-path routing the switch-over problem is reduced to redistributing traffic traversing the failed route across the remaining routes. This minimizes the switch-over latency in the event of network failure, thereby increasing overall throughput and decreasing end-to-end delay.

4 Adaptive Multi-Path On-Demand Routing

In this section we detail the AMOR scheme. We show how extensions [11, 16] to the popular DSR protocol [8] enable us to perform multi-path routing where routes are computed using the ETX metric. In addition, we present the adaptive loading algorithm that dynamically assigns traffic to the node-disjoint routes discovered by our modified DSR algorithm. We consider two cases: when the nodes employ multiple radios tuned to different channels, and when a single radio is present at each node. In the former case, a simple AMOR model is analyzed, while a simulation model is used for the latter case.

4.1 Path Selection Metric Extension to DSR

The highlight of the Dynamic Source Routing (DSR) protocol [8] is that the packet header carries the entire route. In order to transmit a packet to another network host, the sender constructs a source route in the packet's header that includes the address of each intermediate node through which the packet would pass to reach the destination. Each node, upon reception of a data packet checks if it is the intended destination. If not, it simply forwards the packet to the next hop identified in the source route. The packet is, therefore, forwarded hop by hop until it reaches its destination.

The routes are originally constructed on-demand, using the route discovery mechanism of DSR. Each network node maintains route caches and cache entries are updated as new routes are learnt. Route discovery is initiated by the source node and entails broadcasting a route request packet seeking a route to the destination. The *route request* packet has the following fields:

1. address of source node,
2. *route record* containing the sequence of hops taken by the *route request* packet as it travels through the network, and
3. a unique *request id* set by the source node from a locally maintained sequence number.

Upon receipt of a *route request*, a node does the following:

1. If the pair $\{$*source node address, request id*$\}$ for this *route request* is found in this host's list of recently seen requests, the packet is discarded. This preempts the possibility of a duplicate request propagating in the network.
2. If the receiving host's address is already listed in the *route record* of the *route request* packet, the packet is discarded, thus eliminating the possibility of routing loops.
3. If the target of the *route request* is not the receiving host, then the receiving host appends its address to the *route record* and re-broadcasts the *route request* packet.
4. Otherwise, if the receiving host is the destination of the *route request* query, then the *route record* contains the path from the source to the destination. This *route record* is copied from the *route request* packet and sent back to the source in the *route reply* packet. The *route reply* packet traverses the route in the reverse direction. Thus, intermediate nodes along the route may update their caches corresponding to the *route reply* packet.

Route failure occurs when repeated attempts to transmit a packet over a link fail and the retry counter is exhausted. Such a failure results in the generation of a *route error* packet which backtracks to the source. The *route error* packet erases all routes in the route caches of intermediate nodes along its path. In order to transmit additional traffic between the source-destination pair a fresh route discovery must be initiated. The normal DSR, like other on-demand routing protocols, selects the shortest path found from a source to a destination. We modify this path selection criterion and make DSR use ETX for path selection. This is facilitated by means of a simple change. Whenever a node forwards a *route request*, it not only appends its address but also the ETX metric for the hop over which it received the *route request*. These metrics are sent back to the request initiator and the cumulative ETX of all the hops that constitute a route may be computed by the source. The ETX corresponding to each hop and path is computed as detailed in section 4.3.

4.2 Multi-Path Extension to DSR

We adapt our multi-path extension to DSR from that of Nasipuri et al. [16]. Our multi-path extension discovers a node disjoint set of paths between the source-destination pair. The original protocol is altered such that the destination replies to only a selected set of route requests. Since *route request* packets are flooded throughout the network multiple copies of the *route request* may arrive at the destination via different routes. The destination replies to the first *route request*. For all subsequent *route requests* copies corresponding to the pair $\{$*source node address, request id*$\}$, the destination node checks whether the source route of the new request is node-disjoint from requests that it previously replied to. Thus, the destination node replies to a *route request* if and only if the intersection between the set of all intermediate nodes in the *route record* of the request and the set of intermediate nodes of the route records of previously replied to requests yields the empty set. This mechanism ensures that the multiple paths discovered by the route discovery process are internally node-disjoint. The reason for doing so is twofold. A single link or node failure may affect a maximum of one route, and hence the node-disjoint paths represent a higher level of fault tolerance. More importantly, selecting node-disjoint paths implicitly lowers the control traffic overhead [16] by limiting the number of replies, and thus preventing a reply flood.

4.3 Modelling Path Error Probabilities

A successful transmission entails successful delivery of a packet from the sender to the receiver and receipt of an acknowledgement from the receiver. When the acknowledgements function at the MAC layer, the probability that a single-hop transmission is successful is the product of probabilities that the forward transmission and the acknowledgment transmission is successful. If $p^{(h)}$ is the probability of failure on a single-hop, then:

$$p^{(h)} = 1 - (1 - p_f) \times (1 - p_r) \tag{1}$$

where p_f is the packet loss probability at the data link layer in the forward direction from source to destination, and p_r is the packet loss probability in the reverse direction. We numerically estimate p_f and p_r in terms of ETX which, implicity captures the packet size in its computation. The ETX provides a short term running average of the number of transmissions taken to successfully send a packet. This number is a Geometric random variable with a mean given by $\frac{1}{1-p^{(h)}}$.

In a wireless ad hoc network, a typical path from source to destination consists of multiple hops and traverses intermediate nodes. The probability of a path failure can be analytically computed from the packet error probabilities on each hop along the path. For example, for a path i with m hops, the probability of path error is given by:

$$p_i = 1 - \prod_{j=1}^{m} (1 - p_j^{(h)}) \tag{2}$$

Since the metric extension to DSR specified in Section 4.1 specifies that the ETX corresponding to each hop is included in the route record, the source can compute the overall path ETX and uses it to estimate a numerical value of p_i.

Once the path ETX is computed, we no longer consider the number of hops within a path since that notion is implicitly included within the path ETX. Thus, two separate paths with equal ETX are regarded as equivalent, irrespective of their number of hops. Towards this end, we assume that a path is completely characterized by its error probability. Thus, we use:

$$ETX_i = \frac{1}{1 - p_i} \tag{3}$$

$$\implies \quad p_i = 1 - \frac{1}{ETX_i} \tag{4}$$

Since the source can communicate with the destination over multiple disjoint paths established as outlined in section 4.2, we may define the relative path failure probabilities as:

$$p_i^* = \frac{ETX_i}{\sum_{i=1}^{N} ETX_i} \tag{5}$$

where N is the total number of paths found. As explained in section 2, route discovery may result in multiple route reply packets to propagate back to the source, where each reply corresponds to a node-disjoint path. However, the exact number of paths found between a source-destination pair is a function of the exact geographical location of the network nodes at the time of route discovery. Since, node mobility is a random process, the total number of node-disjoint paths is non-deterministic. Therefore, the source node does not wait for all paths to be discovered, and starts transmitting data as soon as the first route is computed. However, subsequent route replies may arrive at the source. Furthermore, mobility may cause some established paths to become disconnected. Thus, we need an adaptive algorithm to send data over a varying number of disjoint paths.

5 Adaptive Loading Algorithm

5.1 Multi-Radio Nodes

We first consider the case when each node has multiple radios that are tuned to different channels. Therefore, a node can simultaneously transmit multiple packets. The node disjoint paths discovered by AMOR act as multiple bandwidth channels increasing the end to end throughput. The adaptive loading algorithm for the multi-radio case uses the path ETX parameter, introduced in section 2, and the path error probabilities computed from the path ETX parameter, as explained in section 4.3. The distribution of a given amount of data, intended to be communicated from the source to the destination, into multiple streams or parallel channels is called loading. The loading of disjoint paths depends upon the packet error probabilities for those paths.

We consider a constant bit rate per path with fixed modulation schemes and no rate adaptation at the physical layer. Each node transmits at a constant bit rate R on each of the N parallel paths by using N of the possible radios . Assume that D is the total amount of data units to be transmitted from a source to a destination, and D_i is the amount transmitted on the $i-th$ path. Thus, $D = \sum_{i=1}^{N} D_i$. The time, T_{CBR}, for transmitting the complete data D after loading it onto different paths is given by $T_{CBR} = \max(T_1, T_2, \ldots, T_N)$, where T_i is the time it takes to successfully transmit data D_i on the $i-th$ path.

The goal is to load different paths with data D_i, such that the each path is used, on average, for the same period of time. Thus, ideally no path should be idle when data is being transmitted along any other path. There are two cases to consider:

1. When T_i values are deterministic, i.e., when ETX depicts the exact number of retransmissions, we have $T_i = \frac{D_i}{R} ETX_i$. The time T_{CBR} is minimized when $T_i = T_j \; \forall \; i, j$. Under this condition, $D_i ETX_i = D_j ETX_j$.

2. When the path ETX values depict the average rather than the actual number of retransmissions, T_i is a random variable drawn according to a negative binomial distribution with parameter $\frac{D_i}{R} ETX_i$ and failure probabilities as given in section 4.3. In this case, we need to judiciously select D_i such that T_{CBR} is minimized. A heuristic solution is to equate the average values of T_i, i.e., $T_i = T_j \; \forall \; i, j$. Since T_i is modelled as a negative binomial random variable, we have:

$$\overline{T_i} = \frac{D_i}{R(1 - p_i)} \tag{6}$$

where we assume that the path error probabilities are computed according to Eq. 4. Equating the finish times for each stream, we get:

$$\frac{D_i}{R(1 - p_i)} = \frac{D_j}{R(1 - p_j)} \tag{7}$$

$$D_i = \frac{1 - p_i}{1 - p_j} D_j \tag{8}$$

Solving for D_j, when the probabilities of Eq. 4 are used,

$$D_j = \frac{1 - p_j}{\sum_{i=1}^{N} (ETX_i)^{-1}} D \tag{9}$$

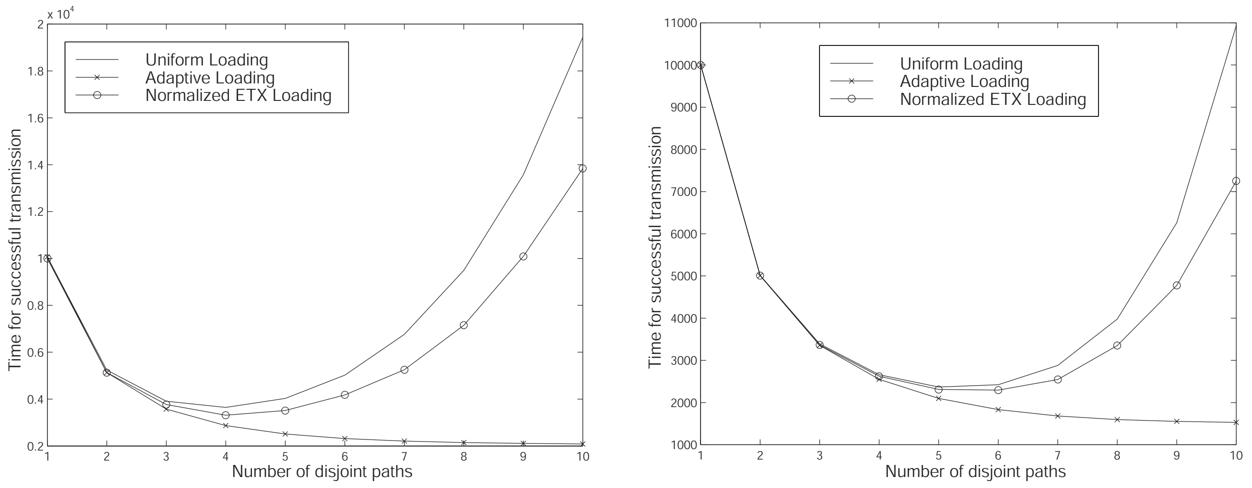
If the error probabilities of Eq. 5 are used, we can solve for D_j as:

$$D_j = \frac{1 - p_j^*}{N - 1} D \tag{10}$$

We consider an ad-hoc network spanning a region of 500 × 500 units having 6 nodes and assume that each node has a transmission range of 300 units. This network (node density = $\frac{6}{250000}$; range = 300 units) results in an area density that provides a connected network with high probability. Figure 1(a) depicts the performance of multi-path routing under various loading algorithms for the this network. For each data point shown on the graph, the ETX values for the $i - th$ path are generated from the probability of finding at least i paths given that $(i-1)$ paths have been found. These probabilities are generated from the node density and transmission range as given in [17]. We note that the adaptive loading algorithm for AMOR results in significantly improved throughput. Figure 1(b) shows similar results for a network of 15 nodes in a 2500 × 2500 area with a transmission range of 1200 for each node.

5.2 Single-Radio Nodes

We now consider the scenario wherein each node has a single radio. In this case, instead of using the adaptive loading algorithm as described in section 5.1, we use a simpler heuristic in our simulations. Each D_j (data transmitted on the $j-th$ path) is selected in inverse proportion to ETX_j. We use OPNET to simulate the control traffic overhead and throughput performance of AMOR. The DSR Model, available in OPNET [18], is modified so that it can also simulate two variants of the DSR algorithm: a) one that uses



(a) node density = $\frac{6}{250000}$; range = 300

(b) node density = $\frac{15}{6250000}$; range = 1200

Figure 1. Performance of various loading algorithms for multi-radio, multi-path routing.

the ETX metric for path selection (ETX-DSR), and b) the adaptive multi-path on demand routing (AMOR) algorithm proposed in Section 4. The typical metrics used for comparing ad-hoc routing protocols are data throughput, control message overhead, end-to-end delay, storage overhead, and energy efficiency [19–22].

We simulate an ad-hoc network with the same node density of $\frac{6}{250000}$ and range of 300 units as in Figure 1(a). Node mobility is simulated using the popular random waypoint mobility model [21]. Initially, nodes are placed randomly in the region. Each node then chooses a random destination within the region and moves towards it at a constant speed that is uniformly distributed between 0 and 3. When a node reaches its destination, it pauses for a constant time interval, chooses another random destination, and then moves toward the new destination at a constant speed. The mobility model with the above parameters emulates pedestrian movement.

We use the IEEE 802.11 protocol working in the DCF mode at the MAC layer. However, OPNET's implementation of 802.11 does not incorporate beacons in the ad-hoc mode. Since the ETX metric uses such beacons for its probe messages, we modified OPNET's implementation to accommodate beacon transmissions. The data packets are transmitted at a rate of 5.5 Mbps. Management and control packets are transmitted at the basic rate of 1 Mbps. As explained in Section 4.3, a packet is considered to be correctly received if the sender of the packet is within range of the receiver, and successfully receives the acknowledgment for the transmitted packet. The maximum number of link layer retransmissions (both long and short) is 7, after which the packet is dropped. RTS and CTS are deactivated. We use UDP at the transport layer since TCP would offer a load conforming to network load perception [21], and its own retransmission scheme would obscure the effects of the ETX metric. Among the 6 nodes, two are chosen to run a video conferencing application between them for 10 minutes. The traffic between the communicating nodes was generated from an uncompressed constant bit rate video stream with a frame-size of 128×120 pixels and frame-rate of 10 frames per second. All other nodes generate background traffic and send the traffic to randomly chosen destinations. The inter-arrival time of the background packets is exponentially distributed with a mean of 0.5 seconds and a constant packet length of 512 bits.

We ran simulations for the three different routing protocols: standard DSR, ETX-DSR, and the proposed AMOR. In the standard DSR case traffic is routed on the minimum-hop path. The second case, ETX-DSR, uses the optimal path in terms of reliability as signified by the ETX metric for data transmission. The last case is for AMOR where traffic is dispersed on multiple node-disjoint paths between a source-destination pair. Figure 2 illustrates the throughput attained in the simulations for the three routing schemes. The graph supports our earlier hypothesis that distributing traffic over multiple paths results in increased throughput. The average throughput of AMOR, at around 5 Mbps, is higher than that of ETX-DSR or standard DSR that have the average throughput between 4.5-4.7 Mbps and 4.0-4.5 Mbps respectively.

6 Concluding Remarks

We have presented an Adaptive Multi-path On-demand Routing (AMOR) mechanism in mobile ad hoc networks. Multiple paths obtained in the route discovery phase are used for data delivery from the source to the destination.

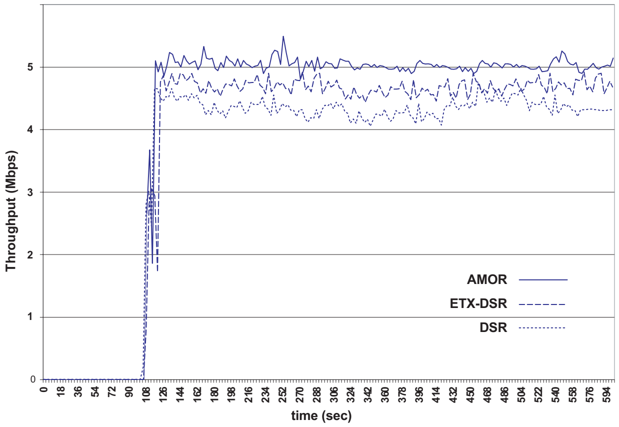


Figure 2. Throughput of DSR, ETX-DSR, and AMOR using the random waypoint mobility model with single radio nodes.

A new loading algorithm is proposed that optimizes the distribution of data onto multiple reliability constrained paths. The algorithm requires knowledge of path error probabilities that are numerically obtained from the ETX metric. As new paths are discovered and/or previous paths cease to exist the loading distribution is recomputed in real time. Our analysis and simulation results confirms the claim that minimum hop count is not the best measure to judge the quality of a path.

AMOR, in comparison to DSR, has an additional control message overhead during the initial route discovery phase. This is due to the multiple route reply messages that are generated for the disjoint multiple paths. However, as described in section 3, the multiple routes in AMOR provide multiple points of failure making multi-path routing more robust to route disconnections. In the event of link or node failure, DSR and ETX-DSR need to re-initiate route discovery, resulting in generating control message traffic and significant switch-over latency. In AMOR, this switch-over problem is reduced to redistributing the traffic scheduled on the failed route over the remaining routes. Therefore, when the probability of path disruption is high, i.e. higher mobility conditions, AMOR will have lesser control message overhead than its single-path counterparts.

The multiple paths of AMOR include paths that have a greater number of hops than the shortest path of DSR or the minimum ETX metric path of ETX-DSR. However, in the multi-radio case, AMOR partitions the traffic onto multiple paths such that the data reception at the destination from each path is expected to be completed at the same time. Hence AMOR has the better throughput characteristics as demonstrated by the results. Moreover, for both the multi-radio and single-radio nodes, in high mobility scenarios when path disruptions are frequent, AMOR has smaller average end-to-end per packet delay in comparison to the other two protocols.

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