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Towards Reliable Mobile Ad Hoc Networks

Ricardo Lent and Javier Barria
Imperial College London
United Kingdom

1. Introduction

It is expected that future networks will interconnect an even larger number of devices then today, ranging from servers to micro-devices embedded in objects. These devices will provide useful services thanks to the possibility of a networked operation, for example, localization services to support a variety of situation-aware applications. A very significant number of these devices will be carried by users-on-the-move. While a wireless infrastructure could serve to provide a near permanent network access to these devices, structural network dynamics and service demand patterns could impact the main features of the solutions relying on this network.

Mobile ad hoc networks (MANETs) may serve to bridge these devices to the network in situations where a connection to a wireless infrastructure may not be feasible or desirable because of coverage limitations, network failures, congestion, policies, or cost. MANETs can be quickly created for a wide variety of applications and whenever needed to operate on virtually any environment. A main feature of a MANET is its self-organizing ability over a network that is assumed by temporarily linking each mobile with other nodes within wireless coverage. In this situation, nodes can serve as routers, at least temporarily, to forward packets for other nodes. One of the main technical drawbacks of these type of networks is that the network tends to change quite often. Nodes may arrive at or depart from the network without notice and direct node-to-node communication may or may not be possible at any given time due to node mobility and changes on the surrounding environment. These characteristics determine a highly dynamic network that makes difficult a reliable forwarding of packets on multi-hop routes over long periods of time. Communications tend to be very unreliable and inefficient, because a route break not only disrupts immediately a communication, but also can introduce additional overhead into the network because of the potential need for retransmissions and re-routing operations.

In this chapter, we discuss a feasible approach to obtain improved routing reliability on a MANET. The approach consists in identifying and using links with the most availability to setup and maintain routes. Link availability is related to the residual lifetime of links, which can be calculated from various sources, including signal power, packet transit times, or nodes' location and moving trends. We focus mainly on the latter possibility as localization services are becoming widespread for mobile devices and the trend is expected to continue in the future. In particular, we explore the case where the localization services are provided by a sensor network purposely deployed to track mobile nodes. Most of the ideas discussed in this chapter are widely applicable to the other cases as well. A simulation-based evaluation under realistic assumptions suggests that the proposed routing approach can significantly improve MANET routing reliability, in particular, for highly dynamic networks.

2. Related work

MANETs are subject of intensive research and many works have been devoted to research their properties and operation (1). Some of the principal works that have explicitly addressed MANET reliability, or are in close relation to this discussion, are mentioned below. The list is not intended to be exhaustive, but representative of the related work previously done.

A possibility that have been explored by various authors is on the selection of the longest-lived links to create stable paths. These works are based on the observation that most randomly moving nodes are likely to drift apart from one another over time (2), so that their main assumption is that a link between two nodes that had survived for a significant long time would be unlikely to change any time soon and so, the link could be classified as stable. In fact, even in static networks wireless links may fail (3; 4; 5). In the *Associativity Based Routing* (ABR) (6), a link lifetime is measured by counting the number of beacons received from neighboring nodes and the links associated with the highest beacon counts are preferred. In the *Signal Stability Adaptive Routing* (SSA) (7), routes are created by giving preference to the selection of strong connected nodes. Nodes are classified as strongly or weakly connected on the basis of their signal strength as measured from beacons, which are exchanged periodically between neighboring nodes. McDonald and Zanti (8) investigated a clustering approach for MANETs and the probability of two nodes remaining within a distance threshold of one another over time.

Another possibility for stable routing is to select links based on estimations of the future network state, as done by Su et al. (10; 11) and a previous work (9). In the *Route Lifetime Assessment Based Routing* (RABR), the average change in received signal strength is calculated and used to predict the time when a link would fail (12). A similar approach is used to define link affinity and path stability metrics from the received signal strength (13). A statistical approach was proposed by Gerharz et al. (14; 15) based on observations of link durations for various mobility models. On the other hand, the network availability as a whole can be improved by avoiding routing traffic through nodes with a low remaining energy (16; 17).

On the definition of adequate metrics for describing a path reliability or link availability, a probabilistic measure was introduced (18) to help in the selection of stable paths. A prediction-based link availability calculation was also proposed and used to develop a metric for path selection in terms of path reliability (19). An approach to evaluate the signal strength variations between neighbors has also been proposed (20).

Most works estimate link lifetimes based on the signal strength of beacon packets or by using the nodes location acquired with a GPS receiver. The beaconing scheme relies on knowledge of a radio propagation model to associate a signal loss to a travelled distance (31). The free space propagation model is commonly used (21) and beacons are transmitted with the highest power level (22). However, the fluctuation in signal strength of the transmitter as perceived by the receiver may not depend only on distance in practice (23). Hence, the distance estimation between transmitter and receiver based solely on signal strength may not be accurate (13). On the other hand, the GPS scheme could produce better distance estimations between nodes (24). However, there are some drawbacks in using GPS receivers. The use of GPS receivers implies an extra power consumption to the nodes and an extra implementation cost, and in some cases the reception of GPS signals may not be possible, for example in some indoor locations or under adverse weather. It is interesting to mention that node localization can also be used to route packets to a given geographic area (25; 26; 27).

An alternative to the use of GPS receivers is to use a sensor network (28; 29; 30; 32) to track and localize mobiles. A practical example is the Cricket Indoor Location System (33) which can provide fine-grained localization information including coordinates and orientation. An optimal sensor network structure would have the minimum number of sensors activated at a particular time (coverage problem) to transmit a minimum amount of acquired data (information accuracy problem). The concept of coverage is environment dependent and is subject to a wide range of interpretation, but in the more general case can be considered as the measure of QoS of a sensor network. A definition of the coverage problem from several points of view including deterministic, statistical, worst, and best case is presented in (34). In (35) the tolerance of a sensor network against both random failure and battery exhaustion from the viewpoint of stochastic node placement is evaluated. In (36) a strategy is presented that maximizes the coverage of the most vulnerable regions under surveillance as well as maintaining an average coverage. In (37) the aim is to optimize the number of sensors and determine their placement to cope with constraints of imprecise detection and terrain properties (i.e., number of sensor vs. miss probability). In (38) the miss probability that quantifies the likelihood that an active sensor fails to detect the mobile target using a low beam sensing radius is studied. Self-organized sensor networks have also been proposed in (39). And in (40) a self-organizing technique for enhancing the coverage of wireless micro-sensor networks after an initial random placement of sensors is proposed.

The other important aspect that could affect sensor networks usefulness to MANET routing relates to the level of information accuracy and error incurred by the sensors' measurements. In this respect, density and structural characteristics, and data acquisition and fusion strategies of the sensor network are relevant. An overview of an information-driven approach to sensor collaboration in ad hoc sensor networks is presented in (41). The idea is that the network should be determined by dynamically optimizing data utility for given communication and computation costs. In (42) the tradeoff relating to sensor accuracy and energy consumption of a grid infrastructure is studied. In (43) the problem of optimal sensor selection and fusion is solved with a Bayesian framework under the tradeoffs of low-power consumption and collaborative information processing, while in (44) energy-quality tradeoffs for target tracking in wireless sensor networks is studied.

3. Model

We assume a mobile ad hoc network (MANET) where wireless nodes communicate using a common broadcast channel by omni-directional antennas. A MANET can be represented by an undirected graph $G = (V, E)$, where V expresses the set of vertices (nodes) and $E \subseteq V \times V$ the set of edges (wireless links).

In this model, we assume that nodes have the same transmission range and so, the graph is undirected: $(u, v) \in E \Rightarrow (v, u) \in E$, i.e., nodes are *neighbors* and it is possible a communication in either way although not at the same time. In more detail, the radio signal encoding a packet sent from a node u with a power level P_t may be received and decoded (with a certain probability) by another node v as long as the reception power $P_r > P_s$, i.e., it is above the *receiver sensitivity* P_s. All nodes $v \in (V - u)$ for which this condition is true are neighbors of u. The set of neighbors of u is denoted by N_u.

The value of P_s is determined by the characteristics of the radio receiver and the communication bit rate. On the other hand, P_r depends on P_t and the path loss, which in turn depends on the distance between nodes and the surrounding environment.

The location vector of node i is denoted by $L_i = (x_i, y_i, z_i)$. In a MANET, the location of each node is not constant. Please note that we omit time indices to improve notation clarity. We assume initially that nodes can learn their location vector precisely. However, the routing algorithm discussed later tolerates localization error.

Each node is identified with a unique number and all its packet transmissions bear this number. Likewise, packet transmissions carry either the identifier of the destination node or broadcast. Note that although packets can carry the destination's identifier, transmissions are done as a physical broadcast, so all neighbors will in fact receive the packet even so it could be intended for a particular node. When a packet is received by a node although not intended to it, the packet is normally discarded at its link or routing layer. Also, the link layer (a MAC protocol) is assumed to resolve media contention by temporal channel reservation, which can be done for any non-broadcast addresses.

G is a function of time. V may change over time because node departures or arrivals to the network, which may occur at any time without notice. E may change as a consequence of node mobility, variations in the surrounding environment, and changes in V.

While it is possible to communicate neighbors with a single transmission hop, a packet transmission between non-neighbors must be relayed between neighbors for a number of steps. Any path is a sequence of vertices that the packets of a particular flow must visit to be delivered: $p = v_1 \rightarrow v_2 \rightarrow . . . \rightarrow v_k$. The condition for the path to be feasible is that $(v_i, v_{i+1}) \in E, 1 \leq i < k$, that is, each hop must be between neighbors. We denote the set of all possible paths between two nodes s to d by Π_{sd}.

A flow f represents a data communication and is expressed by the tuple $f = (s, d, b)$, where $s, d \in V$ are the source and sink of the flow and b the sending rate. We assume routing on demand, so for the purposes of this discussion, routing is the process of associating a flow to a path, i.e., $R : (f, G) \rightarrow p, p \in \Pi_{s,d}$.

3.1 Link lifetime

Link lifetime (also known as link duration) has been suggested previously as a metric to determine stable (long living) paths in ad hoc networks to replace the hop count metric commonly used and which is implicitly approximated by the use of standard flooding. A link's lifetime can be estimated from the receiving signal strength, packet transmission times, or from the distance and mobility trends of nodes, as either a probabilistic or deterministic value.

The lifetime of a path is concave and limited to the lifetime of the weakest link among the ones composing the path. For path $p = v_1 \rightarrow v_2 \rightarrow \cdot \cdot \cdot \rightarrow v_k$ and link lifetime function $\Phi : (v_i, v_{i+1}) \rightarrow \Re$, the lifetime Φ_p of path p is:

$$\Phi_p = \min_{(u,v) \in E_p} L(u,v)$$

In this work, we are interested in expressing link lifetimes in deterministic terms calculating them from the nodes' location information. Localization services for mobiles are becoming widespread, so it makes sense to explore their use to improve MANET routing for future networks. In particular, we look at the use of the *link residual lifetime*, i.e., the remaining time for a link before it is expected to fail rather than the link age (as done in ABR, SSA, etc.), which do not necessarily perform well in all cases.

The residual link lifetime between two neighbors i and j of interest can be calculated from their current separating distance $|D_{ij}|=|L_i - L_j|$, $i \in N_j, j \in N_i$ and their relative speed D'_{ij} :

$$\Phi = \frac{D_m - \alpha |D_{ij}|}{|D_{ij'}|} \quad ;|D_{ij'}| > 0$$

where D_m is the maximum wireless coverage (can be estimated apriori from the properties of both radio transceivers and the surrounding environment).

Φ provides an estimate of the link's time to break when nodes move and diverge. If nodes tend to converge, $\alpha = -1$ allows to add the convergence time to the expected divergence time. Otherwise, $\alpha = 1$. Note that the function is undefined at $|D'| = 0$ (when nodes move in parallel). This situation can be handled as a special case (with a low value) when defining a cost function for routing purposes.

3.2 Localization

The basic assumption is that nodes can learn their own location in a three-dimensional space precisely through an external mechanism. Various alternatives exist to let mobile nodes acquire their location. The Global Positioning System (GPS) is a navigation satellite system that provides physical location information free-of-charge to any GPS receiver, but requires line of sight to at least four of the 24–32 GPS satellites. The information accuracy depends on various factors and could range from 5 m to 100 m in civilian receivers. Another possibility is through trilateration, which allows a node to determine its location from measurements of the transmission time from at least three known references. In contrast, an external system could be deployed to implement hyperbolic positioning (multilateration), which can determine the location of a node by using three or more receivers and computing the time difference of arrival of signals emitted by the node of interest. Multilateration is used by GSM systems and so it is of particular interest for implementing ad hoc network of smart mobile phones. Another alternative is to use a system with antenna diversity, where nodes' location can be determined by triangulation. These localization techniques could be implemented by the mobiles themselves of by an external system, such as the sensor network that we consider in this study.

Regardless of the method used, the localization system that is used would provide periodic updates to each mobile informing them of their relative or absolute coordinates. The mobiles will then estimate their location whenever needed from the data available, for example, from their calculated velocity vector and the previous location update. Note that the length of time between location updates can determine the accuracy of the location estimations. The impact of using imprecise information to MANET routing will be addressed in the simulation study discussed in a later section.

4. Problem formulation

The problem is to find the most durable path p^* from s to d for each flow f:

$$p^* = \underset{p \in \Pi_{sd}}{\operatorname{argmax}} \, \Phi_p$$

By selecting the most durable paths for the flows, less path repairs would be needed, which implies less protocol overhead and a better use of the nodes' energy.

4.1 Evaluation under ideal conditions

To support the idea, we conducted a simulation study to find out the average route lifetime on a mobile ad hoc network to determine whether there would be any reliability improvement over flooding (calculated as the shortest path) with the use of either the oldest links or the links with the longest residual lifetime metrics. The simulation was done at the topology level and assuming ideal conditions, which imply that links are determined solely based on the distance between nodes and that route calculation can be done with full knowledge of the location of nodes and their mobility patterns. Although these assumptions do not hold in practice, the results would suggest the best metric from a route reliability standpoint. We defer to a later section the use of more realistic assumptions.

Nodes move according to the random waypoint point (RWP) model without pause times and at a given speed that is randomly selected in the range [1, *S*]. Nodes move on a rectangular field of 400 × 100 units, all with equal wireless coverage of 50 units. For each simulation instance and after a suitable time (2.5 simulated hours) to let the statistical properties of the RWP model emerge, a route is established between two randomly selected nodes. Routes are established with either a hop count, link age, or link residual lifetime criterium. The results are depicted in Figure 1 for all three cases as a function of the maximum moving speed of the nodes. The plots also indicate the 95% confidence interval resulting from the Monte Carlo simulations.

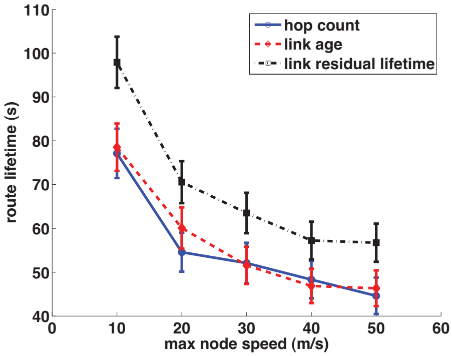

Fig. 1. Average route lifetime with ideal wireless transmissions: radio coverage only limited by the distance between nodes.

From the results, the use of link residual lifetimes clearly produced the most reliable routes. However, these routes tend to be longer than the shortest path (Figure 2).

5. A distributed solution: LDR

In a MANET, it is normally impractical to acquire global information about the network state (such as the nodes' location) to drive routing decisions. We discuss a distributed algorithm to allow each source independently find durable paths on demand with only local information. We call the algorithm *Link Durability Routing* (LDR) and has the following properties:

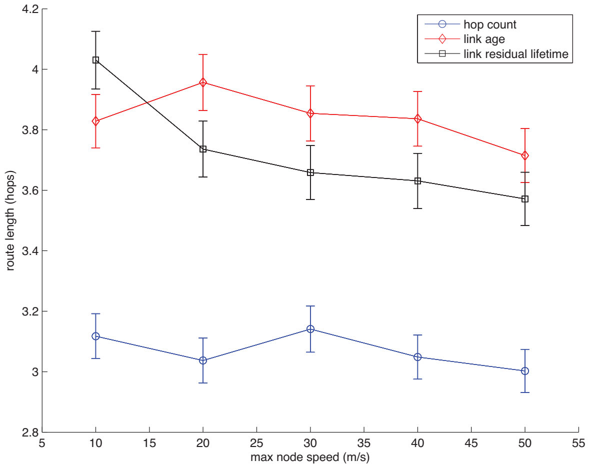

Fig. 2. Average route length (hops) with ideal wireless transmissions.

- LDR uses a modified flooding algorithm, but introduces decisions and actions at each iteration based on the residual lifetime of each link as calculated from local information. Route selection is distributed and not bounded to the source or destination nodes.
- In case localization becomes available partially to some nodes or not available at all in the network, LDR can continue to work, but it would produce less optimal routes.
- Clock synchronization among nodes is not needed.
- Active paths are periodically monitored by piggybacking information into selected data packets, so that preventive re-routing can occur in addition to reactive re-routing in the case of a route failure.
- The algorithm can be incorporated into existing flooding-based MANET protocols (e.g., AODV (45), DSR (46)). However, we will discuss the algorithm in the context of an independent protocol (LDRP), given that some particular operations available in other protocols are not needed, for example, HELLO beacons for neighbor discovery.
- LDR could also enhance the performance of other location-based protocols. For example, it could be used to extend LAR (47) or GPSR (48) to achieve improved route durability in addition to reduce the search area for routes.

5.1 Route setup

As mentioned above, LDR relies on a modified flooding algorithm to discover routes. The standard flooding algorithm is of common use by many on demand ad hoc routing protocols and works as follows. Whenever a new route to a destination is needed, the source broadcasts a route request message. The message indicates the desired destination and a message identifier, in addition to other pieces of information that could be relevant to each particular algorithm. The identifier and origin addresses of the message allows intermediate nodes to discern new from replicated requests, so that they can select to process only the first arrival of each request. If the node receiving the request if not the destination, the node will append its own address to the packet (and possibly other pieces of information depending on the actual protocol being used) and broadcast again the message without delay. On the other hand, if the receiving node's address matches the destination of the route request, the node will respond to the source with a reply message that will list the path used by the route request to reach the destination. The message is forwarded along the reversed path.

If the destination is reachable, there is a high probability that one of the copies generated by the process will eventually reach the destination. The path produced by the process will tend to the shortest path in number of hops, although, network congestion may induce longer routes.

5.2 Link selection

To implement a selection mechanism that will discern links based on their residual lifetime to allow setting up durable routes, we introduce a decision mechanism that is executed at each node participating in a route discovery process.

With standard flooding, each node receiving for the first time a route request message broadcast immediately the message to its neighbors. In LDR, a route request in retained at each node for a certain time before doing a new broadcast. By making the retaining time inversely proportional to the durability of the preceding link, LDR can delay the messages traveling on the less desirable routes and favor the best route request replicas (so, those traveling on the most durable links) to reach first the destination. Before the node re-broadcast the request, it will continue processing other route request arrivals sharing the same request identifier. However, each node will at most broadcast one request per route request ID as in the standard flooding algorithm. Since the destination replies only to the first arriving route request, a robust path will be selected for the flow. We define the route request defer time (δ_{uv}) for link (u, v) as follows:

$$\delta_{uv} = K_0 e^{-K_1 \Phi_{uv}} \tag{1}$$

where K_0 and K_1 are positive scaling constants that are experimentally chosen and Φ_{uv} represents the residual lifetime of link (u, v). K_0 is the maximum defer time that can be introduced to a route request.

The general idea is similar to the one developed by Cheng and Heinzelman (2), but with a different defer function. Also, our approach introduces the monitoring of active routes so that preventive re-routing can occur before a path breaks. If no localization is available, LDRP assumes $\delta = 0$, so that request will be broadcast without delay. LDR on a network without localization would produce results identical to standard flooding.

5.3 LDR protocol

Route selection with LDR is distributed by definition and link selection is implicit by introducing a temporal behavior to the way route requests are handled by nodes rather than by defining a spatial selection of the next hop or by explicitly selecting a route among the choices available at the source or destination nodes.

To calculate the durability of a link, a node requires its current location and velocity vector as well as the vectors from the predecessor node. This information can be easily obtained by augmenting route requests with two fields: `location` and `velocity`. Therefore, in addition to appending its network address, an intermediate node updates these two fields with its own data. Note that these two fields are fixed given that only information from the predecessor is needed and not from the rest of nodes in the path. This procedure allows each intermediate node to obtain fresh information to compute the residual lifetime of links.

After the defer time for a new route request is determined, the message is scheduled at a target time for broadcast or to be delivered to upper layers. The target time is the current time plus the calculated defer time. Note that the defer time is a minimum time that the message is forced to wait in a node. The actual residence time in the node could be longer due to other factors that may occur after the target time, such as queue waiting before transmission. A new route request arrival may replace an existing scheduled message transmission whenever the new target time is less than the existing target time. If the target time for a message is reached, the request is considered processed so any further arrival with the same request id will be dropped.

5.4 Route maintenance

The route setup phase allows to setup durable paths. However, the residual lifetime of each link on a path is likely to change over time as a consequence of node mobility and changes in the operating environment. To reduce the risk of a route break, active routes are periodically monitored by LDRP. For this purpose, selected data packets are augmented to carry the position and velocity vectors of the predecessor node. On arrival of an augmented data path, the node calculates the new residual lifetime of the preceding link. The link would be assumed to be at risk of failure if its residual lifetime is less than parameter `ttb_thr`. If so, a *route information* message will be sent to the source to initiate a preventive re-routing action.

LDRP limits the creation rate (per flow) of control messages, which include augmented data packets, route requests, and route error messages, to place a cap to the monitoring overhead that could be generated. The inverses of the maximum sending rate limits are defined by `rdata_limit`, `rreq_limit`, and `route_error_limit`.

6. Test case: LDR and sensor network for mobile localization

The discussion so far has considered that nodes were able to determine their location accurately. In this section, we evaluate LDR under less favorable assumptions. Furthermore, to enrich the test case we consider that MANET nodes lack a GPS receiver, but that can be localized with the help of a sensor network.

Both the MANET (using LDR) and the sensor network share the same working area but operate nearly independently of each other: MANET nodes route their traffic independently of the sensor's activities and sensor nodes track the location of MANET nodes and pass them the information but unaware of any other MANET activity. MANET nodes use the localization updates sent by the sensor nodes to determine their velocity, so that their location can be calculated when needed. If no updates from the sensors are received within a predefined time, it would be assumed that no localization is available and any new route request arrival will be broadcast without a defer time. Each type of network operates on its own radio channel. However, it is assumed that MANET nodes are able to receive packets from the sensor nodes, so that they have access in fact to both radio channels.

We are interested in observing MANET route reliability, which will be measured in terms of the packet delivery ratio for a test flow. The effect of most factors on packet routing (link failures, congestion, channel contention) are summarized in the packet delivery ratio (and its complement, the packet error ratio). To measure this metric, we consider the packet exchange between two stationary nodes that must relay on mobile nodes to communicate.

The two nodes are located far apart on the test field and are kept stationary to prevent any direct (single hop) communication with their simulated radios. All aspects of LDR have been integrated into a packet-level simulator (49) for this study including support for the concurrent simulation of the two independent wireless networks. Each wireless network was IEEE 801.11 DCF-based at the MAC layer with RTS/CTS enabled only for MANET unicasts. These assumptions produce various sources of localization error for MANETs. Other than the inherent localization error introduced during the sensing phase, MANET nodes can only receive their location estimates at irregular times. To receive a location estimate, a MANET node must be in the vicinity of sensors and their transmissions must be successful (e.g., must not collide). All route reliability measurements will be taken under these less than ideal conditions.

In addition to account for packet transmissions, the simulator also keeps track of the power consumption for communication related tasks (of both networks). The radio transceiver state (transmitting, receiving, sleeping, or idle) is associated with a power consumption as in Table 1.

Transceiver state	Power consumption (MANET)	Power consumption (sensor)
idle	0.035 W	0.0001 W
transmit	(0.532 +Tpwr) W	(0.03 +Tpwr) W
receive	0.395 W	0.0354 W
sleep	0.001 W	3e-06 W

Table 1. Power consumption parameters for mobile nodes and sensor nodes. *Tpwr* represents the transmission power.

The evaluation was done under two cases: obstacle-free and a more realistic obstructed scenario. In all cases, AODV (45) was used as a reference protocol for performance comparison purposes.

6.1 Scenario 1: obstacle-free case

The first scenario consists of 30 MANET nodes (28 mobiles, 2 stationary) that reside on a 300m x 200m field. Mobility is modeled by the random way point model with pause times selected in the range 0 to 10 seconds. The data traffic corresponds to a video stream and is modeled as a single 80 Kbps constant-bit-rate flow of packets. Source and sinks are centered on the field but separated by 200m.

Other simulation parameters were defined as follows. The ideal wireless range is provided as a reference in the table. It is not used in the simulations. Instead, a packet reception is modeled realistically with a probability that depends on the received signal power.

A simulation run consisted in starting node mobility and the video stream, and in measuring the number of packets delivered at the destination plus other relevant observations for 10 simulated minutes. Sensor nodes are placed at fixed random locations to track mobiles within their sensing area. Each τ seconds plus a random jitter to reduce the collision probability, sensors emit their localization results (whenever available). Either 50 or 100 sensor nodes are deployed at the beginning of each simulation run with a τ (average time between sensor broadcasts) of either 10 or 20 s. MANET nodes have two simulated wireless interfaces (one connected to the MANET itself and another to the sensor network). Mobiles listen to the sensor channel and determine their location when needed from observations of their moving trend. The accuracy of the localization will be determined, among other factors, by the sensor density and the probability to remain within a sensor broadcast coverage when a transmission occurs. The expected time between 2 successful receptions of localization broadcasts is depicted in Figure 3 as a function of the sensor node density in the scenario. On the other hand, the location error (ε) is depicted in Figure 4 also as a function of the sensor density.

Parameter	Value
moving speed	from 1to Sm/s
pause times	[0,10] s
Power consumption	Physical layer model
Trans. power (mobile)	Fixed: 8mW
Trans. power (sensor)	Fixed: 2mW
Trans. rate (mobile)	1Mbps
Trans. rate (sensor)	100 Kbps
Ideal wireless range (mobile)	62.82 m
Ideal wireless range (sensor)	31.41 m
max_update_time	10 sec
rreq_limit	0.1
route_error_limit	0.1
K0, K1	0.005, 0.5
ttb_thr	1.0
max_rreq_interval	1.0
update_interval	1.0
τ	10 or 20 sec

Table 2. Simulation parameters used in the test scenario.

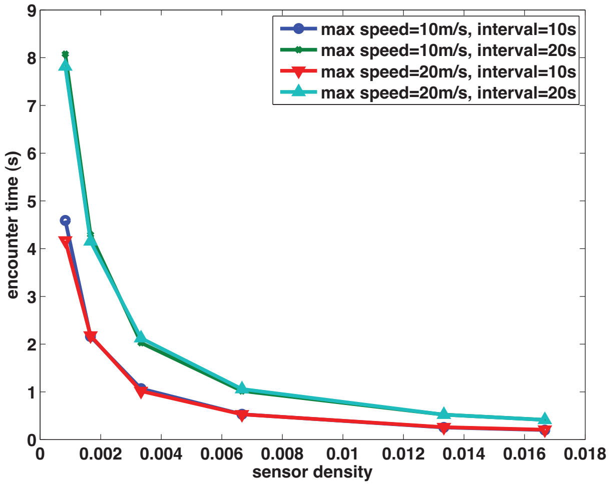

Fig. 3. Expected inter-arrival time between 2 consecutive location updates from the sensor network to any given MANET node.

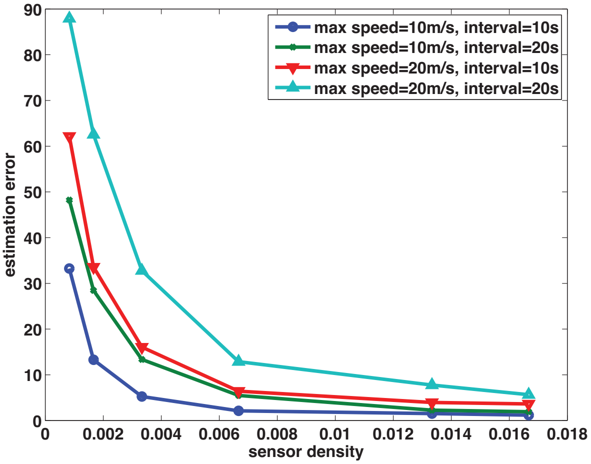

Fig. 4. Localization error of the estimates with respect to the real node location.

For comparison purposes, in the next set of results we include an evaluation of the system when using ideal GPS receivers, which unlike the sensor network case, can provide accurate localization at any time. A large number of runs were conducted to achieve high confidence (confidence intervals were very close to average values, so that there are not shown in the figures for visual clarity).

Figure 5 depicts the average packet loss ratio as a function of the maximum node speed. We naturally observe an increase in the packet error ratio as nodes move faster under all routing cases. LDRP results are labeled as follows: "sn: X I: τ", where "X" indicates the number of sensor nodes and τ the average time interval between sensor broadcasts.

The results suggest that route reliability can be improved with LDRP by exploiting the localization provided by sensors as compared to the standard flooding-based approach of AODV. The improvement is particularly significant when ideal GPS receivers are available to localize nodes. When using a sensor network to localize nodes, the less frequent localization updates produce localization errors than impact route reliability. Nevertheless, the difference between these two cases is small.

On the other hand, LDRP produced longer paths than AODV (Figure 6). The distributed link selection process used by LDRP implicitly takes into account link congestion in addition to link lifetime, given that route requests are transmitted via regular broadcasts. Indirectly, LDRP balances the selection of durable and less congested links. The downside of this approach is that longer paths would tend to increase average packet latency (depicted in Figure 7). However, the increase in individual end-to-end packet latency can be compensated by the reduced number of retransmissions needed to successfully transmit a certain amount of data. The power consumed for communication-related tasks, excluding the power for GPS readings or mobile tracking, is depicted in Figure 8 in terms of the ratio power to throughput. This ratio accounts for the energy required to successfully deliver a certain number of bytes to the destination. The results suggest that LDRP can be more efficient than the standard AODV, even when including the energy costs of the supporting sensor network.

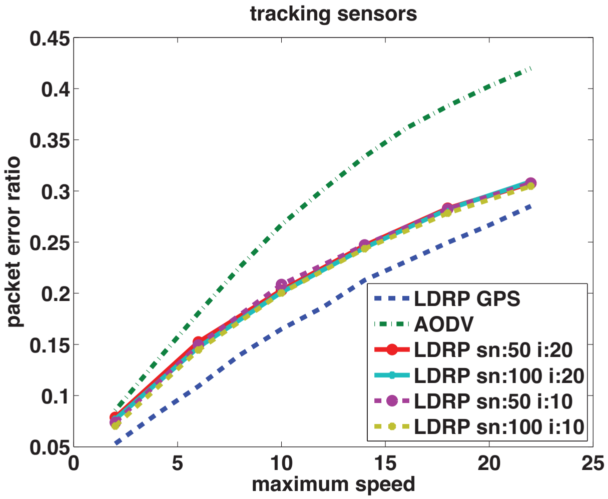

Fig. 5. The packet loss ratio naturally increases in proportion to the maximum speed of mobiles. LDR is tolerant to localization errors but nevertheless the deviations from the real values impact the reliability of MANET paths.

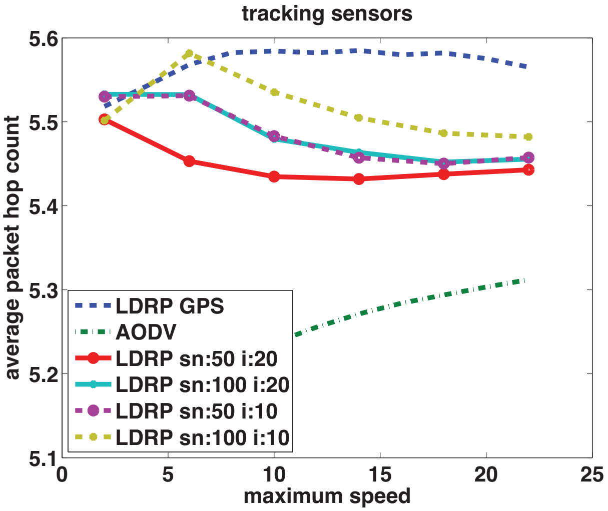

Fig. 6. Average path length in number of hops.

It is interesting to note that localization accuracy when using a sensor network to localize nodes can be improved either by increasing the broadcast rate or by deploying a large number of sensors on the environment. In both cases, there will be an increase in the number of localization update messages arriving at the mobiles, which would result in better location estimates. Figure 9 depicts this situation in terms of the packet delivery rate for the same scenario as a function of the sensor density. The downside of adding more sensors is that the overall energy consumption of the system will also increase as shown in Figure 10.

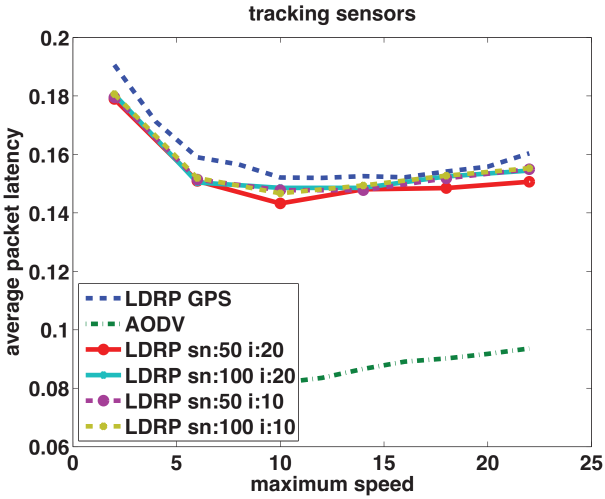

Fig. 7. The reduced need for retransmissions gained from more reliable routing would compensate the higher individual end-to-end latency of packets.

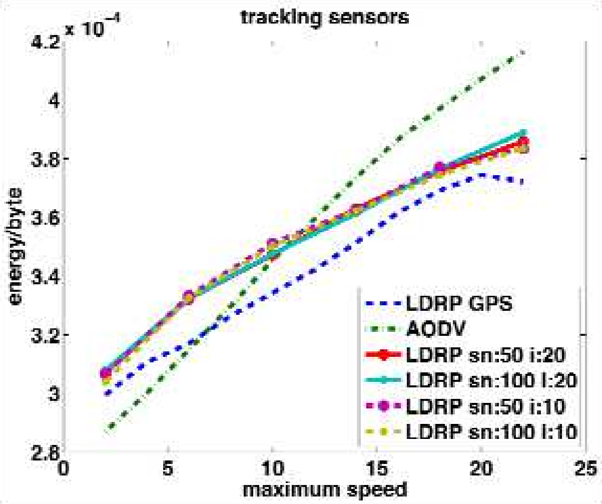

Fig. 8. The power consumption–throughput ratio (Joule/byte) gives an indication of the energetic cost of the network (lower is better).

6.2 Scenario 2: obstructed case

The environment where a MANET operates can affect packet reception leading to a worst routing performance than expected as predicted by the use of ideal unobstructed environments.

To evaluate LDR under more realistic assumptions, we consider the field with obstacles (e.g., buildings) represented in Figure 11. The scenario hosts a hypothetical rescue operation

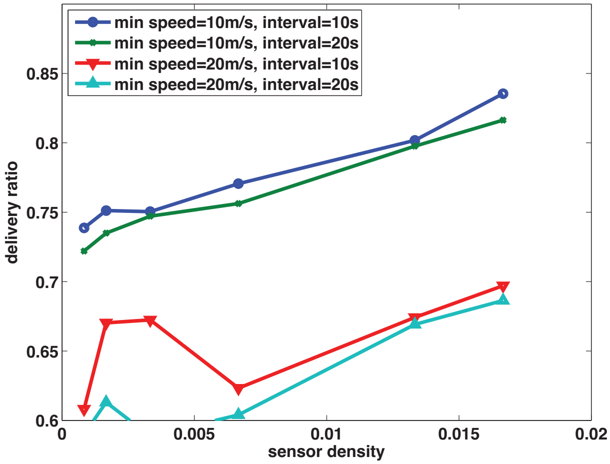

Fig. 9. Delivery ratio as a function of the sensor density (in sensors per square meter) . A larger number of sensors can produce more accurate localization for mobiles, which can directly benefit the reliability of MANET routes.

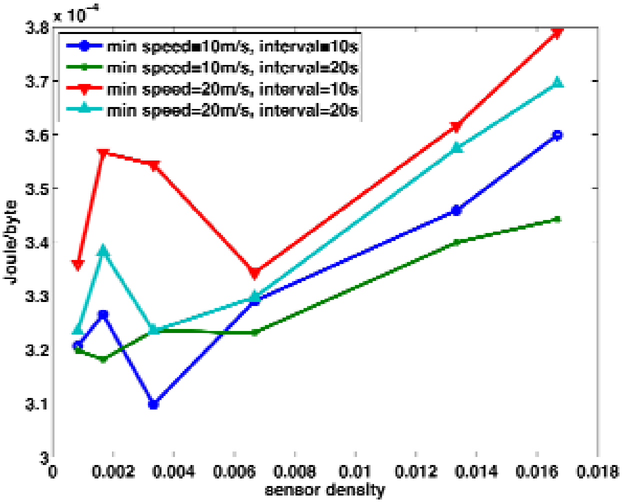

Fig. 10. Energy consumed per delivered byte as a function of the sensor density (in sensors per square meter) in the scenario.

where a number of sensors could have been deployed to gather information relevant for the rescue efforts and at the same time help to localize mobiles. The mobiles on the other hand are carried by the rescuers that need to work on the area.

As in the previous case, we are interested in observing the route reliability of a test traffic flow modeled by a constant bit rate transmission of 40 Kbps between two distant stationary nodes. For this second scenario, we consider 50 MANET nodes (48 mobile) on a 300x200m field. A set of 400 sensor nodes are as well randomly deployed.

Fig. 11. Test case for LDR representing an obstructed simulated field. Sensors are represented by a circular shape and mobiles with a triangular shape.

The field contains a number of different obstacles that may affect both node mobility and packet reception. The field geometry is a (modified) user-contributed model available from Google 3D warehouse. For each packet transmission, the receiving power at each mobile is computed by the simulator. Obstacles that appear on the ray that connects the transmitter and receiver will reduce the receiving power by a pre-determined amount, depending on the predefined obstacle material (concrete walls, wood, etc.) The receiving power determines the probability of a successful packet reception.

On the other hand, node mobility is modeled with an extended random way-point (RWP) model that supports the inclusion of mobility attractors (RWPA). As with the RWP, the destination of each mobile is randomly selected on the field (but not inside an obstacle) and they move at a random speed towards the selected destination. Once they arrive at their destination, mobiles stay there for a random "pause" time before selecting a new random destination to repeat the process. In RWPA, nodes may select with probability p one of the attractors as destination instead of the random destination. If a node decides to move to an attractor, it will move to the point located $\gamma = C + q$ from the attractor (on the line connecting the current mobile location and the attractor location). C is a constant and q is an exponential random variable of parameter Q. γ therefore models how close the mobiles can get to the attractor. In the test case, the attractors represent areas of interest for the rescue operation.

Other simulation parameters are identical to the previous scenario.

Because of the high complexity of this second scenario, we restrict the evaluation scope to a single case of nodes moving with speeds in the range [1, 20] m/s The average packet delivery ratio is depicted in Figure 12.

As with the unobstructed case, path lengths and individual packet latency were higher with LDRP than with AODV (figures 13 and 14). About 5% longer paths and 30–40% higher delay. Finally, results for power consumption indicated similar figures when using AODV or LDRP for this scenario to deliver the same amount of data (Figure 15).

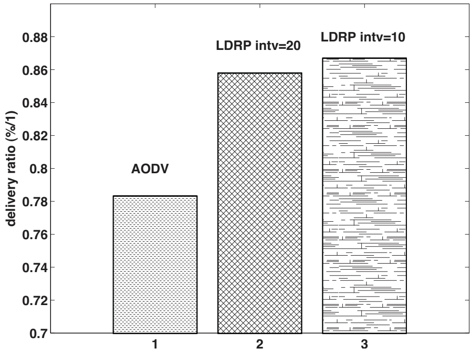

Fig. 12. Delivery ratio of the test flow on the obstructed scenario with nodes moving with speeds from 1 to 20 m/s.

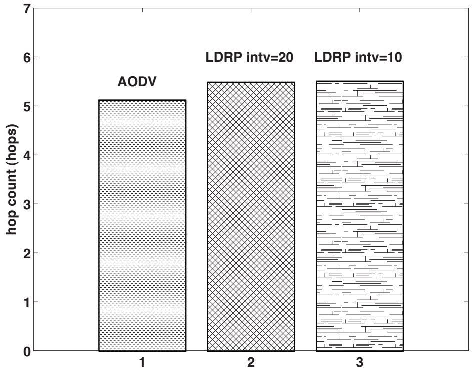

Fig. 13. Path length in number of hops for the test flow between two stationary nodes located at both ends of the test scenario.

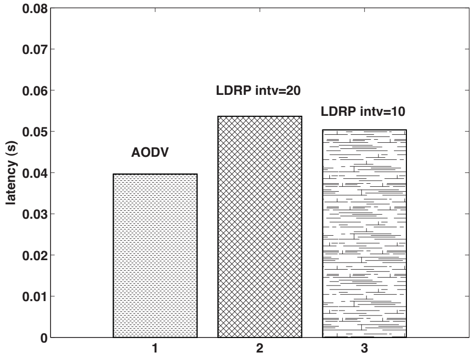

Fig. 14. The individual packet latency is also expected to be higher for LDR in the obstructed scenario.

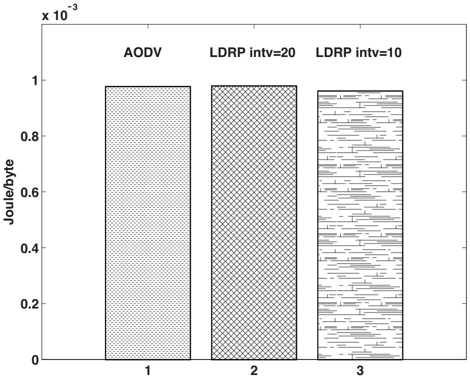

Fig. 15. Energy consumption per byte delivered (Joule/byte)

7. Final remarks

Mobile ad hoc networks can complement existing wireless infrastructure-based networks and bring a plethora of novel services to mobile users. While the lack of need for an existing infrastructure and centralized control, allows MANETs to be quickly created or destroyed as needed, their multihop nature makes them quite sensitive to changes in both the structure of the network and the surrounding environment.

We have discussed reliability issues in MANETs and elaborated on a low-overhead solution to improve the reliability of routes by introducing a mechanism that allows the identification and selection of links with the most availability as measured by their residual lifetime. We have also suggested a realization of the approach whereby the residual lifetime of links are calculated based on node location. We call the algorithm Link Durability Routing (LDR). In addition to a reliable path establishment, the algorithm takes advantage of existing packet flows to constantly monitor the expected availability of links. The algorithm relies solely on local information to operate and without needing a periodic local or global exchange of network information. By means of the continuous monitoring of active paths, LDR can detect paths at risk of become unavailable and enforce preventive or corrective re-routing.

Finally, we have evaluated LDR in the context of a realistic scenario where node localization is acquired from either a GPS receiver of from tracking sensors. The results suggest that path reliability can be significantly increased with the proposed algorithm as compared to a reference case (AODV). The improvement was particularly noticeable in networks where nodes can move at high speeds. While the GPS-based case performed the best in terms of route reliability, the system based on tracking sensor nodes produced results close to the GPS case. On the downside, the routes produced by the algorithm tend to be longer than the shortest path, which could impact the individual end-to-end latency of packets. However, the overall impact to the flows would be small or even non-existing in most cases given that the higher reliability of paths will reduce the need for packet transmissions as suggested by our relative energy consumption comparison results.

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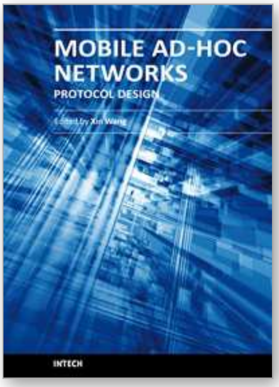

Mobile Ad-Hoc Networks: Protocol Design
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Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of-the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: quality-of-service and video communication, routing protocol and cross-layer design. A few interesting problems about security and delay-tolerant networks are also discussed. This book is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

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Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821