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Improving routing performance through m-limited forwarding in power-constrained wireless ad hoc networks

Guoqiang Wang, Damla Turgut*, Ladislau Bölöni, Yongchang Ji, Dan C. Marinescu

School of Electrical Engineering and Computer Science, University of Central Florida, Orlando, FL 32816, USA

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Abstract

We present m-limited forwarding, a technique to reduce the cost of disseminating information in a power-constrained environment by limiting the cardinality of the subset of nodes which retransmit a packet. We show how this technique can be used to improve the performance of ad hoc routing protocols. m-AODV applies m-limited forwarding to the AODV routing protocol, and is used for networks with symmetric connections. We implemented m-A^{4}LP, a protocol which can take advantage of the asymmetric links found in heterogeneous networks consisting of nodes with different transmission ranges. We quantify the benefits of the enhanced routing protocols and report the results of a simulation study regarding the power consumption of the nodes and the packet loss ratio. We conclude that m-AODV outperforms plain AODV and LAR in general scenarios, and m-A^{4}LP shows a significantly lower packet loss ratio than AODV in heterogeneous networks.

Keywords: Broadcast; m-Limited forwarding; m-AODV; Energy saving

1. Introduction

Ad hoc routing protocols use nodes with limited power reserves for forwarding packets. Most routing protocols disseminate routing information by flooding, a technique which requires a significant consumption of energy and bandwidth.

m-limited forwarding [24] is a technique to reduce the cost of disseminating information in a power-constrained environment by limiting the cardinality of the subset of nodes which retransmit a packet. In case of flooding, the number of messages increases geometrically with the distance from the source while for m-limited forwarding the increase is only linear. In this paper, we analyze m-limited forwarding and report on a simulation study in networks with symmetric and asymmetric links. Our performance studies report on power savings and packet loss for a location-aware mobile ad hoc network.

The paper is organized as follows. Related work is presented in Section 2. Section 3 introduces m-limited forwarding along with two forwarding fitness functions. We also present, m-AODV, a variant of the Ad-hoc On-demand Distance Vector (AODV) routing algorithm [19] that supports m-limited forwarding. Section 4 describes the simulation environment and presents the results of a simulation study and an analysis of the network load, node mobility and node density. The optimal values of m are discussed, followed by a comparison of AODV, Location-Aided Routing (LAR), and m-AODV with two forwarding fitness functions. We also compare m-A^{4}LP using the two forwarding fitness functions with AODV in scenarios with heterogeneous networks. We summarize our findings in Section 5.

2. Related work

Ad hoc routing protocols can be broadly classified as

- *table-driven*, or *proactive*, such as DSDV [18], CGSR [6], DREAM [2], and OLSR [7];
- *on-demand*, *reactive*, or *source-initiated*, such as DSR [11], AODV [19], LAR [13], and TORA [17].

* Corresponding author. Fax: +1 407 823 5835.
E-mail addresses: gwang@eecs.ucf.edu (G. Wang), turgut@eecs.ucf.edu (D. Turgut), lboloni@eecs.ucf.edu (L. Bölöni), yji@eecs.ucf.edu (Y. Ji), dcm@eecs.ucf.edu (D.C. Marinescu).

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In case of proactive routing protocols, nodes periodically propagate routing update advertisements to their neighbors to maintain up-to-date routing information. Routes are immediately available upon request. No periodical route information propagation is required. Proactive protocols are energy inefficient for several reasons: (i) the control message overhead grows quadratically with the number of nodes. The routing advertisement is introduced into the network by frequent system-wide broadcasting; (ii) nodes maintain routes for each destination in the network, which is nearly impossible for most of the nodes in a heterogeneous system [15]; (iii) a considerable fraction of the routes are never used and maintaining them causes unnecessary power consumption.

In reactive routing protocols, a route is discovered on demand when the source needs to send a packet to a destination. Routes are valid only for a limited period, after which are considered to be obsolete. Reactive protocols require less bandwidth and power than proactive ones, but discovering routes on demand lead to higher latency.

Hybrid protocols, such as Zone Routing Protocol (ZRP) [9] combine the features of proactive and reactive protocols. In a hybrid protocol, routes for a subset of nodes are maintained in a routing table proactively while routes for the remaining nodes are discovered when needed.

Location-aware protocols, such as LAR [13] and Distance Routing Effect Algorithm for Mobility (DREAM) [2] use information provided by an attached GPS unit.

LAR is a reactive protocol that makes use of location information during the discovery process to reduce the overhead caused by flooding. LAR allows nodes to forward a packet only if they are located on the path towards the destination. As the location information might be approximate or outdated, instead of point locations LAR defines two zones: the *expected zone* of destination and the *request zone* of the sender. A route request is rebroadcasted only by nodes in the request zone. LAR can be applied in conjunction with existing reactive protocols such as DSR and AODV.

DREAM [2] uses two techniques to reduce the amount of exchanged routing information. The first relies on the *distance effect*: the observation that the greater the distance between two nodes, the slower they appear to be moving with respect to each other. Accordingly, the location information in the routing tables can be updated less often for the nodes farther apart from each other, while preserving the routing accuracy. The second technique requires the nodes to determine their own mobility rate and send location updates more or less often depending on their mobility. Instead of maintaining a routing table of unique next hops for each destination, DREAM forwards packets to a set of recipients it believes to be located in the general direction that guarantees that the destination can be found with a given probability p. The data delivery in DREAM requires a considerable amount of duplicate copies, which consumes a lot of bandwidth and is energy inefficient for networks with high load and/or high node density.

Congestion control schemes [3,10,20] aim to avoid or resolve congestions at a node and divert the traffic to other routes. Boukerche et al. [3] proposed a probabilistic congestion control scheme based on local tuning of protocol parameters for a randomized version of DSDV (R-DSDV). Different nodes can independently determine the routing table advertisement frequency according to probabilities. By reducing the routing table advertisement frequency, the congestion at a node can be resolved as the node reduces the traffic load routed through the node itself probabilistically. In [20], the congestion control problem is addressed as a convex optimization problem with routing and link access constraints, which are described in a network traffic model and a link contention model. The solution is provided via a dual decomposition and sub-gradient algorithm. The scheme proposed in [10] aims to route data packets circumventing congested path so that the traffic load over the network is balanced and the end-to-end delay is lowered. During the route setup stage, the destination selects the path with the minimum nodal activity; congested paths can be avoided as packets are transmitted along the least-active path. In our proposed approach, we aim to reduce the contention and congestion at the locality of a node by limiting the number of nodes to rebroadcast a packet. With the advanced broadcast technique, supported by the m-limited forwarding, the packet delivery fraction and overall power consumption of all nodes are improved.

Low power consumption is critical for wireless communication protocols [12,14]. Many routing protocols select paths to minimize either the hop count or the transmission delay. Nodes along critical paths deplete their power reserves sooner. *Power-aware* routing protocols take into account power consumption when determining a route [21,22,28]. In [1], the authors propose to add a device-type aware into the routing protocol to force the externally powered nodes to forward more traffic and perform additional routing functions than a battery-powered nodes, so that the system lifetime is prolonged.

In this paper, we introduce m-limited forwarding as another approach to increase the bandwidth and reduce the power consumption. In LAR, the sender defines a request zone and all nodes in the zone have the same priority, no matter how reliable they are. m-limited forwarding differs from LAR: the retransmission nodes are chosen not only based on geographical considerations, but based on a fitness function that also considers the reliability and the residual power of the nodes. The size of the retransmission set can also be limited with a proper m.

3. m-Limited forwarding

Maintaining the routing tables of the nodes of an ad hoc network can consume a large fraction of the network bandwidth and require a significant power consumption, especially when high node mobility demands frequent updates and when routing information is disseminated by flooding. Thus, techniques which improve on the dissemination of routing information can significantly improve the performance of the routing protocols.

m-limited forwarding is a technique to reduce the cost of disseminating information in a power-constrained environment by limiting the cardinality of the subset of nodes which will retransmit a packet. In case of flooding, when node j transmits a route update packet, all neighbors within the transmission range of the node retransmit the packet. We wish to limit the size of the subset of nodes which forward the packet to at most m. The nodes in this subset, called *m-forwarding subset* should be the ones optimally positioned vis-a-vis the packet destination node and with the most favorable balance of power. The parameter m must satisfy a subset of sometimes contradictory requirements, e.g., minimize the power consumption, ensure some stability of the routes when the nodes move within a certain area, minimize error rates, and minimize the number of retransmissions.

Whenever a packet is sent from node j to node i the sender of a packet provides a "hint" in the form of a *forwarding cutoff*, $\kappa(i, j)$ which is attached to the transmitted packet. Each node k determines if it belongs to the selected subset by evaluating its own *forwarding fitness function* $\mathcal{F}_k(i, j)$ related to the current transmission and compares the value of this function with the forward cutoff. The node k forwards the packet if and only if its fitness is higher than the forwarding cutoff. If the location of the destination is not known, the sender sets $\kappa(i, j) = -1$ and all nodes will retransmit the packet.

The forwarding cutoff is set such that on average m nodes forward the packet at every hop. The information regarding the position and the residual power of each node in the set may not be very accurate, due to node mobility and to node activity which affects the residual power. As a result, the forwarding cutoff may allow fewer than m nodes to forward, if some have moved away from their location known to node j, or have further depleted their power reserves. The actual number of nodes forwarding the packet may be larger than m if new nodes have moved into the optimal forwarding area, or recharged their batteries.

We assume that none of the nodes attempts to save power by refusing to relay packets. Non-cooperative nodes may affect the proper functionality of the protocol in many ways, as discussed in Section 5.

3.1. Alternative forwarding fitness functions

The forwarding fitness function $\mathcal{F}_k(i, j)$ measures the fitness of a node k as the next hop, where j is the sender and i is the destination. Depending of the definition of "fitness" we can define several alternative fitness functions.

The *distance-based fitness function* $\mathcal{F}^{\mathrm{d}}$ is defined by the following expression:

$$\mathcal{F}^{\mathrm{d}}_k(i, j) = \frac{1}{d_{ik} + 1}, \tag{1}$$

where j is the sender, i is the destination, k is the next hop candidate, d_{ik} is the distance between node i and node k. Note that the function has a value of 1 when the distance to the destination is 0, and is gradually decreasing to 0 as the distance of destination increases.

This function favors the nodes closest to the destination node i and still reachable from node j. This is the optimal choice in a network where all nodes have the same transmission range.

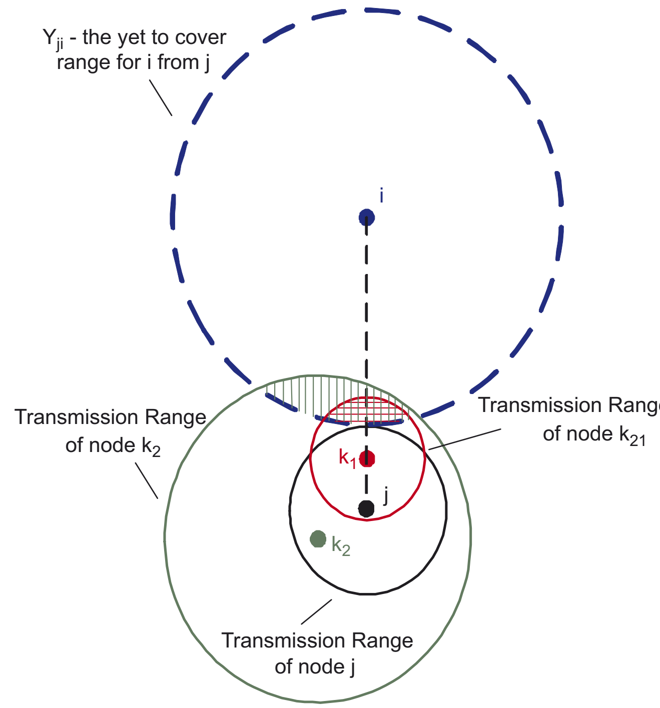

Fig. 1. A configuration including the sender j, the destination i, and two candidate nodes k_1 and k_2 as the next hop on the path from j to i. The circles centered at the current location with the radius equal to the range of these nodes, Π_j, Π_{k_1}, and Π_{k_2} are also shown. The circle centered at the current position of node i and with a radius equal to $d_{ij} - R_j$ is called the "complementary range of j to reach i" and denoted by $\Gamma_{i,j}$. Call $\eta_k(i, j)$ the area of the intersection of $\Gamma_{i,j}$ and Π_k. We see that $\eta_{k_1}(i, j) < \eta_{k_2}(i, j)$.

However, when the nodes have different transmission range, this greedy approach can be suboptimal. To illustrate this, let us consider the scenario in Fig. 1. The scenario contains the sender j, the destination i, and two candidate nodes k_1 and k_2 as the next hop on the path from j to i. The transmission range of the nodes j, k_1, k_2 are circle centered at the current location of the node: Π_j, Π_{k_1}, and Π_{k_2}, respectively. Intuitively, node k_2 is a better choice than node k_1 when routing from j to i, although it is actually in the opposite direction from j; the larger transmission range of node k_2 compensates for its less advantageous geographic location.

Based on this observation, we develop a somewhat more complex *area-based forwarding fitness function* in an attempt to optimize the number of "favorably located" nodes towards the destination reachable from the new node, but not from the current one. We define as "favorably located" the nodes which are closer to the destination than the maximum range of the current node. We assume that the nodes of the network are uniformly distributed, i.e. that the number of nodes in a given area is proportional with the size of the area. This simplifying assumption will be relaxed in the future as discussed in Section 5.

The circle centered at the destination i and with a radius r_{ij} equal to $d_{ij} - R_j$ is called the "complementary range of j to reach i" and denoted by $\Gamma_{i,j}$. Call $\eta_k(i, j)$ the area of the intersection of $\Gamma_{i,j}$ and Π_k. In our example in Fig. 1, $\eta_{k_1}(i, j) < \eta_{k_2}(i, j)$. We will use the *area*$(\eta_k(i, j))$ as the new forwarding

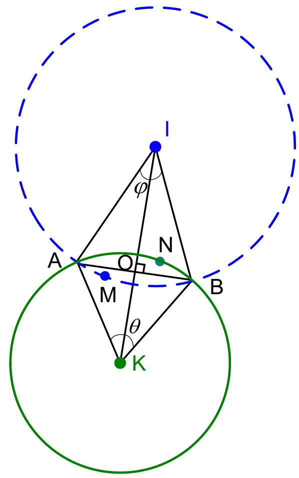

Fig. 2. The area of the overlapping region is the sum of area(ANBO) and area(AMBO). The area(ANBO) is the difference of sector(KANB) and triangle(KAB). The area(AMBO) is the difference of sector(IANB) and triangle(IAB).

fitness function:

$$\mathcal{F}_k^{\mathrm{a}}(i,j) = area(\eta_k(i,j)). \tag{2}$$

In the following, we derive an analytic expression for $area(\eta_k(i,j))$. The relationship between $\eta_k(i,j)$ and Π_k can be *exterior*, *exterior-tangent*, *secant*, *interior-tangent* or *interior*. We notice that interior-tangent and interior cases cannot occur when $\Gamma_{i,j}$ covers Π_k since the center of Π_k is outside of $\Gamma_{i,j}$. In case $d_{ik} \geqslant R_k + r_{ij}$, the two circles $\Gamma_{i,j}$ and Π_k are exterior or exterior-tangent, thus $area(eta_k(i,j)) = 0$. In the case when $d_{ik} \leqslant R_k - r_{ij}$, the two circles $\Gamma_{i,j}$ and Π_k are either interior or interior-tangent, thus $\eta_k(i,j) = area(\Gamma(i,j)) = \pi r_{ij}^2$.

In case $R_k - r_{ij} < d_{ik} < R_k + r_{ij}$, two circles $\Gamma_{i,j}$ and Π_k are secant. In Fig. 2, the area of the overlapping region is the sum of two areas: (1) the area enclosed by arc $\widehat{ANB}$ and line segment $\overline{AOB}$, called *area*(*ANBO*); (2) the area enclosed by arc $\widehat{AMB}$ and line segment $\overline{AOB}$, called *area*(*AMBO*). *area*(*ANBO*) is the difference between area of the sector enclosed by line segment $\overline{KA}$, arc $\widehat{ANB}$ and line segment $\overline{BK}$ and the area of the triangle *KAB*. Denote the $\theta = \angle AKB$, $\varphi = \angle AIB$. By the "law of cosines", $\theta = 2\arccos\left(\dfrac{R_k^2 + d_{ik}^2 - r_{ij}^2}{2\cdot R_k \cdot d_{ik}}\right)$, and

$$\begin{aligned} area(ANBO) &= area(KANB) - area(KAB) \\ &= \frac{1}{2}\theta\left|\overline{KA}\right|^2 - \frac{1}{2}\left(2\left|\overline{KA}\right|\sin\left(\frac{1}{2}\theta\right)\right)\left(\left|\overline{KA}\right|\cos\left(\frac{1}{2}\theta\right)\right) \\ &= \frac{1}{2}R_k^2(\theta - \sin\theta). \end{aligned}$$

Similarly, $\varphi = 2\arccos\left(\dfrac{r_{ij}^2 + d_{ik}^2 - R_k^2}{2\cdot r_{ij}\cdot d_{ik}}\right)$, and

$$area(AMBO) = \frac{1}{2}r_{ij}^2(\varphi - \sin\varphi).$$

Thus, $area(\eta_k(i,j)) = \dfrac{1}{2}(R_k^2(\theta - \sin\theta) + r_{ij}^2(\varphi - \sin\varphi))$.

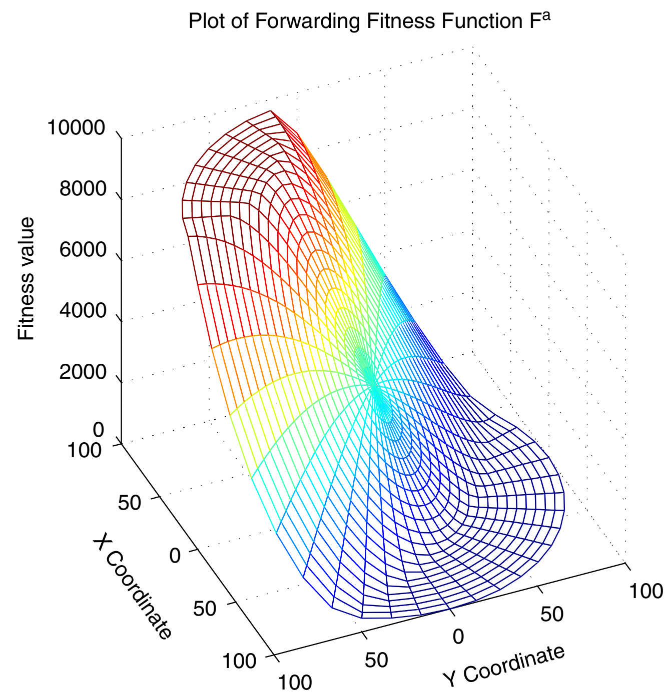

Fig. 3. The plot of the area-based forwarding fitness function $\mathcal{F}_k^{\mathrm{a}}(i,j)$ in function of the location of the candidate node. The current node is at (0,0) and has a transmission range of 100 m. The destination node is at (110,110). The function is plotted for a candidate node k with transmission range of 150 m and locations spanning the transmission range of the current node.

We summarize these cases in a single expression:

$$\mathcal{F}_k^{\mathrm{a}}(i,j) = \begin{cases} 0 & \text{if } R_k \leqslant d_{ik} - r_{ij}; \\ \dfrac{R_k^2(\theta - \sin\theta) + r_{ij}^2(\varphi - \sin\varphi)}{2} & \text{if } d_{ki} - r_{ij} < R_k \\ & \quad < d_{ki} + r_{ij}; \\ \pi \cdot r_{ij}^2 & \text{if } R_k \geqslant d_{ki} + r_{ij}; \end{cases} \tag{3}$$

where R_k is the range of node k, $r_{ij} = d_{ij} - R_j$, $\theta = 2\arccos\dfrac{R_k^2 + d_{ik}^2 - r_{ij}^2}{2\cdot R_k \cdot d_{ki}}$, and $\varphi = 2\arccos\dfrac{r_{ij}^2 + d_{ik}^2 - R_k^2}{2\cdot r_{ij}\cdot d_{ik}}$.

Fig. 3 shows the forwarding fitness function candidate node k with a transmission range of 150 m and varying location. The sender is at location (0, 0), the destination is at location (110, 110), and the current node as well as the destination node has a transmission range of 100. The value of the fitness function is zero in the area where the candidate node can provide no benefit compared to the current node. Similarly, the fitness has a maximum value of 10 000 in the zones where the transmission range of the candidate node is completely covering the transmission range of the destination. The fitness can have positive values for points which are farther from the destination than the current node, because the longer transmission range of the node compensates for its unfavorable location.

Fig. 4 shows the forwarding fitness function $\mathcal{F}^{\mathrm{a}}$ when $\Gamma_{i,j}$ and Π_k are secant, for candidate node k with different location

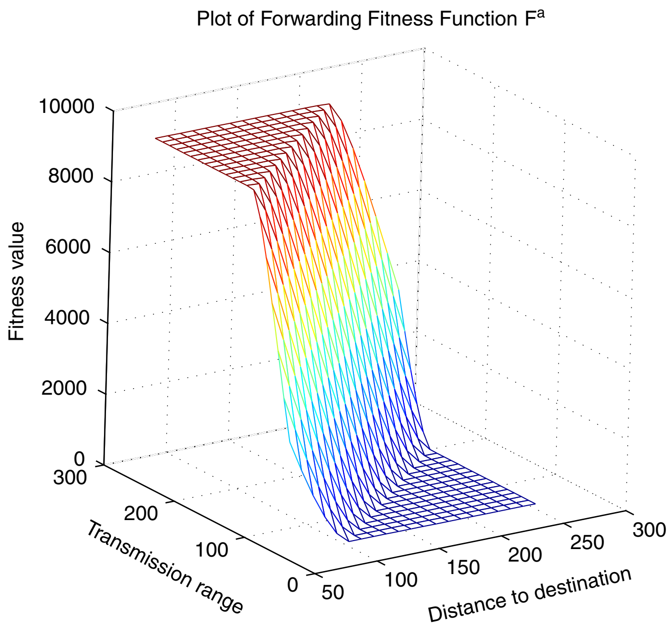

Fig. 4. The plot of the area-based forwarding fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$, for candidate node k with different location and different transmission range. The scenario is the same as the one in Fig. 3 but the transmission range is variable in the range of [50, 250].

and different transmission range. The scenario is the same as above except the transmission range is variable in the range of [50, 250]. We combine the location of candidate node k to a single parameter—distance to the destination. The figure indicates the fitness value increases as the transmission range of candidate node increases, or the distance to the destination decreases, or both. The fitness value achieves maximum when candidate node is nearest to the destination and with largest transmission range.

3.2. AODV routing with m-limited forwarding (m-AODV)

AODV [19] is a reactive routing algorithm where routes are discovered and established only on demand and are maintained only if they are used by some sources. Nodes that do not lie on active paths do not maintain routing information or exchange routing tables. Only symmetric links participate in routing which is ensured by periodical `hello` packets. The freshness of routes is ensured by sequence numbers as well as route maintenance.

We introduce a modified algorithm m-AODV which replaces flooding with m-limited forwarding in the route discovery process, and it is based upon the following modifications to AODV:

(1) We added the transmission range of the node to the `hello` packet of AODV. When a node receives a hello packet from its neighbor, the node adds the neighbor as well as its transmission range into the *neighbor table*.
(2) We introduced the `location-update` packet, an infrequent system-wide broadcast packet. A `location-update` packet contains the id of a node and its location. Whenever a node receives a location update packet from any other node in the system, it adds the sender as well as its location information into a *location table*.
(3) Route discovery is done through the m-limited forwarding algorithm. The forwarding fitness function is evaluated based on the information in the neighbor and location tables. We support both $\mathcal{F}^{\mathrm{d}}$, the distance-based as well as $\mathcal{F}^{\mathrm{a}}$, the area-based fitness functions.

4. Simulation study

In this section, we report the results of a simulation study. The objectives of our simulation study are twofold. First, we aim to determine the optimal values of m for m-limited forwarding. Although theoretical considerations allow us to determine that the optimal range is in the low single digits, the problem is too complex for an analytical solution, thus we resort to simulation. The second objective is to study the impact of m-limited forwarding on the performance of the routing algorithm. For this study, we have implemented in the ns-2 simulator [4,23] the m-AODV routing protocol as discussed in Section 3.2. We implemented m-AODV using the two proposed fitness functions, $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$. We compared our implementation of the m-AODV algorithm with the default AODV implementation from the CMU wireless extension package [16]. We compared the routing algorithms in terms of average power consumption and packet loss ratio.

To perform a meaningful comparison of the algorithms, we created a scenario of a wireless system with mobile nodes and realistic traffic patterns. We used the "random waypoint" model [5,11] to describe the movement of nodes in the system. Each node randomly picks a destination on the map, moves to the destination at a *constant speed*, and then pauses for the *pause time*; after the pause time, it continues the movement following the same pattern.

In our simulations, we use traffic patterns generated by *constant bit rate* (CBR) sources sending UDP packets. A node cannot be simultaneously source and destination. Each CBR source is active for a time interval called *CBR duration*. Our simulation allows a *setup duration* before generating any traffic, during which the sender may transmit `hello` and `location-update` packets. We also set an *end duration*, during which CBR sources are not allowed to send data packets, so that data packets will not be lost due to the lack of simulation time. The remaining simulation time, the time after the *setup duration* and before the *end duration*, is divided into equal time slices. During each time slice we regenerate CBR sources for different sender-destination pairs. The start time of the CBR source is randomly picked in the first half of the time slice, and the *CBR duration* is set to half of the *time slice* so that it will not cross two *time slices*. The CBR sources generate 128 byte packets (in general small data packets favor AODV [8]).

Table 1
The default values and the range of the parameters for our simulation studies

Field	Value	Range
Simulation area	500×500 (m^2)	
Number of nodes	80	50–140
Transmission range	100 (m)	
Speed	1 (m/s)	1–10 (m/s)
Pause time	15 (s)	
Total simulation time	900 (s)	
Setup duration	50 (s)	
End duration	50 (s)	
Duration of time slices	10 (s)	
Number of CBR sources	25	4–40
Offered network load	25 (kbps)	4–40 (kbps)
CBR packet size	128 (bytes)	
CBR sending rate	1 (kbps)	
CBR duration	5 (s)	

In our simulation, we choose a 500×500 square area and the default number of nodes is 80. All nodes have a transmission range of 100 m. We run several simulation experiments and vary the number of nodes, the speed in the “random waypoint” model, and the number of CBR sources. The number of nodes ranges from 50 to 140, the node speed ranges from 1 to 10 m/s, and the number of CBR sources ranges from 4 to half of number of the nodes. Table 1 illustrates the default settings and the range of the parameters for our simulation experiments.

4.1. Performance metrics

We consider two performance metrics:

- *Packet loss ratio*—the ratio of all data packets received to the number of data packets sent during the simulation.
- *Average power consumption per node*—the ratio of total power dissipated by all nodes to the number of nodes in the network. Nodes dissipate power for transmitting packets, receiving (overhearing) packets, and idle listening.

For each setting (fixed number of CBR sources, fixed speed, fixed number of nodes), we repeat the simulation 20 times with different randomization seeds. These two performance metrics are studied for varying network load, node mobility, and node density.

4.2. Determining the optimal value of *m*

Intuitively, the optimal value of m is a small, single digit number. A large value would not provide any benefit compared to flooding, while a too small value would adversely affect the routing performance through the lack of redundancy. The problem is too complex for an analytic solution, but we can determine the optimal value through simulation (as well as experimentally in a real setting).

In a series of experiments, we have investigated 1-, 2-, 3-, and 4-limited forwarding using both fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$. A rough estimation of the average number of neighbors of a node in our scenario follows: the simulation area is $250\,000\,\mathrm{m}^2$ ($500\,\mathrm{m} \times 500\,\mathrm{m}$). The average node density is

$$\frac{80}{250\,000} = \frac{1}{3125}.$$

The transmission range of a node is a disk of 100 m radius, thus the transmission area covers $10000\pi \approx 31\,400\,\mathrm{m}^2$. In average we will have about 10 nodes in that area, one being the node considered and another nine being its neighbors (in fact, considering nodes close to the edge of the simulated area, the average number of neighbors is somewhat lower). Thus, values of m larger than 4 are very close to the flooding technique.

The metrics considered in the determination of the optimal m are the packet loss ratio and average power consumption. We are not considering the average latency, due to its dependency on the packet loss ratio.

Routing performance function of network load: The packet loss for AODV or m-AODV protocols may be caused by the following: (i) the forwarding set calculated by the fitness function excludes nodes on the critical path from source to destination; (ii) nodes move out a region and cause route failure; (iii) due to frequent changes of the network topology the cached routing tables become outdated and (iv) packets are lost at the MAC layer. There are several reasons for a packet to be dropped at the MAC layer. In a static network, a packet is dropped after its transmission was retried 16 times with a limited binary exponential backoff. In a mobile network, however, a failure at the MAC level occurs when the nodes move out from transmission range while waiting for a right to transmit or waiting for their retransmission time. A packet may be lost after the first collision, because by the time it retransmits, the node is no longer in the transmission range. Similarly, a packet can be lost even before the first transmission if the destination node moves out of the transmission range while the source node is waiting for an available transmission slot.

Figs. 5(a) and (b) illustrate the packet loss ratio versus network load, with fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{d}}(i, j)$, respectively. The major reasons why 1-limited forwarding may drop packets are the items (i) and (ii) in the previous list; the major reason for 4-limited forwarding and flooding to drop packets is item (iv). When the traffic load is light, items (i) and (ii) are the major reasons, why 1-limited forwarding performs the worst, while the performance of 2-, 3-, 4-limited forwarding are comparable. When the traffic load is high (iv) becomes the major reason of packet loss. The performance of 4-limited forwarding is worse that the one of is 2-, 3-limited forwarding and tends to increase with the increase of network load. For the flooding-based scheme, (iv) is always the major concern. Flooding-based schemes perform much worse than m-limited forwarding-based scheme in most cases. For flooding-based protocols there is no fitness function-based decision whether to forward a packet or not thus, item (i) is not relevant.

With AODV, power consumption is caused by (i) transmission, reception, or overhearing of data packets and route discovery packets; (ii) idle listening, and (iii) MAC layer overhead including RTS/CTS, retransmission, and so on. With m-AODV, additional power is consumed by (iv) transmission and reception of `hello` packets, and `location-update` packets.

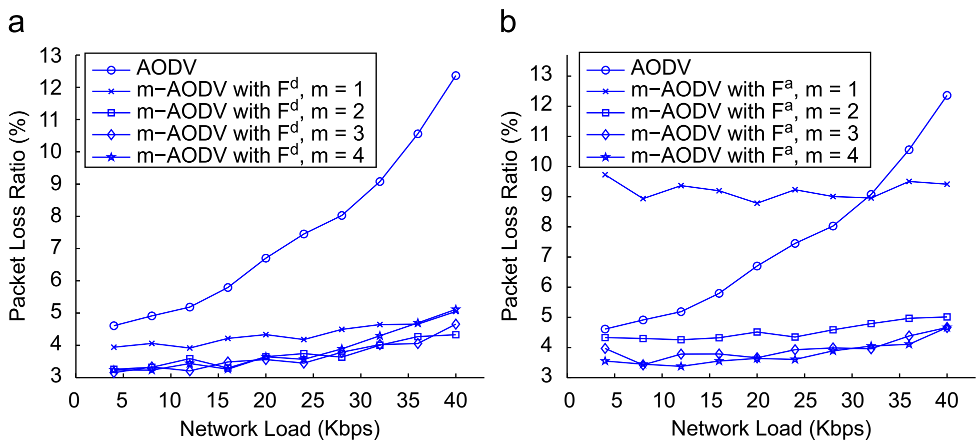

Fig. 5. Packet loss ratio versus network load. Number of nodes = 80, speed = 1 m/s, $m = 1, 2, 3, 4$. (a) m-AODV with distance-based fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$; (b) m-AODV with area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$. m-AODV with both fitness functions outperforms AODV, for values of $m \geqslant 2$.

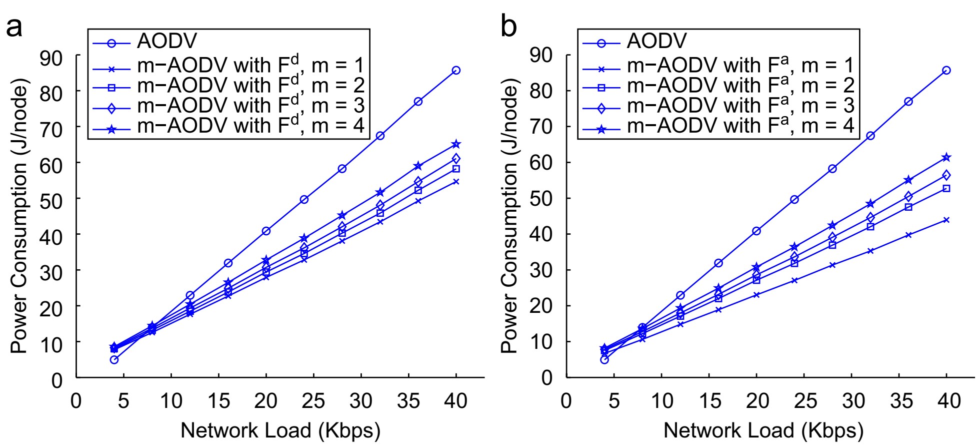

Fig. 6. Average power consumption versus network load. Number of nodes = 80, speed = 1 m/s, $m = 1, 2, 3, 4$. (a) m-AODV with distance-based fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$; (b) m-AODV with area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$. The average power consumption increases linearly as the network load increases. m-AODV with area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$ consumes less power than m-AODV with distance-based fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$ for the same network load.

Figs. 6(a) and (b) illustrate the average power consumption of the nodes function of the network load, for different fitness functions. The average power consumption increases linearly as the network load increases. When the network load is light, AODV consumes the least power since it does not need to send `hello` packets or `location-update` packets. As the network load increases, as expected, AODV needs more power than m-AODV. m_1-AODV consumes less power than m_2-AODV for $1 \leqslant m_1 < m_2 \leqslant 4$, for both fitness functions. m-AODV with fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$ consumes less power than m-AODV with fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$ for the same network load.

Routing performance function of node mobility: Figs. 7(a) and (b) illustrate the packet loss ratio versus node mobility, for different fitness functions. Node mobility is measured by the speed of the node movement. The packet loss ratio of 1-limited forwarding is noticeably greater than all other schemes as the network mobility increases. When the network mobility is relatively high, 4-limited forwarding performs the best, followed by 3-limited forwarding and flooding. As node mobility increases, the performance of 2-limited forwarding become a little worse than AODV. Thus, $m = 1$ is an unacceptable value as it is not suitable for networks with relatively high mobility. $m = 3$ and 4 are better options when network mobility is relatively high.

Figs. 8(a) and (b) illustrate the average power consumption versus node mobility, with different fitness functions. We notice that AODV protocol requires the highest power consumption; among the m-limited schemes, 1-limited forwarding consumes the least power, followed by 2-, 3- and 4-limited forwarding. When node mobility increases, the routing table becomes outdated quickly and additional power is dissipated to find new routes, thus the average power consumption of all routing schemes increases. However, as node mobility is further increased, the packet loss ratio increases; thus, the power consumption for the transmission and the reception of data packets is reduced, as more data packets are dropped. For all schemes based on m-limited forwarding, the portion of power consumption reduced by dropping data packets exceeds the additional power used to find new routes; thus, the overall power consumption is reduced. The power consumption to find new routes by the AODV protocol is still the dominating

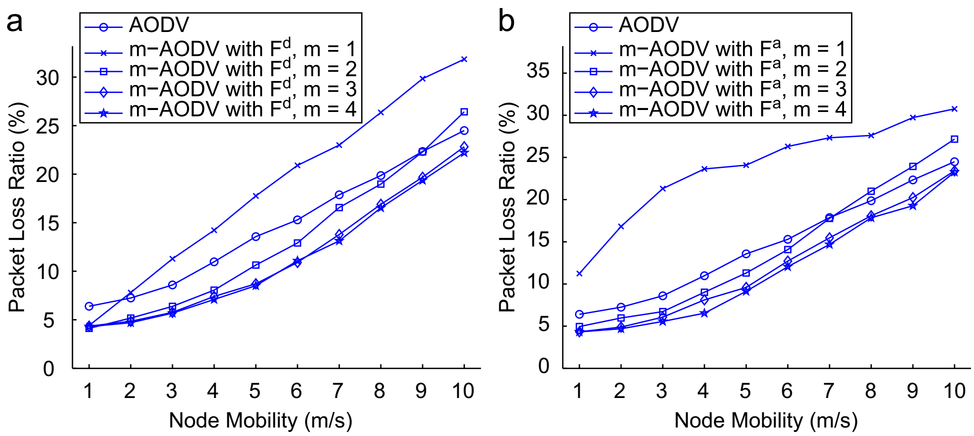

Fig. 7. Packet loss ratio versus node mobility. Number of nodes = 80, offered load = 25 kbps, $m = 1, 2, 3, 4$. (a) m-AODV with distance-based fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$; (b) m-AODV with area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$. The packet loss ratio of 1-limited forwarding is noticeably the greatest. $m = 3$ and 4 are better options when network mobility is relatively high.

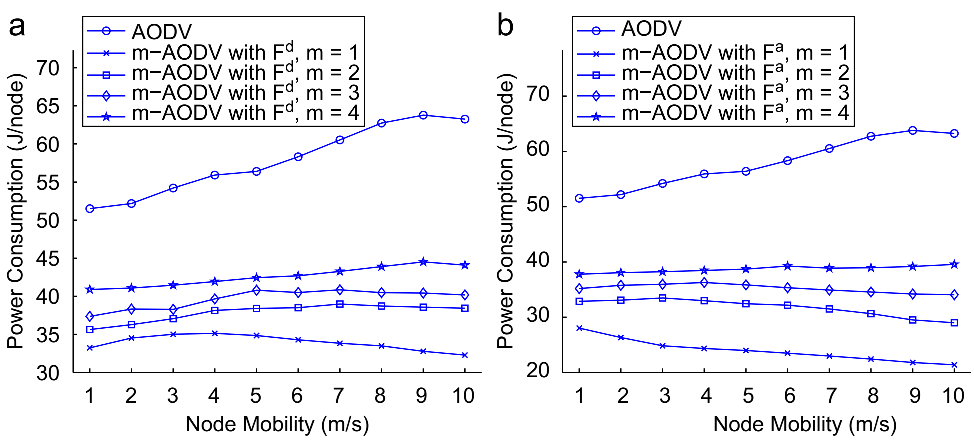

Fig. 8. Average power consumption versus node mobility. Number of nodes = 80, offered load = 25 kbps, $m = 1, 2, 3, 4$. (a) m-AODV with distance-based fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$; (b) m-AODV with area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$. AODV consumes the most power. Among the m-limited schemes, 1-limited forwarding consumes the least power, followed by 2-, 3-, 4-limited forwarding.

factor, thus the average power consumption still increases. Overall, the average power consumption increases steadily with the mobility for the AODV protocol. The average power consumption increases to a maximum value, then decreases with the further increase of the node mobility for the m-AODV protocol.

Routing performance function of network density: Figs. 9(a) and (b) show the packet loss ratio function of the network density for the $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$ fitness functions. We notice that for low network density, the packet loss ratio of all schemes is high—a consequence of the low connectivity. The 1-limited forwarding performs the worst at these values. For higher network densities, the m-limited forwarding-based schemes have a lower packet loss ratio than plain AODV. We note that 2- and 3-limited forwarding have a lower packet loss ratio than 1- and 4-limited forwarding. For 1-limited forwarding, only one hop is chosen to forward a route discovery packet, thus the whole path will fail if one of the hops fails. For m-limited forwarding with ($m \geqslant 4$), the packets are lost due to the higher number of collisions in the forwarding of the route discovery packet.

From Figs. 10(a) and (b), we observe that the average power consumption per node for all schemes increases as network density increases. This is explained by the fact that at a higher network density, more nodes overhear every transmission and the route discovery packet is also retransmitted by more nodes. AODV consumes the most power, followed by 4-, 3-, 2-, and 1-limited forwarding.

Summary: The experiments performed show that there is no single choice of m which performs the best in every situation. 1-limited forwarding performs poorly for low network load and/or high mobility. 2-limited forwarding performs poorly for high node mobility. On the other hand, 4-limited forwarding does not perform well for high network load. We find that 3-limited forwarding exhibits a more consistent performance across a wide range of parameters. Therefore, unless we have the possibility to optimize the algorithm for a specific network and transmission scenario, $m = 3$ is the

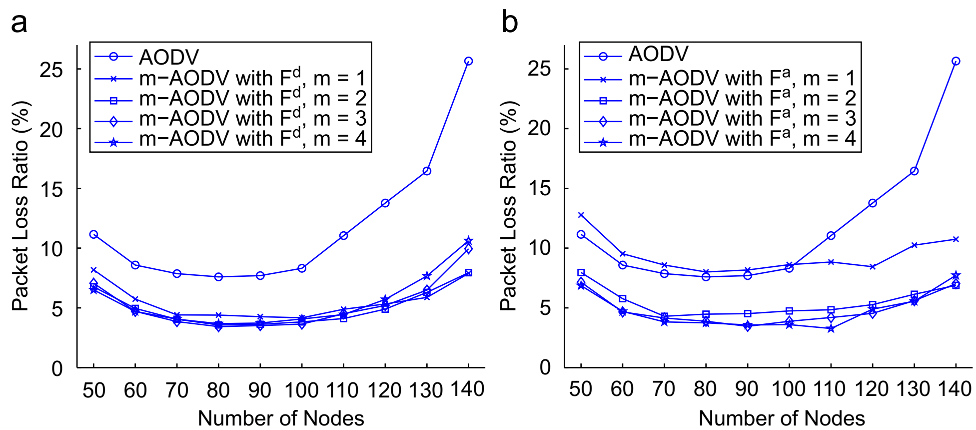

Fig. 9. Packet loss ratio versus node density. Offered load = 25 kbps, speed = 1 m/s, $m = 1, 2, 3, 4$. (a) m-AODV with distance-based fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$; (b) m-AODV with area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$. For low network density, 1-limited forwarding performs the worst at these values. For higher network densities, all m-limited forwarding-based schemes have a lower packet loss ratio than plain AODV. $m = 2$ and 3 are better options when network density is relatively high.

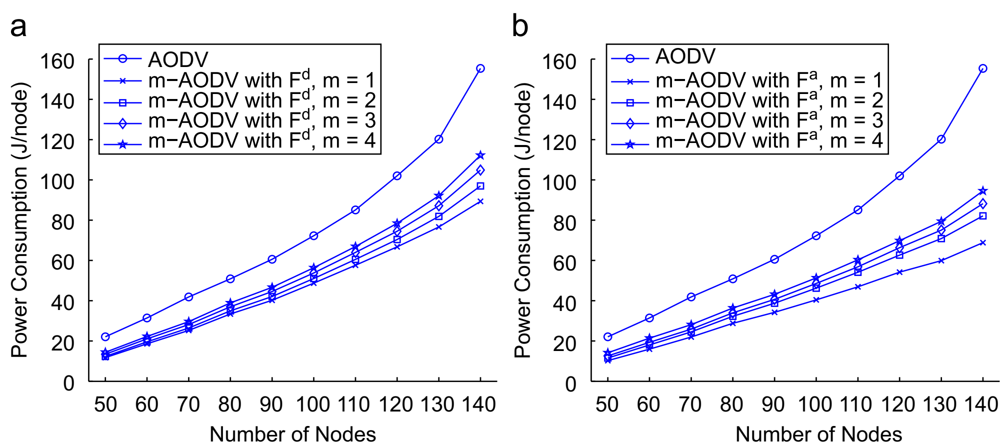

Fig. 10. Average power consumption versus node density. Offered load = 25 kbps, speed = 1 m/s, $m = 1, 2, 3, 4$. (a) m-AODV with distance-based fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$; (b) m-AODV with area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$. The average power consumption per node for all schemes increases as network density increases. AODV consumes the most power, followed by 4-, 3-, 2-, and 1-limited forwarding.

safest choice. We will use this value for the remainder of our simulations.

4.3. Performance improvements of m-limited forwarding in a MANET with bidirectional connections

In the following, we study the performance improvement of m-limited forwarding for an ad hoc network with symmetric connections. We note that this is the most frequently encountered situation in practice, because most of the current MAC protocols cannot handle unidirectional links. The unidirectional connections are therefore ignored at the level of the MAC protocol, and the routing protocol sees a network composed entirely of symmetric connections.

In the following simulation experiments, we compare plain AODV with m-AODV with 3-limited forwarding for the two proposed fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$, as well as the LAR protocol. We use the same scenario and traffic patterns as in the previous simulations.

Routing performance function of network load: The packet loss ratio versus network load is presented in Fig. 11. The packet loss ratio is increasing with the network load for all schemes; for plain AODV it is increasing at a higher rate than LAR and for the two 3-limited forwarding-based schemes. $\mathcal{F}_k^{\mathrm{a}}(i, j)$ strictly requires nodes to forward the traffic on the positive direction to the destination, as a reason, some of the nodes on the critical path but on a negative direction may be excluded. Thus, m-AODV with $\mathcal{F}_k^{\mathrm{d}}(i, j)$ performs a little better than m-AODV with $\mathcal{F}_k^{\mathrm{a}}(i, j)$. LAR and both of 3-limited forwarding-based schemes have a comparable packet loss ratio when the traffic load is light. When the traffic load is high, more packets are dropped by LAR due to collisions or excessive retransmission failures at MAC layer; this is caused by the fact that the number of next hops restricted by LAR is larger than that restricted by 3-limited forwarding-based schemes.

Fig. 12 illustrates the average power consumption versus network load. For lightly loaded networks, 3-limited forwarding requires additional power consumption for the dissemination of

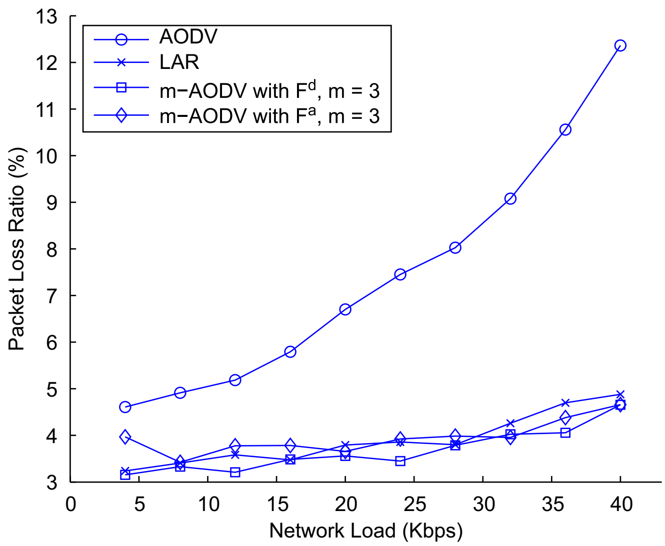

Fig. 11. Packet loss ratio versus network load. Number of nodes = 80, speed = 1 m/s. We compare AODV, LAR, and m-AODV with fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$. AODV performs the worst. m-AODV outperforms LAR when the network load is relatively high.

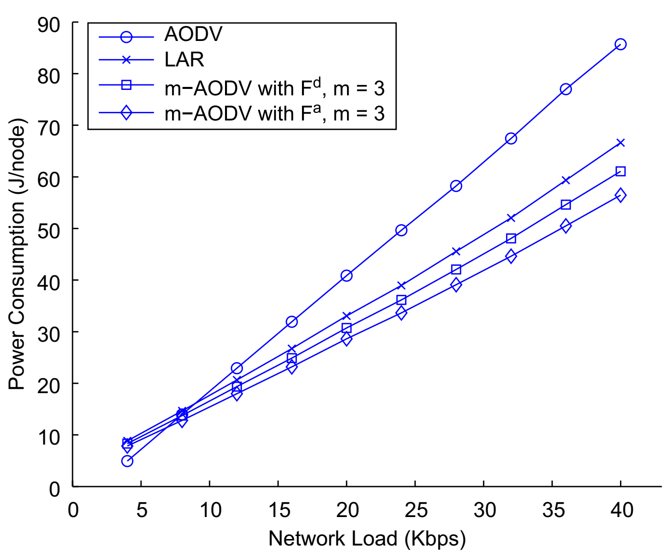

Fig. 12. Average power consumption versus network load. Number of nodes = 80, speed = 1 m/s. We compare AODV, LAR, and m-AODV with fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$. AODV leads to the highest power consumption; m-AODV is more efficient in terms of power consumption than LAR for the same network load.

`hello` and `location-update` packets. When the network load increases, the power dissipation of the plain AODV increases much faster than that of the m-limited forwarding schemes. The next hops to forward traffic established by $\mathcal{F}_k^{\mathrm{a}}(i, j)$ is more restricted, compared to $\mathcal{F}_k^{\mathrm{d}}(i, j)$. Oftentimes, less than three nodes are included in the forwarding set calculated by $\mathcal{F}_k^{\mathrm{a}}(i, j)$, as a result, m-AODV with $\mathcal{F}_k^{\mathrm{a}}(i, j)$ consumes less power than m-AODV with $\mathcal{F}_k^{\mathrm{d}}(i, j)$. Compared to m-limited forwarding schemes, LAR allows more nodes to serve as the next hop as long

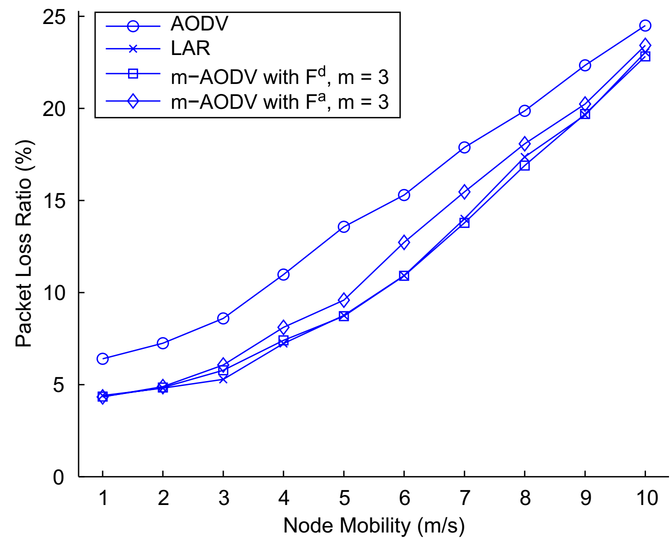

Fig. 13. Packet loss ratio versus node mobility. Number of nodes = 80, offered network load = 25 kbps. We compare AODV, LAR, and m-AODV with fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$. AODV performs the worst. m-AODV with distance-based fitness function $\mathcal{F}_k^{\mathrm{d}}(i, j)$ achieves a similar performance with LAR that in turn performs slightly better than m-AODV with area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$.

as they are inside the request zone, thus, LAR routing scheme consumes more power than 3-limited forwarding with both $\mathcal{F}_k^{\mathrm{d}}(i, j)$- and $\mathcal{F}_k^{\mathrm{a}}(i, j)$-based schemes.

Routing performance function of node mobility: Fig. 13 illustrates packet loss ratio versus node mobility. All routing schemes are very sensitive to node mobility and the packet loss ratio increases when mobility increases. For example, for plain AODV the packet loss ratio increases from 6.40% at 1 m/s to 24.50% at 10 m/s. Plain AODV has a higher packet loss ratio than LAR and m-AODV for relatively high values of mobility. Among the other protocols, m-AODV with $\mathcal{F}_k^{\mathrm{a}}(i, j)$ is slightly worse than LAR and m-AODV with $\mathcal{F}_k^{\mathrm{d}}(i, j)$.

Fig. 14 illustrates the average power consumption versus node mobility. We find the plain AODV and LAR are more sensitive to node mobility than m-AODV. With the mobility increasing, the power dissipated by AODV and LAR increases accordingly, while the power consumption of both 3-limited forwarding-based schemes remain at a certain level. For the two 3-limited forwarding schemes, the $\mathcal{F}_k^{\mathrm{d}}(i, j)$-based scheme consumes less power than $\mathcal{F}_k^{\mathrm{a}}(i, j)$-based scheme.

Routing performance function of network density: Fig. 15 illustrates packet loss ratio versus node density. The packet loss ratio decreases when the number of nodes increases from 50 to 80, and then starts to increase when the number of nodes further increases. When the network density is relatively low, a percentage of packets are dropped due to unavailable routes; when the network density is relatively high, excessive collisions become the major reason that packets are lost during the transmission. The packet loss ratio for AODV and LAR at high node density increases faster than m-AODV due to excessive number of collisions. m-AODV with $\mathcal{F}_k^{\mathrm{a}}(i, j)$ outperforms m-AODV with $\mathcal{F}_k^{\mathrm{d}}(i, j)$ at higher node density.

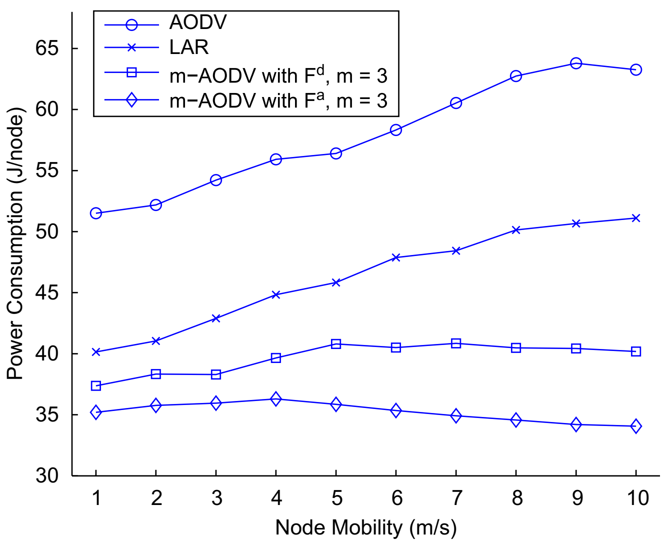

Fig. 14. Average power consumption versus node mobility. Number of nodes = 80, offered network load = 25 kbps. We compare AODV, LAR, and m-AODV with fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$. AODV consumes the most power, and m-AODV consumes less power than LAR, for the same node mobility.

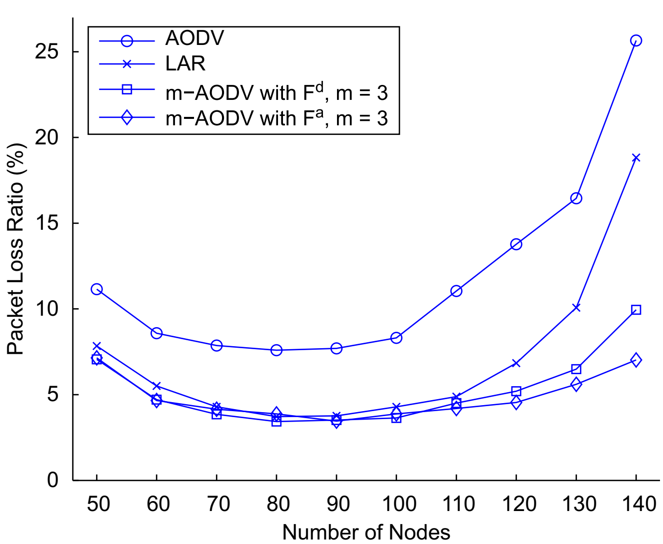

Fig. 15. Packet loss ratio versus network density. Speed = 1 m/s, offered network load = 25 kbps. We compare AODV, LAR, and m-AODV with fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$. AODV performs the worst. m-AODV outperforms LAR when the network density is relatively high.

Fig. 16 illustrates the average power consumption versus network density. With the increase in the network density, the power dissipated by every routing scheme increases accordingly. The increase in the power dissipation by plain AODV is slightly larger than LAR, followed by m-AODV with $\mathcal{F}_k^{\mathrm{d}}(i, j)$, and m-AODV with $\mathcal{F}_k^{\mathrm{a}}(i, j)$. $\mathcal{F}_k^{\mathrm{a}}(i, j)$-based scheme consumes less power than $\mathcal{F}_k^{\mathrm{d}}(i, j)$-based scheme.

Summary: We find that m-AODV exhibits a consistently lower power consumption for almost all operating scenarios, except when network load is low. In that case, the overhead of m-limited forwarding due to the dissemination of the `hello` and `location-update` packets is larger than the benefits of the retransmissions.

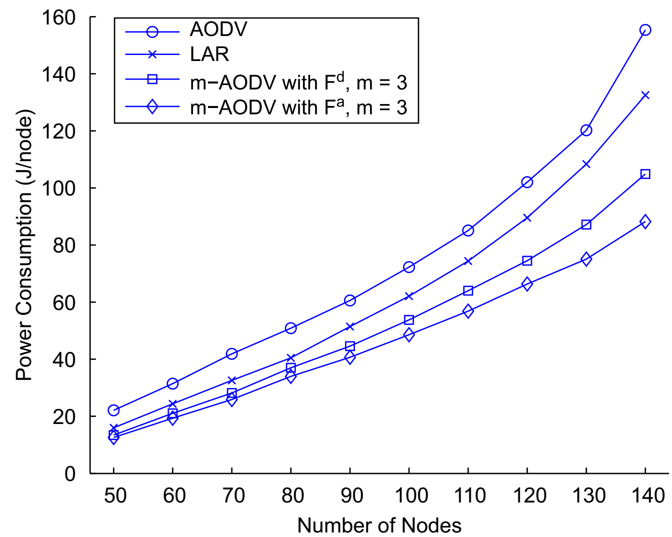

Fig. 16. Average power consumption versus network density. Speed = 1 m/s, offered network load = 25 kbps. We compare AODV, LAR, and m-AODV with fitness functions $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and $\mathcal{F}_k^{\mathrm{a}}(i, j)$. AODV consumes the most power, and m-AODV consumes less power than LAR, for the same network density.

In general, the more "difficult" a scenario is (high network load and/or high node mobility), the greater the benefits of m-limited forwarding in terms of power consumption. The distance-based fitness function $\mathcal{F}^{\mathrm{d}}$ leads to lower power consumption with an approximately constant difference versus the area-based fitness function $\mathcal{F}^{\mathrm{a}}$.

We also find that the m-limited forwarding lowers the packet loss ratio in all scenarios. Although the packet loss ratio is naturally increasing for all algorithms when the scenario becomes more "difficult" (high network load and/or high node mobility), the benefits of m-limited forwarding become greater with the increase in the difficulty of the scenario. The two fitness functions $\mathcal{F}^{\mathrm{d}}$ and $\mathcal{F}^{\mathrm{a}}$ have a similar behavior, with the distance-based function $\mathcal{F}^{\mathrm{d}}$ having a lower packet loss ratio with an approximately constant difference.

The general conclusion is that the m-AODV protocol outperforms plain AODV and LAR for everything but the easiest scenarios (with low load and low node mobility). The distance-based fitness function $\mathcal{F}^{\mathrm{d}}$ is a better choice in these cases, as the benefits of the area-based function $\mathcal{F}^{\mathrm{a}}$ cannot be observed in a network formed exclusively of symmetric links.

4.4. m-Limited forwarding in a MANET with asymmetric connections

We find that for homogeneous MANETs the simpler, distance-based $\mathcal{F}_k^{\mathrm{d}}(i, j)$ forwarding fitness function actually performs slightly better than the more complex, area-based $\mathcal{F}_k^{\mathrm{a}}(i, j)$ function, in terms of packet loss ratio. The reason for this is that, as shown in Section 3, the benefits of the area-based function appear only in the case of asymmetric links. Most wireless networks are composed of heterogeneous

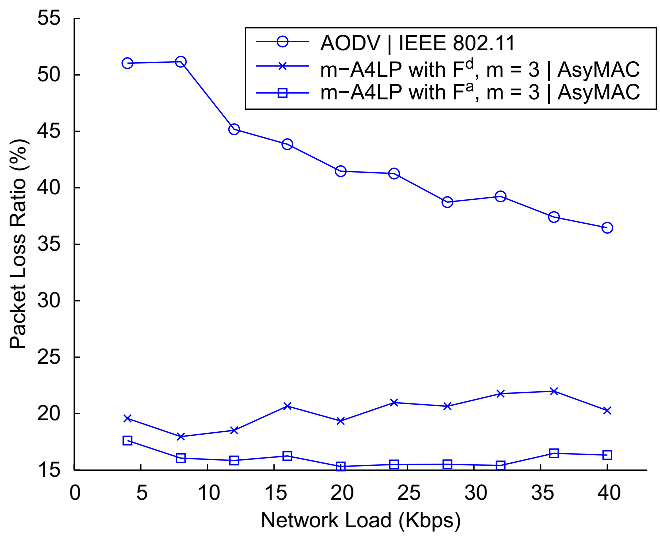

Fig. 17. Packet loss ratio versus network load. Speed = 1 m/s, number of nodes = 80. Nodes fall into four categories with transmission range of 200 (C1), 150 (C2), 100 (C3), and 50 (C4) m. $|C1|:|C2|:|C3|:|C4|$ = 1:2:3:4. AODV/IEEE 802.11, A^4LP based on 3-limited forwarding with $\mathcal{F}_k^{\mathrm{d}}(i, j)$/AsyMAC, and A^4LP based on 3-limited forwarding with $\mathcal{F}_k^{\mathrm{a}}(i, j)$/AsyMAC are compared.

nodes due to the differences in the physical capabilities of the nodes, such as power, size, shape of the antennas, and so on. However, most MAC and routing protocols require the existence of bidirectional connections. These protocols ignore the large number of asymmetric links present in heterogeneous networks. For instance the IEEE 802.11 MAC works only on bidirectional connections, and most ad hoc routing protocols (including AODV) require bidirectional links. This property is also inherited by the m-AODV variant.

To study the improvement provided by the area-based fitness function $\mathcal{F}_k^{\mathrm{a}}(i, j)$, we need to test it with a pair of MAC and routing protocols that support asymmetric links. One such pair is the AsyMAC (Asymmetric MAC) protocols [26,27] and the m-A^4LP routing protocol [24,25].

To show the benefits of the approach, we created a scenario with a set of nodes with different transmission ranges. In our simulation, we have four groups of nodes—C1, C2, C3, C4. The transmission range of nodes in C1, C2, C3 and C4 are 200, 150, 100, and 50 m, respectively. The ratio of the number of nodes of each group is $|C1|:|C2|:|C3|:|C4|$ = 1:2:3:4. Thus, for default 80 nodes, the number of nodes in C1, C2, C3 and C4 is 8, 16, 24, 32, respectively. We run a simulation comparing three protocol stacks: m-A^4LP with the underlying AsyMAC protocol in the variants with the distance-based $\mathcal{F}_k^{\mathrm{d}}(i, j)$ and the area-based $\mathcal{F}_k^{\mathrm{a}}(i, j)$ fitness function and a more traditional ad hoc networking stack with plain AODV on top of the 802.11 MAC protocol.

Note that this is a relatively "difficult" scenario for the AODV/802.11 protocol set, due to the large number of nodes with small transmission range and the relatively low node density node. Therefore, we expect a high packet loss ratio for the AODV/802.11 stack.

The results of the experiments are presented in Fig. 17. We find that the m-A^4LP/AsyMAC-based protocol stacks have a much lower packet loss ratio than AODV/802.11. This is due to their ability to exploit the asymmetric links. Furthermore, in this scenario we find that the area-based fitness function $\mathcal{F}^{\mathrm{a}}$ yields a lower packet loss ratio than the distance-based function $\mathcal{F}^{\mathrm{d}}$. This is due to the fact that $\mathcal{F}^{\mathrm{a}}$ can make a better choice of the forwarding nodes in the presence of asymmetric links.

5. Summary and future work

We introduce m-limited forwarding, a technique to optimize the performance of ad hoc routing algorithms by reducing the power consumption as well as the fraction of the network bandwidth used to disseminate routing information. m-limited forwarding limits the cardinality of the subset of nodes which retransmit a packet to m nodes. A forwarding fitness function $\mathcal{F}$ is used to select the m-nodes; we introduced two alternative functions: a distance-based function $\mathcal{F}^{\mathrm{d}}$ and an area-based function $\mathcal{F}^{\mathrm{a}}$.

We evaluate the performance of m-limited forwarding through a series of simulation studies. Our first objective is to determine the optimal value of m, the cardinality of the set of nodes which retransmit a packet containing routing information. Without additional information about the network, such as average load and node mobility a good compromise is $m = 3$.

A second set of experiments study a wireless network with bidirectional links and investigate two routing algorithms, AODV and LAR enhanced with m-limited forwarding. For most simulation scenarios, m-AODV has lower power consumption and lower packet loss ratio than either plain AODV or LAR. Our simulation studies indicate that the distance-based fitness function $\mathcal{F}^{\mathrm{d}}$ performs better than the area-based fitness function.

Finally, we investigate a network with asymmetric links and compare the performance of the two fitness functions. AODV and the most commonly used MAC protocols cannot take advantage of asymmetric links; thus, we used the m-A^4LP routing protocol and the AsyMAC (asymmetric MAC) protocol on layer 2. Our simulation studies indicate that the m-A^4LP/AsyMAC protocol stack yields a lower packet loss ratio than the AODV/802.11 stack, and the area-based fitness function $\mathcal{F}^{\mathrm{a}}$ outperforms the distance-based function $\mathcal{F}^{\mathrm{d}}$ for this scenario.

A natural extension of the current research is the ability to improve the performance of the routing algorithms by increasing the accuracy of the forwarding fitness function. For instance, the area-based fitness function assumes that the number of nodes is equal to a constant times the size of the area; this approximation is justified only if the density of the nodes is uniform and static. If we have information about a non-uniform node density we can introduce a *density weighted area-based* fitness function where the fitness is expressed as the size of the area times the node density in the given part of the network. If, in addition, we have information about asymmetric and/or dynamically changing transmission ranges, this information can also be integrated into the fitness function.

Naturally, there is a delicate balance between the cost of obtaining additional information, and the performance improvement due to a more accurate fitness function. We conjecture that the cost of obtaining additional information is justified only in "difficult scenarios", such as nodes with highly heterogeneous transmission ranges or scenarios with abrupt changes in node density. The evaluation of this conjecture and the design of low-overhead information gathering and distribution algorithms is a subject of future work.

Another topic for future research is the study of the security and fairness aspects of the protocol. In the current protocol, a node can become a parasite if either (a) refuses to participate in the forwarding by quietly dropping packets or (b) misreports its own position such that the node is avoided by the routes established in the network. While these behaviors can be in principle detected externally, the network needs a service which monitors the participants and takes appropriate actions against misbehaving nodes. Note, that our protocol is not dependent on the power resources of the nodes. It is very difficult to detect nodes which misrepresent their power resources, because external observers do not normally have access to the internal power monitors of a node.

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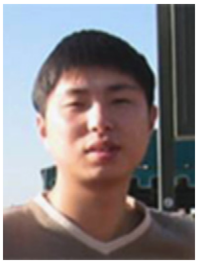
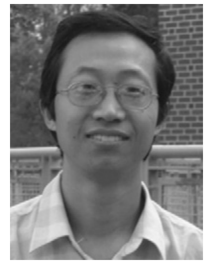


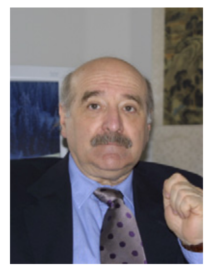
Guoqiang Wang received a BS degree from Southeast University, Nanjing, China, in 2001. He is currently a PhD candidate in the School of Electrical Engineering and Computer Science at the University of Central Florida, Orlando. His research areas include ad hoc routing, grid computing, and parallel simulation.

Damla Turgut is an Assistant Professor with the School of Electrical Engineering and Computer Science at University of Central Florida. She received her BS, MS, and PhD degrees from the Computer Science and Engineering Department of University of Texas at Arlington in 1994, 1996, and 2002, respectively. She has been included in the WHO's WHO among students in American Universities and Colleges in 2002. She has been awarded outstanding research award and has been recipient of the Texas Telecommunication Engineering Consortium (TxTEC) fellowship. She is a member of IEEE, member of the ACM, and the Upsilon Pi Epsilon honorary society. Her research interests include wireless networking and mobile computing, distributed systems, and embodied agents.

Ladislau Bölöni is an Assistant Professor with the School of Electrical Engineering and Computer Science at University of Central Florida. He received a PhD degree from the Computer Sciences Department of Purdue University in May 2000. He received a Master of Science degree from the Computer Sciences Department of Purdue University in 1999 and Diploma Engineer degree in Computer Engineering with Honors from the Technical University of Cluj-Napoca, Romania in 1993. He received a fellowship from the Computer and Automation Research Institute of the Hungarian Academy of Sciences for the 1994–1995 academic year. He is a senior member of IEEE, member of the ACM, AAAI and the Upsilon Pi Epsilon honorary society. His research interests include autonomous agents, grid computing and wireless networking.



Yongchang Ji received the MS and PhD degrees in computer science from University of Science and Technology of China, Heifei, in 1996 and 1998, respectively. He was a Postdoctoral Researcher of computer sciences at Purdue University, West Lafayette, IN. He is currently a Postdoctoral Research Associate of computer science at University of Central Florida, Orlando. He has published more than 30 papers in professional journals and referred conference proceedings. His main research interests include high-performance computing, grid computing, computational biology, parallel and distributed architecture, model, algorithm, and scalability.



Dan C. Marinescu joined the Computer Science Department at University of Central Florida in August 2001 as Professor of Computer Science. He has been an Associate and then Full Professor of Computer Science at Purdue University, in West Lafayette, IN, since 1984. He is the Scientific Director of the I2.Lab, an organization supporting interdisciplinary research in computer and information sciences (http://I2lab.ucf.edu) at UCF.
He is conducting research in parallel and distributed systems, computational biology, quantum computing, parallel and distributed computing, and has published more than 180 papers in journals and referred conference proceedings in these areas. He is the author of "Internet-Based Workflow Management: Towards a Semantic Web," published by Wiley in 2002 and has co-edited "Process Coordination and Ubiquitous Computing." The book "Approaching Quantum Computing," co-authored with Gabriela M. Marinescu was published in September 2004 by Prentice Hall.