Computer Networks xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Sensor-free route stability metric for mobile ad hoc networks

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ARTICLE INFO

Article history:
Received 5 June 2015
Revised 15 February 2016
Accepted 28 February 2016
Available online xxx

Keywords:
Routing metric
Mobile ad hoc networks
Link stability
Route stability
Node mobility

ABSTRACT

The hop count routing metric is widely used in conventional ad hoc routing protocols due to its simplicity and effectiveness. With a lower hop count route, fewer transmissions are required to send a packet from the source to the destination. This can improve the network throughput because fewer transmissions results in less channel contention and interference. In spite of this, the hop count routing metric may not be ideal for mobile scenarios, where the network topology changes constantly and rapidly. Many routing metrics have been proposed to improve route stability. However, they are usually only marginally effective or incur additional cost by requiring the use of information from additional hardware such as GPS sensor and compass. In this paper we propose a routing metric to guide nodes discover/select stable paths to improve route stability. We implemented the proposed routing metric in the AODV routing protocol and proved through simulation studies that it outperforms other routing metrics.

1. Introduction

A mobile ad hoc network (MANET) is a dynamic communication network formed by a collection of mobile nodes. In unicast routing in MANETs, an end-to-end route, which may be multi-hop in nature, is established prior to data transmission. Due to the multi-hop nature of routes in ad hoc networks, an entire route becomes invalid when a single link is broken. When a route becomes invalid, data transmission is halted and the network performs self-reconfiguration where nodes update their route information using control packets. Route breakage not only causes interruptions in data transmission, the communication of control packets during network self-reconfiguration also consumes valuable transmission opportunities that are better used for data transmission. Hence, it is vital that routes that are stable are used to ensure optimum network performance.

A routing metric is used to assign a value to a path to facilitate path selection. The hop count routing metric, which minimizes the number of transmissions required to send a packet from the source to the destination, is one of the most widely used routing metrics in ad hoc routing protocols due to its simplicity and effectiveness. Due to the broadcast nature of the wireless channel, the redundant transmissions incurred when a packet traverses through a longer route means that fewer remaining transmission opportunities are available for other concurrent transmissions (inter-route contention and interference). A long route could also cause nodes belonging to the same route to be in close proximity with each other and compete with each other for transmission opportunities (intra-route contention and interference). By using shorter routes, channel contention and interference, and end-to-end delay can be reduced. Nevertheless, it is well-known that the

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http://dx.doi.org/10.1016/j.comnet.2016.02.025
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hop count routing metric does not perform well in high mobility scenarios because lower hop count routes tend to be more direct and consist of longer links, which are more prone to breakage. In higher node density scenarios, the hop count routing metric is also known to cause links to be formed through border nodes leading to short link lifetimes (the border/edge effect) [1,2]. Such a link is easily broken by a small movement from any of the two nodes forming the link.

Various methods have been proposed to improve route stability in MANETs. Unfortunately, they are only marginally effective or incur additional cost by requiring the use of additional hardware. For instance, some methods require information from sensors such as GPS sensor and compass. In this paper we propose a routing metric for discovering and establishing stable routes that can be used without sensors. We show through analysis and simulation studies that the proposed routing metric is effective and outperforms the hop count and other related routing metrics. The contributions of this paper are summarized as follows:

1. The design of a routing metric that uses link length information and node mobility information to facilitate the selection of stable paths for improved network performance.
2. The proposal of a method to estimate the information used in the proposed routing metric so that the routing metric can be used without additional hardware (sensors) to reduce cost and node hardware complexity.
3. The proposal of a method to store a node's neighbor set, which is required to estimate the link length information used in the proposed routing metric, compactly in Route Request (RREQ) and Route Reply (RREP) packets.

The remainder of this paper is organized as follows. Related work is reviewed in Section 2. In Section 3 we provide further details of our routing metric. Results and discussion are provided in Section 4. Finally, we conclude our work in Section 5.

2. Related work

Route instability is one of the key problems affecting unicast routing in MANETs. Several routing metrics for wireless mesh networks (WMNs) are reviewed in [3], such as Expected Transmission Count (ETX) [4], Expected Transmission Time (ETT) [5], Weighted Cumulative Expected Transmission Time (WCETT) [5], and Metric of Interference and Channel Switching (MIC) [6]. However, these routing metrics were not designed for route stability; hence, they are not suitable for the problem that we seek to solve.

Many attempts have been made to resolve the route instability issue. These methods can be broadly categorized into two categories: (1) methods using information from sensors, and (2) methods using only readily available information. Methods from the first category usually offer good performance gains; however, they incur additional cost as additional hardware is required. While methods from the second category reduce cost, they usually offer only negligible performance gains when compared to the hop count routing metric, which does not consider route stability.

2.1. Methods using information from sensors

Node location information and node velocity information are used to estimate the remaining time before a link breaks called Link Expiration Time (LET) in the Flow Oriented Routing Protocol (FORP) [7]. In FORP, the path with the highest Route Expiration Time (RET), which is the minimum LET of the LETs of the links in a path, is preferred over other paths. In addition to LET, the Power and Mobility Aware Routing (PMAR) [8,9] protocol also employs RREQ propagation control using node location information. This method was first used in location-aided routing protocols such as LAR [10] and PMLAR [11].

In the AODV-Reliable Route Selection (AODV-RRS) [12] routing protocol, only nodes that are inside stable zones forward RREQs during a route discovery. This reduces the number of RREQ transmissions and results in the discovery of routes with short links. However, as some RREQs are dropped in a route discovery, a route between a pair of nodes might not be discovered even if multiple paths exist between these two nodes.

In the work in [13], link length is mapped onto a value called Link Availability, and the path with the highest path availability, which is the minimum link availability of all the link availabilities in a path, is chosen for data transmission. A possible consequence of selecting the max–min path is that a much longer path might be chosen over a shorter one with only slightly lower path availability.

Node heading direction information, which can be obtained using compass, is used in the Heading-direction Angles Routing Protocol (HARP) [14]. The main idea is to propagate RREQs along a single direction from the source to the destination. As the nodes in a route established in such a manner move in the same direction, the links in the route are less prone to breakage.

The Node Stability Factor (Nsf) and Link Stability Factor (Lsf) are used in the On-demand Bandwidth and Stability based Unicast Routing (OBSUR) protocol [15]. Nsf is an aggregate metric that takes into account a node's own mobility, the mobility of its neighbors, and its remaining buffer ratio while Lsf maps the estimated remaining lifetime of a link to a value in the interval [0, 1].

In Link Stability based Multicast Routing Scheme in MANET (LSMRM) [16], a metric called Stability Factor, which is a value computed for a link based on power level, distance, and Bit Error Rate (BER), is used to measure link stability. However, the use of BER information means that support from lower layers is required.

2.2. Methods using only readily available information

In the Associativity-Based Routing (ABR) protocol [17], link stability is measured using associativity ticks, which is the measure of time the two nodes of a link are connected. A node can measure the associativity of a neighbor by counting the number of beacon packets it received from the neighbor. It was claimed that links that are stable for at least a threshold amount of time are more likely to remain stable.

Associativity ticks are also used in [18]. A metric called node stability, which is the exponential weighted moving average of the mean associativity ticks of a node's neighbors, is used to categorize the degree of mobility of a node. Nodes are assumed to run multiple routing protocols concurrently and use different routing protocols to build paths depending on their degree of mobility. However, using multiple routing protocols simultaneously is highly complex and impose unnecessary requirements on the nodes.

While many methods are based on the prevention of route breakage, the work in [19] tries to improve the ability of the routing protocol to quickly repair route breakage. The weighted Bridge Node Density (wBND) of a path is the average number of bridging nodes of a link (common neighbors of the two nodes of the link) in the path divided by the hop count of the path. The effect of using this routing metric is forming routes over high bridge node density areas in the hope that when such a route is broken, it can easily be repaired with local route repair therefore reducing the communication overhead during route breakage and improving network performance. However, this method is outperformed by lifetime prediction methods in low node density scenarios.

The Q-Learning AODV (QLAODV) [20] routing protocol uses distributed Q-Learning to infer network status and takes into consideration link stability and bandwidth efficiency when selecting a path. In QLAODV, link stability is measured using a metric called Mobility Factor (MF), which is computed using only local connectivity (neighborhood) information. MF is also used in the MQ-Routing [21] protocol, which is mobility-aware, GPS-aware, and energy-aware. A metric quite similar to MF called Neighbor Change Ratio (NCR) was proposed in [22].

The AD-AODV [23] routing protocol uses a routing metric based on neighbor set change and hop count. However, these two considered factors should be normalized prior to aggregation as different factors should not be compared directly.

The Path Encounter Rate (PER) [24] routing metric guides nodes discover and establish stable routes by preferring paths with low PER values, i.e., paths consisting of nodes with low Average Encounter Rates (AERs) of new neighbors. It was claimed that PER outperforms the hop count routing metric because PER leads to the formation of routes that are formed by low mobility nodes or nodes in low node density areas.

The Link Stability Based AODV (LSB-AODV) [1] routing protocol is quite similar to the work in [13] discussed in Section 2.1. Link length is mapped onto a value called Link Stability Factor (LSF) and the destination selects the path with the highest Path Stability Factor (PSF), where the PSF of a path is the minimum LSF of all the LSFs in the path. The primary difference between the two routing protocols is that in LSB-AODV, link lengths are estimated using signal strengths of received packets. However, signal strengths of received packets are highly fluctuating even in mainly static scenarios; hence, this method of link length estimation is not reliable.

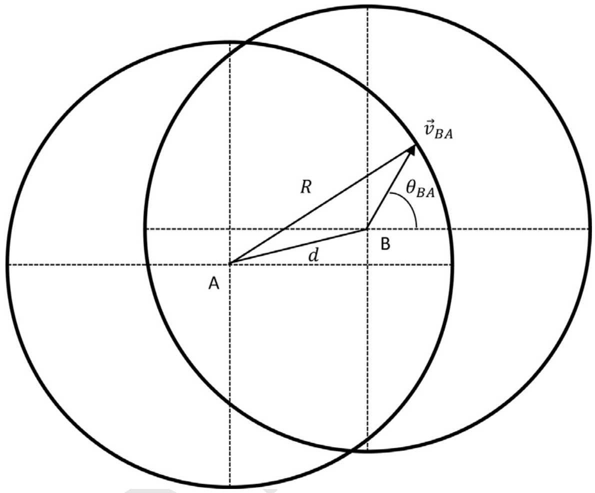

Fig. 1. Estimating the remaining lifetime of a link using node location information and node velocity information.

In the STable OLSR (ST_OLSR) [25] protocol, the variance of the received packet powers is used as the measure of the stability of a link. Since signal strengths of received packets are highly fluctuating, the variance of the signal strengths is also not reliable.

3. Route stability metric

3.1. Estimating link remaining lifetime

In MANETs, it is desirable to discover, establish, and use stable routes, i.e., routes consisting of links with long link remaining lifetime (LRL). If nodes are equipped with Global Positioning System (GPS) sensors, the remaining lifetime of a link can be estimated based on node location information and node velocity information. Fig. 1 shows two nodes A and B initially separated by distance d.

To derive the time link A–B remains up, we compute the amount of time node B remains within transmission range denoted as R from node A. The position of node B with respect to node A is given by $(x_{BA},\ y_{BA}) = (x_B - x_A,\ y_B - y_A)$. The distance of node B from node A is given by $d = \sqrt{{x_{BA}}^2 + {y_{BA}}^2}$. Subsequently, due to the individual motion of the two nodes, the position of node B with respect to node A after t seconds is given by $({x_{BA}}',\ {y_{BA}}')$, where: Q2

$$\begin{aligned} {x_{BA}}' &= x_{BA} + |\vec{v}_{BA}|t\cos\theta_{BA} \\ &\text{and} \\ {y_{BA}}' &= y_{BA} + |\vec{v}_{BA}|t\sin\theta_{BA} \end{aligned} \tag{1}$$

We would like to determine the amount of time t before node B goes out of range from node A and vice versa. Assuming that the velocity of node B with respect to node A is constant, the critical time at which node B goes out of range from node A can be determined by solving the following equation, where d' is the critical distance between nodes A and B before they are out of range from each other.

$$(d')^2 = \left({x_{BA}}'\right)^2 + \left({y_{BA}}'\right)^2 = R^2 \tag{2}$$

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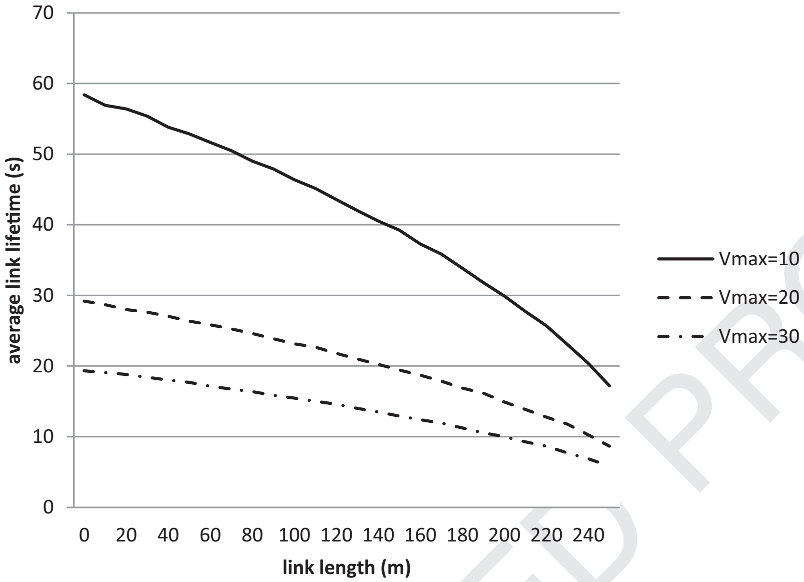

Fig. 2. Average link lifetime versus link length.

Substituting Eq. (1) into Eq. (2) and then rearranging, we obtained the following equation:

$$|\vec{v}_{BA}|^2t^2 + 2|\vec{v}_{BA}|(x_{BA}\cos\theta_{BA} + y_{BA}\sin\theta_{BA})t + d^2 - R^2 = 0 \quad (3)$$

where :

$$\vec{v}_A = (|\vec{v}_A|\cos\theta_A)\vec{i} + (|\vec{v}_A|\sin\theta_A)\vec{j}$$

$$\vec{v}_B = (|\vec{v}_B|\cos\theta_B)\vec{i} + (|\vec{v}_B|\sin\theta_B)\vec{j}$$

$$\vec{v}_{BA} = \vec{v}_B - \vec{v}_A = (|\vec{v}_B|\cos\theta_B - |\vec{v}_A|\cos\theta_A)\vec{i} + (|\vec{v}_B|\sin\theta_B - |\vec{v}_A|\sin\theta_A)\vec{j}$$

$$|\vec{v}_{BA}| = \sqrt{(|\vec{v}_B|\cos\theta_B - |\vec{v}_A|\cos\theta_A)^2 + (|\vec{v}_B|\sin\theta_B - |\vec{v}_A|\sin\theta_A)^2}$$

$$\theta_{BA} = \tan^{-1}\left(\frac{(|\vec{v}_B|\sin\theta_B - |\vec{v}_A|\sin\theta_A)}{(|\vec{v}_B|\cos\theta_B - |\vec{v}_A|\cos\theta_A)}\right)$$

Note that Eq. (3) is a quadratic equation of the form $ax^2 + bx + c = 0$, where $x = t$, $a = |\vec{v}_{BA}|^2$, $b = 2|\vec{v}_{BA}|(x_{BA}\cos\theta_{BA} + y_{BA}\sin\theta_{BA})$, and $c = d^2 - R^2$. The root of a quadratic equation can be computed by using the method of completing the squares with the following equation:

$$x = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (4)$$

Since $d \le R$, i.e., the two nodes are initially connected, we have $c = d^2 - R^2 \le 0$. Since $a = |\vec{v}_{BA}|^2 \ge 0$ and $c = d^2 - R^2 \le 0$, we have $b^2 - 4ac \ge b^2$. Hence, we have $\sqrt{b^2 - 4ac} \ge b$ and one of the root of Eq. (3) is positive while the other is negative. Since we cannot have negative duration, the positive root is the correct answer.

3.2. Using link length information to improve route stability

Link remaining lifetime (LRL) information is an obvious and direct indicator for route stability. Indeed, if a route consists of links with high LRLs, then the route can be expected to be highly stable. However, to calculate LRLs, nodes are required to obtain their locations and velocities. In addition, from Eq. (3), it can be observed that node velocities that are sampled at one time are used to estimate LRLs. In other words, current information is used to estimate a future outcome. Note that a node does not necessarily move at a constant (the sampled) velocity; it could change its velocity abruptly after its velocity is sampled. Since using LRL information not only increases cost by requiring information from additional hardware (sensors) but also does not guarantee accurate LRL values, an alternate way of quantifying link stability is required.

Intuitively, shorter links have longer LRLs than longer links. To verify this, we performed the following experiment. We put a node A at the origin and another node B to the right of node A, separating the two nodes with a certain distance less than or equal to the transmission range *R*. Then we assign a random node velocity to each of the two nodes and determine the time required for the two nodes to move out of range from each other by solving Eq. (3). For a particular value of the initial link length, we repeat the experiment many times. Varying the initial link length and using different maximum node speeds, we obtained the graphs in Fig. 2.

From the figure, it can be observed that shorter links are indeed more stable than longer links. In addition, as the maximum node speed increases, the average link lifetime decreases. However, since the maximum node speed is not something that we can enforce because the nodes

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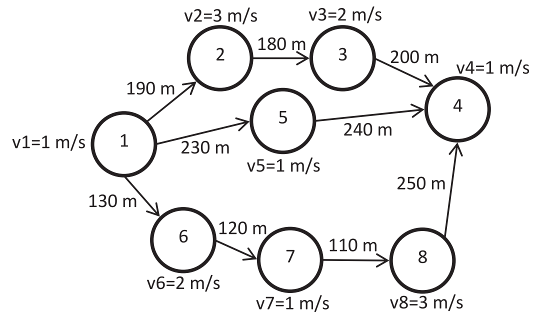

Path	RS Value	Selected
1-2-3-4	$((190-190)+1\times 3)^2 + ((180-180)+1\times 2)^2 + ((200-200)+1\times 1)^2 = 14$	✓
1-5-4	$((230-200)+1\times 1)^2 + ((240-200)+1\times 1)^2 = 2642$	×
1-6-7-8-4	$((130-130)+1\times 2)^2 + ((120-120)+1\times 1)^2 + ((110-110)+1\times 3)^2 + ((250-200)+1\times 1)^2 = 2615$	×

Fig. 3. How the RS routing metric is computed and used.

in a network often belong to different owners and hence move on their own will, we focus on reducing link length.

3.3. Route stability metric

In this section, we present the *Route Stability (RS)* metric; its equation is given as follows:

$$RS_p = \sum_{l\in p,\ n\in p} ((length_l - \min(length_l,\ THRESHOLD\_LENGTH)) + k \times mobility_n)^2 \quad (5)$$

where l is a link in the considered path p, n is a node in path p, $mobility_n$ is the measure of the mobility of node n, and $k \in \{0,\ 1\}$ is a tunable constant to select whether or not to consider node mobility information in the routing metric. When node mobility information is available, $mobility_n$ is the amount of distance in meters node n moves in 1 s. Generally, this corresponds to the speed at which node n moves. With this design, both $(length_l - \min(length_l,\ THRESHOLD\_LENGTH))$ and $mobility_n$ have the same unit of measurement, i.e., meters. The selected path p^* is defined as follows:

$$p^* = \arg\min_{p\in \boldsymbol{P}}(RS_p) \quad (6)$$

where $\boldsymbol{P}$ is the set of available paths.

The central idea of the RS routing metric is to penalize: (1) links that exceed a threshold length, and (2) mobile nodes. Even if we do not consider node mobility information (by letting $k = 0$ in Eq. (5)), the RS routing metric is capable of handling the unpredictability of node mobility by selecting paths consisting of short links. Even when we consider the worst case scenario, i.e., the two nodes of a link move directly away from each other, as the link is short, it takes some amount of time for the link to break. Since the RS routing metric does not make any assumption regarding node mobility, it is effective in all node mobility situations.

The RS routing metric uses a parameter called the threshold link length (*THRESHOLD_LENGTH*) to avoid nodes from selecting very short links leading to the formation of routes with very high hop count [25,26]. Either heuristics or experimentation methods could be used to determine a suitable value for this parameter. One heuristic is to set the parameter according to a desired minimum LRL. From Fig. 1, it can be observed that if nodes A and B are moving directly away from each other, the LRL of the link between them is shortest. Assuming that nodes have a maximum speed of v_{max}, the desired link length threshold can be set to the value of $length_l^{max}$ using Eq. (7), where $t_l^{desired\_min}$ is the desired minimum LRL of a considered link l, and R is the node transmission range.

$$t_l^{desired\_min} = \frac{R - length_l^{max}}{2v_{max}} \Rightarrow length_l^{max} = R - 2v_{max}t_l^{desired\_min} \quad (7)$$

We now illustrate how the RS routing metric is computed and used with the example shown in Fig. 3. We consider the full case, i.e., $k = 1$. The link length values are given next to the links while the node mobility values are given next to the nodes. Suppose nodes 1 and 4 are the source and destination, respectively, and *THRESHOLD_LENGTH* is 200 m. Three paths exist between nodes 1 and 4: 1-2-3-4, 1-5-4, and 1-6-7-8-4. According to the RS routing metric, path 1-2-3-4 has the lowest RS value and so is selected.

3.4. Estimating information used in the route stability metric

In the RS routing metric, link length information (for both $k = 0$ and $k = 1$) and node mobility information (for $k = 1$ only) is required. A method to obtain this

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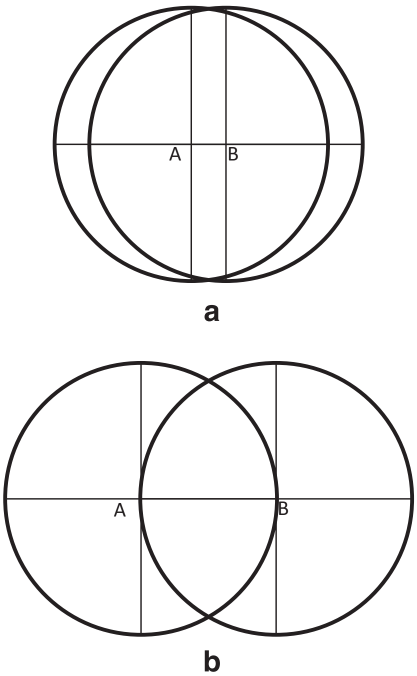

Fig. 4. Estimating the length of the link between two neighboring nodes.

information is through the use of GPS sensors. However, the use of GPS sensors is not desired as it would incur additional cost. For instance, we found the price of the GPS sensor board MTS420 to be about thrice the price of the IRIS mote XM2110. Besides, there are scenarios where GPS sensors are inapplicable, for example in indoor environments or low power nodes.

3.4.1. Estimating link length

One of the two information used in the RS routing metric is link length information. In some ad hoc routing protocols, nodes periodically broadcast HELLO messages to allow other nodes to sense their presence. This feature could be exploited to estimate the length of the link between two neighboring nodes.

In Fig. 4a, nodes A and B are located close to each other while in Fig. 4b the nodes are at a maximum distance from each other, subject to link A-B not broken. From these figures, it can be observed that there seems to be a relationship between the length of the link between the two nodes, and the area of the intersection of their transmission coverage areas. Unfortunately, two neighboring nodes are unable to determine the area of the intersection of their transmission coverage areas. However, the length of the link between nodes A and B can be estimated by evaluating the ratio of the number of nodes in the intersection of sets $\boldsymbol{U}$ and $\boldsymbol{V}$ to the number of nodes in the union of sets $\boldsymbol{U}$ and $\boldsymbol{V}$, where $\boldsymbol{U} = \{A\} \cup \boldsymbol{N}_A$, $\boldsymbol{V} = \{B\} \cup \boldsymbol{N}_B$, and $\boldsymbol{N}_x$ is the neighbor set of node x. For simplicity, we refer to this ratio as *overlap_ratio*.

$$overlap\_ratio = \frac{|\boldsymbol{U} \cap \boldsymbol{V}|}{|\boldsymbol{U} \cup \boldsymbol{V}|} \quad (8)$$

Assuming that nodes are uniformly distributed, the limit of *overlap_ratio* as node density approaches infinity is equal to the ratio of the area of the overlapping region of two equal circles to the area jointly covered by the two circles. The area of the overlapping region of two equal circles as shown in Fig. 5 is given in Eq. (9).

$$\begin{aligned} area_{overlapping\_of\_two\_equal\_circles} &= 2 \times (area_{ACFD} - area_{ACD}) \\ &= 2\left(R^2\cos^{-1}\frac{d}{2R} - \frac{d}{4}\sqrt{4R^2 - d^2}\right) \\ &= 2R^2\cos^{-1}\frac{d}{2R} - \frac{d}{2}\sqrt{4R^2 - d^2} \end{aligned} \quad (9)$$

The ratio of the area of the overlapping region of the two circles to the area jointly covered by the two circles is given as follows:

$$\frac{area_{overlapping\_of\_two\_equal\_circles}}{area_{union\_of\_two\_equal\_circles}} = \frac{\left(2R^2\cos^{-1}\frac{d}{2R} - \frac{d}{2}\sqrt{4R^2 - d^2}\right)}{\left(\pi R^2 + \left(\pi R^2 - \left(2R^2\cos^{-1}\frac{d}{2R} - \frac{d}{2}\sqrt{4R^2 - d^2}\right)\right)\right)} \approx overlap\_ratio \quad (10)$$

In Eq. (10), *overlap_ratio* is made approximately equal to the ratio of the area of the overlapping region of the two circles to the area of the union of the two circles. The ratios of the two areas is determined only by the distance between the centers of the two circles d, and the node transmission range R. The graph of the relationship between d and *overlap_ratio* is plotted in Fig. 6. Using the curve fitting method with a polynomial function of degree two, the relationship between link length ($length_l$) and *overlap_ratio* is given in Eq. (11).

$$length_l = 225.31 overlap\_ratio^2 - 600.85 overlap\_ratio + 378.29 \quad (11)$$

The value of *overlap_ratio* is generally in the range of approximately 0.25–1.00. For values smaller than that, we let the estimated length of the considered link to be 250 m.

The accuracy of the estimated link lengths is governed by how closely the considered regions in a real scenario agree on the assumptions made in deriving the relationship between the overlap ratio and link length: (1) the uniformity of the node distribution in the considered regions, and (2) node density in the considered regions. The accuracy of the estimations will be higher when node distribution is more uniform or node density is higher. We also identified stale neighborhood information as another source of estimation inaccuracy. For example, suppose node y was previously a neighbor of node x but has moved out of transmission range from node x but the neighbor list entry of node y in node x's neighbor list has not expired yet. Hence, node x still regards node y as its neighbor. A similar scenario is encountered when a new node z has moved within transmission range from node x but has not broadcast a new HELLO message. In this case, node x does not yet recognize node z as its neighbor.

3.4.2. Estimating node mobility

A link length estimation method was presented in Section 3.4.1. A method to estimate node mobility

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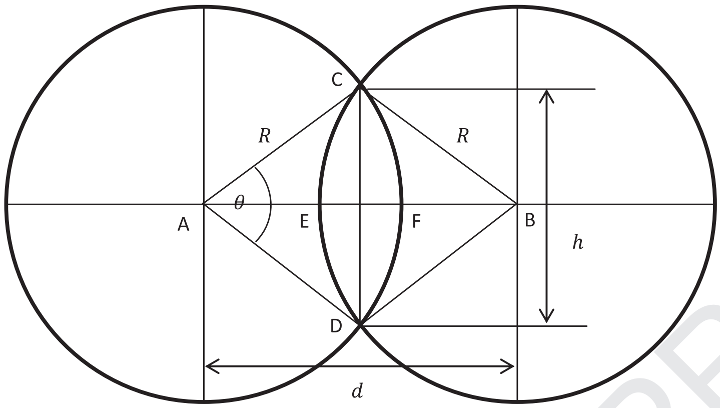

Fig. 5. Finding the area of the overlapping region of two equal circles.

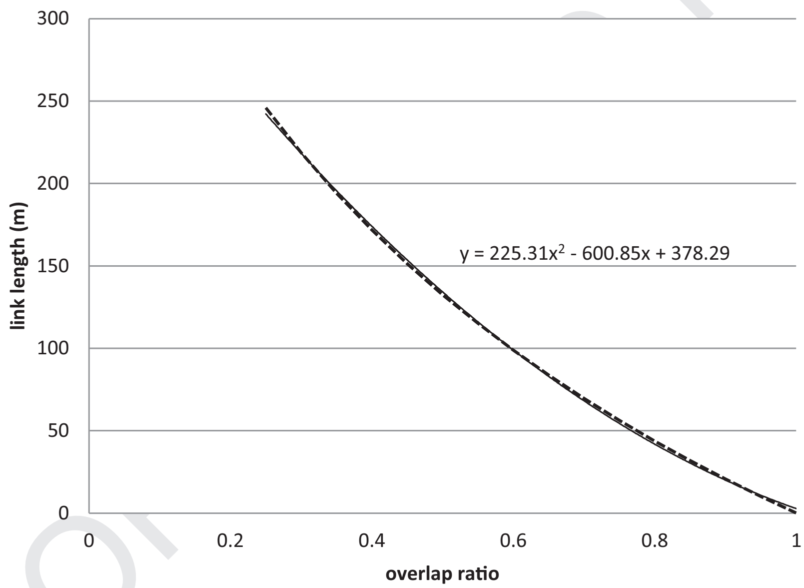

Fig. 6. The relationship between link length and overlap ratio.

information is also required so that the RS routing metric can be used entirely without depending on sensors. With some modifications, the link length estimation method presented in Section 3.4.1 can also be used to estimate the amount of distance a node has moved from its previous location. Instead of computing *overlap_ratio* using the neighbor sets of two neighboring nodes (Eq. 8), we compute *overlap_ratio* using the current and previous neighbor sets of a considered node x, as shown in Eq. (12).

$$overlap\_ratio = \frac{\left|\boldsymbol{N}_x \cap \boldsymbol{N}_x^p\right|}{\left|\boldsymbol{N}_x \cup \boldsymbol{N}_x^p\right|} \tag{12}$$

In other words, Eq. (13) can be used to estimate the mobility of a considered node x with the *overlap_ratio* value calculated using Eq. (12).

$$mobility_x = 225.31 overlap\_ratio^2 - 600.85 overlap\_ratio + 378.29 \tag{13}$$

To clearly identify the difference between these two estimation methods, Fig. 7 shows the difference between: (1) estimating the length of the link between two neighboring nodes, and (2) estimating the amount of distance a node has moved from its previous location.

The overlap ratio in Eq. (12) measures the degree of change in the neighbor set of a node between two successive sampling times. A higher change in the neighbor set of a node signifies higher relative velocities between the node and its neighbors. The change in neighbor set of a node is also used in many other routing metrics to measure node mobility, for example, Mobility Factor (MF) [20] and Neighbor Change Ratio (NCR) [22].

3.5. Modifications to routing protocols

As the RS routing metric is a routing metric, it is universal and can be used in any ad hoc routing protocols. In this paper, we consider its implementation in the popular AODV routing protocol [27].

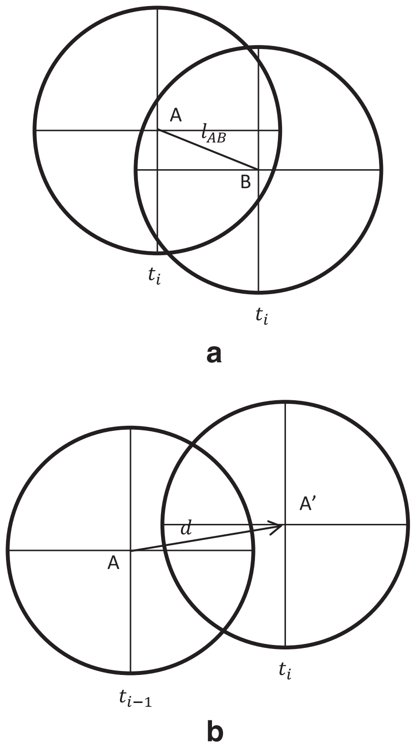

Fig. 7. (a) Estimating the length of the link between two neighboring nodes, versus (b) estimating the distance a node has moved from its previous location.

3.5.1. Route discovery and maintenance

The route discovery process in AODV is modified slightly to enable it to use the RS routing metric. The flowcharts for the processing of RREQs and RREPs at a node are shown in Fig. 8. The route maintenance process in AODV is unchanged.

3.5.2. Packet header modification

In the RS routing metric, if true link length information is used, the location information of a transmitting node is required. As a result, a RREQ and a RREP are each extended by three fields of type float to store the *x*- and *y*- coordinates of a transmitting node, and the aggregate metric value of a path. The aggregate metric value of a path is initialized to 0 at the RREQ source for a RREQ, and initialized to 0 at the RREQ destination for a RREP.

If estimated link length values (obtained using the link length estimation method proposed in Section 3.4.1) are used in place of actual link length values, a RREQ and a RREP are each extended by one field of type float, and *m* fields sized 1 byte each. Like before, the field of type float is used for storing the aggregate metric value of a path and is initialized to 0 at the RREQ source for a RREQ, and initialized to 0 at the RREQ destination for a RREP. To estimate the length of the link between a node and its previous hop, the node requires the neighbor set of its previous hop. To store all of the addresses of the neighbors of a node using conventional methods incurs high packet overhead. To resolve this problem, we propose a method to store node addresses compactly. We line up *m* bytes contiguously and encode whether a node is a neighbor of a considered node using a binary value, as shown in Fig. 9. The number of bytes required with this method depends on the number of nodes in the network. For example, for a network consisting of 200 nodes, $m = 200/8 = 25$, which is arguably quite manageable compared to 200 bytes if node addresses are stored using 1-byte fields.

As opposed to estimating the length of the link between two neighboring nodes, estimating the amount of distance a node has moved from its previous location using the method proposed in Section 3.4.2 requires no additional packet overhead. This is because when estimating the mobility of a considered node, the overlap ratio is computed using only local information, i.e., the current and previous neighbor sets of the node.

4. Results and discussion

Performance evaluation was done using network simulator 2 (ns-2) [28] with the following configurations. Seventy five nodes were placed in a rectangular region of dimension 1500 m by 300 m (same setup as used in [24]). The node mobility model used is the Random Waypoint Model. The degree of node mobility was varied by changing the maximum node speed from 5 m/s to 25 m/s in increments of 5 m/s while the pause time was set to 0 s so that nodes were constantly moving. The network traffic in each simulation instance consists of five pairs of CBR traffic flows, each flowing at the rate of 40 Kibps (512 B packet size at the rate of 10 packets/s; $1\ Ki = 2^{10} = 1024$, $1\ K = 10^3 = 1000$) and starting at a random time in the interval [0, 20] seconds simulation time. The physical and MAC related configurations were set to emulate the IEEE 802.11 ERP-DSSS physical layer [29,30]. Nodes had a transmission range of 250 m and a carrier sensing range of 550 m. The packet overhead required when the RS routing metric is used, as described in Section 3.5.2, was taken into account in the simulations for a fair and accurate comparison. Each scenario was repeated 20 times using different seed numbers in the interval [1, 20] when generating the node mobility and network traffic patterns. The performance metrics used for evaluation are as follows:

1. *Packet delivery ratio (%):* the number of data packets that were successfully delivered divided by the number of data packets sent by all sources.
2. *Normalized routing load:* the number of transmissions of all routing control packets (RREQ, RREP, RERR, and HELLO) divided by the number of data packets that were successfully delivered. It measures the average number of transmissions required for routing control packets for every data packet successfully delivered.
3. *Average packet latency (milliseconds):* the average of the end-to-end delays of data packets that were successfully delivered
4. *Average hop count:* the average hop count of data packets that were successfully delivered.
5. *Number of route discoveries:* In AODV, a route discovery is uniquely identified by a <source, broadcast ID> pair. The number of route discoveries is a measure of the

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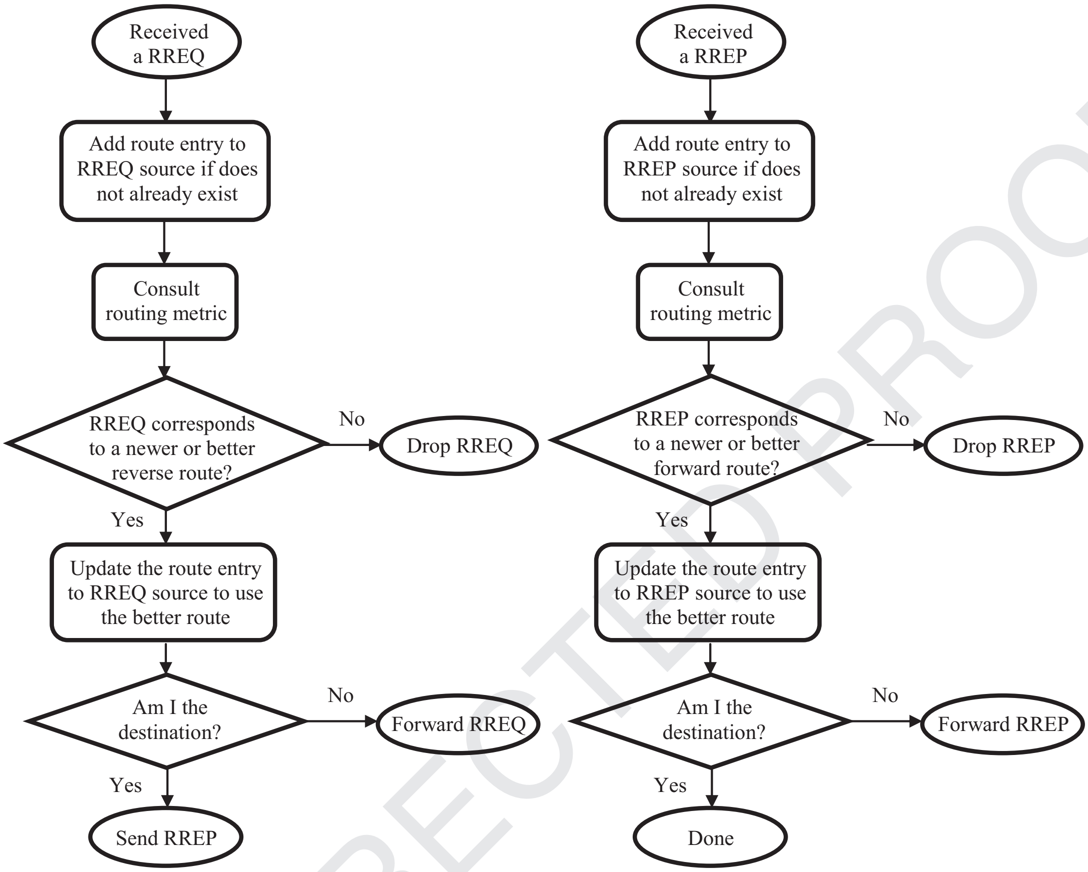

Fig. 8. Flow chart for processing RREQ and RREP packets.

1st byte	1	2	3	4	5	6	7	8
2nd byte	9	10	11	12	13	14	15	16
. . .								
mth byte	1+(m-1)8	2+(m-1)8	3+(m-1)8	4+(m-1)8	5+(m-1)8	6+(m-1)8	7+(m-1)8	8+(m-1)8

Fig. 9. Storing neighbor set of a node compactly in RREQs and RREPs.

stability of the discovered routes as more route discoveries are needed when there are more route breakages.

4.1. Performance of the route stability metric

To evaluate the performance of the RS routing metric, we implemented the following methods: (1) AODV using LRL information for path selection (LRL), (2) AODV using the RS routing metric with $k = 0$ and using true information (RS-k0-true), (3) AODV using the RS routing metric with $k = 1$ and using true information (RS-k1-true), (4) AODV using the RS routing metric with $k = 0$ and using estimated information (RS-k0-est), (5) AODV using the RS routing metric with $k = 1$ and using estimated information (RS-k1-est), (6) AODV using the PER [24] routing metric (PER), (7) AODV using the MF [20] routing metric (MF), and (8) AODV using the hop count routing metric (HC). The various routing metrics were implemented in the AODV routing protocol by making simple changes to its route discovery process. More specifically, changes were made to the “consult routing metric” part in the flow charts in Fig. 8. For the RS methods using true information (RS-k0-true and RS-k1-true), we assume that those information were obtained from sensors. For the RS methods using estimated information (RS-k0-est and RS-k1-est), those information were obtained using the link length and node mobility estimation methods introduced in Section 3.4. The threshold link length parameter was set to 0.7R = 175 m for the RS methods using true information; this selection was made to balance the tradeoff between path remaining lifetime and hop count. From Fig. 2, it can be observed that 175 m links have an average remaining lifetime of approximately 60% of the average remaining lifetime of 0 m links. We did not use a smaller threshold value due to diminishing returns. Using a very small threshold value could result in paths with very high hop count and very short links. The threshold link length value used for the RS methods using estimated information is 0.5R = 125 m. A lower threshold link length value was used for the RS methods using estimated information as they generally perform worse than their counterparts due to the use of less accurate information. The equation of MF was defined as follows:

$$\mathrm{MF} = \begin{cases} \sqrt{1 - \dfrac{\left|\left(\boldsymbol{N}_x \cap \overline{\boldsymbol{N}}_x^p\right) \cup \left(\overline{\boldsymbol{N}}_x \cap \boldsymbol{N}_x^p\right)\right|}{\left|\boldsymbol{N}_x \cup \boldsymbol{N}_x^p\right|}}, & \text{if } \boldsymbol{N}_x \cup \boldsymbol{N}_x^p \neq \emptyset \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

where $\boldsymbol{N}_x$ is the current neighbor set of a considered node x, and $\boldsymbol{N}_x^p$ is the previous neighbor set of node x. When the MF routing metric is used, we consider the path with the higher product of the MFs of its constituent nodes to be the more stable path.

4.1.1. Comparison with the LRL method

The LRLs of the links in a path have a direct relationship with the path's lifetime; hence, we first compare the RS-k0-true and RS-k1-true methods with the LRL method.

We found that the RS-k0-true method performed quite closely to the LRL method even when the RS-k0-true method does not use node velocity information. At lower degrees of node mobility (5–10 m/s maximum node speed), the RS-k0-true method even produced higher packet delivery ratio (Fig. 10a) than the LRL method. The RS-k0-true method also produced lower normalized routing load (Fig. 10b), lower average packet latency (Fig. 10c), and lower number of route discoveries (Fig. 10e) than the LRL method. Due to lower average hop count of packets (Fig. 10d), the RS-k0-true method produced lower average packet latency than the LRL method. From this comparison, it can be observed that even if we do not consider node mobility information, the RS routing metric does a fine job at approximating the performance of and even outperforms the path remaining lifetime routing metric (the LRL method) at lower degrees of node mobility. This shows that link length is a good indicator of route stability.

Additional performance could be gained by also considering node mobility information. Indeed, it can be observed from Fig. 10 that the RS-k1-true method outperforms the RS-k0-true method. The RS-k1-true method obtained higher packet delivery ratio (Fig. 10a), lower normalized routing load (Fig. 10b), lower average packet latency (Fig. 10c), and lower number of route discoveries (Fig. 10e). However, there is little difference between the average hop counts of the delivered packets obtained by the two methods, as shown in Fig. 10d. When we compare the LRL, RS-k0-true, and RS-k1-true methods together, it

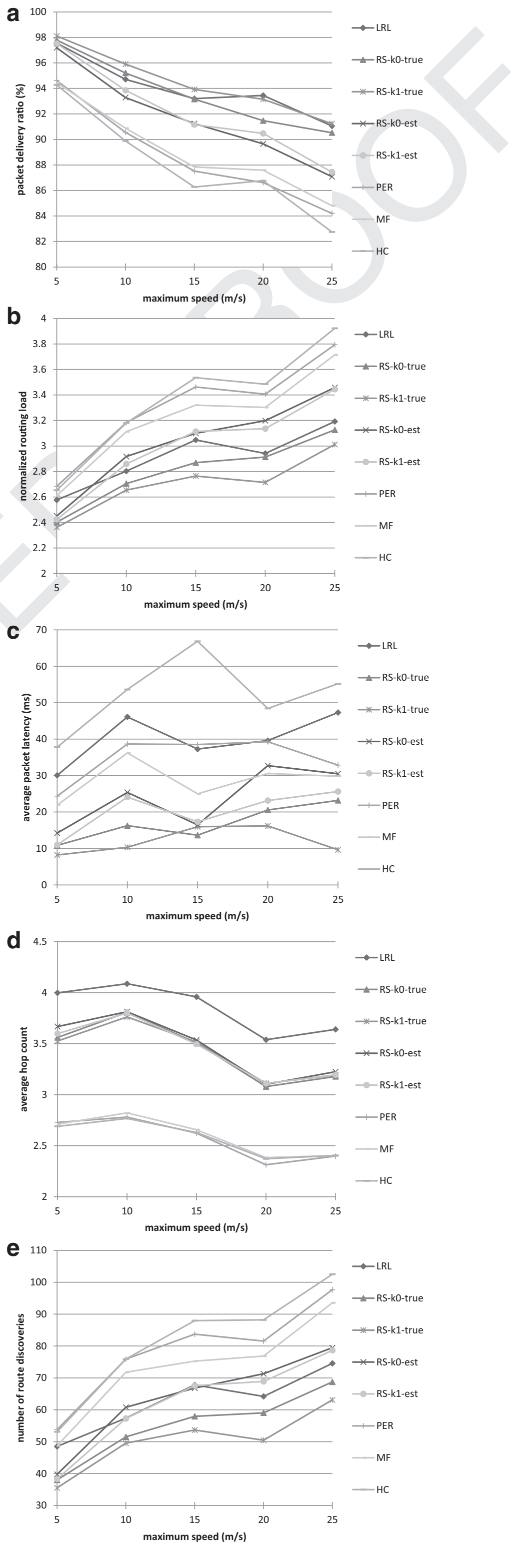

Fig. 10. Performance evaluation of the RS routing metric: (a) packet delivery ratio, (b) normalized routing load, (c) average packet latency, (d) average hop count, (e) number of route discoveries.

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can be observed that RS-k1-true method performed the best overall.

4.1.2. Comparison with other sensor-free methods

In this section, we limit the comparison to the *sensor-free* methods, i.e., RS-k0-est, RS-k1-est, PER, MF, and HC.

Similar to when true information was used (RS-k0-true versus RS-k1-true in Section 4.1.1), we found that RS-k1-est outperforms RS-k0-est. Furthermore, both outperformed the PER, MF, and HC methods in terms of packet delivery ratio (Fig. 10a), normalized routing load (Fig. 10b), and average packet latency (Fig. 10c). Even when node mobility information was not used, the RS-k0-est method produced approximately 3.1%, 3.8%, 5.8%, 3.3%, and 5.2% higher packet delivery ratio than the HC method at 5, 10, 15, 20, and 25 m/s, respectively. In contrast, the PER method produced approximately 0.4%, 0.7%, 1.4%, -0.2%, and 1.8% higher packer delivery ratio than the HC method at 5, 10, 15, 20, and 25 m/s, respectively. The routes discovered by the RS-k0-est and RS-k1-est methods were more stable than the routes discovered by the PER, MF, and HC methods. The RS-k0-est method produced approximately 25.1%, 19.9%, 24.0%, 19.2%, and 22.5% fewer route discoveries than the HC method at 5, 10, 15, 20, and 25 m/s, respectively. On the contrary, the PER method produced approximately -1.3%, 0%, 4.8%, 7.5%, and 4.7% fewer route discoveries than the HC method at 5, 10, 15, 20, and 25 m/s, respectively. The RS-k0-est and RS-k1-est methods obtained better average packet latency (Fig. 10c), even when the average hop count of delivered packets obtained by these methods are higher than those obtained by the PER, MF, and HC methods (Fig. 10d). This is because the routes established by the RS-k0-est and RS-k1-est methods were more stable (Fig. 10e). One of the factors contributing to packet latency is route stability. When routes are unstable, data transmission is frequently interrupted and this causes data packets to have high latencies.

Another advantage of the RS routing metric over the MF, PER, and HC routing metrics is that additional performance could be gained when accurate information is used. Indeed, it can be seen from Fig. 10 that RS-k0-true and RS-k1-true outperformed RS-k0-est and RS-k1-est, respectively. On the contrary, no further performance gain is possible with the MF, PER, and HC methods as they already use accurate information. Hence, the RS routing metric is a flexible routing metric that performs well when only estimated information is available, and performs even better when accurate information is available.

4.1.3. True versus estimated information

In this section, we compare the performance of the RS routing metric when it is used with true and estimated information.

The sensor-free RS methods (RS-k0-est and RS-k1-est) performed worse than their sensor-using counterparts (RS-k0-true and RS-k1-true) in most aspects, i.e., packet delivery ratio (Fig. 10a), normalized routing load (Fig. 10b), and average packet latency (Fig. 10c). This is due to the generally more stable routes found by the sensor-using RS methods (Fig. 10e). The average hop count (Fig. 10d) obtained by all the methods however are quite similar to each other.

The sensor-free RS methods perform worse than their sensor-using counterparts. This is to be expected considering that the sensor-free RS methods use less accurate estimated link length information and node mobility information. However, we argue that this is acceptable considering that cost is reduced when sensors are not used. Besides, in Section 4.1.2, it was shown that the RS-k0-est and RS-k1-est methods outperformed the other sensor-free methods, i.e., MF, PER, and HC. The gains of the sensor-free RS methods over the HC method are respectable. In contrast, the PER and MF methods provide only negligible gains over the HC method.

4.2. Effect of threshold link length

In this section, we investigate the effect of threshold link length using the RS routing metric when node mobility information is not considered (i.e., $k = 0$ in Eq. (5)). We conducted the experiment using both true and estimated link length values. We varied the threshold link length value as follows: (1) 75–225 m in increments of 25 m when true link lengths were used, and (2) 25–175 m in increments of 25 m when estimated link lengths were used. Fig. 11 shows the results obtained. The solid lines correspond to the results obtained when true link lengths were used while the dotted lines correspond to the results obtained when estimated link lengths were used.

Fig. 11a shows the packet delivery ratio. It can be observed that packet delivery ratio increases as the threshold link length value decreases regardless of whether true or estimated link length information was used. It can also be observed that the packet delivery ratio lines are closer together at smaller threshold link length values. This shows that there are diminishing returns at smaller values of threshold link length. For this reason, we should not set the threshold link length to a value that is too small. That is also why we have considered the values of $0.7R = 175$ m and $0.5R = 125$ m for the threshold link length when true or estimated link length values were used in our simulations in Section 4.1, respectively.

Fig. 11b shows the normalized routing load. From this figure, we observed that when true link length values were used, setting the threshold link length value to 175 m gave the overall best results. When the estimated link length values were used, setting the threshold link length value to 125 m seems to give good results.

Fig. 11c shows the average packet latency. We observed that in general, average packet latency decreases with the threshold link length value although it becomes difficult to identify the overall best performing scheme at small threshold link length values as the lines are converged in the 10–25 ms region.

Fig. 11d shows the average hop count. From this figure, we observed an inverse relation between average hop count and the threshold link length value. This can be expected because a smaller threshold link length value gives higher penalty to links and favors higher hop count paths consisting of shorter links. We also observed that a threshold link length value difference of 25 m corresponds to approximately 0.25 point in average hop count difference.

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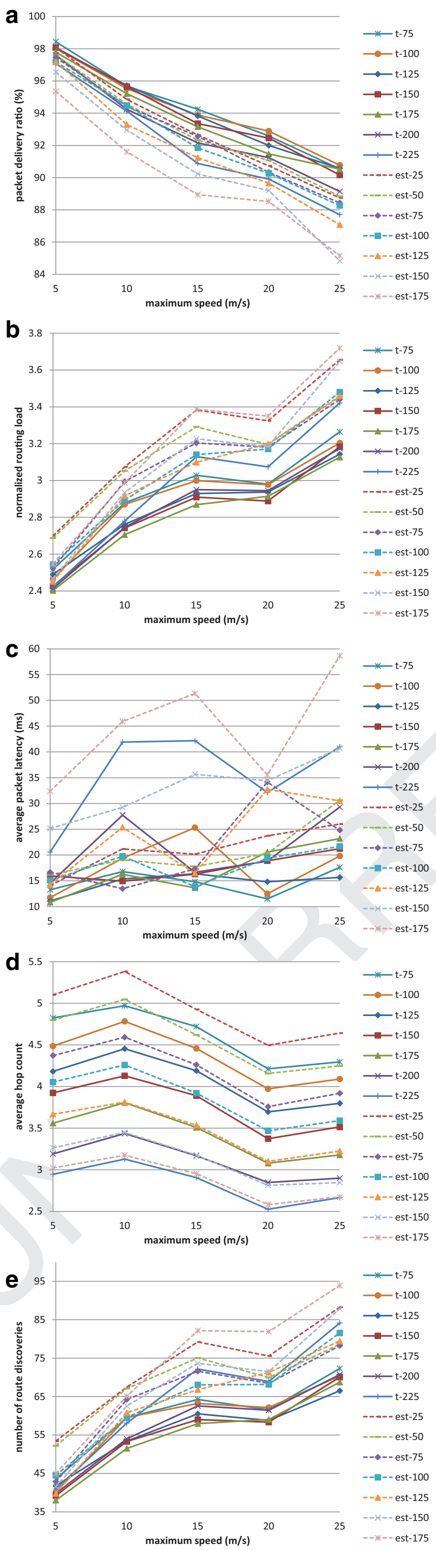

Fig. 11. Performance of the RS routing metric ($k = 0$) with various threshold link length values: (a) packet delivery ratio, (b) normalized routing load, (c) average packet latency, (d) average hop count, (e) number of route discoveries.

Fig. 11e shows the number of route discoveries. We observed that the overall best performance was obtained when the threshold link length value is about 175 m when true link length values were used, and about 125 m when estimated link length values were used.

5. Conclusions

In this paper, we proposed the RS routing metric, which uses link length information and optionally node mobility information, to improve route stability in MANETs. It works by assigning a penalty to links exceeding a threshold length and mobile nodes. When accurate information is available, for example, by using GPS sensors, the RS routing metric performs well and generally exceeds the level of performance possible with the link remaining lifetime (LRL) method. However, the true beauty of the RS routing metric is that it can even be used without sensors. From our investigation, we found the RS routing metric to be highly effective and outperformed other sensor-free routing metrics and the hop count metric even when used without accurate information.

Acknowledgments

We take this opportunity to thank the Editor and the anonymous reviewers for their efforts spent in reviewing the paper. This work was supported by Ministry of Science, Technology and Innovation (MOSTI) Malaysia under eScienceFund (01-01-03-SF-0782).

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