An efficient metric for reliable routing with link dependencies

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***Abstract*—To improve the robustness and adaptation to node mobility, ad hoc routing protocol uses as route selection criterion, the route reliability metric between end points. In the first part of this paper, we derive an analytical closed form expression for the computation of route reliability metric, that takes into account dependencies between adjacent links. Based on our analytical formulation, the route reliability metric computation does not introduce any complexity. Simulations show that our model can obtain more accurate results than the traditional methods. However, the route reliability metric increases network resources used in terms of intermediate nodes between source and destination. It may also increase packet delay. Moreover, the interference and collision probability between packet increase when the number of relays in the same range increases. In order to overcome these inconveniences, in the second part of this paper, we propose a new routing metric which combines reliability and hop count criteria. Simulations results show that the introduced metric allows better results.**

***Index Terms*—link reliability, link dependencies, routing metrics, analytical models**

I. Introduction

Due to the unreliability characteristics of wireless communications, and nodes mobility, Mobile Ad hoc Networks (MANETs) suffer from frequent failures and reactivation of links along these routes. Consequently, the routes frequently change. Frequent route changes cause significant number of routing packets to discover new routes, leading to increased network congestion and transmission latency [1]. Therefore, MANETs demand robust routing protocol design for which main challenge is to choose the best routing metric. Selecting route reliability as routing metric, minimizes route failure occurrence, can reduce the overhead of route discovery effectively, and improve packet delivery ratio, as shown in [2]–[4]. Considering that the metric is the route reliability value, it is determined according to the reliability of each link [5]. The link reliability between adjacent mobile nodes have been studied for different methods (measurements [6]–[8] and analytical models [4], [9]–[13]). After the determination of the link reliability, the main challenge is the computation of route reliability metrics. If the assumption of link independence is adopted, then route reliability can also be computed directly by multiplying the reliabilities of all links along this route. In fact, in ad hoc networks, the existence of wireless links is correlated [5], [14], [15].

In this paper, we treat the link dependency problem. The main motivation is to efficiently compute reliability metric between end points without any assumptions on links along the route. In the first part of this paper, we propose a new efficient algorithm to compute route reliability metric with a realistic assumption (link dependencies). Introducing this metric as route selection criteria in routing protocol, improves packet delivery ratio compared to minimum hop-count metric. However, the established routes use numerous unnecessary relays, which leads to an inefficient use of resources. Based on this observation, in the second part, we propose a new metric which combines the two metrics: route reliability and minimum hop-count.

II. Route Reliability

Let's assume that, the route $P_{(n_0 \leftrightarrow n_m)}$ from a source n_0 to a destination n_m is composed of m links. Each link L_i is established between two adjacent nodes n_i and n_{i+1}; with $0 \leq i \leq m-1$. Neglecting collisions and interferences, the route reliability $P_{(n_0 \leftrightarrow n_m)}$ depends on the reliability of the links along this route. Link reliability, also related to link stability in literature, is obtained either from real measurements or from analytical modeling based on a predictable node movement. Without loss of generality, this paper focuses on analytical model of link reliability where nodes move according to Semi-Markov Smooth (SMS) mobility model proposed in [16]. The Semi-Markov Smooth (SMS) mobility is a *microscopic* mobility which integrates a variety of nice properties of existing mobility models and overcomes theirs limitations such as speed decay and sharp turn. SMS mobility is flexible to mimic nodes movement in the realistic mobile networks. Each movement contains three consecutive phases: 1) Speed Up (α-) 2) Middle Smooth (β-) and 3) Slow Down. Each SMS node movement is performed with two parameters: a direction ϕ_α and target speed v_α as expected direction and speed of the movement. Our analysis is based on the model of link reliability proposed in [17]. The main originality of this paper is the modeling of link reliability as a function of initial nodes pair distance whatever relative speed of nodes pair, nodes transmission range and mobility.

A. Analytical link reliability model [17]

A Markov chain model (MCM) is used to describe the distance evolution between nodes in an ad hoc network, moving according to memoryless smooth mobility model. Node *w* moves into reference node *u*'s transmission range r which

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is divided into n equivalent length bins of width ε meters. Hence, $r = n \cdot \varepsilon$ assuming n states in node u's transmission range; $E = \{e_1, e_2, \ldots, e_i, \ldots, e_n\}$. Communication time T is partitioned into small intervals of fixed length time, termed epoch. In each epoch, the link L_i between the nodes n_i and n_{i+1} is active, if the distance $d_{i,i+1}$ between a pair of given nodes is less than the transmission range r.

Given an active link at epoch 0 between two nodes, its reliability $R_L(k)$ after k epochs is defined as the probability that the link will continuously be available until at least the epoch k. The link reliability is based on the reliability distance probability vector $RV(k)$:

$$R_L(k) = \sum_{i=1}^{n} rv_{iL}(k) \tag{1}$$

where $rv_{iL}(k)$ are the elements of the reliability distance probability vector after the epoch k, $RV_L(k)$. It is a vector with $(n+1)$ elements defined as follow:

$$RV_L(k) = P(0)\, P_R^k \tag{2}$$

where P_R^k is the reliability matrix of transition probability after k epochs; $P(0)$ is the initial probability vector which denotes the probability of initial distance between a pair of nodes at the epoch 0.

$$P(0) = [p_1(0), p_2(0), p_3(0), \cdots, p_n(0), \cdots] \tag{3}$$

$P(0)$ depends of the objective of the computing of the links parameters.
If the objective is to compute parameters for a given link,

$$P(0) = [p_1(0) = 0, \cdots, p_i(0) = 1, \cdots, p_n(0) = 0, \cdots] \tag{4}$$

where i corresponds to the initial distance on the link.
If the objective is to compute an average value for the parameters of the network.

$$P(0) = \left[p_1(0) = \tfrac{1}{n}, p_2(0) = \tfrac{1}{n}, \cdots, p_n(0) = \tfrac{1}{n}, \cdots\right] \tag{5}$$

where all the elements are equiprobable in our study. Interested readers can refer to [1] for a more thorough explanation about P(0).

The transition matrix of reliability P_R is the transition matrix probability with an absorbing state e_{n+1} (modeling, any nodes pair with a distance greater than r). The link is considered to be broken, if the distance between the pair of nodes reaches the absorbing state. There are $(n+1)$ possible states, thus, P_R is a $(n+1)\times(n+1)$ size matrix. Each element of P_R, $p_{i,j}$ corresponds to the probability of transition from state e_i to state e_j in a given epoch. Note that for all i,j, $p_{i,j} \geq 0$ and $\sum_i p_{i,j} = 1$. This probability is formulated as follows for smooth mobility model [17]:

$$\begin{aligned} p_{i,j} &= Pr(e_i \rightarrow e_j) \\ &\approx \tfrac{0.2}{v_\alpha} \times \sqrt{\tfrac{2j-1}{2i-1}} \times \left[\ln \tfrac{|4(v_\alpha+\delta_v)^2 - \varepsilon^2(j-1)|(i+j-1)^2}{|\varepsilon^2(i+j-1)^2 - 4(v_\alpha+\delta_v)^2|(j-1)^2}\right]^{\frac{1}{2}} \end{aligned} \tag{6}$$

Route reliability is computed in discovery phase of routing protocol. Using independence assumption or not, the node must include its actual position in discovery request packet. When first intermediate node A receives Route Request (RREQ) packet, it contains only source parameters (positions and speed). Node A, based on its actual position and speed, computes the reliability of link $L_{S,A}$. The RREQ packet sent by node A contains two new parameters: 1) speed and position of node A and, 2) reliability of $L_{S,A}$. Thus, the request received by all other intermediate and destination nodes has this two parameters.

B. On the independence assumption

If the link independence assumption is adopted, then the route reliability is the product of the reliabilities of all links along this route [4], [9]–[13].

$$\begin{aligned} R_{P_{(n_0 \leftrightarrow n_m)}}(k) &= R(L_0(k) \cap L_1(k) \cdots \cap L_{m-1}(k)) \\ &= \prod_{j=0}^{m-1} R_{L_j}(k) \end{aligned} \tag{7}$$

Meanwhile, this independence assumption is not true in general. Since, two adjacent links along a route share an intermediate node. Therefore, link reliability of two links depends on the mobility of its intermediate node [14] [5], [15].

C. Proposition: Route Reliability Computation model with links dependence

In [14], the authors propose an analytical formulation of route reliability with dependence assumption, as follows:

$$\begin{aligned} R_{P_{(n_0 \leftrightarrow n_m)}} &= R(L_0 \cap L_1 \cdots \cap L_{m-1}) \\ &= R_{L_0} \times R_{L_1/L_0} \times R_{L_2/L_0 \cap L_1} \times \cdots \\ &\quad \times R_{L_{m-1}/L_0 \cap L_1 \cdots \cap L_{m-2}} \\ &= R_{L_0} \times \prod_{j=0}^{m-1} R_{L_{j+1}/L_j} \end{aligned} \tag{8}$$

where $R_{L_j/L_{j-1}}$ is the reliability metric of L_j knowing that the link L_{j-1} exists. The main challenge for computing $R_{P_{(n_0 \leftrightarrow n_m)}}$ is to compute $R_{L_j/L_{j-1}}$. For that purpose, we first consider the case of a route with two links, and after propose a generalization.

The route reliability between nodes n_0 and n_1 after k epochs is defined as the product of two data a) reliability of link L_1 between nodes n_0 and n_1, b) reliability of link L_2 between nodes n_1 and n_2 knowing link L_1 exists.

$$\begin{aligned} R\left(P_{n_0 \leftrightarrow n_1 \leftrightarrow n_2}\right)(k) &= Pr\left\{R_{L_0}(k) \cap R_{L_1}(k)\right\} \\ &= R_{L_0}(k) \times R_{L_0/L_1}(k) \end{aligned} \tag{9}$$

Reliability of link L_0 is computed according to equation (1). The reliability of link L_1 knowing link L_0 exists, depends on the distance evolution between nodes n_0 and n_1. Note that $d_{L_0}(t_0)$ and $d_{L_0}(k)$ respectively distances between nodes n_0 and n_1 at time t_0 and k.

- Distance d_{L_0} decreases: This means that node n_1 moved towards node n_0 of a distance $u = d_{L_0}(t_0) - d_{L_0}(k)$.

Suppose that distance $d_{L_1}(t_0) = r$ (*ie* $d_{L_1} \in e_n$ last no absorbing state), therefore link L_1 exists at time k, if node n_2 gets closer to node n_1 of a distance superior or equal to u. The distance between node n_1 and n_2 must be in the set $\{e_j \ / \ 1 \leq j \leq n - u = n - d_{L_0}(t_0) + d_{L_0}(k)\}$.

$$rv_{iL_1/L_0}(k) = rv_{iL_0}(k) \times \sum_{j=1}^{n+i-d_{L_0}(t_0)} rv_{jL_1}(k) \quad \text{if} \quad i \leq d_{L_0}(t_0) \tag{10}$$

where $rv_{iL_0}(k)$ and $rv_{jL_1}(k)$ are computed according to equation (1).

- Distance d_{L_0} increases: This means that node n_1 went away from node n_0 of a distance $v = d_{L_0}(k) - d_{L_0}(t_0)$. The distance between node n_1 and n_2 must be in the set $\{e_j \ / \ v = d_{L_0}(k) - d_{L_0}(t_0) \leq j \leq n\}$.

$$rv_{iL_1/L_0}(k) = rv_{iL_0}(k) \times \sum_{j=i-d_{L_0}(t_0)}^{n} rv_{jL_1}(k) \quad \text{if} \quad d_{L_0}(t_0) < i \leq n \tag{11}$$

Compared to the algorithm based on the independence assumption, the computation of $P_{n_0 \leftrightarrow n_1 \leftrightarrow n_2}$ in node n_2 considers a third parameter $d_{L_0}(t_0)$ between nodes n_0 and n_1.

The conditional reliability R_{L_{j+1}/L_j} can be approximated as follows:

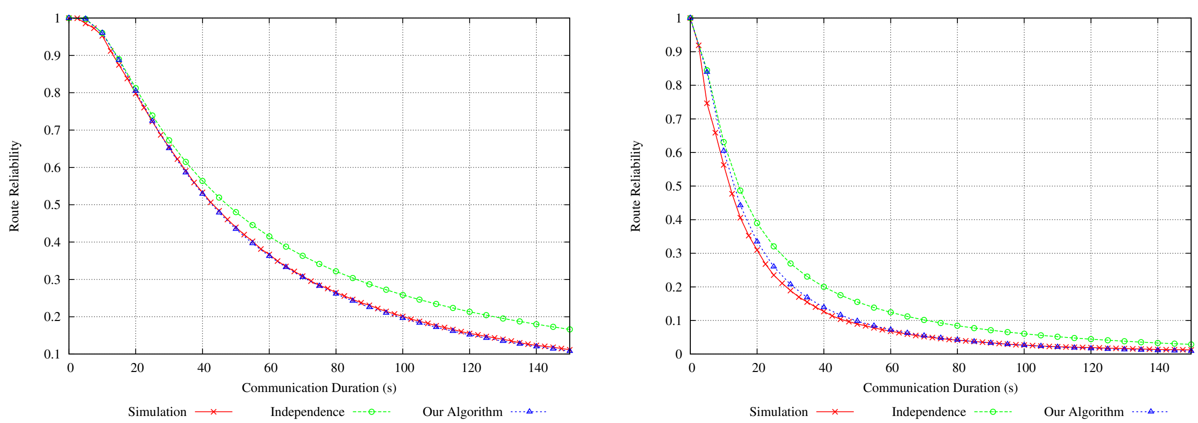
$$R_{L_{j+1}/L_j}(k) = \sum_{i=1}^{n} rv_{iL_{j+1}/L_j}(k) \tag{12}$$

where $rv_{iL_{j+1}/L_j}(k)$ is:

$$rv_{iL_{j+1}/L_j}(k) = \begin{cases} rv_{iL_j}(k) \times \sum_{p=1}^{n+i-d_{L_j}(t_0)} rv_{pL_{j+1}}(k) \\ \quad \text{if} \quad i \leq d_{L_j}(t_0) \\ \\ rv_{iL_j}(k) \times \sum_{p=i-d_{L_0}(t_0)}^{n} rv_{pL_{j+1}}(k) \\ \quad \text{if} \quad d_{L_j}(t_0) < i \leq n \end{cases}$$

The formula above is generalized for route $R_{P_{(n_0 \leftrightarrow n_m)}}(k)$ of length m. The computation is step-wised and start in n_0.

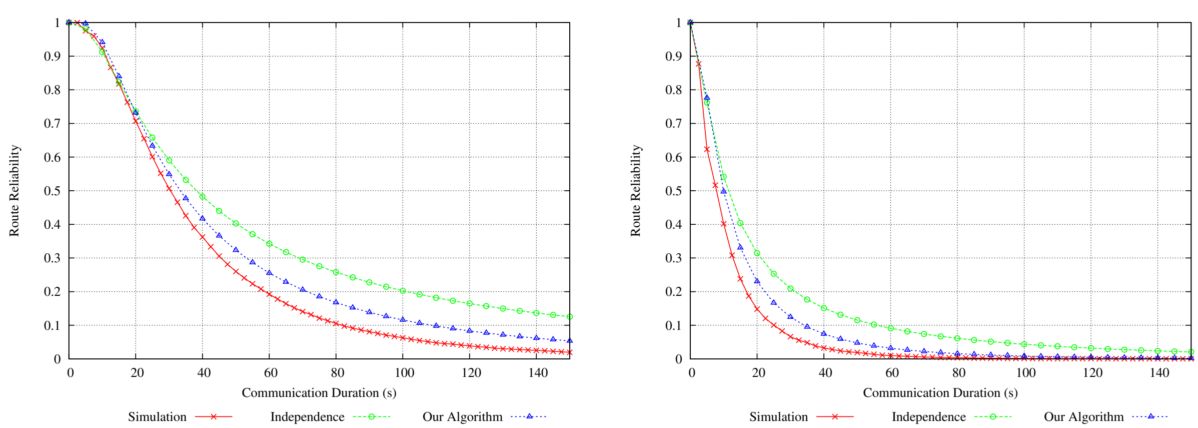
- n_0 send to n_1 its positions (X_{n_0}, Y_{n_0}).
- The node n_i receives data from n_{i-1}, send to n_{i+1} its positions (X_{n_i}, Y_{n_i}), the computed reliability of route



(a) Mean Node Speed= 7m/s

(b) Mean Node Speed= 12m/s

Fig. 1. Route with Two Links Reliability vs Communication Duration *(Initial Nodes Distance=200 m)*



(a) Mean Node Speed= 7m/s

(b) Mean Node Speed= 12m/s

Fig. 2. Route with Three Links Reliability vs Communication Duration *(Initial Nodes Distance=200 m)*

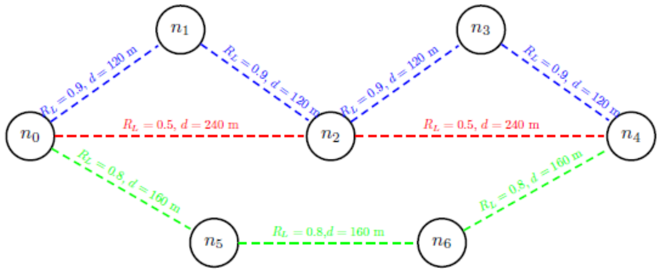


Fig. 3. Example of Routing Metrics ($R = 250m$)

from n_0 to n_i and the computed distance $d_{L_i}(t_0)$ (where L_i is the link between nodes n_{i-1} and n_i).

D. Evaluations

We focus on the validation of our formulation of the route reliability with link dependencies assumption. We suppose that all nodes have the same transmission range 250m. To validate our approximation (equation (12)), we compare the three hops route reliability metrics obtained by simulation, with independence assumption algorithm and our proposed algorithm. Note that in this paper, we present the results for medium node speeds (7m/s and 12 m/s). For small (4m/s) and high (20m/s) speeds, the two studied algorithms and simulation return quite the same values. When nodes move with high speed the link reliability between adjacent nodes value is close to zero. Therefore, route reliability values are also close to zero. Fig. 1 and Fig. 2 show the best accuracy of our algorithm (equation (12)), where the initial nodes distance are 200m with two and three links. Our algorithm always approximates route reliability better than independence assumption based algorithm whatever is the number of links along this route.

III. Routing Metrics

Route reliability and minimum hop count metrics have opposite characteristics, *ie* minimum hop criterion advantages are reliability metric drawback and vice-versa. An interesting question is: How to take advantage of these two opposite metrics? In this paper, we propose a new metric uses route reliability as the basic routing metric but incorporates hop-count metric to reduce the number of unnecessary used relays, and collisions and interferences over the routing path.

Let the topology of Fig. 3, where source n_0 wants to communicate with the destination n_4. All nodes have the same transmission range $R = 250$m. Using hop-count metric, routing protocol establishes route R_1 of two hops ($n_0 \leftrightarrow n_2 \leftrightarrow n_4$), while routing protocol uses as selecting criteria the reliability, constructs route R_2 with four hops ($n_0 \leftrightarrow n_1 \leftrightarrow n_2 \leftrightarrow n_3 \leftrightarrow n_4$). This route R_2 has the highest reliability but uses two intermediate nodes (n_1 between n_0 and n_2, n_3 between n_2 and n_4). Our new metric establishes the optimal route R_3 ($n_0 \leftrightarrow n_5 \leftrightarrow n_6 \leftrightarrow n_4$). It ensures the best compromise between the two metrics: route reliability $R_{R_3} = 0.512$, number of hops ($hc_{R_3} = 3$ hops).

A. Proposition of new metric: Combining Hop-Count and Reliability metrics

The new metric is defined as the product of link reliability between nodes and the probability not using unnecessary relays. To compute the probability of using unnecessary relay, we need information on two hops neighbors. We model the distance probability after the epoch k between nodes pair knowing that their initial separation distance is less than twice the transmission range The probability that relay n_{i+1} between two nodes n_i and n_{i+2} becomes unnecessary in $[t, t+T]$ is defined as the percentage of time that node-pair distance $d_{(n_i,n_{i+2})}(t, t+T)$ will be less than the transmission range R, in this interval. As in section II-A, we use a Markov chain model (MCM) to describe the distance evolution between nodes from 0m to $2 \times R$, $AV(k)$.

$$U_{n_{i+1}}(k) = Pr\left[d_{(n_i,n_{i+2})}(k) < R | d_{(n_i,n_{i+2})}(0) < 2 \times R\right] = \sum_{i=1}^{n} av_i\,(k) \quad (13)$$

where $av_i\,(k)$ are the elements of the separation distance probability vector. The separation probability vector $AV(k)$ after the epoch k is a vector (with $(2 \times n + 1)$ elements):

$$AV(k) = P(0)P_A^k \quad (14)$$

Where P_A^k is the separation matrix of transition probability after k epochs, its elements are defined by equation (6); $P(0)$ is the initial probability vector which denotes the probability of initial distance between a pair of nodes at the epoch 0. In our case, the objective is to compute parameters for a given link, thus $P(0)$ has only one nonzero element, as in equation (5).

As reliability metric, our new metric is used by routing protocol in discovery phase. When a node receives a RREQ packet, if it has no route to source or new route has better value than its known route, then it forwards the packet. Our new metric helps an intermediate node to know if the node from which it has received the RREQ are probable unnecessary relay or not.

In the next section, we present the performance evaluation of our metric compared to the two classical metrics: minimum hop-count and reliability.

B. Simulation and Performance Analysis

We used OMNeT++ simulator. The channel capacity of mobile hosts are set to 11 Mbps. We use the DCF (Distributed Coordination Function) of IEEE 802.11 for wireless LAN as the MAC layer protocol, and the free-space model as radio propagation model. All the nodes have the same transmission range of 250 meters. At the beginning of each simulation, 50 nodes are placed randomly inside the simulation area which is specified by a 1000m $\times$ 1000m square region. During 900 seconds simulation time, all nodes move (direction and speed change randomly each second) according to the Semi-Markov Smooth (SMS) mobility model proposed in [9]. In each simulation, source node uses CBR (Constant Bit Rate),

TABLE I
ROUTING PROTOCOL DYMO'S PARAMETERS

ROUTE AGE MIN TIMEOUT	1 s
ROUTE AGE MAX TIMEOUT	60 s
ROUTE NEW TIMEOUT	5 s
ROUTE USED TIMEOUT	5 s
ROUTE DELETE TIMEOUT	10 s
RREQ RATE LIMIT	10 s
RREQ BURST LIMIT	3 s
RREQ WAIT TIME	2 s
RREQ TRIES	3 s

generates 5 packets per second with the size of 512 bytes. We use DYMO [18] as routing protocol.

1) Performance metrics: Each metric value is an average value obtained from 500 simulations runs. The following metrics are used to evaluate the performance of the protocols:

- **Packet delivery ratio:** the ratio of the data packets delivered to the destination.
- **Route Discovery delay:** is the delay between a message being queued for delivery by routing protocol and its removal from the queue when a route was established. It should be noted that this measure does not reflect cases where a message was not queued because a route was already known, neither does it reflect cases where a message was discarded because no route could be discovered in the time interval set.
- **Mean wait time of packets:** is the mean time which packets wait in source. Contrary to previous performance, it takes into account all sent packets by source even the messages that were not queued.
- **Average of unnecessary relays:** It is the number of unnecessary relays to forward a packet from source to destination.
- **Average hop count:** between source and destination.
- **Average end-to-end delay:** from sources to destinations. It includes queuing delay and propagation delay.

2) Simulation results: We compare the performance of DYMO using: minimum hop-count, route reliability and, our proposed metric. The routing parameters, used in simulation, are summarized in table I.

In Fig. 4, we observe that packet delivery ratio decreases when node speed increases, because of route failures increasing. Reliability metric has the highest delivery ratio than the two other metrics. However, it leads to the use of numerous intermediate nodes between source and destination, therefore its hop count and used unnecessary relays increase, as shown in Fig. 8 and Fig. 7. Consequently, the discovery delay increases. Our metric performs packet delivery ratio compared to minimum hop count criteria, while slightly increasing the number of used nodes. Concerning the end-to-end delay performance, its fluctuation is due to the dropped packets by intermediate nodes. As shown in Fig. 9, reliability metric increases end-to-end delay compared to other two metrics, because of route discovery delay increasing Fig. 5. Moreover, we observe in Fig. 6 that the packet waiting time at source with our metric is always better than values obtained by reliability.

IV. CONCLUSIONS

In this paper, we have proposed a realistic route reliability computing model based on link dependencies assumption. It uses an analytical link reliability model that takes into account the initial distance between two nodes and the transmission range. As shown by our simulation results, our algorithm approximates accurate route reliability whatever are the initial nodes distance, the nodes speed and the number of links. Integrating this metric as route selection may be the good idea in order to improve the packet delivery ratio. However, this can lead to numerous unnecessary relays used between source and destination. Therefore, we propose in the second part of this paper a new metric as route selection criteria. It is defined as the product of link reliability between nodes and the probability of not to use unnecessary relays between these two nodes. As shown in simulation results, our metric presents a good agreement between these opposite metrics (minimum hop count and route reliability). Future work include integrating these analytical model (route reliability and our metric) to a multipath routing protocol.

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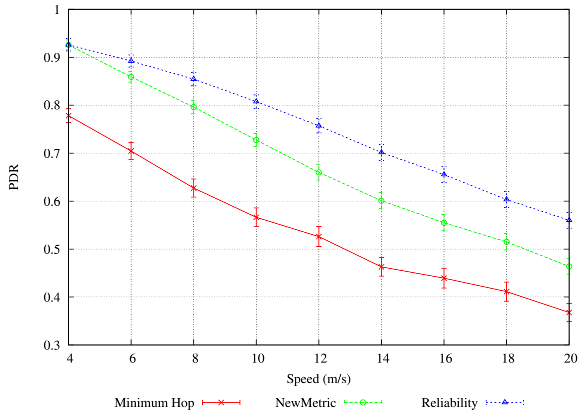

Fig. 4. Packet Delivery Ratio vs Nodes Speed

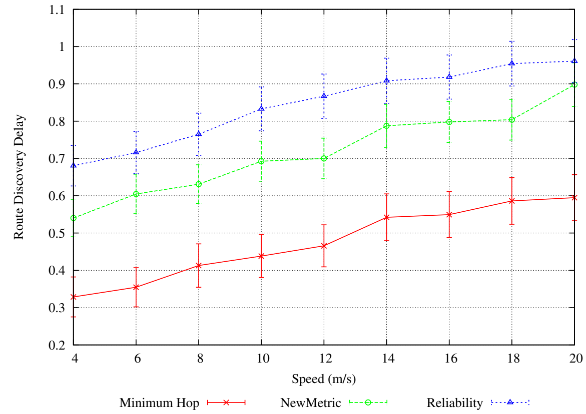

Fig. 5. Route Discovery delay vs Nodes Speed

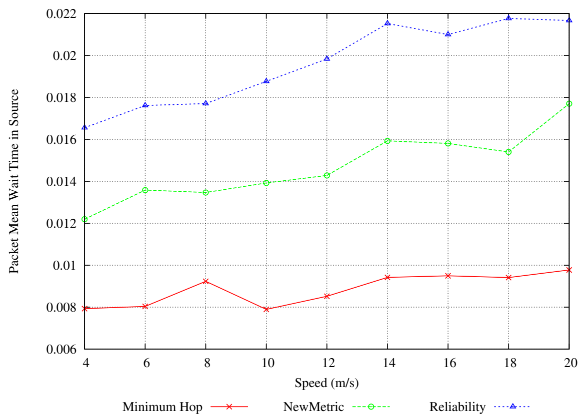

Fig. 6. Mean wait time of packets vs Nodes Speed

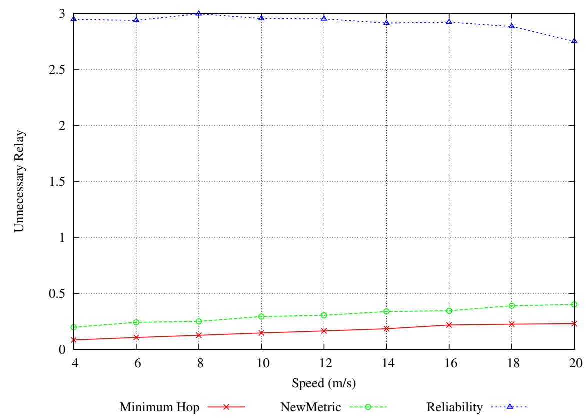

Fig. 7. Unnecessary relays vs Nodes Speed

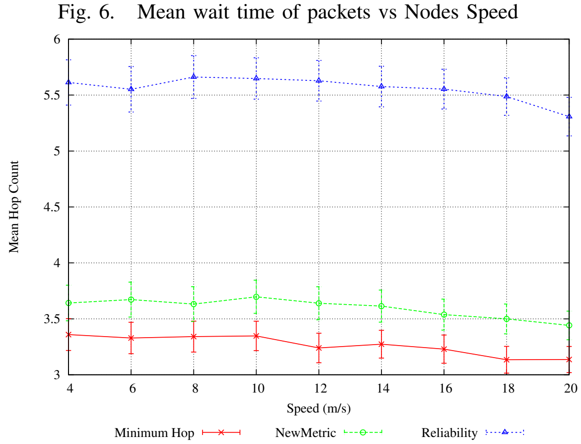

Fig. 8. Average hop count vs Nodes Speed

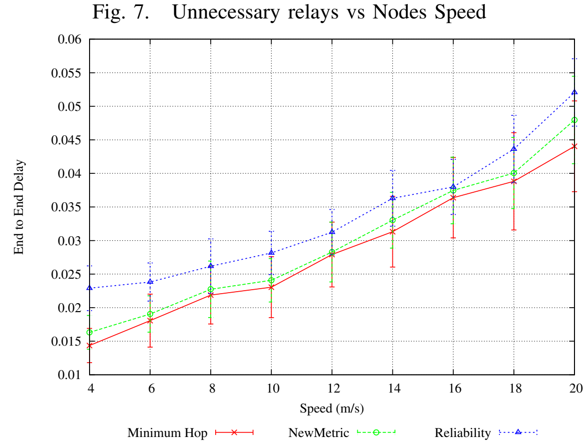

Fig. 9. Average end-to-end delay vs Nodes Speed

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