Computing Two-Terminal Reliability in Mobile Ad hoc Networks

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***Abstract*— Most of the existing techniques for network reliability evaluation are based on assumptions that all the nodes are perfect and the communication links are static and irreplaceable. However, these assumptions are not applicable for mobile ad hoc networks because of the rapid changes in connectivity and link characteristics due to nodes' mobility. Reliability computations in mobile ad hoc networks should consider the failures of nodes and links in addition to the dynamic of network connectivity caused by nodes' mobility. In this paper, we consider the computation of the two-terminal reliability in ad hoc networks by extending the algorithm proposed by Rai *et al* [1] to handle imperfect nodes and the dynamic network connectivity. The effect of nodes failure rates and the mobility pattern on the two-terminal reliability are presented.**

I. INTRODUCTION

With the growing dependency of the information and communication technology on wireless networks, network reliability becomes one of the primary concerns in the design, planning and deployment of wireless networks. The degree to which a wireless network is able to provide the required services needs to be quantitatively assessed by defining proper measurable quantities. These measurable quantities are called the *network reliability measures*. The typical network reliability problem is *to calculate the probability that a certain set of nodes can communicate with each other for a given period of time*. Based on the number of communicating nodes, there are three main formulations of the network reliability problem: two-terminal, K-terminal and all-terminal reliabilities [2].

In this paper we deal with the two-terminal reliability computation in mobile ad hoc networks. Two nodes are distinguished as source and destination nodes. The rest of the nodes function as relays to provide a communication path between the source and destination nodes. In wireless environment, relays and wireless links connecting them may fail randomly. Therefore, network operation is supported by the redundancy relays whose interconnections provide redundant paths between source and destination nodes. By understanding the contribution of redundant paths to the network operation, network designer can analyze the potential impact of nodes and links failures on the network performance. Hence, the methods for computing the network reliability are a valuable tool in network design and evaluation.

The two-terminal reliability problem has been studied extensively for wired networks with unreliable links under assumptions that the nodes are fault-free, static and their locations are known. In addition, links connecting the nodes are assumed to be irreplaceable with known probabilities of operation [1] [3] [4]. However, the two-terminal reliability problem in wireless networks is quite different from that for wired networks. Wireless networks have several aspects that make them more susceptible to failures and loss of connectivity. These aspects include the medium characteristics and the properties of wireless devices [5]. For instance, the broadcast nature of wireless communication links makes them unique in their vulnerability to loss of connectivity due to interference, weather conditions, terrain effects and security breaches. Additionally, wireless mobile devices have limited power supplies, limited transmission range and ability to change their locations. Thus, the reliability computation techniques developed for wired networks cannot directly be utilized in wireless networks.

A little research has been conducted in two-terminal reliability problem in wireless networks [6] [7]. Chen & Lyu [6] investigated the problem of two-terminal reliability in wireless networks resembled by Common Object Request Broker Architectures (CORBA) specifications [8]. Chen & Lyu also proposed a new reliability term, the end-to-end expected instantaneous reliability (EIR), to accommodate for the hand-off procedures and different communication structures in wireless CORBA specifications. Only nodes are prone to failures, while wireless links, if exist, are fault-free. AboElFotoh *et al* [7] proposed two algorithms for computing the two-terminal reliability and computing the expected and the maximum message delay between sensors and the data sink in an operational distributed sensor networks (DSN). In this work, failures of static nodes are considered, whereas links are assumed to be fault-free. Both works ignored links failures and the nodes understudy are either static or their movement is comprehended by the hand-off process. Nevertheless, the reliability and survivability aspects of wireless and mobile networks imply that each component in a wireless network is a potential point of failure and the reliability depends on the components' reliability and the degree of build-in redundancy in the wireless network architecture [9].

Therefore, this paper seeks a simple method for computing the two-terminal reliability in wireless ad hoc networks in which nodes and links are prone to failures. Furthermore, the links establishments/disconnections due to nodes' mobility are considered. The remaining sections are organized as follows: Section II presents the preliminaries necessary for two-terminal reliability evaluation. In Section III, we present the problem statement and assumptions. Section IV describes the algorithm used for computing two-terminal reliability in ad hoc networks. In Section V, we present simulation environment and results. Section VI contains the conclusion.

II. PRELIMINARIES

Generally, the methods used for evaluating the two-terminal reliability are based on writing a symbolic reliability expression describing all the available paths between the source and destination nodes [1] [4]. These methods are based on assumption that all the nodes in the network are perfect, but this is not a realistic assumption for mobile ad hoc networks. In this section, we present some of the efforts in evaluating two-terminal reliability using symbolic expression and the compensation of imperfect nodes in reliability computation.

A. Symbolic reliability expression

Aggarwal & Rai [4] introduced a method of computing the two-terminal reliability ($Rel_{s,d}$) in a general network. This method consists of two steps. The first step is to write the logical relation between nodes starting from the destination node and proceeding toward the source node. This step results in a symbolic reliability expression for the paths between the source and the destination nodes. In the second step, the operational probability values are substituted into the correspondent variables in the reliability expression obtained in the first step. This method is appropriate for relatively small networks. However, it does not scale for moderate and large networks. Rai *et al* [1] proposed an algorithm to compute the minimum *cut-set*, links whose removal disconnect the routes between source and destination nodes, of a directed network. They constructed a connection matrix whose elements represent the connections between adjacent nodes. This connection matrix is manipulated recursively to construct a tree of events (i.e., failure of links) associated with the resulting subnetworks. When the procedures end, a logical expression for unreliability ($URel_{s,d}$) is obtained by traversing the resultant tree from the root to the pendant vertexes that indicate a failure of communication between the source and the destination nodes (i.e., cut). Then, the reliability expression is

$$Rel_{s,d} = 1 - URel_{s,d}. \tag{1}$$

B. Imperfect Nodes

In communication networks, nodes have certain probability of failure and reliability evaluation assuming perfect nodes is unrealistic. Aggarwal *et al* [3] introduced a basic concept that the failure of a node implies the failure of all links incident from it. The operational probability of each communication branch is considered as a series combination of operational probabilities of the nodes and the link connecting them as shown in Fig. 1. This concept is useful in the extension of any reliability algorithm to account for imperfect nodes. First, the reliability expression is derived in term of the communication branches assuming perfect nodes. Then, each communication branch is replaced with a function of the nodes and links probabilities of operation.

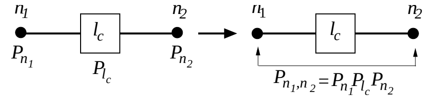


Fig. 1. Modification of a link reliability.

Torrieri [10] addressed the equivalence between the successful communication over a link and the event that the link and its terminal nodes are operational. Thus, a network with unreliable nodes is replaced with an equivalent network in which nodes are perfect. Nodes and links reliabilities are combined to produce new probabilities for the links in the equivalent network. Then, node-pair reliability/Torrieri (NPR/T) method was used to compensate for unreliable nodes with the expense of a cost that increases linearly with the number of links.

Based on these previous bodies of work, we evaluate the two-terminal reliability in mobile ad hoc networks by extending the algorithm proposed by Rai *et al* [1] to acclimate with the characteristics of wireless networks. The effect of nodes failure rate and mobility pattern on the two-terminal reliability are also considered by integrating the method proposed by Aggarwal *et al* [3] into [1]. In addition, we present the effect of nodes reliability on network's performance parameters such as packet loss and control message overhead. It is apparent that more research should be conducted in investigating the reliability problem in wireless networks.

III. ASSUMPTION AND PROBLEM STATEMENT

In this section, we formalize the problem statement and the assumptions considered in computing the two-terminal reliability in mobile ad hoc networks.

A. Problem statement

Given an ad hoc network G with N nodes, E edges, a source node, s, and a destination node, d. Each node has an operation probability of p_n. The problem is to compute the probability that there exists an *operational path* between source node, s, and destination node, d, which is denoted as $Rel_{s,d}(G)$. All nodes, but source and destination nodes, are allowed to move freely according to a known mobility model. In addition, the nodes fail according to an exponential distribution with a parameter ρ (i.e., $\frac{1}{\rho}e^{-\frac{1}{\rho}t}$). Therefore, the two-terminal reliability is a function of time and changes frequently due to nodes' movements and nodes' failures. Each edge in E has an operational probability, p_e, which depends on the operational probabilities of the nodes the edge is connecting. Therefore, p_e of edge e connecting node n_i and n_j can be expressed as p_e=Pr(e exists | n_i and n_j are operating). Since each of the E

edges can have one of two states, working or failed, the state of the network can be represented using a vector **S(t)**=$\big[S_1(t)$, $S_2(t)$, …, $S_E(t)\big]$. The e^{th} component of **S(t)** equal to 1 if edge e is working and 0 otherwise. Thus, the probability of a given state $S(t)$ is

$$Pr(S(t)) = \prod_{e=1}^{E} p_e^{S_e(t)}(1-p_e)^{1-S_e(t)}. \qquad (2)$$

The states are examined using structure function $\phi_{s,d}(.)$. This structure function checks if there exists at least one path between the source node, s, and the destination node, d. If state **S(t)** contains one path or more between the two nodes, then $\phi_{s,d}(S(t)) = 1$, otherwise $\phi_{s,d}(S(t)) = 0$. Then, the two-terminal reliability can be formulated as follows:

$$Rel_{s,d}[G(t)] = \sum_{all\ S(t)} \phi_{s,d}(S(t))Pr(S(t)). \qquad (3)$$

B. Assumptions

We consider a wireless network consisting of N nodes with omnidirectional antennas and equal transmission ranges, R. In this network, wireless links, if exist, are assumed to be bidirectional. A bidirectional wireless link exists between two nodes if and only if these nodes are within each other transmission range and signal-to-interference-plus-noise-radio (SINR) exceeds a certain threshold value at both nodes. For two nodes to communicate with each other, there should be at least one *operating path* between them. An $operating\ path$ implies that all the intermediate nodes and links are operating. A node is operating if and only if it preforms its indicated functions. A wireless link is operating if and only if it allows communication from its initial node to its terminal node. At any moment of time, the components of the network (i.e., nodes and links) can be either in operational or failed state. Once a node fails, it stays in the failed state. On the other hand, wireless links can be brought back to the operational state if the two mobile nodes come close again in each other transmission range and satisfy the SINR requirement. At any time, the locations of the nodes are known or can be determine using the GPS techniques [11]. Fig. 2 depicts an ad hoc wireless network of five nodes.

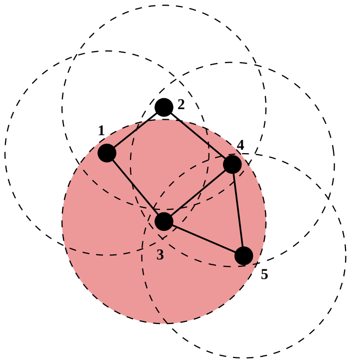


Fig. 2. Wireless multi-hop network with five nodes.

IV. ALGORITHM FOR COMPUTING TWO-TERMINAL RELIABILITY

We propose a computation method based on the algorithm in [1] in order to derive an instantaneous expression for the two-terminal reliability in mobile ad hoc networks. In this algorithm, there are three main operations: *constructing connection matrix*, *substitutions* and *derivation of the reliability expression*, which are described in the subsequent sections.

A. Constructing connection matrix

The existence of the links is based on the locations of the nodes with respect to each other at any given time. There will be a bidirectional radio link between two nodes if they were in the transmission range of each other. Therefore, a *connection matrix* $M[c](t)$ represents connection relations between different nodes at any given time. In a connection matrix, $M[c](t)$, each element represents a radio link between two communicating nodes. An element of the matrix is labeled as $X_{i,j}$, where i and j are the nodes at the ends of the radio link. The index i is always lower than the index j, thus element in the i^{th} row and j^{th} column is similar to the element in j^{th} row and i^{th} column (i.e., bidirectional links). This label is used in the evaluation phase, because it indicates the nodes participating in creation of the wireless link. The connection matrix for the ad hoc network in Fig. 2 is

$$M[c](t) = \begin{pmatrix} 0 & x_{1,2} & x_{1,3} & 0 & 0 \\ x_{1,2} & 0 & 0 & x_{2,4} & 0 \\ x_{1,3} & 0 & 0 & x_{3,4} & x_{3,5} \\ 0 & x_{2,4} & x_{3,4} & 0 & x_{4,5} \\ 0 & 0 & x_{3,5} & x_{4,5} & 0 \end{pmatrix} \qquad (4)$$

The connection matrix is modified by adding it to the identity matrix I_N (N=5) and removing the first column and last row. This modification is required by the computations algorithm.

B. Substitutions

The procedures for computing the two-terminal reliability involve two main substitution operations: *0-sub operation* and *1-sub operation*. We present these two operations as follows:

1) 0-Sub Operation: This operation substitutes 0 value in the entry of interest in the first row of the modified connection matrix. It is obvious that this operation basically resembles removing the radio link from the wireless network. A simple example is given below to explain how 0-sub operation is performed on the modified version of the connection matrix in (4). The first row contains the following non-zero element: $x_{1,2}$ and $x_{1,3}$. Applying the 0-Sub operation to element $x_{1,2}$ yields the following matrix:

$$A_{new}[x] = \begin{pmatrix} 0 & x_{1,3} & 0 & 0 \\ 1 & 0 & x_{2,4} & 0 \\ 0 & 1 & x_{3,4} & x_{3,5} \\ x_{2,4} & x_{3,4} & 1 & x_{4,5} \end{pmatrix} \qquad (5)$$

2) 1-Sub Operation: This operation substitutes 1 value in the entry of interest in the first row of the modified connection matrix. The theme of this operation is to move one step (i.e., one link) in path toward the destination node. Therefore, it resembles discovering the path between two nodes. This operation is preformed as follow:
   - Substitute 1 in the entry of interest in first row.
   - In the column corresponding to the 1 substitution, obtain the row that contains an entry of one (e.g. row r) and perform the following procedures:
     - row(first row) ← row(first row) + row(r)
     - Delete row(r)
   - Delete the column corresponding to 1 substitution.

   Applying the 1-Sub operation to element $x_{1,2}$ in the modified version of the connection matrix in (4) yields:

$$A_{new}[x] = \begin{pmatrix} x_{1,3} & x_{2,4} & 0 \\ 1 & x_{3,4} & x_{3,5} \\ x_{3,4} & 1 & x_{4,5} \end{pmatrix} \tag{6}$$

C. Derivation of the reliability expression

The reliability expression is the summation of all the possible paths between the source and destination nodes. These paths are obtained by transversing the resultant tree of matrices from the root to the pendant vertexes of non-zero variables as shown in the example in Section IV-D.

Next, we present the algorithm used in obtaining the reliability expression for a given source and destination nodes.

1) Set time $t = 0$.
2) Obtain $M[c](t)$ and modify it by adding it to the identity matrix, I_N, where N is the total number of operational nodes in the network. Then, remove the first column and the last row.
   a) Set level to be $l \leftarrow 0$.
   b) Let $(X_{1,2}, X_{1,3}, X_{1,4}, ...)$ be the non-zero entries in the first row. These entries are arranged in the following way: the entries whose corresponding columns contain no ones come first and after that the rest of entries are arranged in ascending order based on their indexes.
   c) Use the logic expansion of the type 1, 01 , 001,...,000...01 in the substitution operations. The first term corresponds to $X_{1,2} = 1$ followed by $X_{1,2} = 0, X_{1,3} = 1$ and so on.
   d) Preform 0-sub and 1-sub operations with the logic expansion to obtain a modified two-array matrix. If the value of 1 does not exists in same column where 1-substitution operation is performed, the resultant of the substitution is 1.
   e) Repeat the step 2d) for all the non-zero elements in the first row.
3) Increment l and repeat the above procedures for the next level until one of the following cases: (a) 1, (b) 0 and (c) branch with variable is obtained.
4) By traversing the tree from the root to the pendant vertex of type (a) 1 and (b) branch with variable, the logical expression of the two-terminal reliability is obtained for the instant of time t $Rel_{s,d}(t)$.
5) Increment the time t, check if the end of simulation time is reached. If yes; skip the next step and exit.
6) Obtain the new location of the nodes and go to 2) and repeat until the end of the simulation time.

As a result, a tree structure of matrices is constructed as shown in Fig. 3. In this structure, the variables in the rectangular boxes represent the used variables in the substitution operations to obtain new two-dimension matrices. At the last level, all the non-zero variables in the parentheses indicate a potential paths between the communicating nodes. Then, variables in the reliability expression can be substituted with corresponding nodes failure probability. The probability of a variable $X_{i,j}$ consists of three components: probability of node i, probability node j and probability of link e connecting them.

D. Example

In this section, we will walk through an example to demonstrate how the two-terminal reliability is computed. The computing algorithm is applied to the wireless network in Fig. 2. The two-terminal reliability is calculated for the source node $s = 1$ and the destination node $d = 5$. Fig. 3 shows how the algorithm was carried out recursively. In this example, there are 3 levels (e.g. $N - 2$ where N is total number of nodes). In the first level (i.e., level 0), there is only one matrix with two elements in the first row $X_{1,2}$ and $X_{1,3}$. Therefore, the substitution operations 1 and 01 are applied with correspondence to $X_{1,2}$ and $\overline{X}_{1,2}X_{1,3}$, respectively. Thus, there are two possible paths toward the destination node. One path through link $X_{1,2}$ and the other one through $X_{1,3}$ if $X_{1,2}$ link is not available (i.e., $\overline{X}_{1,2}X_{1,3}$). In the second level, there are two matrices to be manipulated. The same discovering procedure is repeated for each matrix and new link is added to the path between s and d. When the recursive procedures finish, all the paths with non-zero variables at the last pendant vertex (i.e., variables between parentheses) are summed to construct the reliability expression. The resultant expression for the instantaneous two-terminal reliability between $s = 1$ and $d = 5$ at time t_0 $Rel_{s=1,d=5}[G(t_0)]$ is shown in (7). Although this network is relatively small (i.e., number of nodes is small), the number of states is quite high because the number of possible wireless links in this network is six which leads to 64 possible states. Therefore, obtaining two-terminal reliability expression implies manipulating all 64 states. On the other hand, the used algorithm only implies manipulating seven terms with the expense of manipulating six matrices as shown in Fig. 3.

$$\begin{aligned} Rel_{1,5}[G(t_0)] &= X_{1,2}X_{1,3}X_{3,5} + X_{1,2}X_{1,3}\overline{X}_{3,5}X_{2,4}X_{4,5} \\ &+ X_{1,2}X_{1,3}\overline{X}_{3,5}\overline{X}_{2,4}X_{3,4}X_{4,5} + X_{1,2}\overline{X}_{1,3}X_{2,4}X_{4,5} \\ &+ X_{1,2}\overline{X}_{1,3}X_{2,4}\overline{X}_{4,5}X_{3,4}X_{3,5} + \overline{X}_{1,2}X_{1,3}X_{3,5} \\ &+ \overline{X}_{1,2}X_{1,3}\overline{X}_{3,5}X_{3,4}X_{4,5} \end{aligned} \tag{7}$$

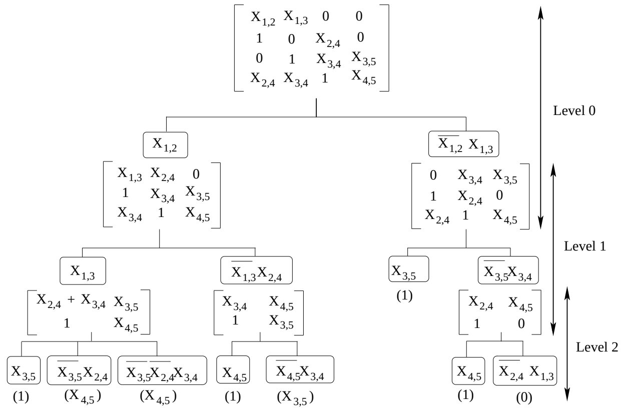
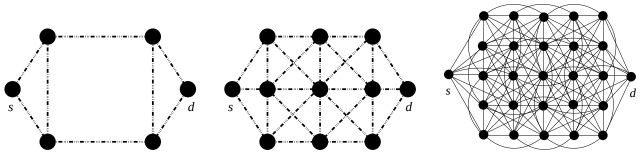


Fig. 3. An example of calculating the two-terminal reliability.

V. Simulation and Results

In this simulation, we first study the effect of different failure rates of nodes on the networks performance parameters such the packet lost rate and number of control messages. Then, we present the effect of network dynamics on the two-terminal reliability.

We have consider ad hoc networks of 6, 11 and 27 nodes placed in $600m \times 600m$ plane to construct a grid structure as shown in Fig. 4(a) to Fig. 4(c). Grid structure was selected to ensure that high level of reliability can be obtained in each case. The transmission range of the wireless nodes was chosen to be $250m$ with two-ray ground propagation model [5]. Therefore, three hops at least are needed to create a path between the source node the destination node. Random way point mobility model (RWP) [12] is used to resemble the movement pattern of the wireless nodes. In this model, nodes are initially stay stall (i.e., paused) for a certain time. Then, they start to move around within the area of simulation with a known average speed for a given time. After the nodes reach their destination, they stay stall in their position for some time (i.e, pause time). After that, nodes again choose another random destinations in the simulation field and move towards them. The whole process is repeated again and again until the simulation ends. If a node hits the simulation edge during its movement, it bounces back to the simulation area with the same speed and with an angle equal to the one it hits the border with. In this simulation, we consider different values for the average speed and pause time. The simulation environments and parameters of the ad hoc networks are shown in Table I



(a) 6 nodes (b) 11 nodes (c) 27 nodes

Fig. 4. Ad hoc networks with nodes placed in grid structure.

TABLE I

Parameters and constants used in all the simulations.

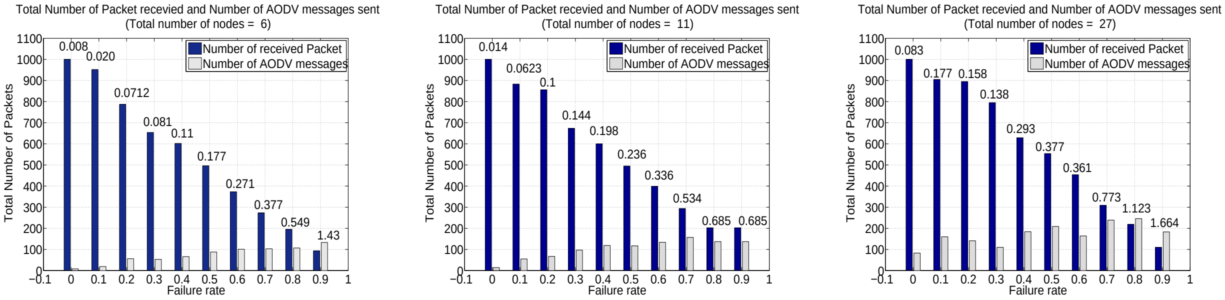
Field space	600 x 600 flat space
Number of nodes	6, 11, 27
Average node speed	5, 10, 15, 20, 25 ,30 (m/s)
Node mobility	Random waypoint model [12]
Simulation run time	500 sec
Node pause time	5, 10, 15, 20, 25 ,30 sec
MAC layer type	IEEE 802.11
Transmission range	250 m
Number of packet	1000 packet
Size of the packet	1000 byte
Interval between packets	0.5 sec
Routing Protocol	AODV [13]

A. Effect of the node failure rates on network performance

The failure of a wireless node implies the failure of all wireless links which are incident from it. Therefore, the failure of any node may alter the network topology and affect the reliability of the network. We investigated the effect of nodes failures rates on network performance parameters such as packet loss and control message load. As the failure rate increases, the network is flooded with control messages (i.e., RREQ and RREP in ADOV protocol) and the packet loss increases dramatically as shown in Fig. 5. Accordingly, the routing protocol will try to cope with the failure of the nodes by discovering new paths between the remaining set of nodes. However, the impact of failures rates is decreased by considering different topologies with more deployed nodes within the simulations area. For example, the failure rate of 0.3 allows only 65.4 % of data to be delivered between the source and destination nodes in the network in Fig. 4(a). For the same failure rate, the percentage of received data for the networks in Fig. 4(b) and Fig. 4(c) increases to 67.3 % and 79.5 % as shown in Fig. 5(b) and Fig. 5(c), respectively. Hence, the reliability of a wireless network does not depend only on the components' reliability but also on the degree of build-in redundancy in the topology of the network.

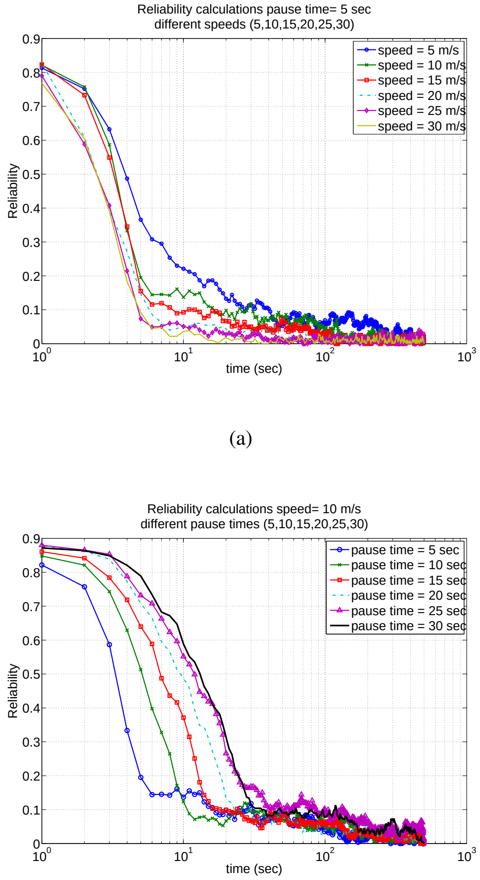
B. Effect of the nodes mobility on two-terminal reliability

The node mobility can be characterized by its speed and pattern of movement such as direction and pause times. With slow speeds and large pause times, the reliability of the network shows better stability. This is due to the stability of the network routes for longer time. As the average speed of the mobile nodes increases, more links are broken and which result in less paths between the source and the destination nodes as shown in Fig. 6(a) and Fig. 6(b). As the time passes, we noticed that network reliability is bounded by an asymptotic value of 0.1. This is due to the non-uniform distribution of nodes caused by the mobility RWP mobility model. RWP mobility model leads to concentration of nodes in the middle of the simulation area [14]. Hence, less paths are available between the source and the destination nodes.



(a) (b) (c)

Fig. 5. Control messages vs. received messages.



(a)

(b)

Fig. 6. Effect of Node movement patterns on the two-terminal reliability.

VI. CONCLUSION

In this paper, a simple algorithm for evaluating the two-terminal reliability in mobile ad hoc networks was developed. The proposed algorithm is an extension of algorithms for wired networks [1]. It overcomes the limitation of the existing techniques which consider only the failures of static nodes. Additionally, this algorithm considers links failures and the connectivity changes due to nodes mobility. We find that the reliability of a wireless network depends not only on the components' reliability but also on the degree of redundancy in the network's topology and the distribution of nodes in the network.

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