The Influence of Scenario Metrics on Network Reliability of Mobile Ad Hoc Network

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Abstract: A wireless mobile ad hoc network (MANET) is a collection of solely independent nodes that communicate with each other by forming a single hop/multi-hop network, and maintain connectivity in a decentralized manner. The important characteristic of the ad hoc network is that the nodes move randomly around the area of deployment making the topology highly dynamic. Because of this configuration and absence of infrastructure, an ad hoc network has been in increasing demand during emergency situations like human-induced disasters, military conflicts, emergency grounds, commercial applications and so on. The reliability of the ad hoc network is the most challenging and interesting issue because of its changing topology. This paper addresses and illustrates the effect of few scenario metrics, viz., network size, transmission range, and network coverage area, on the reliability measures (i.e., $2TR_m$ and $ATR_m$) by modeling MANET as Geometric Random Graph.

Keywords: Ad hoc networks, infrastructureless networks, geometric random graph, network reliability

Acronym

BDD Binary Decision Diagram
BFS Breadth First Search
GRG Geometric Random Graph
MANET Mobile Ad Hoc Network
MCS Monte-Carlo Simulation
MN(s) Mobile Node(s)
OMDD-A Augmented Multivariate Decision Diagram
RWPM Random Waypoint Mobility Model
SDP Sum-of Disjoint Product
TR Transmission Range

Notation

$\theta$ Scale parameter of the Weibull failure distribution of the node
$\beta$ Shape parameter of the Weibull failure distribution of the node
$G(U,L)$ An undirected graph
$U \{u_1, u_2, ... , u_n\}$: Set of $n$ mobile nodes
$L \{l_1, l_2, ..., l_m\}$: Set of $m$ links
$k$ Set of $k \subseteq U$ nodes in $G(U,L)$
$\Delta \tau$ Incremental change in time
$(x_i(\tau), y_i(\tau))$ Position of node $u_i$ in XY - plane at time $\tau$
$2TR_m$ 2-terminal network reliability
$ATR_m$ All-terminal network reliability
$D$ Network Coverage Area in square distance - units
$A(\tau)$ Adjacency matrix of MANET at time $\tau$
$C_i(q, \tau)$ Connectivity of the $i^{th}$ node to the source at time $\tau$ of $q^{th}$ iteration
$d_{ij}(\tau)$ Euclidean distance between node $u_i$ and node $u_j$ at time $\tau$
Network derived from $G(U,L)$ by setting the success probability of nodes of $k \subseteq U$ equal to 1.

$L_{ij}(\tau)$ Link status between node $u_i$ and node $u_j$ at time $\tau$

$u_i(\tau)$ Status of the $i^{th}$ node at time $\tau$

$\phi$ Direction of node movement in radians

$Q$ Total number of simulation runs.

$q$ One complete iteration of $Q$ number of simulation runs

$R_{G}(\tau)$ Reliability of MANET at a particular instant of mission time

$R_{u_i}(\tau)$ Reliability of node $u_i$ at time $\tau$

$s$ Source node

$t$ Terminal node

$r_i$ Transmission range of a node $u_i$ in distance units

$(s,t)$ Source – Terminal pair

$\Delta$Mission Mission time in time-units

$Var(R_{G}(\tau))$ Variance of $R_{G}(\tau)$

$V_{\text{max}}$ Average maximum node speed

$V_{\text{min}}$ Average minimum node speed

1. Introduction

Network reliability has become an important criterion for any communication system (wired/wireless) because of the recent technological innovations that demand for a reliable communication. Qualitatively, the network reliability could be defined as the ability of the network to continue services in the case of component failures [1]. The purpose of reliability analysis is to quantify the network services with the impact of component failures and identify the weakness in the network. Quantitatively, reliability can be defined as the probability of existence of at least one feasible path between a specified set of $k$-nodes under predefined conditions [2]. Obviously, $k$-terminal reliability reduces to 2-terminal reliability when $k=2$ and to all-terminal when $k = n$.

The Mobile Ad Hoc Network (MANET) is a self-organizing network, which is a loose collection of independent mobile nodes or wireless mobile hosts with an arbitrary motion that can communicate through single hop/multi-hop communication using the wireless channels. These networks have gained importance because of features such as no requirements on supporting infrastructure, nodes mobility, self-administrating, decentralization, homogeneous/heterogeneous type, flexibility, rapid deployment, dynamic topology and specified applications [3], [4]. Since, most of these parameters affect the connectivity of the network, directly or indirectly; therefore, a connectivity criterion becomes an important measure of network reliability.

Traditionally, any infrastructure based engineering system (communication systems/water distribution systems/transportation systems/homeland security systems/environment monitoring systems/mission critical military systems [5]) can be modelled as graph with nodes and edges. Nodes may be homogeneous, static/dynamic, and unpredictable whereas, the edges may be wired/wireless, uni-/bi-directional, and fixed/arbitrary. However, if these two entities (nodes and edges) have certain probability of success/failure of their operations, the graph is known as probabilistic graph and has extensively been used to model many complex systems in reliability literature. The reliability literature is in abundance and one can find plethora of methods for infrastructure based network systems (based on factoring theorem, Sum of Disjoint Product (SDP) techniques, enumeration, transformation, reduction and decomposition,
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binary decision diagrams (BDD), direct and approximation methods and more recently augmented ordered multivariate decision diagram (OMDD-A) etc.) that deal with the reliability analysis, evaluation and other related issues by employing numerous analytical and/or simulation based algorithms/techniques [6] – [12]. However, these methods of modelling and analysis cannot be applied directly to the MANET because of their special features mentioned earlier.

The random graph could be an alternative way of modelling MANET. The most fundamental assumption in random graph is that the existence or non-existence of a link between two nodes is entirely independent of the existence or non-existence of any other link in the network. This may not be true in the case of MANET as the active nodes which are within the coverage area of each others are certainly connected. In other words, the existence of links is a function of the geometric distance between the nodes and the transmission range of the nodes. Therefore, modelling networks by using Geometric Random Graphs (GRG) is a more realistic alternative to the classical random graph models of Erdos and Renyi [13] [14]. Many researchers have given a detailed study on the mobility patterns and mobility models- from classification to their applicability using simulation. Survey of the literature indicates that to model the mobility pattern of MANET, the Random Way Point Mobility Model (RWPM) has widely been used for the ad hoc network applications [15]-[18].

The demand for reliable network for specific application has attracted the researchers to work on the reliability aspect of the MANET by extending the measures of infrastructure based networks to MANET. In [19] a symbolic $2TR_m$ reliability expression was derived using an algorithm which can handle imperfect nodes and dynamic network connectivity. This paper mainly focuses on the reliability of the network components (node/link) of static topologies. In [20] a combination of random graph theory, percolation theory and linear algebra were used for analyzing the mobile sensor multi-hop networks. A probabilistic version of adjacency matrix was applied to analyse the connectivity of such networks. But this paper does not address the mobility and movements of MN. In [21], [22], the analytical concepts of ad hoc network along with the Monte Carlo simulation to determine the $2TR_m$ is provided. The authors have considered the existence of the link as a probabilistic event with respect to the nodes status in [21] and mobility has been addressed in [22]. As their algorithm simulates the status of $(s,t)$ pair as well, the reliability estimate turns out to be a conservative estimate. For instance, the example taken by the authors for a transmission range of 8 miles, i.e., each node covers almost the entire area of simulation boundary; the network reliability should have been closer to the reliability of the product of the $(s,t)$ pair. However, their algorithm provides a very low figure of 0.7652 with highly reliable MNs. Similar arguments can be put forward on the results where the node-density increases or area of simulation decreases. Moreover, BFS algorithm has been used for the connectivity analysis, which may be impractical for networks of larger size.

In this paper, a Monte Carlo simulation (MCS) approach is applied to evaluate the terminal-pair reliability and all-terminal reliability of MANET whose node failure is governed by a known statistical distribution whereas links between the nodes are established dynamically, depending on the transmission range of nodes. Besides, we also emphasize on the influence of the scenario metrics on the reliability of the MANET. In our approach of simulation for $2TR_m$, we employ the idea that at any instant of mission time, the network topology will be momentarily fixed, and then the reliability of the network at that particular instant can be computed as the product of reliabilities of $(s,t)$ pair and the reliability of the network with perfect $(s,t)$ pair of nodes. The same notion can
be easily extended to determine $k$-terminal or all-terminal reliability. This simple treatment also reduces the number of random variables involved in MCS.

The remainder of the paper is organized as follows. Section 2 presents a brief description on MANET scenario metrics and MANET failures. In Section 3, we state the assumptions that are concerned with our network model. The methodology and algorithm to compute the network reliability is discussed in Section 4. Section 5 provides a numerical example for the purpose of implementation, followed by extensive simulation results in Section 6 (effect on $2TR_m$) and Section 7 (effect on $ATR_m$). The conclusion of this work is provided in Section 8.

2. MANET Scenario Metrics and MANET Failures

2.1 MANET Scenario Metrics

Ad hoc networks can be classified into two types of networks, viz., homogeneous and heterogeneous ad hoc networks [3]. In a homogeneous network all the scenario metrics are same for all the nodes whereas in a heterogeneous network each node has different scenario metrics. Ad hoc network scenario metrics namely node movement/dynamic topology based on the average velocity of the nodes, network size, terrain, node density, pause time, transmission range, and traffic patterns and number of links are some of the metrics that describe the network environment and define the scenario [23].

Node Velocity defines the speed with which the mobile nodes traverse within the given geographical region. Network size defines the number of nodes that move (i.e., which actively participate) in a given geographical area. This parameter has considerable effect on the network connectivity. A node in the network can be a source, sink or router. Terrain also known as network coverage area/service area/coverage area is the boundary within which the nodes move in and/or out. It affects the arrangement of the nodes and the length of the path between the source and the destination. Throughout this paper we refer terrain as the network coverage area. The transmission range is the range, with respect to the transmitting node/receiving node, within which a communication can be successfully received/transmitted. In a wireless ad hoc network, two nodes are neighbours or connect each other if the distance between them is at most equal to the transmission range. When a node wants to communicate with a node outside its transmission range, a multi-hop routing strategy is used involving some intermediate nodes.

2.2 MANET Failures

The failure of the MANET may occur due to a variety of reasons that can be due to the failure of a node and/or link, e.g., low transmission range, out of coverage area, atmospheric effects, physical obstacles, and limited battery life. A node can fail by itself which may lead to failure of network, i.e., if the source and/or terminal nodes is isolated or experiences failure; or intermediate nodes serving as router become unavailable due to these failure modes then the network is a failed network. Even if it does not happen, the fast movements of nodes make the available nodes move out of coverage area for establishing a connection. The node and link failures are depicted in Fig. 1(a) and 1(b) respectively.
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Figure 1: (a) Node Failure (b) Link Failure

In Fig. 1(a), $u_1$ is the source node, $u_2$ is the sink node and the remaining nodes are the intermediate nodes. The single-hop/multi-hop communication between the source and sink does not exist since the sink node $u_2$ lies outside the transmission range of all other nodes. There may be situations where the source node $u_1$ or sink node $u_2$ may be completely isolated from all other nodes of the network and hence transmission or reception of signals is lost. It can also happen that when no direct communication is possible, then source and sink have to communicate through the intermediate nodes which can also fail (say node $u_3$), perhaps, due to technical reasons like hardware/software failure or low battery life. Similarly, connectivity might not establish between the nodes in a network as shown in Fig. 1(b), because of occurrence of obstacles, viz., buildings, hills, trees etc. The other reasons could be signal fading, and excessive interference etc. In summary, all types of failure can lead to path failure and hence will have adverse effects on the MANET reliability.

3. Assumptions
   1. Network is homogeneous and operational at the start of the mission time.
   2. The node movement follows Random Way Point Mobility (RWPM) model with zero pause time, uniformly distributed node velocity ($V_{min},V_{max}$), and direction $(0,2\phi)$.
   3. Times to failure of nodes are assumed to follow Weibull distribution with scale parameter ($\theta$) and shape parameter ($\beta$).
   4. Failures of node are statistically independent and once a node fails, it remains failed for the remaining period of the mission time.
   5. All links are bidirectional without any constraint on their load carrying capacity.
   6. The creation and destruction of the link depends on the distance ($d_{ij}$) between the nodes and the transmission range ($r_j$).

4. The Methodology

4.1 Network Model

At any instant of mission duration, MANET can be represented as a fixed geometric random graph $G(U, L)$ consisting of a set of $U$ number of mobile nodes, a set of $L$ number of communicating links. Both nodes and links are prone to failure. However, time-to-failure of nodes follow a known failure distribution and links are established in a single or multi-hop fashion based on the nodes’ proximity and transmission range.

The successful communication between the specified set of nodes is a random event with a probability $R_G(\tau)$ given that all nodes in $k\subseteq U$ must be operational. For instance, for communication to exist between the designated node-pair $k = (s,t)$, it is necessary that the
(s, t) pair must be operational. Therefore, the reliability of the network will be equal to the product of the reliability of (s, t) pair and the reliability of the network with perfect (s, t) pair of nodes. It can also be expressed mathematically as, let \( G(U, L) \) be a representative network with a set of, \( k = \{u_1, u_2, \ldots, u_k\} \) designated nodes. Then reliability of the network can be expressed as (1) by employing factoring theorem and by noting that the failure of designated nodes will certainly lead to network failure.

\[
R_G(\tau) = \left( \prod_{n \in k \subset U} R_{u_n}(\tau) \right) R_{G(k)}(\tau)
\]

(1)

Therefore, (1) can be utilized to compute the reliability of MANET at a particular instant of mission duration in our MCS.

### 4.2 Node Status and Link Status

Each node \( u_i \) has an operational probability and is defined as in (2)

\[
\Pr(u_i(\tau)) = e^{-\frac{(\tau - \theta)}{\beta}}
\]

(2)

where, \( u_i(\tau) = \begin{cases} 
1, & \text{if node is operational at time } \tau \\
0, & \text{if node fails }
\end{cases} 
\]

(3)

The status of the links, \( L_{ij}(\tau) \), between a pair of nodes \( (u_i, u_j) \) is determined by Euclidian distance, \( d_{ij}(\tau) \), between them at time ‘\( \tau \)’, and transmission range, \( r_i \) (or \( r_j \)), of the nodes, i.e.,

\[
L_{ij}(\tau) = \begin{cases} 
1, & \text{if } d_{ij}(\tau) \leq r_i \text{ (or } r_j) \\
0, & \text{otherwise}
\end{cases}
\]

(4)

where, \( d_{ij}(\tau) = \sqrt{(x_j(\tau) - x_i(\tau))^2 + (y_j(\tau) - y_i(\tau))^2} \)

(5)

Therefore, at time ‘\( \tau \)’, the network can be represented by an adjacency matrix, \( A(\tau) \) of size \(|U| \times |U|\), with its elements, \( L_{ij}(\tau) \). This matrix is utilized to determine the connectivity between the \((s, t)\) pairs [24, 25], where connectivity \( C_q(\tau) \) is defined as in (6)

\[
C_q(\tau) = \begin{cases} 
1, & \text{if } k \subseteq U \text{ nodes are connected at time } \tau \\
0, & \text{otherwise}
\end{cases}
\]

(6)

### 4.3 Random Waypoint Mobility Model (RWPM)

RWPM is a random-based synthetic mobility model used for mimicking the real-time movements of the nodes in wireless mobile networks. The MN move randomly and the movement is not limited to a special geometry. Because of its simplicity and wide applicability, it has been extensively used in simulations to study the performance of dynamic source routing in MANET [18].

In our approach, the moving pattern of the mobile nodes within the simulation boundary is implemented by employing RWPM [17]. Here, the nodes move to new location by selecting a velocity between \((V_{min}, V_{max})\) and direction, \((0, 2\phi)\). The new positions of the nodes over time were determined at regular time intervals \( \Delta \tau \). The new node positions at every incremental time interval can be calculated as a function of velocity and direction using the equation:
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\[ \begin{align*}
  x_i(\tau + \Delta \tau) &= x_i(\tau) + \Delta \tau v_i(\tau) \cos \phi_i(\tau) \\
  y_i(\tau + \Delta \tau) &= y_i(\tau) + \Delta \tau v_i(\tau) \sin \phi_i(\tau)
\end{align*} \] (7)

In case, a MN violates the boundary due to its movements then the MN is forced to move within the boundary based on its location and velocity. This can be achieved by modifying the direction of the MN with which it moves. For example, when a MN moves in the region \((x(\tau) > X_{\text{max}}, y(\tau) > Y_{\text{max}}))\), i.e., outside the right top corner of the first quadrant, then the direction is changed to about 225°, and the MN is made to reach the position \((X_{\text{max}}, Y_{\text{max}}))\). These eight positions work as validity checks in implementation of RWPM for nodes to move within the simulation area. Fig. 2 depicts direction change at different locations of simulation boundary of the MN whereas Fig. 3 depicts the movement of a mobile node, \(u_i\), moving around a square area of simulation according to our implementation of RWPM model in Matlab\(^\circ\). The numbers in the plot shows the location of node at different time instants.

**Figure 2:** Direction change for different locations of the MN.

**Figure 3:** Random Waypoint Mobility of a Node \(u_i\) for the entire mission time

The reliability \(R_G(\tau)\) of MANET \(k \subseteq U\) is defined as function of time by averaging the results for simulation run at each incremental time \((\tau)\) of the total mission duration \((8)\).

The variance \([26]\) associated with the reliability can be approximated using \((9)\)

\[ R_G(\tau) = \frac{\left( \prod_{u_i \in U} R_{u_i}(\tau) \right) \sum_{q=1}^Q C_q(\tau)}{Q} \] (8)

\[ \text{Var}(R_G(\tau)) = \frac{R_G(\tau)(1 - R_G(\tau))}{Q} \] (9)

### 4.4 Algorithm for Computing MANET Reliability

Based on the descriptions and discussions in earlier sections, an algorithm is developed to compute reliability of the MANET. The algorithm first converts the network with the network that has perfect \(k \subseteq U\) nodes as per \((1)\). This converted network is then analyzed for its connectivity by simulating the node status, positions of nodes and movement of nodes around the simulation boundary, and determination of links between nodes. This process is repeated at each increment of \(\Delta \tau\) till the specified mission time, thus, becoming the first complete iteration of \('Q'\) numbers of iterations in our simulation study.

The network parameters, which are required to be initialized for the simulation involve – number of mobile nodes in the given network \((U)\), transmission range of each node \((r)\),
maximum and minimum velocity of the mobile nodes \((V_{\text{min}}, V_{\text{max}})\), mission time \((t_{\text{Mission}})\), Network Coverage area \((D)\), time increment \((\Delta \tau)\), Weibull scale parameter \((\theta)\) and shape parameter \((\beta)\) of node’s failure times and number of simulation runs \((Q)\). The step-by-step procedure of the MC simulation is as follows:

**Step 1:** Initialize network parameters \((U, D, t_{\text{Mission}})\), node parameters (parameter of time to failure pdf \((\theta, \beta, (V_{\text{min}}, V_{\text{max}}))\), \((0, 2\phi, r_{p}, (X_{i}, Y_{i}))\), \(q = 1\); \(C_{q}(\tau) = 0\).

**Step 2:** Initialize, \(R_{G}(\tau) = \prod_{u \in k} R_{u}(\tau)\).

**Step 3:** Simulate the node status vector of size \(|U|-|k|\). The probability of success of a node is time-dependent and can be determined using (10).

\[
Pr\{u_{i}(\tau)\} = e^{-\left(\frac{\Delta \tau}{\sigma}\right)\theta - \beta \tau}
\]

**Step 4:** Simulate the link status vector of size \(1 \times (U^{*}(U-1)/2)\) by computing the Euclidean distances between each pair of the mobile nodes using (5).

**Step 5:** Check for connectivity of nodes \(k \subseteq U\) of the network at time ‘\(\tau\)’. If network is connected then increment the \(C_{q}(\tau)\) and set \(\tau = \tau + \Delta \tau\).

**Step 6:** Simulate the mobility of the nodes according to RWPM by uniformly and randomly choosing the velocity of nodes between \((V_{\text{min}}, V_{\text{max}})\) and the direction between \((0, 2\phi)\).

**Step 7:** Compute the new node positions at every time increments using (7). Repeat Step 3 through Step 6 if \(\tau <= t_{\text{Mission}}\).

**Step 8:** Repeat Steps 2 to Step 7 for \(Q\) number of simulation runs.

**Step 9:** Compute \(R_{G}(\tau)\) and \(Var(R_{G}(\tau))\) as per (8) and (9).

The above steps of the algorithm are implemented using Matlab® 2009a on a Windows® XP running on Pentium dual processor @1.60GHz speed.

5. Example

The proposed algorithm is applied to evaluate reliability of the MANET [22], which is restated here for the sake of brevity.

A network is composed of 18 (\(|U| = 18\)) dismounted infantry soldiers on foot equipped with identical non-portable radios. Each radio is required to operate for duration of 72 hours. Each radio has a transmission range of 3 miles; with its time-to-failure distribution modelled by Weibull distribution with parameters of \(\theta = 1000\) and \(\beta = 1.5\). The soldiers move randomly inside a square coverage area of 64 square miles with a maximum and minimum velocity of 6 and 3 miles per hour respectively.

The location of nodes and the topology of the network at different instant of mission duration \((\tau = 0, 25, 50, 72)\) by setting \(\Delta \tau = 1\) hour are shown in Fig. 4 to show that the proposed algorithm captures the unpredictable and dynamic nature of the problem in our implementation. As the network is dynamic, the connectivity among the nodes very often varies with time because of the node departures and node arrivals to form and break the links/paths. For instance, the network topology at \(\tau = 50\) hr in Fig. 4 shows that, albeit, all 18 nodes are active, yet 16th node is found to be isolated as its distance with the other nodes is greater than the transmission range of the nodes. Besides, in this iteration 17th node failed at \(\tau = 55\) hrs and remained failed throughout the remaining period of mission duration (topology not shown for \(\tau = 55\)). It is noted that a larger/smaller value of \(\Delta \tau\) has no significant impact on the reliability of the MANET.
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Figure 4: Network Topology on Normalized Simulation Boundary from start to end of Mission for Single Iteration of MCS

6. Simulation Results on the Effect of Metrics on $2TR_m$

The effect on 2-terminal reliability by various parameters, viz., varying network size, varying transmission range and varying network coverage area are studied. Before doing so, the effect on the $2TR_m$ by varying simulation runs is studied and the results are provided in Table 1. From the results it is observed that there is not much change in the estimated reliability once we change the number of iterations from 5,000 to 15,000 iterations in our simulation. Therefore, other studies are conducted by running 10,000 simulation runs.

Table 1: The Effect of Simulation runs on $2TR_m$ and Variance

<table>
<thead>
<tr>
<th>Simulation Runs</th>
<th>5000</th>
<th>7500</th>
<th>10000</th>
<th>11250</th>
<th>15000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2TR_m$ (72 Hours)</td>
<td>0.6946</td>
<td>0.6959</td>
<td>0.6944</td>
<td>0.6925</td>
<td>0.6893</td>
</tr>
<tr>
<td>Variance ($2TR_m$)</td>
<td>0.000042</td>
<td>0.000028</td>
<td>0.000021</td>
<td>0.000019</td>
<td>0.000014</td>
</tr>
</tbody>
</table>

6.1 Effect of the Transmission Range on 2-Terminal Reliability

The transmission range ($r_j$) of a node $u_j$ denotes the maximum distance within which the data transmitted by node $u_j$ can be correctly received by its adjacent nodes. The simulation to evaluate $2TR_m$ is performed by considering the transmission range from 1 mile to 8 miles while keeping the other input parameters same. Figure 5 shows the variation of $2TR_m$ with changes in the transmission range. It can be observed from Fig. 5 that there is
not much gain (only about 0.45%) in reliability if the transmission range is increased beyond 5 miles, i.e., increase in transmission range has no significant effect on reliability beyond this value of transmission range.

Figure 6 depicts the effect of varied transmission range on the $2TR_m$ for the entire mission time. As the operating time ($\tau$) increases; reliability of the network reduces and the trend is similar for all transmission ranges. The results also confirm the fact that with increase in the transmission range, more nodes get connected with each other and hence reliability increases.

6.2 Effect of the Network Coverage Area on 2-Terminal Reliability

The network coverage area of the ad-hoc network is the whole geographical area where nodes are distributed. Here the effect on the $2TR_m$ by varying the coverage area of the network is studied. The simulation is performed with coverage area ranging from 64 to 400 square miles while keeping the transmission range of nodes same, say 3 miles. Intuitively, as the coverage area increases, the reliability of the network decreases. The change in $2TR_m$ with the varying coverage area shown in Fig. 7 clearly indicates a sharp decline in reliability and the unsuitability of transmitters for a coverage area beyond 50-60 mile. The effect of network coverage area on $2TR_m$ for the entire mission time is depicted in Fig. 8. From the results it’s clear that for small coverage area, reliability is high and vice-versa.
6.3 Effect of the Network Size on 2-Terminal Reliability

Network size is another important factor that has influence over the reliability of the ad hoc network. The effect of this parameter ranging between 9 and 100 nodes is simulated to evaluate $2TR_m$ of the networks by keeping all other input parameters same. The pictorial representation of the variation of $2TR_m$ with network size is shown in Fig. 9. Obviously, as the number of nodes in the network increases, the link density increases leading to the availability of large number of paths and hence high reliability. The effect of varying network size on $2TR_m$ for the entire mission duration is shown in Fig. 10. It can be observed that the $2TR_m$ is maximum, say 0.9621 and is not more than $R_{u}$ for $|U| = 100$ (largest size considered) and is about 0.4475 when $|U| = 9$ (smallest size considered). It implies that as the network size increases, the connectivity is strong and hence maximum reliability is achieved with its value $R_{u}$.

![Figure 9: Effect of Network Size on $2TR_m$](image)

![Figure 10: Effect of Network Size on Expected $2TR_m$ with mission duration](image)

7. Simulation Results on the Effect of Metrics on All-terminal Reliability

7.1 Effect of the Transmission Range

From the foregoing discussion on the results of $2TR_m$, the metrics play an important role in MANET’s reliability. By employing large number of nodes, long transmission range or smaller coverage area, the MANET can achieve a maximum value of reliability constrained by reliabilities of designated nodes. Similar outcomes have been resulted once the proposed algorithm is applied to study the effect on all-terminal reliability ($ATR_m$), albeit, this requirement becomes quite stringent with large number of nodes even with small transmission range or coverage area. The effect on the performance metric $ATR_m$ with varying transmission range is shown in Fig. 11. The maximum reliability possible to achieve for mission duration of 72 hours with 18 Weibullian nodes would be 0.7063. This could nearly be achieved for a transmission range of 5 miles and increase in transmission range beyond 5 miles may not be economically justifiable.

7.2 Effect of the Network Size

Varying number of nodes becomes a major factor in deciding the maximum $ATR_m$ that can be achieved. Large number of nodes has an adverse effect on achievable reliability. However, for a given number of nodes, the achievable reliability can only be attained by increasing the transmission range or decreasing the coverage area. Fig. 12 shows the variation of $ATR_m$. For the example taken for this study, it can be seen from Fig. 12 that if
the number of nodes are increased to 22, we can achieve a reliability of about 0.5625 by keeping other parameters unaltered (although the achievable reliability 0.6528) whereas for other cases, say for 35 or more nodes, the network achieves the maximum reliability but it will not give a confidence to management for its deployment. In other words, to achieve a maximum reliability of 0.8399 corresponding to 9-nodes, the options are either decrease coverage area or increase transmission range of nodes.

8. Conclusions

In this paper, a Monte Carlo Simulation based approach has been proposed to evaluate network reliability of a MANET by modelling network as undirected geometric random graphs, whereas the mobility of nodes is governed by RWPM. The proposed algorithm takes the advantage of converting a network with imperfect nodes and links to a network with a perfect set of $k$-designated nodes. The proposed algorithm has been implemented in Matlab and simulation studies on the effect of varying the scenario metrics, viz., network size, transmission range, network coverage area on the mean reliability have extensively been conducted and presented in this paper. In general, the maximum achievable reliability of any network with imperfect nodes and links will never exceed the product of the reliabilities of set of $k$-designated nodes. This restriction poses a challenge to designers to choose an optimal number of nodes with an appropriate transmission range to cover a given geographical region. The simulation results on MANET example taken in this paper have proven this point for all the cases of scenario metric. It has also been observed that on varying the scenario metrics, the trends in reliability variation is similar for all the cases of scenario metric.

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