Reliability Evaluation of Mobile Ad Hoc Network: With and Without Mobility Considerations

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Abstract

A Monte Carlo Simulation based evaluation of mobile ad hoc network reliability is proposed which considers different mobility models along with the effect of different scenario metrics and different values of tuning parameter. Through our approach we show that the mobility considerations have no significant impact on reliability as the same results are obtained by just implicitly simulating the node locations. Considering no mobility models reduces computational burden, number of random variables involved making the algorithm more efficient is the added advantage. A comparative study of the results of the network reliability estimate considering with and without mobility is provided.

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1. Introduction

Most of the researchers have modeled the ad-hoc network by randomly, uniformly distributing the mobile nodes in a defined two dimensional simulation boundary region\textsuperscript{1,2}. Each node is associated with two uniform random variables (node’s x and y coordinate). There exists a high probability of a link existence called connectivity between the mobile node (MN) when the mobile nodes (MNs) of the network are in the proximity of each other. Typically, in
wireless ad hoc networks, a node estimate their position relative to their neighbors by processing the location information (node speed, node direction), certain physical properties of the signal they receive, such as signal strength, bit error rate, or time difference of arrival and is called mobility. The movement of the MN in and out of the transmission range of the neighbor nodes not only changes their relationship with its neighbor at every time instant but also changes its topology resulting in frequent link breaks. This link breakage in the network leads to connectivity failure between the nodes which further has a resultant impact on the reliability of the network.

**Acronym**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>GRG</td>
<td>Geometric Random Graph</td>
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<td>GMMM</td>
<td>Gauss Markov Mobility Model</td>
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<td>MANET</td>
<td>Mobile Ad Hoc Network</td>
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<td>MCS</td>
<td>Monte-Carlo Simulation</td>
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<td>MN(s)</td>
<td>Mobile Node(s)</td>
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<td>RWPM</td>
<td>Random Waypoint Mobility Model</td>
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**Notation**

- $\theta$: Scale parameter of the Weibull failure distribution of the node
- $\beta$: Shape parameter of the Weibull failure distribution of the node
- $\alpha$: Tuning parameter (Degree of randomness); $(0 \leq \alpha \leq 1)$
- $\Delta \tau$: Incremental change in time
- $2TR_m$: 2-terminal network reliability
- $A(\tau)$: Connection matrix of MANET at time $\tau$
- $C_i(\tau)$: Connectivity of the $i^{th}$ node to the source at time $\tau$ of $q^{th}$ iteration
- $D$: Network Coverage Area in square distance – units
- $d_i(\tau)$: Euclidean distance between node $u_i$ and node $u_j$ at time $\tau$
- $G(U,L,\tau)$: An undirected graph at particular time instant $\tau$
- $(G|k)$: Network derived from $G(U,L,\tau)$ by setting the success probability of nodes of $k \subseteq U$ equal to 1.
- $k$: Set of $k \subseteq U$ nodes in $G(U,L,\tau)$
- $L$: $\{l_1, l_2, ..., l_m\}$: Set of $m$ links
- $L_{ij}(\tau)$: Link status between node $u_i$ and node $u_j$ at time $\tau$
- $q$: One complete iteration of $Q$ number of simulation runs
- $Q$: Total number of simulation runs.
- $R_c(\tau)$: Reliability of MANET at a particular instant of mission time
- $R_{ui}(\tau)$: Reliability of node $u_i$ at time $\tau$
- $r_j$: Transmission range of a node $u_j$ in distance units ($j=1,2,...,n$)
- $s$: Source node
- $(s,t)$: Source – Terminal pair
- $t$: Terminal node
- $T$: Mission time in time-units
- $U$: $\{u_1, u_2, ..., u_n\}$: Set of $n$ mobile nodes
- $u_i(\tau)$: Status of the $i^{th}$ node at time $\tau$
- $Var(R_c(\tau))$: Variance of $R_c(\tau)$
- $(x_i(\tau), y_i(\tau))$: Position of node $u_i$ in $XY$-plane at time $\tau \forall i=1,2,...,n$.

Network reliability is an important criterion and is of major importance in systems whose topology change dynamically and is arbitrary (e.g., Mobile Ad hoc NETwork - MANET). The highly dynamic feature has been a challenging feature for the reliability estimate of such systems because the nodes of these networks move randomly (appear/disappear) constituting to frequent connectivity failures. The connectivity failure of the network may be due to either node failure or link failure or both. This implies that the connectivity is an important factor that influences
the network reliability. The reliability evaluation methods/techniques have been proposed in areas of wired networks have an exponential growth as the network size increases making the computations complex and unfeasible. The techniques of wired systems are generally not capable to deal with the wireless systems because of its prominent challenges like node movements, dynamic topology, and rapid deployment etc.

The reliability evaluation of the infrastructure based (fixed) networks/systems till date had been estimated by modeling the network using the traditional approaches like graph theory and Boolean algebra. The application of these traditional approaches is incapable of modeling infrastructureless networks because the existence of link of such networks is defined as a function of distance (Euclidean) and node’s transmission range. Hence, MANET cannot be modeled using Probabilistic Graphs
\[ G = (V, E), \] However, the reliability measures of the wired networks viz., 2-terminal (terminal-pair), all terminal and k-terminal reliabilities have been extended for MANET\(^4,5,8\). The 2-terminal reliability is the probability that a specified \((s, t)\) node pairs can communicate with each other successfully. All terminal reliability of a network is defined as the probability that each and every node of the network communicate with each other node. While, k-terminal is the probability that a specified set of k-nodes are able to communicate with one another. The 2-terminal and all-terminal reliability are the special case of k-terminal when \(k = 2\) or \(n\).

Among various studies, viz., topological properties, communication properties, sensing properties, scaling properties and routing; the connectivity of networks is most extensively studied\(^9\). Recently, some researchers have emphasized on studying the connectivity based reliability evaluation\(^5,8\) of mobile ad hoc networks using Geometric Random Graph (GRG)\(^7,10\). A Monte Carlo Simulation (MCS) based approach which considered mobility based on random waypoint mobility model (RWPM) for the evaluation of MANET reliability was proposed by\(^5\) and later\(^4\) modified the approach of\(^5\) to obtain a better estimate. The algorithm\(^8\) uses BFS (Breadth First Search) approach to check for the connectivity in the network and becomes complicated, impractical as the network size increases. In addition to this their algorithm simulates the \((s, t)\) pair status pair and therefore obtained reliability values are a conventional approximation. This statement is supported as each and every node has a transmission range of 8 miles \(i.e.,\) each can cover the entire simulation boundary 64 Sq. Miles thereby defining the network reliability to be as nearer to the product of the reliability of the \((s, t)\) pair. And their results provide a low estimate (a maximum of 0.7652) either for a larger node size or higher transmission range under the condition that nodes are highly reliable. A reality model called propagation based link reliability model was proposed by\(^5\) to show that, the probability of existence of link generally diminishes with the distance up to their transmission range. The above mentioned model considers the link existence “iff” the distance between the MNs is within their transmission range \(i.e.,\) a binary model. A symbolic reliability expression derived by\(^11\) focuses on the reliability of the network components (node/link) for grid structured static topologies by employing the conventional reliability evaluation algorithm such as graph decomposition (or factoring).

An approach by\(^12\) calculates the network reliability of MANET by identifying the critical links within the network. \(^13\) Derived certain mathematical expressions for calculating hop-based connectivity of a network and further used them for the reliability evaluation. The drawback of this work was deriving the expressions when hop count was 3 and more than 3. All the aforementioned works\(^4,5,8,11,12\) have considered mobility parameters of the MN for MANET reliability evaluation. In\(^4,5,8\) MNs have been located with respect to mobility model RWPM which appear to be simply a computational burden while in \([11]\) except the source and the destination nodes, all other nodes move according to RWPM. Few researchers have emphasized that to evaluate the MANET performance accurately, it is important that the chosen mobility model must emulate the actual movements or real life movements closely in wireless networks. The real-life scenario movements can be obtained with the use of entity mobility models (Gauss-Markov and Manhattan Grid)\(^14,15\).

In this paper, we attempt to study the effect of different mobility models (RWPM and Gauss Markov mobility model (GMMM)) on the MANET reliability. We show that using mobility considerations in such methods\(^4,5,8\) appear to be an unnecessary computational burden. In other words, considering mobility explicitly play no role on reliability estimation of MANET. Intuitively, a MN can place itself randomly in a given geographical area to generate different topologies at different time instants. This can be done either by explicitly considering the random velocity and direction of nodes or placing nodes in a random fashion within the geographical region. In other words, the mobility of the MN can also be accounted implicitly through simulating the location of nodes in a random
fashion within the simulation region. However, if we generate the node locations in a random fashion within the simulation zone, it should provide the same reliability estimate, i.e., the node movements should not have a significant effect on the reliability estimate whether we consider mobility or no mobility.

Further, 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 designated \((s, t)\) pair of nodes. These treatments will avoid simulating the failure/success of designated nodes and also the mobility parameters of the nodes in the simulation. These simple treatments also reduce the number of random variables and computational effort involved in MCS under the absence of any analytical technique to deal with reliability evaluation of such dynamic configurations. This notion easily can be extended to determine \(k\)-terminal or all-terminal reliability. However in this paper, we illustrate the idea by evaluating two-terminal reliability of a MANET using MCS.

The paper is organized as follows: Section 2 states the assumptions considered for the network modeling. Section 3 provides the theoretical background and the methodology adopted. Section 4 describes the algorithm for network reliability evaluation followed by a numerical example that illustrates the methodology with and extensive results in section 5. Finally, section 6 summarizes the conclusions of this work.

2. Assumptions

The time-to-failure of network nodes can follow any failure distribution, i.e., exponential, normal or Weibull. As the ubiquitous Weibull distribution has widely been used to model the failure pattern of various systems and components due to its versatility to mimic the behavior of the product during its entire life cycle\(^{16,17}\), it is quite reasonable to assume that all nodes are identical and their time-to-failure is governed by Weibull failure distribution. The RWPM model, a benchmark model is chosen as it has wide applications in simulation studies\(^ {14}\) that imitate the moving pattern of the MN. Therefore, for the evaluation of the MANET reliability, the following assumptions are to be considered:

1. Network is homogeneous and operational at the start of the mission time.
2. Node movements follow –
   (2.1) RWPM with zero pause time, with uniformly distributed node velocity \((V_{\text{min}}, V_{\text{max}})\) and node direction \((\theta, 2\phi)\) (or)
   (2.2) GMMM with each node assigned a mean speed \((\bar{S})\), mean direction \((\bar{\theta})\) and degree of randomness \((\alpha)\) (or)
   (2.3) The nodes are uniformly and randomly distributed around the deployment region.
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 fail for the remaining period of the mission time.
5. All links are bidirectional without any constraint on their load carrying capacity.
6. The presence (absence) of the link depends on the distance \((d_{ij})\) between the nodes and the transmission range of the nodes \((r_j)\).

3. Theoretical Background

Given a MANET with \(n\) mobile nodes, the network can be modeled as a fixed network geometric random graph \(G(U, L, \tau)\) at any time instant, \(\tau\). It is assumed that all MN have equal transmission range, \(r_j\) and their time to failure distribution is governed by Weibull distribution with scale parameter \(\theta\) and shape parameter \(\beta\). The links can be created which can be direct (indirect) i.e., single (multi-hop) communication based on the location of nodes, nodes proximity and transmission range.
3.1. Network Model

The probability of success $R_G(\tau)$ under the condition that all nodes in $k$, a subset of $U$ must be operational is always a random event. 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 $G(U, L, \tau)$ be a representative network with a set of, $k = \{u_1, u_2, \ldots u_{|k|}\}$ designated nodes. Then reliability of the network by employing factoring theorem can be expressed as (1) by noting that the failure of designated nodes will certainly lead to network failure.

$$R_G(\tau) = \prod_{u_{i} \in k \subseteq U} R_{u_{i}}(\tau) R_{(G/k)}(\tau)$$

(1)

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

3.2. Mobility Model

Realistic models are needed to represent the moving patterns of the MN in simulation in order to evaluate the system performance. The mobile systems are characterized by the movement of their constituents$^{18}$. Most of the models the MN movements are expressed based on the nodes velocity and directions while few of them have been addressed in terms of velocity, location and trajectory. Movement trajectories are accountable when the MN movements are confined along pathways which can be realized with either pathway mobility model or obstacle model.

However, to maintain connectivity, a prior knowledge of MN movement and its exact trajectory is essential to determine the resource availability$^{19}$. This way of anticipating the requirements may also help in maintaining the connectivity. According to$^{20}$ the movement of the MN varies depending on the environment like, moving as an individual randomly in different directions or moving as group. This freedom of movement of the MN makes wireless communication attractive and simultaneously brings challenges owing to bandwidth, infrastructurelessness, influencing the performance of routing protocols, power constraints, cluster stability etc. Since, direct implementation/experimentation with the real wireless network is expensive and time consuming; researchers usually find a way out through simulation$^{21}$.

Literature$^{14,22,23}$ shows that a variety of mobility models are currently available in both simulation and analytical studies of wireless systems. But still most of the literature project that, simulators viz., NS-2; JisT/SWANS; OMNet++; GloBalSim; Blocksim; etc., are few simulators that are in use to study the behavior of ad hoc networks$^{24}$. The choice of mobility model has a significant effect on the performance of MANET in terms of efficiency, throughput, routing protocols, delay and capacity$^{25}$, packet delivery ratio, control overhead packets. The choice also depends on the region of deployment, type of environment to be simulated viz., pedestrian, vehicular, urban/suburban scenarios, and so on. The characteristic of each mobility model is provided in Table 1 followed by its classification as depicted in Fig. 1.

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Characteristics</th>
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<tbody>
<tr>
<td>Random Based</td>
<td>Without any reliance and limitation summon the model</td>
</tr>
<tr>
<td>Temporal Dependencies</td>
<td>A node actual movement depends on its past history</td>
</tr>
<tr>
<td>Spatial Dependencies</td>
<td>The movement of a node is influenced by node around it</td>
</tr>
<tr>
<td>Geographical Restrictions</td>
<td>Node movement is limited in certain coverage area</td>
</tr>
<tr>
<td>Hybrid Structure</td>
<td>All Mobility metrics classes are included to attain the this model</td>
</tr>
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</table>
The models (RWPM and GMMM) that have been considered in this paper are purely random help to analyzing the moving patterns of the MN in terms of node speed and positions through simulation and these parameters are directly related with the link creation and deletion for successful connectivity. RWPM and GMMM are dealt with in detail in the forthcoming subsections.

### 3.2.1. Random Waypoint Mobility Model

In the moving pattern of the MNs within the defined simulation boundary was implemented by employing RWPM. In this model the MNs next destination is got by choosing a velocity between \((V_{max}, V_{min})\) and direction \((0, 2\pi)\). The next node position at every incremental interval \(\Delta t\) is generally determined using (2):

\[
\begin{align*}
x_i(t + \Delta t) &= x_i(t) + \Delta t v_i(t) \cos \phi_i(t) \\
y_i(t + \Delta t) &= y_i(t) + \Delta t v_i(t) \sin \phi_i(t)
\end{align*}
\]

Fig. 2 depicts the MN route change at various positions of the simulation boundary and the shown valid eight positions ensures in realizing of RWPM for MN to travel inside the simulation area.
In case, a MN breaks the periphery due to its moving pattern then the MN is enforced to be in motion inside the periphery based on its position and speed and can be attained by changing the direction of the MN with which it moves. For example, when a MN moves in the XY-region ($x_i(\tau) < X_{\text{min}}, y_i(\tau) < Y_{\text{min}}$), i.e., outside the left top corner of the second quadrant, then the direction is changed to about $315^\circ$ and the node is made to move along the new path.

### 3.2.2. Gauss-Markov Mobility Model

Liang and Haas were first to propose and design the Gauss-Markov mobility model to adapt to different levels of randomness through the tuning parameter $\alpha$ ($0 \leq \alpha \leq 1$) which has been used to correlate the behavior of the nodes movements over time. However, the literature shows that the GMMM has been widely used to study the performance metrics like, routing protocols\(^{28,29}\), packet-delivery ratio\(^{15}\), network connectivity, hop count, network lifetime\(^{15,30}\) and quality of service\(^{21}\).

The RWPM is a memory less model i.e., RWPM generates the velocity and node positions without considering the previous history and results in abrupt stops and spiky turn problem. In GMMM, the nodes are placed at random locations in the defined simulation area similar to that of the RWPM and the movement of the node (with mean speed, $\ddot{S}$ and mean direction, $\ddot{\phi}$) is independent of the other nodes in the network. For every constant period of time, a node calculates the speed and the direction during the previous time period, along with a certain degree of randomness incorporated in the calculation. The node is assumed to move with the new speed and new direction during the time period. At any instant of time $\tau$, the speed and direction of the nodes can be calculated using (3). The instance of the past speed ($\dot{S}_{\tau-1}$) and past direction ($\dot{\phi}_{\tau-1}$) at $(\tau - 1)^{th}$ interval influence the current speed ($\dot{S}_\tau$) and current direction ($\dot{\phi}_\tau$) computation. The moving pattern of the MN changes with tuning parameter ($\alpha$) i.e., the mobility is completely random when $\alpha = 0$ and $\alpha = 1$ makes the MN take a linear motion.

$$S_\tau = \alpha S_{\tau-1} + (1-\alpha) \ddot{S} + \sqrt{(1-\alpha^2)} S_{\tau-1}^G$$

$$\phi_\tau = \alpha \phi_{\tau-1} + (1-\alpha) \ddot{\phi} + \sqrt{(1-\alpha^2)} \phi_{\tau-1}^G$$

At each time interval $\tau$, the current nodes position is computed based on the previous node positions at $(\tau - 1)^{th}$ time interval is given by (4).

$$x_\tau = x_{\tau-1} + s_{\tau-1} \cos(\phi_{\tau-1})$$

$$y_\tau = y_{\tau-1} + s_{\tau-1} \sin(\phi_{\tau-1})$$

However, if we generate the node locations in a random fashion within the simulation zone, it should provide the same reliability estimate; in other words, the node movements should not have a significant effect on the reliability estimate whether we consider mobility or no mobility.

### 3.3. Node Reliability and Link Reliability Model

The probability that the node being operational is defined in equation (5).

$$R_{ui}(\tau) = \text{Pr}(u_i(\tau) = 1) = e^{-\lambda \phi}$$

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

The presence (or absence) of a link depends on the Euclidean distance $d_{ij}(\tau)$ between the node pair $(u_i, u_j)$ and the nodes’ transmission range. That is, links exist only when the distance between the MN pair is not more than the transmission range of MN. Therefore, the link status $L_{ij}(\tau)$ can be defined using equation (7).

$$L_{ij}(\tau) = \begin{cases} 1, & \text{if } d_{ij}(\tau) \leq r_j \quad \forall i, j = 1, 2, 3, \ldots, n \text{ and } i \neq j \\ 0, & \text{otherwise} \end{cases}$$
where, \( d_{ij}(\tau) = \left( (x_j(\tau) - x_i(\tau))^2 + (y_j(\tau) - y_i(\tau))^2 \right)^{1/2} \) (8)

Further, at time \( \tau \), the network can be represented by a connection matrix, \( A(\tau) \) of size \( n \times n \), with its elements, \( L_{ij}(\tau) \). The connectivity between the designated node pair \( s \) can be determined using connection matrix, where connectivity \( C_q(\tau) \) is defined as in (9)

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

Finally, the reliability \( R_G(\tau) \) of MANET is defined as function of time by averaging the results for simulation run at each incremental time \( \tau \) of the total mission duration (10). The variance associated with the reliability can be approximated using (11).

\[
R_G(\tau) = \left( \prod_{u \in k \subseteq U} R_u(\tau) \right) \sum_{q=1}^{Q} C_q(\tau) \left/ \frac{Q}{Q} \right.
\]

\[
Var(R_G(\tau)) = \frac{R_G(\tau)(1-R_G(\tau))}{Q} \] (11)

4. Algorithm for Computing MANET Reliability

The simulation based algorithm first simulates random locations of \( n \) nodes around the simulation area \( D \) assuming same transmitting/receiving range \( r_j \) for all nodes. The node status of the network is simulated assuming Weibull distribution for node time-to-failure distribution parameters \( (\theta, \beta) \). The algorithm first converts the original network with the network that has perfect \( k \leq U \) nodes using (1). Further, the link formation is represented in a connection matrix by comparing the Euclidean distance between the node pairs and the nodes’ transmission range. Finally, using the connectivity matrix\(^{31,32} \), the connectivity of the network is checked. This process continues at each time increment of \( \Delta \tau \) when the node position change until the defined mission duration \( T \), thus, becoming the initial full iteration of \( Q \) total iterations in our study.

4.1. Algorithm using MCS for MANET Reliability without Mobility

**Step 1**: Initialize the network parameters: \( n, D, T, r_j, \theta, \beta, q=1, C_q(\tau) = 0, Q \).

**Step 2**: Generate \((x_i, y_i)\) random locations for \( i = 1, 2, \ldots n \).

**Step 3**: Simulate the node status (6).

**Step 4**: Determine the Euclidean distance between each pair of MN (8).

**Step 5**: Check for the link existence by comparing the Euclidean distance and the transmission range (7).

**Step 6**: Check for connectivity of the network using the connection matrix at time \( \tau \). If network is connected then increment the \( C_q(\tau) \) by one and update \( \tau = \tau + \Delta \tau \).

**Step 7**: Revisit step 2 through step 6 until \( \tau \leq T \).

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

**Step 9**: Compute \( R_G(\tau), Var(R_G(\tau)) \) (10) and (11).

4.2. Algorithm using MCS for MANET Reliability with Mobility

**Step 1**: Initialize network parameters \((U, D, \text{Mission})\), node parameters (parameter of time to failure pdf \((\theta, \beta), (V_{\text{min}}, V_{\text{max}}), (0,2\Phi), r_j, (X_i, Y_i)\)), \( q = 1, C_q(\tau) = 0 \).

**Step 2**: Initialize, \( R_G(\tau) = \left( \prod_{u \in k \subseteq U} R_u(\tau) \right) \).

**Step 3**: Simulate the node status vector of size \(|U|-|k|\). The probability of nodes’ success calculated using (6).
Step 4: Simulate the link status vector of size $1 \times (U \times (U - 1)/2)$ by computing the $d_{ij}$ using (8).

Step 5: Check for connectivity of nodes $k \subseteq U$ of the network at time $\tau$. If network is connected then increment the $C_0(\tau)$ using (9) and set $\tau = \tau + \Delta \tau$.

Step 6: Simulate the node movements according to RWPM by uniformly and randomly choosing the nodes speed and position (or) simulate the same according to GMMM.

Step 7: Compute the next positions at every time increments using (2) for RWPM (or) using (3) and (4) for GMMM. Revisit Step 3 through Step 6 until $\tau <= t_{Mission}$.

Step 8: Revisit Step 2 to Step 7 for $Q$ number of simulation runs.

Step 9: Compute $R_G(\tau), \text{Var}(R_G(\tau))$ as per (10) and (11).

The algorithms are executed using Matlab® 2009a on a Windows® 8 running on Intel® Pentium® CPU processor B940 @2.00GHz speed. However for the case of MANET without mobility, there is no necessity for initializing the node parameters (velocity and direction) and computing the node positions (instead positions are generated randomly).

5. Example and Results

The proposed algorithm is applied to evaluate reliability of the MANET example provided in 4,5,8 which is restated here for the sake of completeness.

A network composed of 18 ($U = 18$) dismounted infantry (soldiers on foot) equipped with identical non-portable radios. Each radio is capable of ad hoc networking connectivity and is required to operate for duration of 72 hours. Each node has a transmission range of 3 miles; $r_j = 3$ miles each with a reliability that is described by Weibull distribution with parameters of $\theta = 1000$ and $\beta = 1.5$. The soldiers move randomly about a square coverage area of 64 square miles with a maximum and minimum velocity of 6 and 3 miles per hour respectively.

5.1. Simulation Results

The MN nodes move in and around the simulation boundary in accordance with the RWPM (random based model) and GMMM (temporal dependency model) to mimic the motion of the MN. The simulations have been conducted for 10 000 simulation runs for varying node density (9 to 100 nodes), transmission range (1 to 8 miles) and coverage area (64 to 225 mile$^2$). Using the developed algorithm the MANET reliability has been estimated. Our previous works$^{4,5}$ deal with reliability estimation under RWPM through simulation in detail. In this paper we put forward the results obtained with GMMM and without mobility and have compared the obtained results with those achieved in$^5$. In this section, we present some of the $2TR_m$ analyzed results obtained from our simulation (i) the impact of no mobility and (ii) impact of GMMM on MANET reliability.

5.1.1. MANET Reliability without Mobility

In this case, the node locations ($x_i, y_i$) are randomly generated. The location of the nodes and their network topologies at different instant of mission duration ($\tau = 0, 5, 50, 65$) for the case of no mobility is shown in Fig. 3(a) – Fig. 3(d). Fig. 3(a) – Fig. 3(d) shows the dynamic nature of the network and this dynamicity implies that connectivity among the node very often varies with time. The numbers in the Fig. indicates the position of $i^{th}$ node at each time instants. Besides this, Fig. 3(b) shows topologies with isolated nodes at $\tau = 5$; albeit of all nodes being active. The nodes 7 and 8 are called as isolated nodes, since the Euclidean distance with other nodes is greater than the transmission range of the nodes, ($d_{ij} > r_j$) or it may be due to speedy node movements.

It may be seen that also during a particular iteration nodes failed at certain time instants and remained failed thereafter until the mission time as seen in the case when $\tau = 65$. The filled square boxes in Fig. 3(d) indicate the failed nodes, which may also be isolated nodes. The nodes in the network fails due to varied reasons like hardware/software failure, low battery life, limited transmission range, out of coverage area, atmospheric effects,
and physical obstacles. Even though the intermediate nodes are isolated or failed, the network can still remain connected as seen in the topologies at $\tau=5$ and $\tau=65$ of Fig. 3(b) and Fig. 3(d) respectively.

It can be observed from Fig. 3(e), that, the node positions are totally random. Fig. 3(e) depicts a few sample node positions of $u_1$ and $u_{18}$ from the start of the mission to the end of the mission time. This random position of the node at different time instant has been generated without considering the mobility parameters (velocity and direction). However the node positions at time $\tau$ is independent of the node positions at time $\tau - \Delta \tau$. More interesting
fact is that the same topologies as shown in Fig. 3(a) – Fig. 3(d) can be obtained for MANET with RWPM (or GMMM) but may be at different time instants (can be seen in\textsuperscript{3}).

5.1.2. Impact of Mobility Model

The characteristics of the RWPM and GMMM on MANET reliability are analyzed through simulation and have been observed that the results of GMMM closely match with RWPM results\textsuperscript{4}. Extensive simulations to study the performance MANET using GMMM for different values of degree of randomness ($\alpha$) ($0 \leq \alpha \leq 1$) is conducted and the observations are summarized as follows. When tuning parameter $\alpha = 0$; the result obtained indicates that the reliability achieved is almost same as that of the networks in which the mobility is totally random which do not depend on the past history i.e., RWPM. Another interesting observation is that $\alpha$ has no significant influence on the network reliability because $\alpha$ has no influence on network connectivity\textsuperscript{33} i.e., $\alpha = 0$ (absence of randomness) or $\alpha > 0$ (presence of randomness/nodes move linearly) has no impact on reliability with coverage area, transmission range and node density.

From the simulations of the GMMM it was noted that this model eliminates some unrealistic movement in the simulations for tuning parameter greater than zero. The sudden stops and abrupt turns as encountered in RWPM are less frequent due to the influence of past speeds and directions on future values of both speed and direction. The GMMM provides movement patterns that might be expected in the real world, if appropriate tuning parameters are chosen. The resultant travel pattern of simulations of a mobile node using the GMMM is same as RWPM when $\alpha = 0$ was observed and is shown below in Fig. 4(a). It can be visualized in Fig. 4(b) that the sharp turns and sudden stops are eliminated thereby making the movement to be smoother when $\alpha = 0.5$. When $\alpha = 1.0$, the nodes motion is purely linear as seen in Fig. 4(c).

![Fig. 4: Gauss Markov Mobility of a node $u_i$ for the entire mission time at (a) $\alpha = 0.0$, (b) $\alpha = 0.5$ and (c) $\alpha = 1.0$.](image)
The comparative study of the estimated network reliability of MANET which considers mobility (RWPM, GMMM) and MANET without node movements is provided in Fig. 5(a)–Fig. 5(c), respectively. From the results it is clear that the estimated reliability for all the cases turns out to be almost same with negligible difference due to random generation function used in our MCS for any combination of the scenario metrics i.e., coverage area, transmission range and node density.

Fig. 5(a) indicates that intuitively the network reliability drastically reduces as the MN covers a larger coverage area. It can also happen that if the node density increases with no change in the coverage area then good results can be obtained as seen in Fig. 5(b) i.e., when high node density (say \( U = 100 \)) are deployed in coverage area of 64 Sq. Miles, the achieved reliability is 0.9621 (RWPM, GMMM, No mobility) which implies that the network is almost fully connected and with low node density (say \( U = 9 \)) deployed in the same coverage area of 64 Sq. Miles, the network is very sparingly connected with a reliability of 0.4475 (RWPM), 0.4519 (GMMM), 0.4472 (No mobility), respectively.

Indeed as the node density increases more connecting links increases in the defined simulation zone making the network more stable with improved reliability of about 51% of the reliability attained for low density network. Similarly, the transmission range of the node plays a major role in achieving a reliable communication. Fig. 5(c) indicates that the MANET reliability increases monotonically as the transmission range the MN increases. This happens because more active MN gets connected with increasing distance i.e., longer transmission range allows more MN to get connected. But beyond a threshold level stability in network reliability is attained or in other words the curve is flattened and hence varying the transmission range further is of no significance. This threshold value is the required choice for designing a network with good reliability. It can be concluded that best performance can be achieved by decreasing the coverage area with high node density and increasing transmission range. In support to the Fig. 5(a)–Fig. 5(c), the impact on reliability with operating time is also conducted. Fig. 6 portrays the \( 2TR_{mn} \) changes with operating time for the entire mission duration. As the operating time (\( t \)) increases; reliability of the
network reduces and the trend is similar and also the achieved reliability values are almost same for no mobility movements and the mobility models considered. The results also confirm the fact that the obtainable reliability of any network with imperfect vertices and edges will not go beyond the product of the reliabilities of $k$ (say 2 for $2TR$) set of designated nodes irrespective of the mobility model or no mobility considered.

Our results implies that the designer can design a reliable MANET without the need for choosing a suitable mobility model to mimic the node movements; and moreover the network reliability analysis can help communication engineers to install an MANET by choosing the optimum number of nodes with a sufficient transmission range needed to be operable in a suitable simulation boundary that provides a reliable communication with an acceptable reliability.

6. Conclusions

The proposed method considers the impact of various mobility models (i.e., RWPM, GMMM) on MANET reliability. In this paper, in another experiment, we implicitly generate the node positions in random and the obtained results are found to be same as that of MANET by considering node movements using RWPM and GMMM. The advantage of this approach is simple and efficient with reduced number of random variables. Further the computation complexity in generating the uniformly distributed node locations within the simulation boundary is also apparently reduced. The argument has been supported with a suitable example and is further demonstrated by varying the metrics viz., network coverage area, network size and transmission range of the MANET example.

However, in this paper, the uniform node distribution has been considered. Initially the nodes are uniformly distributed and with due course of time the distribution does not remain uniform. The variation of the distribution is due to the border effects of the nodes and moreover the nodes spend more time crossing through the centre of the coverage area as seen in RWPM. The future extension of this work is to consider the effect of non-uniform distribution of the node location on the MANET reliability.
References