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Evaluation of mobile ad hoc network reliability using propagation-based link reliability model

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ABSTRACT

A wireless mobile ad hoc network (MANET) is a collection of solely independent nodes (that can move randomly around the area of deployment) making the topology highly dynamic; nodes communicate with each other by forming a single hop/multi-hop network and maintain connectivity in decentralized manner. MANET is modelled using geometric random graphs rather than random graphs because the link existence in MANET is a function of the geometric distance between the nodes and the transmission range of the nodes. Among many factors that contribute to the MANET reliability, the reliability of these networks also depends on the robustness of the link between the mobile nodes of the network. Recently, the reliability of such networks has been evaluated for imperfect nodes (transceivers) with binary model of communication links based on the transmission range of the mobile nodes and the distance between them. However, in reality, the probability of successful communication decreases as the signal strength deteriorates due to noise, fading or interference effects even up to the nodes' transmission range. Hence, in this paper, using a propagation-based link reliability model rather than a binary-model with nodes following a known failure distribution to evaluate the network reliability ($2TR_m$, ATR_m *and* $AoTR_m$) of MANET through Monte Carlo Simulation is proposed. The method is illustrated with an application and some imperative results are also presented.

1. Introduction

In recent past, networks have been developing at a faster pace by connecting large number of devices from servers to micro-devices embedded in objects. These devices provide services that can support variety of applications like; environment monitoring, medical services, military applications, disaster recovery (fire, flood, earthquake etc.,), law enforcement etc. There are many instances where the network supporting such applications are mobile wireless networks, whose necessary infrastructure support is installed either in a permanent or ad hoc manner. For instance, MANET serves in situations where setup of the infrastructure based network may not be feasible or desirable because of the coverage limitations, network failures, congestion etc. The special feature of MANET such as self-organizing ability and high mobility of mobile nodes (MN) thus giving a dynamic topology, but strong linking of each MN within the coverage area distinguished it from other types of networks. The node failure in a MANET may be due to variety of reasons, e.g., low transmission range, out of coverage area, atmospheric effects, physical obstacles and limited battery lifetime. In other words, MN time-to-failure follows some statistical distribution. Similarly, the links between the nodes are assumed to have failed when either the distance between the nodes are beyond the specified transmission range of each node, or it may be due to mobility, interference, highly dynamic topology and/or congestion of wireless links. These characteristics make the modelling and the reliability analysis of such networks a challenging and formidable task.

In general, any system can be modelled using random graphs or probabilistic graphs with each user/terminal termed as nodes and the links between them as edges. Based on the number of communicating nodes, the network reliability for infrastructure based networks are defined as 2-terminal (*2TR*), all-terminal (*ATR*), *k*-terminal (*KTR*) and all operational terminal (*AoTR*) reliabilities. The probability that a specified pair of nodes (the source, *s* and the sink, *t*), with known success/failure probabilities of its elements, remain connected by a path created by the operating nodes and links is defined as 2-terminal reliability. The probability that every node be able to communicate with every other node in the network is all-terminal reliability. Similarly, the probability that at least $|k|$ designated nodes can communicate

Abbreviations: FS, Free-Space propagation; MANET, Mobile Ad Hoc Network; MCS, Monte Carlo Simulation; MN, Mobile Node; NCA, Network Coverage Area; NS, Network Size (Number of nodes in the network); RWPM, Random Way Point Mobility Model; TR, Transmission Range; TRG, Two Ray Ground Propagation

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Nomenclature

θ	Scale parameter of Weibull failure distribution of the node
β	Shape parameter of Weibull failure distribution of the node
ϕ	Direction of node movements in radians
$\Delta\tau$	Incremental change in time
D	Network Coverage Area in square distance units
δ	Threshold Distance for FS model, $0 < \delta \leq 1$
γ	Distance greater than δ *for TRG model*; $\delta < \gamma \leq 1$,
TR_m	MANET 2-terminal reliability
$A(\tau)$	Connection matrix at time τ
$AoTR_m$	MANET All-operational terminal reliability
ATR_m	MANET All-terminal reliability
Q	Total number of simulation runs
q	One complete iteration of Q number of simulation runs.
$C_q(\tau)$	Network status at time τ at the q^{th} iterations of simulation cycle
L	$\{l_1, l_2 \ldots l_p\}$: set of p links
U	$\{u_1, u_2 \ldots u_n\}$: set of n mobile nodes
$G(U, L, \tau)$	A network graph
k	Set of $k \subseteq U$ nodes in $G(U, L, \tau)$
$(G\|k)$	Network derived from $G(U, L, \tau)$ by setting the success probability of the k *nodes* of equal to 1.
$d_{ij}(\tau)$	Euclidean distance between node u_i and node u_j at time τ
$L_{ij}(\tau)$	Link Status between node u_i and node u_j at time τ
$R_G(\tau)$	Reliability of MANET at a particular instant of mission time.
$R_l(d_{ij}(\tau))$	Link Reliability at distance $d_{ij}(\tau)$
$R_{ui}(\tau)$	Reliability of node u_i at timeτ
r_j	Transmission range of a node u_j in distance units
(s, t)	Source-Terminal Pair
tMission	Mission time in time units
$u_i(\tau)$	Status of the i^{th} node at time τ
$Var(R_G(\tau))$	Variance of $R_G(\tau)$
V_{max}	Average maximum node speed
V_{min}	Average minimum node speed
$(x_i(\tau), y_i(\tau))$	Position of node u_i in XY-plane at time τ

with each other is *k*-terminal reliability. The probability that all the operational nodes can communicate with each other is termed as all-operational terminal reliability. The demand for reliable network for specific applications has attracted the researchers to work on their reliability aspects by extending the measures of infrastructure based networks to MANET. In [1], authors have presented an algorithm to solve all-terminal reliability allocation problem by minimizing the network design cost subject to a known constraint on all terminal reliability. They assumed that the network contains a known number of functionally equivalent components that can be used to provide redundancy. As noted by them that, terminal reliabilities measures have been used since a long for reliability studies and these measures have become important and extended in new areas of reliability research such as mobile ad-hoc wireless networks, grid computing systems, and telecommunications [1].

The reliability literature is in abundance and one can find plethora of methods that deal with the reliability analysis, evaluation and other related issues for infrastructure based networks. These algorithms have been based on graph theory and Boolean algebra, e.g., factoring theorem, pathsets/cutsets, event enumeration, network transformation, reduction and decomposition, sum-of disjoint product technique, binary decision diagrams, ordered binary decision diagrams, direct and approximation method. The interested reader may refer some of the recent work of infrastructure based networks [2–7]. However, these approaches are not directly applicable to the MANET because of nodes' movement thereby rendering a topology that changes from one instant to another. Therefore, the modelling of MANET can be accomplished by using geometric random graphs rather than the classical random graph models of Erdos and Renyi [8,9] to study the connectivity of such networks.

In [10], authors have provided the attributes of a MAWN and described how the classical analysis of network analysis, where the configuration is known a priori, can be extended to analyse dynamic networks such as MAWN by acknowledging their dynamic, scalable nature and absence of infrastructure. They performed the reliability evaluation by considering the link existence as a probabilistic function, i.e., assuming the links to have fixed probability. Further, the authors have provided analytical relevant formula and derivations to determine the 2-terminal reliability of MANET and further validated their analytical approach using MC-based methods. In [11], two-terminal reliability is evaluated as the sum of *i*-hop connectivity through (*n*-1) and also mathematical expressions are provided for determining the 1-hop and 2-hop connectivity of the network. However, the computation becomes cumbersome and complicated for finding paths of three or more hops. Recently, researchers have studied the performance of ad hoc networks by assuming unreliable nodes and *Euclidian* distance based binary model of links i.e., the link exists only when the *Euclidean* distance between the mobile nodes is lower than a threshold value, called as the transmission range of the MN [12,13]. However, in reality, the probability of successful communication within the transmission range of nodes generally decreases. Therefore, the assumption that perfect reception exists only within a particular transmission range is unrealistic and can lead to erroneous results and conclusions with an under designed network [14]. Hence to achieve a significant impact on the reliability measure of the MANET, we need to consider this feature of links existence to model the reality in a closer manner.

Link reliability can be defined as the reliability that is closely related with the physical conditions (exist/not exist) between any two MNs [15]. Literature indicates that several researchers [16–21] have developed and proposed various link reliability models for establishing connectivity and also achieving successful communication between the designated nodes. Link reliability models are used as a global measure to study the performance of ad hoc networks [16]. In [17] two different link reliability models for wireless communication networks have been proposed. First model assumes that the destination node receives information with certainty provided that the information transmitted by source node is with a minimum transmitter power level, which is dictated by its distance from the destination node; second model defines link reliability as the probability of correct reception at the destination node and is modelled as a function of transmission range, distance between designated node pairs and channel fade state. Using these models the reliability analysis for fixed routes has been performed with its extension to find optimal reliable path in [18]. The idea of [18] is further applied in [19] on multi-hop wireless broadcast networks to find the optimum link reliability between a designated node pairs with respect to transmitted power, distance and signal to noise ratio.