Wireless Engineering and Technology, 2016, 7, 24-35
Published Online January 2016 in SciRes. http://www.scirp.org/journal/wet
http://dx.doi.org/10.4236/wet.2016.71003

Issues and Challenges in Node Connectivity in Mobile Ad Hoc Networks: A Holistic Review

Mohit Jain, Satish Chand

Division of Computer Engineering, Netaji Subhas Institute of Technology (NSIT),
University of Delhi, New Delhi, India
Email: Jain.mohit@nsitonline.in, Satish@nsit.ac.in

Received 10 September 2015; accepted 19 January 2016; published 22 January 2016

Abstract

One of the fundamental properties of an ad hoc network is its connectivity. Maintaining connectivity in wireless networks is extremely difficult due to dynamic changing topology of MANETs. There are several techniques to understand the connectivity level for a given network topology. In this paper, we examine the existing methods and discuss the issues and challenges that are still insurmountable in order to enhance the connectivity properties of wireless multi hop networks.

Keywords

Ad Hoc Networks, Connectivity, Topology Control, Critical Transmitting Range, Node Density, Energy Consumption Routing, Critical Points, k-Connectivity

1. Introduction

Amobilead hoc network (MANET) is formed by a group of wireless autonomous mobile nodes to create a typical environment for dynamic communication with no fixed infrastructure or administration. They operate in a decentralized and self organizing manner [1] [2]. This type of network has been existing since 1970s [3] [4], but only last couple of years has witnessed a tremendous research in this area [5]-[7]. There are several issues related to MANETs that include route construction with minimum overhead [8]-[12], less bandwidth consumption, energy issue, security attacks [13]-[15], node misbehavior [16]-[18], etc. Some of the important routing protocols, broadcast protocols, and clustering protocols designed especially for ad hoc networks have been discussed in [19]-[27]. Some of them are designed for energy-efficient operation in an existing network topology, some deal with the effects of mobility, and some consider both the aspects. There are various studies in literature, but

How to cite this paper: Jain, M. and Chand, S. (2016) Issues and Challenges in Node Connectivity in Mobile Ad Hoc Networks: A Holistic Review. *Wireless Engineering and Technology*, **7**, 24-35. http://dx.doi.org/10.4236/wet.2016.71003

none discusses the latest developments related tothe ad hoc network connectivity. To the best of authors' knowledge, this is the first such study that reviews the importance of node connectivity unlike other properties like stable route construction, bandwidth, energy consumption, etc. in multihop wireless networks.

The advantage of ad hoc networks is that the mobile devices communicate with each other in a peer-to-peer fashion, establish a self organizing network without the need of any access point or any pre-existing infrastructure. In short, they can be formed in a spontaneous way, that's why they are known as ad hoc networks. In these networks, each node plays two vital roles: as mobile node and as router to transfer the packets of other nodes. To achieve a fully connected ad hoc network, there must be a multihop path from a node to every other node depending on two topology attributes: radio transmission range and node density. Their combination plays a vital role in node connectivity.

In a cellular network, also known as infrastructure network, the mobile devices remain connected even if there is a wireless link to at least one of the base stations within its communication range. In ad hoc networks, there are no fixed routers; all nodes are capable of movement that can be dynamically connected in an arbitrary manner. Each node acts as router to maintain the connectivity of the entire network. In case the communication gets broken, the connectivity between other nodes also gets destroyed. If the substantiality or spatial density of nodes is too low, the multihop system for communication will not perform well. In this paper, we study and analyze various techniques related to network connectivity along with their impact on the network topology. The organization of the remaining paper is as follows. Section II discusses the importance of connectivity in ad hoc networks. Section III discusses the research works done in the area. Section IV points out the major issues and challenges in ad hoc network connectivity. Finally, the paper is concluded in section V.

2. Why Node Connectivity Is Important?

Connectivity in ad hoc networks varies because of the continuous movement of the nodes due to their dynamic nature. It is possible that the movement of one or more nodes from one point to another causes the network partitioning. Maintaining connectivity is a challenge due to unstructured nature of the network topology and the frequent occurring of links and nodes failures due to interference, mobility, radio channel effects, and battery limitations [27]. This makes connectivity as one of the main problems in an ad hoc network. Many researchers have discussed methods to improve the network connectivity, which will be discussed in next section. The factors leading to network failure that partitions it into two or more components and can annihilate the end-to-end connectivity as well may be divided into the following four categories:

- Node or Device Failure
- Critical Points or Weak Points
- Link or Edge Failure
- Power or Battery Failure

a) ***Node Failure*:** The node failure occurs when an intermediate node or device acting as router is not available due to hardware/software failure or the node moves out of the communication range or the network. The situation has been described in **Figure 1**. Here node A and Dare communicating through node C. If node C fails due to battery failure or it moves out of the communication range, then an alternate route must be discovered and communication should be restored by rerouting the traffic through some other node B. The amount of time that two mobile nodes will stay connected is calculated by expression:

$$LET_{ij} = \frac{-(ab+cd)+\sqrt{(a^2+b^2)r^2-(ad-bc)^2}}{a^2+c^2}$$

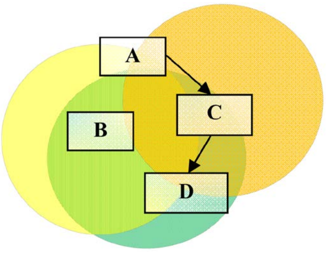

Figure 1. Illustration of Node Failure or Power Failure of Node C.

where

$a = v_i \cos\theta_i - v_j \cos\theta_j$

$c = v_i \sin\theta_i - v_j \sin\theta_j$

$b = x_i - x_j, \quad d = y_i - y_j$

In the above equations v_i, v_j are the speeds and θ_i , θ_j are the moving directions of two nodes I and j respectively.

After calculating the link expiration time (LET) in all

Links within the network, the highest amount of LET is determined:

The probability of the proper operation of link between node I and node j is obtained by:

$$p_{ij}^{link} = 1 - \frac{LET_{\max} - LET_{ij}}{LET_{\max}}$$

where $LET_{\max}$ is the biggest time period which the two nodes are connected in the network.

b) ***Power Failure*:** Power failure occurs when the battery of the node is too low, making it unable to serve as router. The situation has been explained in **Figure 1**.

c) ***Link Failure*:** Link failure can occur due to various factors: link obstacle between communication nodes, fading, node mobility and excessive interference. **Figure 2** illustrates the link fault when node Y moves to different position, resulting in communication link between X and Y, degrading because of an obstacle. Obviously these failures break the local connectivity between nodes and can disrupt the end-to-end connectivity as well. The path stability can be expressed by the following mathematical expression:

$$LEP_s(D) = \text{Min}\left(LET_{N_k}(N_k - 1)\right)$$

$K = 1 : k_0$, where $LEP_s(D)$ is the expiration time of the path joining S & D, $LET_{N_k}(N_k - 1)$ is the expiration time of the link connecting node N_k and the node $N_k - 1$, k is an integer where $1 < k \le k_0$

d) ***Critical Points*:** The weak or critical points of a topology are those links and nodes whose failure results in partioning the network into two or more components. For example, the critical node or articulation node is defined as a node that partitions the network due to its failure. The node C in **Figure 3** is a critical node because the network is partitioned if this node fails. Similarly the link CD in **Figure 4** is a critical link since failure of the link CD partitions the network into two components. Such links are also known as bridge links.

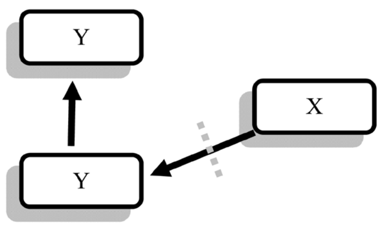

Figure 2. Illustration of Link between X and Y breaks due to some obstacle.

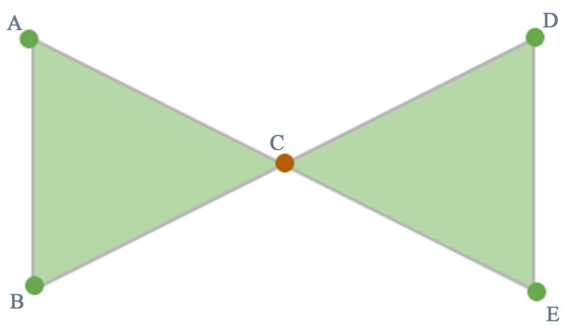

Figure 3. Illustration of critical node C.

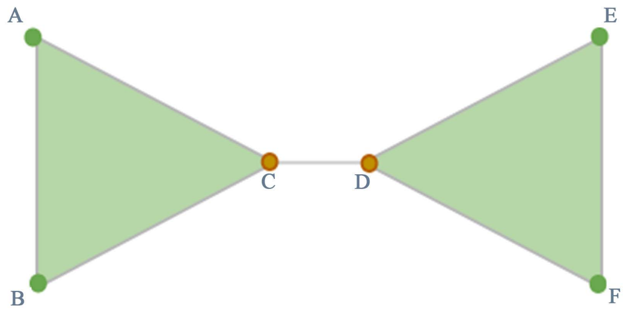

Figure 4. Illustration of critical link CD.

3. Literature Overview

The problem of node connectivity was very first time discussed by Cheng and Robertazziin 1989 [28]. They investigated the influence of node density and transmission range of a node's broadcast in a multihop radio network modeled by spatial Poisson process. They suggested that for optimizing the transmission range, its value should be lower bounded to maintain desired network connectivity. However, they could not implement it in real scenario. The paper [29], an extension of [28], discusses the disconnectedness of Poisson distributed nodes. It provides some insights on critical coverage range vs. critical transmission range of the nodes placed in a square area according to Poisson fixed density. This problem is further discussed in [30] for one dimensional line segment that determines the critical transmitting range for Poisson distributed nodes in square area. However, these works [29] [30] are difficult to apply in real scenarios because in a Poisson process the actual number of deployed nodes is a random variable itself whose only average value can be found. The paper [31] discusses the critical power of nodes in a network for transmission to ensure network connectivity by using the percolation theory [32]. The probabilistic lower and upper bounds for isolated and connected nodes fail to explain about nodes not placed independently in a disc. The paper [33] investigates the connectivity of hybrid ad hoc networks consisting the Poisson distributed nodes using the percolation theory. It reports that for populated regions one dim sparse network is well suited and the pure ad hoc network is useful relatively low density areas. For density critical areas, the cellular network can provide the acceptable connectivity. The paper [34] estimates the nearest neighbors when network becomes disconnected. In this work, the same number of nearest neighbors is maintained for each node. If each node is connected to less than 0.074 logn nearest neighbors the network is asymptotically disconnected. If each node is connected to more than 5.1774 logn nearest neighbors, then it is asymptotically connected. The paper [35] discusses the connectivity augmentation problem and determines a set of edges of minimum weight to be inserted in order to make the resulting graph λ-vertex edge connected. It is reported that the problem is NP hard for $\lambda > 1$. In [36], the same work has been discussed by using the concept of minimum geometric disk cover (MGDC) problem, commonly used in wireless networking applications or facility location problems. The MGDC problem is "*for a given set of points P in Euclidean plane and a rational number r* > 0, *it intends to find a set of centers C with minimum cardinality such that every point P is covered by a r radius disk centered at one of the points in C.*" This problem is however NP–hard problem. The paper [27] uses the random graph theory and theory of Kolmogorov complexity to establish the network connectivity via building local cluster head connections between nearby cluster heads without considering global network topology. In [37], the radio transmission range problem is analyzed and the probabilistic bounds for isolated nodes and connected nodes with uniform nodes on 1 - 2- and 3-dimension are calculated. It reports that the transmitting range of nodes can be reduced substantially from the deterministic requirements if there is high probability of connectedness. The paper [38] extends the work [37] and discusses the asymptotic minimum node degree of a graph on uniform points in d dimension .Some more studies on radio transmission range problem are discussed in [39]-[44]. The works [39]-[42] however do not consider inhomogeneous nodes. The issue of k-connectivity with respect to different transmission ranges has been discussed in [40] [41]. The same has been analyzed using the stochastic connectivity properties of the wireless multihop networks in [43]. The paper [44] discusses the connectivity for inhomogeneous node distributions with random waypoint (RWP) nodes. The paper [45] extends the Bettsetter's work [44] by incorporating the deployment border effects on the range to provide k-connectivity. In [46], the critical transmission power based on Bettsetter [44] is discussed to maintain k-connectivity, ensuring k-neighbors of a node is a necessary condition but not the sufficient condition for k-connectivity. It is because the network graph may have critical points which can cause the network failure and destroys the end-to-end network connectivity. In [47] [48], the critical transmitting range for connectivity in both stationary and mobile ad hoc networks has been analyzed. The paper [47] also discusses the probability for establishing a multihop path between two Poisson distributed nodes on an infinite line with a given distance. The paper [49] discusses about the node that keeps a multihop path to a fixed base station with the nodes moving in a straight line away from the base station. The k-connectivity concept has been further extended in [50] that studies the critical number of neighbors needed for k-connectivity. There are critical or weak points that play a major role in destroying the network connectivity. The works [40] [41] [43] [45] [50] have not discussed critical points. The paper [51] characterizes the critical transmitting range by using the asymptotic distribution of the longest minimum spanning tree [52] [53]. In [54], the problem of minimizing the maximum of node transmitting ranges while achieving connectedness is discussed. The basic assumption here is that the relative distance of all nodes is considered as input to the centralized topology control algorithm. In [55], a distributed topology control protocol is discussed to minimize the energy required to communicate with a given master node. In this work, every node is equipped with a GPS receiver to provide position information. Initially every node iteratively broadcasts its position to different search regions. When the node is able to calculate a set of nodes, called as its enclosure, based on the position information obtained from neighbors, this process stops. Its major drawback is that the number of iterations to determine the enclosure depends on the definition of initial search region, which affects the energy consumption of the protocol. The same problem has been analyzed in [56] using directional information obtained by using multi-directional antenna. But such setup is not possible in sensor networks because the nodes are very simple and have no centralized communication facility.

In order to prevent failures from partitioning the network and to maintain end-to-end connectivity, researchers recommend the network topology to be K-connected. The K-connectivity refers that the network should have K-disjoint routes between each node pair, which may be edge disjoint or noded is joint. Till now, the main focus has been on to determine the combination of node density and transmission range in order to provide k-node cconnectivity in a specific deployment scenario in homogeneous nodes or non-homogenous nodes in MANETs. However, very few papers [57]-[59] have defined the critical points or weak points in MANETs which results in the network partition in two or more components.

The work of different authors have been analyzed with their viewpoints on the ad hoc network connectivity along with techniques used and defects in more pristine manner in **Table 1**. Besides such rigorous works, there are still some major issues and challenges left that need be looked uponin order to have better node connectivity in MANETs.

4. Issues and Challenges

***a*) *Mobility Prediction*:** Mobility prediction of a node is the estimation of its future locations. The definition of location depends on the type of wireless networks. In infrastructure networks location refers to the access points to which mobile terminal is connected. In infrastructureless networks the location refers to geographical coordinates. Its main advantage is to predict the link expiration time to improve the node connectivity and routing performance. Many location prediction methods are discussed in literature [60] [61]. However, no studies discuss about the prediction of future locations considering realistic scenarios. This is one of the biggest challenges in MANETs.

***b*) *Connectivity Efficiency and Cost Objective*:** Since in order to deploy static nodes in place of critical nodes in which lack of nodes are felt, deployment cost of static nodes must be considered. While placing such nodes attention must be paid on to maximize the connectivity and to have minimum cost. But to achieve both connectivity efficiency and cost objective while deploying the critical points is a NP-complete problem. Since few authors have attempt this part [62] but no work has done to find the critical links and critical nodes considering the both factor cost objective and connectivity efficiency. Since it is NP-complete problem, more optimized technique need to be followed in order to achieve this goal

***c*) *Energy Consumption issues*:** One of the key challenges is to save the limited energy and use it to prolong the network lifetime considering the network connectivity constraints. Since the energy is the most valuable resources in MANETs, its status should continuously be monitored after network deployment. The paper [53]-[56] [63] discusses this issue. Researchers have considered the random waypoint mobility model, which is unrealistic model. There is a need to look this aspect in real scenarios.

Table 1. Analysis of the existing work related to network connectivity in ad hoc networks.

Methods	Assumptions	Findings	Drawbacks
Random Network Model [27]	Given Cluster head that form a dominant independent set in the network graph [64] [65].	Provides Network connectivity with very high probability [66].	Results are of theoretical interest and cannot be apply to real scenarios
Spatial Poisson Process and Percolation theory [28]	Considers mobile stations that are confirmed to a single dimensional line. At a particular instant in time it is assumed that stations spatial positions can be modeled as a one dimensional Poisson process.	Node's broadcast message percolate, if the nodes are randomly distributed according to homogeneous Poisson point process on an infinitely large area	Work did not consider the actual distance between nodes.
Packet radio network model [29]	• Nodes in the network lie in bounded area. • The homogeneous Poisson assumption. • Each node is able to communicate with any other node that is at most R unit distance from it. • All nodes generate Poisson streams of traffic at an identical rate.	No optimal number of nearest neighbor or magic number can exist.	Difficult to apply in real scenario. Also in disk based models, fading, interference and attenuation does not considerer.
Connectivity of radio networks [30]	• Transmitters are distributed according to one dimensional Poisson process of density d. • Two transmitters are connected by an edge apart at most i distance of their communication range.	Solve s the problem of [29] in 1-dim. Studies uniform distributed nodes on 1-dim line segment and estimates critical transmitting range for Poisson distributed nodes	Difficult to be apply in real scenario, only the expected number of deployed nodes can be controlled
Critical power for asymptotic connectivity in wireless networks [31]	Nodes placed randomly in disc of unit area.	Estimates the critical power of a node, needed to transmit to ensure that the network connectivity.	Not applicable for real applications.
Connectivity in ad hoc and hybrid networks [33]	• Assumes a large scale wireless network with low density of nodes per unit area. • Power constraints are modeled by a maximum distance above which two nodes are not directly connected.	Base stations significantly help in increasing the network connectivity only for large density	Findings restricted only to one dimensional case.
Number of neighbors needed for connectivity of wireless networks [34]	• In a network with n randomly placed nodes each node should be connected to Θ (log n) neighbors. • N nodes are placed uniformly and independently in unit square region. • Critical constant appear to be close to 1.	• Increasing number of nodes should not effect the number of nearest neighbor otherwise once obtained a disconnected network • Asymptotic connectivity results when every node is connected to its nearest 5.1774logn neighbors, while asymptotic disconnectivity results when each node is connected to less then 0.074logn nearest neighbors.	Result is of theoretical interest and cannot be applicable to real scenario
Approximation algorithms and Connectivity Augmentation Problem [35]	Network is treated as undirected graph [67] and each possible link is either feasible or infeasible.	Determines a set of edges of minimum weight to be inserted so that so that the resulting graph is λ-vertex (edge) connected. The problem is NP hard for $\lambda > 1$	Does not consider the possibility of adding new vertices into the graph
A probabilistic analysis for the radio range assignment problem in ad hoc networks [37]	N nodes having same transmission range are distributed in d-dimensional region.	Estimates bounds for isolated nodes and connected nodes on a one dimensional line segment.	It is only for static networks. It does not incorporate the possibility of transient or permanent node failures in their model. That will lead to requirements for desirable topological characteristic to be harsher compared to theoretical prediction

Continued

Phase transition [39]	n nodes located randomly in some service area, each assumed to transmit with a fixed radio power in an idealized environment where it can be heard by other nodes within same radius.	Discusses the theory of Bernoulli random graphs [65] that can help in proving when the phase transition in ad hoc network occurs.	Classical theory of random graph models is not suitable to model the ad hoc network problems.
Minimum node degree and connectivity of wireless multi hop network [40]	1. Random uniform distribution of nodes and a simple link model 2. All nodes are free to move in the system area according to a certain mobility model 3. Radio link model is assumed	Finds the uniform distribution of homogeneous nodes in a rectangular deployment area and establishes a relationship between the minimum transmission range and the probabilistic behavior of minimum node degree	Results are of theoretical interest and require a very high node density to ensure k-connectivity which would lead to interference and low throughput in real networks
Minimum node degree and k-connectivity of a wireless multi hop network in bounded area [45]	Circumvent the border effect which assumes boundless network deployment area.	Eliminate the border effects in order to provide an improved estimation of probabilistic characteristic, including the upper bound and lower bound of minimum node degree and k-connectivity.	High node density would lead to interference and low throughput in real networks
Torus Convention [46]	Nodes are distributed on a unit square according to a homogeneous Poisson point process with density λ.	Eliminate the need to consider boundary effects that may affect the critical transmission range for k-connectivity	It is of theoretical interest, requiring a very high node density to ensure k-connectivity which would lead to interference and low throughput in real networks.
Critical transmitting range for connectivity in sparse wireless ad hoc networks [47]	• Nnodes, each capable of communicating with nodes within a radius of r, randomly and uniformly distributed in d–dimensional region of side of length l. • Consider both stationary and mobile nodes	Estimates tolerating parseness *i.e.* Requiring 90% of nodes to be in the same connected component results in the significant reduction in the required transmission ranges of nodes.	If physical node degree is upper bounded by a constant, then the resulting communication graph is disconnected
Connectivity in finite ad hoc networks [48]	Uniform distribution of nodes in [0,z] where z > 0 for one dimensional network	Finds the probability of connectivity of one dimensional finite ad hoc network formed by uniform distribution of nodes	Probability of network was not correct and has been corrected by [68]
Cell extension and Mobility patterns [49]	• All relay nodes are randomly distributed and fixed. • Mobile nodes and relay nodes move right at same velocity. • Relay nodes are classified into two groups. In first group both relay nodes never move and in other group relay nodes move left at velocity	Finds that multi-hop networking with two kind of mobile relay nodes degrades cell extension performance compared with fixed relay nodes.	It is of theoretical interest and cannot be apply to real scenarios. Also, Distributions of mobile nodes are considered only on street not on plane.
Asymptotic critical transmission radius and critical neighbor number for k-connectivity [50]	Uniform n point process over a unit area disk or square.	Obtained the improved asymptotic almost sure upper bound on the critical neighbor number for k-connectivity.	It does not consider interference, though dense networks produce strong interference. Decrease the network throughput.

Continued

Geometric random graph theory [51]	• Number of nodes placed in uniformly distributed area. • Homogeneous topology control	Asymptotic distribution to analyze the critical transmission range	It can only be used to model dense ad hoc networks, not for sparse ad hoc networks [69]
Centralized topology control algorithm [54]	Relative distance of all nodes are given as input to a centralized topology control algorithm	Minimize the maximum transmitting range of nodes. Also, reduce the energy consumption and improve the network throughput	No information has been given to select the appropriate number of neighbors for LINT heuristic (Local Information No Topology). Danger of Network partition in LINT.
Distributed position based network protocol [55]	Every node is equipped with a GPS receiver. Also, The number of iteration needed to determine the enclosure is based on the definition of the initial search engine	Minimizes the energy needed to communicate with a single master node.	The search engine is a critical aspect which affects the energy consumption of the protocol.
Cone-based distributed topology control algorithm [56]	Each node has some power function which transmits the minimum power needed to establish a communication link to a node far away from that node.	Reduce the power consumption and discuss the modification to deal with mobility.	Initial range assignment for nodes and its step increase has not been discussed.
Depth first search algorithm [57]	Nodes know their location and periodically update their neighbors with their current locations.	Determine the critical links whose failure cause partitioning of the network and then supporting these links either by modifying the trajectory of the nodes involved in the critical links or bringing an outside node to reinforce them.	Increase delivery rates due to Prolonged network connectivity. Communication overhead due to running DFS (Depth First Search) for detecting critical links was not measured.
Localized algorithm for testing k-connectivity [59]	• Each node makes its own decision based on the information available in its local neighborhood. • Each node verifies whether or not itself and each of its p-hop neighbors of a given node is k-connected. • All nodes declare themselves locally 1-connected.	Find the critical nodes and links using local topology and location information	Detected critical points may not be global critical points due to existence of alternate routes
Genetic Algorithm and Fish Swarm Algorithm [62]	Realistic Mobility Model	Improve the node connectivity issue by adding static nodes with consideration to deployment cost	Energy loss while deploying static nodes is not considered
Linear Programming and Neural Networks [63]	Consider a network of homogeneous and energy constrained sensor nodes that are randomly deployed in a sensor field.	scheme is quite effective to deliver 95% of packets to their destination with increase in network coverage	It cannot guarantee the full sensing coverage of the network.
Fractal Propagation Model [70]	For every two nodes within the transmission range will be connected with a probability as function of their geometrical distance.	Giant component size can be characterized by a single parameter *i.e.* average node degree.	Giant component size has been estimated empirically rather than analytically
Undirected Geometric Random Graph [71]	n nodes are randomly and uniformly distributed on a square and link exist between two nodes if the power received at one node from the other nodes is greater then a given threshold.	It shows an empirical formula relating the giant component size and the average node degree in random geometric graphs.	Giant component size of network has been estimated empirically rather then analytically.

5. Conclusion

In this paper, we have reviewed the existing literature with respect to network connectivity. The network connectivity is an important property of ad hoc network because the mobile nodes change the network topology very frequently. If the network becomes disconnected, the data may not be sent to the desired destination. Most of the existing works have considered unrealistic scenarios and very less works discuss the major factors contributing to network disconnectivity in MANETs. We have highlighted important parameters that affect the network connectivity, which include battery/power failure, link failure, critical points, and node failure. The main issues in network connectivity are mobility prediction, energy consumption and connectivity efficiency along with connectivity cost and these issues need to be explored further to understand network connectivity.

References

[1] Basu, S.S. and Chaudhari, A. (2003) Self Adaptive Topology Management for Mobile Ad Hoc Network. *Journal of the Institution of Engineers* (*India*), **84**, 7-13.

[2] Johnson, D.B. and Maltz, D.A. Dynamic Source Routing in Ad Hoc Wireless Networks. Computer Science Department, Carneige Mellon University, Pittsburg, 213-3891.

[3] Jublin, J. and Tornow, J. (1987) The DARPA Packet Radio Network Protocols. *Proceedings of the IEEE*, **75**, 21-32. http://dx.doi.org/10.1109/PROC.1987.13702

[4] Leiner, B.M., Nielson, D.L. and Tobagi, F.A. (1987) Issue in Packet Radio Network Design. *Proceedings of the IEEE*, *Special Issue on Packet Radio Networks*, **75**.

[5] Haas, Z.J., Gerla, M., Johnson, D.B., Perkins, C.E., Pursley, M.B., Steenstrup, M. and Toh, C.-K. (1999) *IEEE Journal on Selected Areas in Communications*, *Special issue on Wireless Ad Hoc Networks*, **17**.

[6] Kermani, P. and Vaidya, N.H. (2001) *IEEE Personal Communication*, *Special Issue on Advances in Mobile Ad Hoc Networking*.

[7] Perkins, C.E. (2001) Ad Hoc Networking. Addison-Wesley, Boston.

[8] Royer, E.M. and Toh, C.-K. (1999) A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks. *IEEE Personal Communications Magazine*, **6**, 46-55. http://dx.doi.org/10.1109/98.760423

[9] Hong, X., Xu, K. and Gerla, M. (2002) Scalable Routing Protocols for Mobile Ad Hoc Networks. *IEEE Network*, **16**, 11-21. http://dx.doi.org/10.1109/MNET.2002.1020231

[10] Abolhasan, M., Wysocki, T. and Dutkiewicz, E. (2004) A Review of Routing Protocols for Mobile Ad Hoc Networks. *Elsevier ADHOC Networks Journal*, **2**, 1-22.

[11] Mauve, M., Widmer, J. and Hartenstein, H. (2001) A Survey On Position—Based Routing in Mobile Ad Hoc Networks. *IEEE Network*, **1**, 30-39. http://dx.doi.org/10.1109/65.967595

[12] Costa, L.H.M.K., Amorim, M.D. and Fdida, S. (2004) Reducing Latency and Overhead of Route Repair with Controlled Flooding. *ACM/Kluwer Wireless Networks*, **10**, 347-358.

[13] Yih-Chun, H. and Perrig, A. (2004) A Survey of Secure Wireless Ad Hoc Routing. *IEEE Security and Privacy Magazine*, **2**, 28-39. http://dx.doi.org/10.1109/MSP.2004.1

[14] Karlof, C. and Wagner, D. (2003) Secure Routing in Wireless Sensor Networks: Attacks and Countermeasures. *Ad Hoc Networks*, **1**, 293-315. http://dx.doi.org/10.1016/S1570-8705(03)00008-8

[15] Wood, A.D. and Stankovic, J.A. (2002) Denial of Service in Sensor Networks. *IEEE Computer*, **35**, 54-62. http://dx.doi.org/10.1109/MC.2002.1039518

[16] Aad, I., Hubaux, J.-P. and Knightly, E.W. (2004) Denial of Service Resilience in Ad Hoc Networks. *Proceedings of ACM MobiCom*'04, 202-215. http://dx.doi.org/10.1145/1023720.1023741

[17] Hollick, M., Schmitt, J., Sepil, C. and Steinmetz, R. (2004) On the Effect of Node Misbehavior in Ad Hoc Networks. *Proceedings of IEEE ICC*'04, **6**, 3759-3763.

[18] Srinivasan, V., Nuggehalli, P., Chiasserini, C.F. and Rao, R.R. (2003) Co-Operation in Wireless Ad Hoc Networks. *Proceedings of IEEE INFOCOM*'03, 30 March-3 April 2003, 808-817.

[19] Basagni S., Bruschi, D. and Chlamtac, I. (1999) A Mobility Transparent Deterministic Broadcast Mechanism for Ad Hoc Networks. *IEEE Transactions on Networking*, **7**, 7999-807. http://dx.doi.org/10.1109/90.811446

[20] Gerla, M. and Tzu-Chen Tsai, J. (1995) Multicluster, Mobile, Multimedia Radio Network. *Wireless Networks*, **1**, 255-265.

[21] Intanagonwiwat, C., Govindan, R. and Estrin, D. (2000) Directed Diffusion: A Scalable and Robust Communication

Paradigm for Sensor Networks. *Proceedings of the* 6*th Annual International Conference on Mobile Computing and Networking*, Boston, 6-11 August 2000, 56-67. http://dx.doi.org/10.1145/345910.345920

[22] Ko, Y.B. and Vaidya, N.H. (1998) Location-Aided Routing (LAR) in Mobile Ad Hoc Networks. *Proceedings of the* 4*th Annual ACM International Conference on Mobile Computing and Networking*, Dallas, 25-30 October 1998, 66-75. http://dx.doi.org/10.1145/288235.288252

[23] Murthy, S. and Garcia-Luna-Aceves, J.J. (1996) An Efficient Routing Protocol for Wireless Network. *Mobile Networks and Applications*, **1**, 183-197. http://dx.doi.org/10.1007/BF01193336

[24] Park, V.D. and Corson, M.S. (1997) A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks. *Proceedings of the Sixteenth Annual Joint Conference of the IEEE Computer and Communications Societies*. *Driving the Information Revolution*, Kobe, 7-12 April 1997, 1405-1413.

[25] Perkins, C.E. and Bhagwat, P. (1994) Highly Dynamic Destination Sequenced Distance Vector Routing (DSVD) for Mobile Computers. *Proceedings of the ACM SIGCOMM*'94 *Conference on Communications Architectures*, *Protocols and Applications*, London, 31 August-2 September 1994, 234-244. http://dx.doi.org/10.1145/190314.190336

[26] Ramanathan, S. and Steestrup, M. (1996) A Survey of Routing Techniques for Mobile Communication Networks. *Mobile Networks and Applications*, **1**, 89-104. http://dx.doi.org/10.1007/BF01193330

[27] Chlamtac, I. and Fargo, A. (1999) A New Approach to the Design and Analysis of Peer to Peer Mobile Networks. *ACM/Kluwer Wireless Networks*, **5**, 149-156. http://dx.doi.org/10.1023/A:1019186624837

[28] Cheng, Y.-C. and Robertazzi, T.G. (1989) Critical Connectivity Phenomena in Multihop Radio Models. *IEEE Transactions on Communications*, **37**, 770-777. http://dx.doi.org/10.1109/26.31170

[29] Philips, T.K., Panwar, S.S. and Tantawi, A.N. (1989) Connectivity Properties of a Packet Radio Network Model. *IEEE Transactions on Information Theory*, **35**, 1044-1047. http://dx.doi.org/10.1109/18.42219

[30] Piret, P. (1991) On the Connectivity of Radio Networks. *IEEE Transactions on Information Theory*, **37**, 1490-1492. http://dx.doi.org/10.1109/18.133276

[31] Gupta, P. and Kumar, P.R. (1998) Critical Power for Asymptotic Connectivity in Wireless Networks. In: McEneany, W.M., Yin, G. and Zhang, Q., Eds., *Stochastic Analysis*, *Control*, *Optimization and Applications*: *A Volume in Honor of W. H. Fleming*, Birkhauser, Boston, 547-566.

[32] Meesterand, R. and Roy, R. (1996) Continuum Percolation. Cambridge University Press, Cambridge, MA. http://dx.doi.org/10.1017/CBO9780511895357

[33] Dousse, O., Thiran, P. and Hasler, M. (2002) Connectivity in Ad Hoc and Hybrid Networks. *Proceedings of the Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies*, New York, 23-27 June 2002, 1079-1088. http://dx.doi.org/10.1109/infcom.2002.1019356

[34] Xue, F. and Kumar, P.R. (2004) The Number of Neighbors Needed for Connectivity of Wireless Networks. *Wireless Networks*, **10**, 161-181. http://dx.doi.org/10.1023/B:WINE.0000013081.09837.c0

[35] Khuller, S. (1996) Approximation Algorithms for Finding Highly Connected Subgraphs. In: Hochbaum, D.S., Ed., *Approximation Algorithms for NP Hard Problems*, PWS Publishing Co., Boston.

[36] Ausiello, G., Crescenzi, P., Gambosi, G., Kann, V., Marchetti-Spaccamela, A. and Protasi, M. (1999) Complexity and Approximation: Combinatorial Optimization Problems and Their Approximability Properties. Springer-Verlag, Berlin. http://dx.doi.org/10.1007/978-3-642-58412-1

[37] Santi, P., Blough, D.M. and Vainstein, F. (2001) A Probabilistic Analysis for the Radio Range Assignment Problem in Ad Hoc Networks. *Proceedings of the Symposium on Mobile Ad Hoc Networking and Computing*, Long Beach, 4-5 October 2001, 212-220.

[38] Appel, M.J.B. and Russo, R.P. (1997) The Minimum Vertex Degree of a Graph on Uniform Points in $[0,1]^d$. *Advances in Applied Probability*, **29**, 582-594. http://dx.doi.org/10.2307/1428077

[39] Krishnamachari, B., Wicker, S.B. and Bejar, R. (2001) Phase Transition Phenomenon in Wireless Ad Hoc Networks. *Proceedings of the IEEE Global Telecommunications Conference*, San Antonio, 25-29 November 2001, 2921-2925.

[40] Bettstetter, C. (2002) On the Minimum Node Degree and Connectivity of Wireless Multihop Network. *Proceedings of the* 3*rd ACM International Symposium on Mobile Ad Hoc Networking & Computing*, Lausanne, 9-11 June 2002, 80-91. http://dx.doi.org/10.1145/513800.513811

[41] Bettsetter, C. (2002) On the Connectivity of Wireless Multihop Networks with Homogeneous and Inhomogeneous Range Assignment. *Proceedings of the IEEE* 56*th Vehicular Technology Conference*, Vancouver, 24-28 September 2002, 1706-1710.

[42] Bettstetter, C. and Zangl, J. (2002) How to Achieve a Connected Ad Hoc Network with Homogeneous Range Assignment: An Analytical Study with Consideration of Border Effects. *Proceedings of the IEEE Conference on Mobile and Wireless Communication Networks* (*MWCN*), Stockholm, 9-11 September 2002, 125-129.

http://dx.doi.org/10.1109/MWCN.2002.1045708

[43] Bettstetter, C. (2004) On the Connectivity of Ad Hoc Networks. *The Computer Journal*, **47**, 432-447.

[44] Bettstetter, C. (2003) Topology Properties of Ad Hoc Networks with Random Waypoint Mobility. *Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing*, Annapolis, 1-3 June 2003.

[45] Ling, Q. and Tian, Z. (2007) Minimum Node Degree and K-Connectivity of a Wireless Multihop Network in Bounded Area. *Proceedings of the IEEE Global Telecommunications Conference*, Washington DC, 26-30 November 2007, 1296-1301. http://dx.doi.org/10.1109/glocom.2007.249

[46] Zang, H.H. and Hou, J.C. (2005) On the Critical Total Power for Asymptotic K-Connectivity in Wireless Networks. *Proceedings of the* 24*th Annual Joint Conference of the IEEE Computer and Communications Societies*, Miami, 13-17 March 2005, 466-476.

[47] Santi, P. and Blough, D.M. (2003) The Critical Transmitting Range for Connectivity in Sparse Wireless Ad Hoc Networks. *IEEE Transactions on Mobile Computing*, **2**, 25-39. http://dx.doi.org/10.1109/TMC.2003.1195149

[48] Desai, M. and Manjunath, D. (2002) On the Connectivity in Finite Ad Hoc Networks. *IEEE Communications Letters*, **6**, 437-439.

[49] Nakano, K., Shirai, Y., Sengoku, M. and Shinoda, S. (2003) On Connectivity and Mobility in Mobile Multi Hop Wireless Networks. *Proceedings of the* 57*th IEEE Semiannual Vehicular Technology Conference*, Jeju, 22-25 April 2003, 89-98. http://dx.doi.org/10.1109/vetecs.2003.1208793

[50] Wan, P.J. and Yi, C.W. (2004) Asymptotic Critical Transmission Radius and Critical Neighbor Number for K-Connectivity in Wireless Ad Hoc Networks. 5*th ACM Symposium on Mobile Ad Hoc Networking and Computing* (*MobiHoc*).

[51] Panchapakesan, P. and Manjunath, D. (2001) On the Transmission Range in Dense Ad Hoc Radio Networks. *Proceedings of IEEE SPCOM*'01.

[52] Penrose, M.D. (1999) A Strong Law for the Longest Edge of the Minimal Spanning Tree. *The Annals of Probability*, **27**, 246-260. http://dx.doi.org/10.1214/aop/1022677261

[53] Penrose, M.D. (1999) The Longest Edge of the Random Minimal Spanning Tree. *The Annals of Probability*, **15**, 340-361.

[54] Ramanathan, R. and Rosales-Hain, R. (2000) Topology Control of Multihop Wireless Networks Using Transmit Power Adjustment. *Proceedings of the* 19*th Annual Joint Conference of the IEEE Computer and Communications Societies*, Tel Aviv, 26-30 March 2000, 404-413. http://dx.doi.org/10.1109/infcom.2000.832213

[55] Rodolpu, V. and Meng, T.H. (1999) Minimum Energy Mobile Wireless Networks. *IEEE Journal on Selected Areas in Communications*, **17**, 1333-1344. http://dx.doi.org/10.1109/49.779917

[56] Li, L., Halpern, J.H., Bahl, P., Wang, Y. and Wattenhofer, R. (2001) Analysis of a Cone-Based Distributed Topology Control Algorithm for Wireless Multi Hop Networks. *Proceedings of the ACM Symposium on Principles of Distributed Computing*, Newport, 26-28 August 2001. http://dx.doi.org/10.1145/383962.384043

[57] Goyal, D.D. and Caffery, J.J. (2002) Partioning Avoidance in Mobile Ad Hoc Networks Using Network Survivability Concepts. *Proceedings of the Seventh International Symposium on Computers and Communications*, Sicily, 1-4 July 2002.

[58] Milic, B. and Malek, M. (2007) Adaptation of the Breadth First Search Algorithm for Cut Edge Detection in Wireless Multihop Networks. *Proceedings of the* 10*th ACM Symposium on Modeling, Analysis, and Simulation of Wireless and Mobile Systems*, Chania, 22-26 October 2007, 377-386.

[59] Jorgic, M., Goel, N., Kalaichevan, K., Nayak, A. and Stojmenovic, I. (2007) Localized Detection of K-Connectivity in Wireless Ad Hoc, Actuator and Sensor Networks. *Proceedings of the* 16*th IEEE International Conference on Computer Communications and Networks* (*ICCCN*), Honolulu, 13-16 August 2007, 33-38. http://dx.doi.org/10.1109/icccn.2007.4317793

[60] Kumar, V. and Venkataram, P. (2002) A Prediction Based Location Management Using Multi-Layer Neural Netwoks. *Journal of the Indian Institute of Science*, **82**, 7-21.

[61] Kanniche, H. and Kamoun, F. (2010) Mobility Prediction in Wireless Ad Hoc Networks Using Neural Networks. *Journal of Telecommunications*, **2**, 95-101.

[62] Romoozi, M. and Babaezi, H. (2011) Improvement of Connectivity in Mobile Ad Hoc Networks by Adding Static Nodes Based on Realistic Mobility Model. *International Journal of Computer Science Issues*, **8**, 176-183.

[63] Kumar, N., Kumar, M. and Patel, R.B. (2010) Coverage and Connectivity Aware Neural Network Based Energy Efficient Routing in Wireless Sensor Networks. *Journal on Application of Graph Theory in Wireless Ad Hoc Networks and Sensor Networks*, **2**, 45-60.

[64] Janson, S., Luczak, T. and Rucinski, A. (2000) Random Graphs. John Wiley & Sons, New York.

http://dx.doi.org/10.1002/9781118032718

[65] Bollobas, B. (1998) Modern Graph Theory. Springer, New York.

[66] Feller, W. (1950) An Introduction to Probability Theory and Its Applications. John Wiley & Sons, New York.

[67] Diestel, R. (2000) Graph Theory. 2nd Edition, Springer, New York.

[68] Gore, D.A. (2006) Comments on the Connectivity in Finite Ad Hoc Networks. *IEEE Communication Letters*, **10**, 88-90.

[69] Diaz, J., Penrose, M.D., Petit, J. and Serna, M. (2000) Convergence Theorems for Some Layout Measures on Random Lattice and Random Geometric Graphs. *Combinatorics*, *Probability and Computing*, **9**, 489-511. http://dx.doi.org/10.1017/S0963548300004454

[70] Nemeth, G. and Vattay, G. (2003) Giant Clusters in Random Ad Hoc Networks. *Physical Review E*, **67**, Article ID: 036110. http://dx.doi.org/10.1103/PhysRevE.67.036110

[71] Hekmat, R. and Mieghem, P.V. (2006) Connectivity in Wireless Ad-Hoc Networks with a Log-Normal Radio Model. *Mobile Networks and Applications*, **11**, 351-360. http://dx.doi.org/10.1007/s11036-006-5188-7