

# Wireless Multi-hop Networks: Current Research and Future Challenges

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**Abstract**—Wireless multi-hop networks, in various forms and under various names, are being increasingly used in military and civilian applications. Studying connectivity and capacity of these networks is an important problem. The scaling behavior of connectivity and capacity when the network becomes sufficiently large is of particular interest. In this paper, we briefly overview recent development and discuss research challenges and opportunities in the area, with a focus on the network connectivity. We demonstrate some intrinsic connections between the connectivity analysis and capacity analysis and point out the fundamental parameters determining the capacity of a wireless multi-hop network.

**Index Terms**—Wireless multi-hop networks, connectivity, capacity

## I. INTRODUCTION

Wireless multi-hop networks, in various forms, e.g. wireless sensor networks, underwater sensor networks, vehicular networks, mesh networks and UAV (Unmanned Aerial Vehicle) formations, and under various names, e.g. ad-hoc networks, hybrid networks, delay tolerant networks and intermittently connected networks, are being increasingly used in military and civilian applications. There are three defining features that characterize a wireless multi-hop network:

- 1) Wireless devices are self-organized or assisted by some infrastructure to form a network. The former case corresponds to ad-hoc networks whereas the latter case corresponds to infrastructure-based multi-hop networks. Depending on the applications, the forms of the infrastructure can be quite flexible, e.g. a subset of devices connected via wired

connections, a subset of devices with more powerful transmission capability such that they form a wireless backbone for the network, or in a UAV formation, the infrastructure may assume the form of a subset of UAVs with satellite links.

- 2) Communication is mostly via wireless multi-hop paths.
- 3) Packets are forwarded *collaboratively* from the source to the destination.

The implication of the first feature is that ad-hoc networks form an important special case of wireless multi-hop networks but the concept of wireless multi-hop networks has much broader meaning. Particularly, the prospect of including infrastructure into the ad-hoc network addresses shortcomings of the ad-hoc network in scalability and providing reliable service. The second feature sets wireless multi-hop networks apart from the traditional one-hop networks, i.e. cellular networks and wireless LANs. Therefore, there is a unique set of challenging problems specific to wireless multi-hop networks. The third feature implies that collaborative communication, either centrally designed and operated or performed distributedly, is an important consideration in wireless multi-hop networks.

Studying connectivity and capacity of wireless multi-hop networks is an important problem [1]–[3]. The scaling behavior of connectivity and capacity when the network becomes sufficiently large is of particular interest. In this paper, we briefly overview recent development and discuss research challenges and opportunities in the area, with a focus on the network connectivity. We also demonstrate some intrinsic connections between the connectivity results and capacity results and point out the fundamental parameters determining the capacity of a wireless multi-hop network.

A network is said to be *connected* iff (if and only if) there is a (multi-hop) path between any pair of nodes. Further, a network is said to be *k*-connected if there are *k* mutually independent paths between any pair of nodes that do not have any node in common except the starting and the ending nodes. *k*-connectivity is often required for robust operations of the network.

The rest of the paper is organized as follows: Section II discusses connectivity of large-scale random networks; Section III discusses connectivity of giant component; Section IV discusses recent development, research chal-

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allenges and opportunities in mobile networks and Section V concludes the paper.

## II. CONNECTIVITY OF LARGE-SCALE RANDOM NETWORKS

### A. Unit disk model and connectivity

Extensive research has been done on connectivity problems using the well-known *random geometric graph* and the *unit disk model*, which is usually obtained by randomly and uniformly distributing  $n$  nodes in a given area and connecting any two nodes iff their Euclidean distance is smaller than or equal to a given threshold  $r(n)$ , known as the *transmission range* [3], [4]. Significant outcomes have been achieved for both asymptotically infinite  $n$  [1], [3], [5]–[10] and finite  $n$  [11]–[14].

Research on the connectivity of large-scale random ad-hoc networks under the unit disk model is spearheaded by Penrose [15], [16] and Gupta and Kumar [1]. Specifically, Penrose [15], [16] and Gupta and Kumar [1] proved using different techniques that if the transmission range is set to  $r(n) = \sqrt{\frac{\log n + c(n)}{\pi n}}$ , a random network formed by uniformly placing  $n$  nodes on a unit-area disk in  $\mathbb{R}^2$  is *asymptotically almost surely* (a.a.s.) connected as  $n \rightarrow \infty$  iff  $c(n) \rightarrow \infty$ . An event  $\xi_n$  depending on  $n$  is said to occur a.a.s. if its probability tends to one as  $n \rightarrow \infty$ . Penrose’s result is based on the fact that in the above random network, as  $n \rightarrow \infty$  the longest edge of the minimum spanning tree converges in probability to the minimum transmission range required for the above random network to have no isolated nodes (or equivalently the longest edge of the nearest neighbor graph of the above network) [3], [15], [16]. Gupta and Kumar’s result is based on a key finding in the continuum percolation theory [17, Chapter 6]: Consider an infinite network with nodes distributed in  $\mathbb{R}^2$  following a Poisson distribution with density  $\rho$ ; and a pair of nodes separated by a Euclidean distance  $x$  are directly connected with probability  $g(x)$ , independent of the event that another distinct pair of nodes are directly connected. Here,  $g : \mathbb{R}^+ \rightarrow [0, 1]$  satisfies the conditions of non-increasing monotonicity and integral boundedness [17, pp. 151-152]. As  $\rho \rightarrow \infty$ , a.a.s. the above network in  $\mathbb{R}^2$  has only a unique unbounded component and isolated nodes.

In [6], Philips et al. proved that the average node degree, i.e. the expected number of neighbors of an arbitrary node, must grow logarithmically with the area of the network to ensure that the network is connected, where nodes are placed randomly on a square according to a Poisson point process with a constant density. This result by Philips et al. actually provides a necessary condition on the average node degree required for connectivity. In [5], Xue et al. showed that in a network with a total of  $n$  nodes randomly and uniformly distributed on a unit square, if each node is connected to  $c \log n$  nearest neighbors with  $c \leq 0.074$  then the resulting random network is a.a.s. disconnected as  $n \rightarrow \infty$ ; and if each node is connected to  $c \log n$  nearest neighbors with  $c \geq$

5.1774 then the network is a.a.s. connected as  $n \rightarrow \infty$ . In [8], Balister et al. advanced the results in [5] and improved the lower and upper bounds to  $0.3043 \log n$  and  $0.5139 \log n$  respectively. In a more recent paper [10] Balister et al. achieved much improved results by showing that there exists a constant  $c_{crit}$  such that if each node is connected to  $\lfloor c \log n \rfloor$  nearest neighbors with  $c < c_{crit}$  then the network is a.a.s. disconnected as  $n \rightarrow \infty$ , and if each node is connected to  $\lfloor c \log n \rfloor$  nearest neighbors with  $c > c_{crit}$  then the network is a.a.s. connected as  $n \rightarrow \infty$ . In both [8] and [10], the authors considered nodes randomly distributed following a Poisson process of intensity one on a square of area  $n$ . In [7], Ravelomanana investigated the critical transmission range for connectivity in 3-dimensional wireless sensor networks and derived similar results as the 2-dimensional results in [1].

In [12], Bettstetter empirically investigated the minimum node degree and connectivity of a finite network with  $n$  ( $100 \leq n \leq 2000$ ) nodes randomly and uniformly placed on a square of area  $A$ . Tang et al. [13] proposed an empirical formula relating the probability of having a connected network to the transmission range for a finite network with  $n$  ( $n \leq 125$ ) nodes randomly and uniformly distributed on a unit square. Bettstetter [11] studied the network connectivity considering different node placement models, i.e. uniform distribution, Gaussian distribution. Note that most results for finite  $n$  are empirical results.

### B. More general connection models and connectivity

All the work described in the last subsection is based on the unit disk model. This model may simplify analysis but no real antenna has an antenna pattern similar to it. The log-normal shadowing connection model, which is more realistic than the unit disk model, has accordingly been considered for investigating network connectivity in [18]–[23]. Under the log-normal shadowing connection model, two nodes are directly connected if the received power at one node from the other node, whose attenuation follows the log-normal model [24], is greater than or equal to a given threshold.

In [18], Hekmat et al. proposed an empirical formula for computing the average size of the largest connected component through simulations, where a total of  $n$  nodes are randomly and uniformly distributed in a bounded area in  $\mathbb{R}^2$ . In [22], Bettstetter derived a lower bound on the minimum node density  $\rho$  required to ensure that a network with nodes Poissonly distributed in an area in  $\mathbb{R}^2$  with density  $\rho$  is  $k$ -connected with a high probability. The analysis is based on the observation that the minimum node density required for a  $k$ -connected network is larger than that required for the network to have a minimum node degree  $k$ , and the assumption that the event that a node has a degree greater than or equal to  $k$  is independent of the event that another node has a degree greater than or equal to  $k$ . Using simulations, they showed that the bound is tight when the node density is sufficiently large. Using

the same model as in [22], Bettstetter et al. obtained in [23] a lower bound on the minimum node density required for an almost surely connected network using essentially the same technique as that in [22]. The analysis relies on the assumption that the event that a node is isolated and the event that another node is isolated are independent, hereafter referred to as the *independence* assumption. Orriss et al. [19] considered nodes uniformly and randomly distributed on a plane and communicating with each other following the log-normal shadowing model in the framework of cellular networks. They investigated the distribution of the number of base stations that communicate with a given mobile and found that the number of base stations able to communicate with a given mobile *and* lying within a specified range of the mobile follows a Poisson distribution. In [21], Miorandi et al. presented an analytical procedure for computing the node isolation probability in the presence of channel randomness, where nodes are distributed following a Poisson point process in  $\mathbb{R}^2$  (which extends their earlier work in [20]). They further obtained an estimate of the probability that there is no isolated node in the network based on the above independence assumption. The previous results in [18]–[23] dealing with a necessary condition on the critical transmission power for connectivity under the log-normal shadowing model all rely on the independence assumption that the node isolation events are independent, which has only been validated by simulations. Realistically however, one may expect that the event that a node is isolated and the event that another node is isolated will be correlated whenever there is a non-zero probability that a third node may exist which may have direct connections to both nodes. In the unit disk model, this may happen when the transmission range of the two nodes overlaps. In the log-normal model, *any* node may have a non-zero probability of having direct connections to both nodes. This observation and a lack of rigorous analysis on the node isolation events to support the independence assumption raised a question mark over the validity of the results of [18]–[23].

Other work in the area includes [25]–[28], which studies from the percolation perspective, the impact of mutual interference caused by simultaneous transmissions, the impact of physical layer cooperative transmissions, the impact of directional antennas and the impact of unreliable links on connectivity respectively.

### C. Random connection model and connectivity

In the more recent work [29], [30], the authors considered a network where all nodes are distributed on a unit square  $A \triangleq [-\frac{1}{2}, \frac{1}{2}]^2$  following a Poisson distribution with known density  $\rho$  and a pair of nodes are directly connected following a *random connection model*, viz. a pair of nodes separated by a Euclidean distance  $x$  are directly connected with probability  $g_{r_\rho}(x) \triangleq g\left(\frac{x}{r_\rho}\right)$ , where  $g: [0, \infty) \rightarrow [0, 1]$ , independent of the event that

another pair of nodes are directly connected. Here

$$r_\rho = \sqrt{\frac{\log \rho + b}{C\rho}} \quad (1)$$

and  $b$  is a constant. The function  $g$  is required to satisfy the properties of non-increasing monotonicity and integral boundedness [17], [31, Chapter 6]. Further, it is required that  $g$  satisfies the more restrictive requirement that

$$g(x) = o_x\left(\frac{1}{x^2 \log^2 x}\right) \quad (2)$$

in order for the impact of the *truncation effect*, which accounts for the difference between an infinite network and a finite (or asymptotically infinite) network, on connectivity to be asymptotically vanishingly small [29]. Denote the above network by  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$ .

A number of results were obtained based on the connectivity of  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$ :

- 1) Using the Chen-Stein technique [32], [33], it was shown that as  $\rho \rightarrow \infty$ , the distribution of the number of isolated nodes in  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$  asymptotically converges to a Poisson distribution with mean  $e^{-b}$ ;
- 2) The number of isolated nodes due to the boundary effect in  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$  is a.a.s. zero, i.e. the boundary effect has asymptotically vanishing impact on the number of isolated nodes;
- 3) As  $\rho \rightarrow \infty$ , the number of components of finite order  $k > 1$  in  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$  asymptotically vanishes;
- 4) As  $\rho \rightarrow \infty$ , the number of components in  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$  of unbounded order converges to one;
- 5) Finally, based on the above results, it was shown that as  $\rho \rightarrow \infty$ , a.a.s. there are only a unique unbounded component and isolated nodes in  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$ , and a sufficient and necessary condition for  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$  to be a.a.s. connected is that there is no isolated node in the network. Further, the probability that  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$  has no isolated nodes and the probability that  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$  forms a connected network both converge to  $e^{-e^{-b}}$  as  $\rho \rightarrow \infty$ . As a ready consequence of these results,  $\mathcal{G}(\mathcal{X}_\rho, g_{r_\rho}, A)$  is a.a.s. connected iff  $b \rightarrow \infty$  as  $\rho \rightarrow \infty$ ; and is a.a.s. disconnected iff  $b \rightarrow -\infty$  as  $\rho \rightarrow \infty$ .

The above results extend the earlier work by Penrose [15], [16] and Gupta and Kumar [1] from the unit disk model to the more generic random connection model and bring theoretical research in the area closer to reality. It can be readily shown that the results on the random connection model include the work of Penrose [15], [16] and Gupta and Kumar [1] on the unit disk model and the work on the log-normal model [18]–[23] as two special cases.

### D. Challenges

There remain significant challenges ahead.

Most results in the area, including the results in [29], [30], rely on three main assumptions: a) the connection function  $g$  is isotropic, b) the connections are independent, c) nodes are Poissonly or uniformly distributed.

We conjecture that assumption a) is not a critical assumption, i.e. under some mild conditions, e.g. nodes are independently and randomly oriented, assumption a) can be removed while the above results, particularly the ones obtained assuming a random connection model, are still valid. It however remains to validate the conjecture.

The above results however critically rely on assumption b), which is not necessarily valid in some networks due to channel correlation and interference, where the latter effect makes the connection between a pair of nodes dependent on the locations and activities of other nearby nodes. In [34], some preliminary work was conducted on the connectivity of CSMA networks considering the impact of interference. The work essentially uses a decoupling approach to solve the challenges of connection correlation caused by interference by developing an upper bound on the interference experienced by any receiver in the network and then studying the connectivity of the CSMA network using the bound. Their results suggest that when some realistic constraints are considered, i.e. carrier-sensing, the connectivity results, e.g. transmission power required for a connected network, will be very close to those obtained under a unit disk model. This conclusion is in stark contrast with that obtained under an ALOHA multiple-access protocol [25]. Other work in the area includes the work of Haenggi and his colleagues (see e.g. [2], [35]), which characterizes various properties of multi-hop networks subject to interference by using Poisson distribution to approximate the distribution of the set of concurrent transmitters. The major obstacle in dealing with the impact of channel correlation is that there is no widely accepted model in the wireless communication community capturing the impact of channel correlation on connections.

Finally, it is a logical move after the above work to consider connectivity of networks with nodes distributed following a generic distribution other than Poisson or uniform. This remains a major challenge in the area.

### III. CONNECTIVITY OF GIANT COMPONENT

A *giant component* is a component with a designated large percentage of nodes in the network, say  $p$  where  $0.5 < p < 1$ . A *component* is a maximal set of nodes where there is a path between any pair of nodes in the set.

Results on connectivity of large-scale random networks under both the unit disk model [1], [15], [16] and the more generic random connection model [29], [30] revealed the same scaling law. That is, when the number of nodes, denoted by  $n$ , in a network increases, the transmission range (or power) has to increase at a rate to maintain an average node degree of  $\Theta(\log n)$  in order to achieve connectivity. For two functions  $f(x)$  and  $h(x)$ ,  $f(x) = \Theta(h(x))$  iff there exist a sufficiently large  $x_0$  and two positive

constants  $c_1$  and  $c_2$  such that for any  $x > x_0$ ,  $c_1 h(x) \geq f(x) \geq c_2 h(x)$ . For example, the critical transmission range for connectivity is  $r(n) = \sqrt{\frac{\log n + c(n)}{\pi n}}$  under the unit disk model for a random network formed by uniformly placing  $n$  nodes on a unit-area disk [1], [15], [16]<sup>1</sup>. In other words, a connected network poses a very demanding requirement on the transmission range (or power). This in turn causes many undesirable effects on increased interference and reduced throughput.

In the following, we demonstrate the connections between the results on connectivity and the results on network capacity. In [36], it was shown that the end-to-end throughput between a randomly chosen source-destination pair in the above network is  $\Theta\left(\frac{W}{\sqrt{n \log n}}\right)$ , where  $W$  is the link capacity. Refer to [36] for a rigorous definition of network capacity. This result on capacity can be intuitively explained using the results on connectivity as follows: as the number of nodes  $n$  increases, the average distance, measured by the number of hops, between a randomly chosen pair of nodes is  $\Theta\left(\frac{1}{r(n)}\right) = \Theta\left(\sqrt{\frac{\pi n}{\log n}}\right)$ . That is, for a *typical* node, for every packet transmitted for itself, there are  $\Theta\left(\sqrt{\frac{\pi n}{\log n}}\right)$  relay packets transmitted for other source-destination pairs. Further, the average node degree is  $n\pi r^2(n) = \Theta(\log n)$ , which implies that in a neighborhood of a typical node, at any time there can only be one out of every  $\Theta(\log n)$  nodes active. It follows that the end-to-end throughput between a typical source-destination pair is  $\frac{W}{\Theta\left(\sqrt{\frac{\pi n}{\log n}}\right)\Theta(\log n)} = \Theta\left(\frac{W}{\sqrt{n \log n}}\right)$ , hence comes the result in [36]. The above result can be more rigorously derived by following similar steps as those in [36] on analyzing the capacity of a random network. Therefore the reduced capacity as  $n \rightarrow \infty$  is attributable to the more demanding requirement on the transmission range (or power) to maintain connectivity as  $n \rightarrow \infty$ .

The above observation motivates a question: since the network connectivity is a very demanding requirement, whether there is any benefit in backing down from such a demanding requirement and requiring most nodes, instead all nodes, to be connected?

Indeed in many applications, it is unnecessary for *all* nodes to be *always* connected to each other [37]. Examples of such applications include a wireless sensor network for habitat monitoring [38], [39] or environmental monitoring [40], [41] and a mobile ad-hoc network in which users can tolerate short off-service intervals [42].

In environmental monitoring, there are scenarios where the size of the monitored phenomenon is very large (e.g. rain clouds) or the parameters (e.g. temperature, humidity) that are monitored change slowly both in space and in time. When the number of nodes for monitoring the phenomenon or measuring the parameters is very large,

<sup>1</sup>By scaling, it can be shown that assuming an extended network model where nodes are distributed on a disk of area  $n$  with a constant density of 1 node per unit area, the critical transmission range for connectivity is  $r(n) = \sqrt{\frac{\log n + c(n)}{\pi}}$ .

having a few disconnected nodes will not cause a statistically significant change in the monitored parameters. One example of such applications is a wireless sensor network that was deployed underneath the Briksdalsbreen glacier in Norway to monitor the pressure, humidity, and temperature of ice to understand glacial dynamics in response to climate change [40]. In habitat monitoring, there are scenarios where the number of objects (e.g. zebras and cane toads [38]) that are monitored is large. Having a few nodes disconnected or lost may not significantly affect the accuracy of the monitored parameter. In many mobile ad-hoc networks, having a number of nodes temporarily disconnected is also not critical, as long as users can tolerate short off-service intervals. For example, in a campus-wide wireless network, students and staff can share information using wireless devices (e.g. laptops and personal digital assistants) around the campus [42]. When a wireless device temporarily loses connection, it can store the data and complete the work after becoming connected later.

In [43], [44], considering a network with a total of  $n$  nodes uniformly and i.i.d. on a unit square in  $\mathbb{R}^2$ , it was shown analytically that under both the unit disk model [44] and the log-normal model [43], the transmission range (or power) required for having a designated large percentage of nodes connected, say  $p$  where  $0.5 \leq p < 1$ , is asymptotically vanishingly small compared to that required for having a connected network, irrespective of the value of  $p$ . This result implies that significant energy savings can be achieved if we require only most nodes (e.g. 95%, 99%) to be connected, instead of requiring all nodes to be connected; given a network with most nodes connected, a sharp increase in the transmission range (or power) is required to connect the few remaining hard-to-reach nodes; and the transmission range (or power) required for a large network to be connected is dominated by these hard-to-reach nodes or rare events. It was further shown using simulations that under the unit disk model, in a network with 1000 nodes, the transmission range required for having 95% nodes connected is only 76% of that required for having all nodes connected. Based on a conservative estimate that the required transmission power increases with the square of the required transmission range, an energy saving of at least 42% can be achieved by sacrificing 5% of nodes. That energy saving will further increase with an increase in the number of nodes in the network. Other benefits of the reduced transmission range or power requirement is the reduced interference, hence better throughput.

It remains to find the value of the transmission range (or power) required for guaranteeing a designated large percentage of nodes to be connected in a large scale network. This problem has some intrinsic connections to the problem of finding the percolation probability in the continuum percolation theory [17], which is a well-known open problem in the area. Further, it remains to quantitatively characterize the benefit in capacity due to the reduced transmission range (or power) required for a

giant component.

Other researchers approached the problem caused by the demanding requirement of a connected network on the transmission range (or power) from a different perspective and considered the use of infrastructure instead. Here the infrastructure can be quite flexible. It can be a subset of nodes connected through wired connections [45], or a subset of nodes with possibly more powerful transmission capability that forms a wireless backbone of the network [46], [47], or a subset of nodes with satellite links as one would possibly encounter in UAV formations [48]. The use of infrastructure does not change the wireless multi-hop nature of the end-to-end communication, instead the infrastructure assists the end-to-end communication by leapfrogging some long hops and reducing the number of hops between two nodes, hence improving the performance. Accordingly the concept of  $k$ -hop connected networks was proposed and investigated [49]–[52]. In a  $k$ -hop connected network, the maximum number of hops between any two nodes is smaller than or equal to  $k$ . Some research in the area was also conducted under the name of hybrid networks [45], [53].

Despite previous research in the area of hybrid networks or  $k$ -hop connected networks, no conclusive results have been obtained yet on the role of infrastructure in wireless multi-hop networks with many problems remain unanswered. Some examples include: for randomly deployed infrastructure nodes and “ordinary” nodes, how many infrastructure nodes (versus ordinary nodes) are required for a  $k$ -hop connected network; for deterministically deployed infrastructure nodes and randomly deployed ordinary nodes, how many infrastructure nodes are required for a  $k$ -hop connected network and what is the optimum deployment of infrastructure nodes; how to combine the use of infrastructure-based communications and ad-hoc communications in one network in order to provide some performance guarantee, in terms of capacity or delay. These problems are important for wireless multi-hop networks to provide reliable services, particularly for wireless vehicular networks in which both infrastructure-based communications and ad-hoc communications will co-exist [54].

#### IV. DEVELOPMENT AND CHALLENGES IN MOBILE NETWORKS

In [55], Grossglauser and Tse studied the capacity of mobile ad-hoc networks. Particularly, they considered a network with a total of  $n$  nodes distributed on a unit-area disk, the trajectories of different nodes are i.i.d. and the nodes’ movement is such that the spatial distribution of nodes are stationary and ergodic with stationary uniform distribution on the disk. They showed that in the above network with *unbounded delay requirement*, the throughput between a randomly chosen source-destination pair can be kept *constant* even as  $n$  increases. This result is in stark contrast with its counter-part in static networks in which the throughput between a randomly chosen source-destination pair is shown to be  $\Theta\left(\frac{W}{\sqrt{n \log n}}\right)$  [36].

Following the seminal work of Grossglauser and Tse, other researchers have conducted further research trying to quantitatively characterize the relationship between delay, mobility and capacity in mobile ad-hoc networks [49], [56]–[59] and the obtained results vary greatly with the mobility models and network settings.

A fundamental reason why mobility increases throughput is that in mobile networks message transmissions generally follow the store-carry-forward pattern versus the store-forward pattern found in static networks. As nodes move, new opportunity may arise such that a mobile node can carry the message until it meets a node, which is in a better position than itself to transmit the message to the destination, or until it meets the destination directly. In this way, the number of relay nodes (number of hops) involved in transmitting a message to its destination can be greatly reduced and the required transmission range (or power) for a node to reach another node via a multi-hop path can also be greatly reduced, hence the benefit in improved capacity. The cost in achieving this benefit in capacity is the increased delay.

Following the techniques demonstrated in Section III, the results in [55] on the capacity of mobile networks can also be obtained as follows. In the network model considered in [55], a two-hop relaying strategy is employed. Therefore as the number of nodes  $n$  increases, the average distance, measured by the number of relay hops, between a randomly chosen pair of source-destination is bounded by 2. Further, the value of the transmission range  $r$  does not have to increase with  $n$  because connectivity (in the sense that every pair of nodes can exchange packets) can be achieved through node movement. Therefore the average node degree is also  $\Theta(1)$ . It then readily follows that the capacity of the mobile network is  $\Theta(1)$ . The end-to-end delay can be analyzed by evaluating the time that two balls with radius equal to  $r/2$ , representing the source and the relay node respectively, hit a (randomly chosen) third ball, representing the destination, with radius  $r/2$ .

The above observation motivates us to conclude that the fundamental factors that determine the capacity of a mobile (or static) network are:

- 1) The expected number of simultaneously active transmissions. This is further determined by the spatial node distribution and the transmission range (or power).
- 2) The average number of relay hops between a source and its destination. It determines the average number of times that a packet need to be transmitted before reaching its destination, i.e. the transmission capacity consumed for an end-to-end transmission.

Therefore the only difference between mobile and static networks is that some part of the job involved in moving a packet, originally taken care of entirely by wireless transmissions in static network, can now be taken care of by the physical movement of nodes in mobile networks. By viewing both the physical movements of nodes and the wireless transmission as simply a way to move packets physically over a distance, a unified theory for analyzing

the performance of both mobile and static networks can be established.

By analogy, mobility can also improve connectivity. There are three fundamental differences between mobile networks and static networks [60] from a graph theory perspective: in mobile networks

- the wireless link between two directly connected nodes and the end-to-end path only exists temporarily;
- two nodes may never be part of the same connected component but they are still able to communicate, i.e. exchange messages, with each other; and
- while any one wireless link may be (or assumed to be) unidirectional, the path connecting any two nodes is directional, i.e. there is a path from node  $v_i$  to node  $v_j$  within a designated time period does not necessarily mean there is a path from  $v_j$  to  $v_i$  within the same period.

These are illustrated in Fig. 1. Particularly the last difference implies that it is important to consider the temporal order of links when analyzing mobile networks, which has been incorrectly neglected in some previous work.

Due to these differences, many established concepts in static networks must be revisited for mobile networks. For example, a static wireless multi-hop network is said to be connected iff there is a path between any pair of nodes in the network. However a more meaningful definition of connectivity in mobile networks is to say that a mobile network is connected in time period  $[0, T]$  if any node can exchange a message with any other node within  $[0, T]$ . The above definition implies that the tradeoff between connectivity, mobility and delay is the prime issue when analyzing the connectivity of mobile networks. Despite intensive research on the properties of mobile networks, no conclusive results have been obtained on the above problem and it remains a major challenge in the area.

## V. SUMMARY

Wireless multi-hop networks have attracted significant research interest. This interest is expected to grow further with the proliferation of applications, particularly in the areas of wireless vehicular networks and sensor networks. In this paper, we briefly overviewed recent development and discussed research challenges and opportunities in the area mainly from the perspective of network connectivity. We also showed how the results on network connectivity are related to the study of other performance metrics, i.e. capacity and delay. We pointed out the fundamental parameters determining the capacity of a wireless multi-hop network and the fundamental difference between mobile and static networks.

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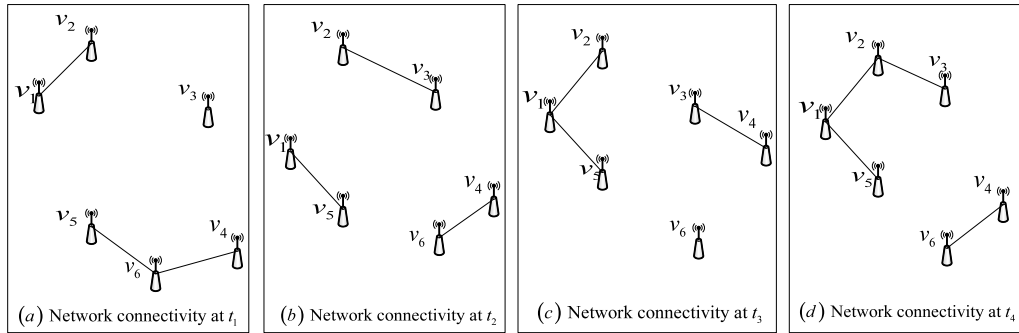


Figure 1. An illustration of connectivity in a mobile ad-hoc network. A solid line represents a connection between two nodes. The network is disconnected at any time instant but there is a path from any node to any other node in the network. For example, nodes  $v_1$  and  $v_6$  are never part of the same connected component but a message from  $v_1$  can still reach  $v_6$  through the following path:  $t_1 : v_1 \rightarrow v_2, t_2 : v_2 \rightarrow v_3, t_3 : v_3 \rightarrow v_4, t_4 : v_4 \rightarrow v_6$ . Further, a message from  $v_6$  can reach  $v_1$  at  $t_2$  but a message from  $v_1$  can only reach  $v_6$  at  $t_4$ .

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