

Preface

Wireless ad hoc networks are useful when there is a lack of infrastructure for communication. Such a situation may arise in a variety of civilian and military contexts like sensor network applications and communication in harsh environments. Since the seminal work by Gupta and Kumar [3], the study of wireless ad hoc networks has focused on understanding its fundamental capacity limits. The capacity per source-destination (S-D) pair of random ad hoc network developed by Gupta and Kumar is $\Theta(1/\sqrt{n \log n})$,¹ which is pessimistic because the capacity goes to 0 as the number of nodes in a fixed area $n \rightarrow \infty$. Since then there are three kinds of works that focus on the study of capacity.

One of the topics is to extend the original work done by Gupta and Kumar. This kind of work includes completing the proofs on unicast [46], extending the number of receivers to the case of multicast [9, 47, 148], broadcast [48], and convergecast [152, 153]. It also contains the extension of the unicast and the generalization of different kinds of transmission possibilities in the real networks such as user-centric networks [145]. However, the results are also pessimistic because the per-node capacity tends to 0 as the number of nodes $n \rightarrow \infty$.

Another topic is on the tradeoff between capacity and other network variables like delay and power consumption. In 2002 Grossglauser and Tse [2] found that mobility can increase the capacity. The per-node capacity can be bounded by a constant according to the 2-hop scheme proposed in [2]. However, the end-to-end

¹ The following notations are used throughout our book.

1. $f(n) = O(g(n)) \Leftrightarrow \limsup_{n \rightarrow \infty} \frac{f(n)}{g(n)} < \infty$,
2. $f(n) = \Omega(g(n)) \Leftrightarrow \liminf_{n \rightarrow \infty} \frac{f(n)}{g(n)} < \infty$,
3. $f(n) = \Theta(g(n)) \Leftrightarrow f(n) = O(g(n))$ and $g(n) = O(f(n))$,
4. $f(n) = o(g(n)) \Leftrightarrow \lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 0$,
5. $f(n) = \omega(g(n)) \Leftrightarrow \lim_{n \rightarrow \infty} \frac{g(n)}{f(n)} = 0$.

delay is very large when mobility is introduced. Following this work, there are a group of people working on the capacity-delay tradeoff [13, 18, 147, 149, 150, 160]. There is also another issue that needs consideration in the network: energy consumption [89]. Since we are quite interested in the capacity-delay tradeoff, we present this issue in [Sect. 3.2](#). Due to limited time, we will not consider other types of tradeoffs in our report.

Thirdly, other works are related with changing the ad hoc network model. The classical model is so-called random homogeneous ad hoc networks. To have a change on this, some people studied arbitrary networks [50], some studied inhomogeneous networks (clusters) [51–53, 159], some combined the cellular network and ad hoc network and worked on hybrid networks [54–56, 157], some used directional antenna to enhance the capacity performance [155], some let nodes cooperate and build a hierarchical MIMO network [114, 151], some studied the scaling law for cognitive radio networks (CRNs) [144, 146, 154, 156, 158], still others used network coding [57–61] and MPR [62, 63] to improve the network capacity.

Connectivity is also a fundamental issue in wireless networks and has been extensively studied in recent years. Generally speaking, there are two types of definitions on connectivity. One is in the sense of percolation, i.e., the existence of a component that consists of infinite connected nodes. The other is defined as the ability that each node in the network can find at least one path to any other node, either directly or with the help of several other nodes acting as relays. A network is said to have k -connectivity if there exist at least k mutually independent paths connecting each pair of nodes. According to [23], this definition is equal to the statement that a network is k -connected if and only if removal of any $k - 1$ nodes does not disconnect the graph.

Based on the definitions on connectivity, the research works mainly fall into two categories. Some study connectivity from the percolation perspective. These works consider continuum percolation with the Poisson Boolean model. Let λ be the node density. Then there exists a critical value λ_c for which percolation occurs. If $\lambda > \lambda_c$ (supercritical case), there will be a cluster consisting of infinite connected nodes almost surely. If $\lambda < \lambda_c$ (subcritical case), the network has no infinite connected component and is separated into an infinite number of finite connected components. In the literature, the accurate value of the percolation threshold has not been decided yet, while [24, 25] demonstrate that the analytical upper and lower bounds for the threshold are 10.526 and 2.195, respectively. [26] provides simulation results to show that if connected nodes use cooperation techniques to further connect isolated nodes that cannot be connected separately, the percolation threshold of the cooperative network is less than that of the non-cooperative network for 2-D extended network. [27] analytically obtains this result when the path loss exponent is less than 4.

For the second type of definition on connectivity, extensive research investigates from various aspects the critical conditions to ensure (k -)connectivity. One concern is to determine the critical transmission range, as presented in [28, 29, 30]. In this context, all nodes in the network possess uniform transmission power. In

[28], by using the theory of continuum percolation, Gupta and Kumar provide the critical transmission range for asymptotic connectivity 2-D dense network with n nodes independently and identically distributed in a disc of unit area. It is shown that if each single node has a transmission area $\pi r^2 = \frac{\log n + c(n)}{n}$, the network is asymptotically connected with probability one if and only if $c(n) \rightarrow +\infty$. Then in [29], Wan and Yi offer a precise asymptotic distribution of the critical transmission radius for k -connectivity.

Another concern concentrates on the minimum number of neighbors [29, 31, 32]. Each node is assumed to have the ability to adjust its transmission power so as to maintain direct connections with a certain number of neighbors. In [31], Xue and Kumar point out that each node should be connected to $\Theta(\log n)$ nearest neighbors to ensure the connectivity of the network with n uniformly and independently placed nodes in a unit square. [32] regards the minimum node degree for connectivity of a wireless multi-hop network.

The rest of this book is summarized as follows.

1. In [Chap. 1](#), we investigate the impact of base stations on the capacity of MotionCast. Here MotionCast means multicast between mobile nodes. The mobility pattern is assumed to be i.i.d. mobility. Three protocols are analyzed, i.e., 2-hop relay algorithm without redundancy, 2-hop relay algorithm with redundancy, and multihop relay algorithm. This network model combines multicast, mobility, and base stations together and thus brings significant enhancement to the capacity and delay tradeoff.
2. In [Chap. 2](#), we turn to the connectivity issues in clustered networks. A new kind of connectivity, (k, m) -connectivity, is defined. Its critical transmission range for i.i.d. and random walk mobility models are derived respectively. By the term of (k, m) -connectivity, we mean that in each time period consisting of m time slots, there exist at least k time slots, during any one of which every cluster member can directly communicate with at least one cluster head. For random walk mobility, two heterogeneous models, *velocity model with constant number of values* and *velocity model with constant number of intervals*, are proposed and studied. For random walk mobility with either of the two heterogeneous velocity models and i.i.d. mobility model, under weak parameters condition, we provide bounds on the probability that the network is (k, m) -connected and derive the critical transmission range for (k, m) -connectivity. For random walk mobility with *velocity model with constant number of values* and i.i.d. mobility model, under strong parameters condition, we present a precise asymptotic probability distribution of the probability that the network is (k, m) -connected in terms of the transmission radius.
3. In [Chap. 3](#), we conduct a survey on existing scaling law results on wireless networks. We will give you a global perspective about the researches on capacity in the past years. We set up a system model to analyze and compare the results for wireless networks. First, we introduce the network models and some important definitions which have been widely used in the past researches. Then we discuss the capacity-delay tradeoff problems in wireless networks.

After that, the capacity in random networks and arbitrary networks are illustrated respectively. Furthermore, based on the capacity discussion, we give some points on the factors that can have a great impact on capacity. In the end, we come up with some popular techniques and show how they contribute to capacity respectively.



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