International Journal of Research (IJR)
e-ISSN: 2348-6848, p- ISSN: 2348-795X Volume 2, Issue 10, October 2015
Available at http://internationaljournalofresearch.org

Scaling Laws for Throughput Capacity and Delay in Wireless Networks – A Survey

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***Abstract*—**

The capacity scaling law of wireless networks hasbeen considered as one of the most fundamental issues. In this survey, we aim at providing a comprehensive overview of the development in the area of scaling laws for throughput capacity and delay in wireless networks. We begin with back-ground information on the notion of throughput capacity of random networks. Based on the benchmark random network model, we then elaborate the advanced strategies adopted to improve the throughput capacity, and other factors that affect the scaling laws. We also present the fundamental tradeoffs between throughput capacity and delay under a variety of mobility models. In addition, the capacity and delay for hybrid wireless networks are surveyed, in which there are at least two types of nodes functioning differently, e.g., normal nodes and infrastructure nodes. Finally, recent studies on scaling law for throughput capacity and delay in emerging vehicular networks are introduced.

Index Terms—Fundamental limits; scaling laws; through put capacity; delay; wireless networks.

I. INTRODUCTION

Wattentions over the past decades, including medium access control, routing, security, cooperation, and energy-efficiency, among others. Despite significant advances in the field of wireless networking, a fundamental question remains unsolved: how much information can a wireless network transfer? To answer this question, we should resort to the study of network capacity which is a central concept in the field of network information theory [1]. Intuitively, if the capacity of a wireless network could be known, the network limit of information transfer would be obtained. Moreover, having such knowledge would shed light on what the appropriate architectures and protocols were for operating wireless networks. Although significant efforts have been put on the investigation of network capacity, developing a general theory of such a fundamental limit for wireless networks is a long standing open problem [2]. In [3], Claude Shannon successfully determined the maximum achievable rate, called the capacity, for a point-to-point communication channel, below which the reliable communication can be implemented while above which the reliable communication is impossible. However, general wireless networks with sources and desti-nations sharing channel resources are much more complex, making the quest for fundamental limits of wireless networks a formidable task. For example, even for a simple-looking three-node relay channel [4], the exact capacity still has yet to be determined.

As a retreat when exact fundamental limits are out of reach, capacity scaling laws, first investigated by Gupta and Kumar in [5], characterize the trend of node throughput behavior when the network size increases. The most salient feature of capacity scaling laws is to depict the capacity as a function of the num-ber of nodes in the network, without distractions from minor details of network protocol. This approach is quite different from that of studying network information theory, which is to determine exact capacity region of wireless networks. The seminal work [5] not only provides an alternative and tractable way to study the network capacity, but also obtains insightful capacity results. Great efforts have been made thereafter to derive capacity scaling laws for different paradigms of wireless networks. Scaling laws for network delay and its tradeoff with the capacity have also been investigated.

The study of scaling laws can lead to a better understanding of intrinsic properties of wireless networks and theoretical guidance on network design and deployment [6]. Moreover, the results could also be applied to predict network performance, especially for the large-scale networks [7]. We provide the following illustration. We consider to deploy a large-scale sensor networks for a certain geographic area. Scaling laws show that the network scales poorly when the number of sensors grows, i.e., the throughput of each sensor would decrease. In order to enhance the throughput capacity, we may need to adopt some advanced technologies, such as directional antennas and network coding. However, scaling laws show that exploiting network coding cannot change the trend of throughput capacity; whereas exploiting directional antennas can introduce capacity gains (refer to Section III-A, Table I). Furthermore, suppose we have deployed a sensor network of 100 sensors with directional antennas. Typically we can obtain the throughput performance (denoted by λ_A) of the network through real measurement. If we need to extend the network to a larger one of 1000 sensors, with the same network settings, by capacity scaling results (denoted by $f(N)$), we are able to have a rough idea that how much throughput (denoted by λ_B) can be supported by the network that we will deploy, i.e.,

$\lambda_B=\lambda_A \cdot f(1000)/f(100)$.

This paper aims to provide a comprehensive survey of the state of the arts in the area of throughput capacity and delay scaling studies in wireless networks, which serves the following purposes.

- There has been a large body of research on capacity scaling laws. For new researchers in this area, confusion may rise since similar capacity bounds may be derived

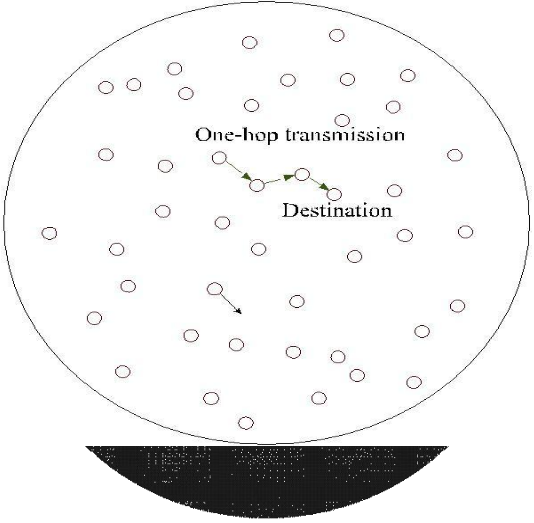


Fig. 1.A static ad hoc network in a unit disk.

for networks with different settings; while for the same network, different methodologies or techniques adopted in the study often yield different results. This paper is a modest attempt to summarize this field and provide rapid access to research results scattered over many papers.

- The research of scaling laws has undergone phenome-nal growth in wireless communication and networking community. Since this research topic is also of practical significance, it should be accessible to general readers. We try to provide an overview of capacity and delay scaling laws in this regard. The premier is to show what the basic problem is and how different technologies and network settings affect scaling results, instead of demonstrating detailed theoretical derivations.

The remainder of this paper is organized as follows: Section II provides preliminaries of capacity scaling from Gupta and Kumar's ground-breaking work [5], including the notion of throughput capacity and random networks. Section III elabo-rates the advanced strategies to improve throughput capacity of ad hoc networks, and other factors that affect capacity scaling laws. Section IV presents the fundamental tradeoffs between throughput capacity and network delay for ad hoc networks under a variety of mobility models. Section V particularly surveys the capacity and delay for hybrid wireless networks. Section VI introduces the recent studies on capacity and delay scaling of emerging vehicular networks. Section VII discusses the future work and concludes the paper.

II. PRELIMINARIES: MILESTONE OF THROUGHPUT CAPACITY SCALING

Capacity scaling laws offer fundamental understanding on how per-node capacity scales in an asymptotically large net-work. The line of investigation began with [5], where Gupta and Kumar introduced two new notions of network capacity: *transport capacity* and *throughput capacity*. In this survey, wefocus on the throughput capacity. We first introduce the notion of throughput capacity and the capacity result for random networks, as preliminaries for reading the remaining sections.

A. Notion of Throughput Capacity

Let N denote the number of nodes in a network. The per-node throughput of the network, denoted by $\lambda(N)$, is the average transmission rate, measured in bits or packets per unit time, that can be supported uniformly for each node to its destination in the network. A per-node throughput of $\lambda(N)$bits per second is said to be *feasible* if there existsa spatial and temporal scheme for scheduling transmissions, such that each node can send $\lambda(N)$ bits per second on average to its destination node. The throughput capacity of the network is said of order $\Theta(f(N))$[1] bits per second if there are deterministic constants $c_1 > 0$ and $c_2 < \infty$ such that

$$\lim_{N \to \infty} \Pr \lambda(N) = c1 f(N) \text{ is feasible } = 1$$

$$\liminf_{N \to \infty} \Pr \lambda(N) = c_2 f(N) \text{ is feasible } < 1.$$

Therefore, vanishingly small probabilities are allowed for in this definition of "throughput capacity" when considering the randomness involved in the network, such as the location and the destination of each node. Note that the notion of throughput capacity is different from the information-theoretic capacity notion that describes the exact region of simultaneous rates of communications from many senders to many receivers in the presence of interference and noise [8].

B. Random Networks

A wireless random network consisting of *N* identical im-mobile nodes randomly located in a disk of unit area in the plane and operating under a *multi-hop* fashion of information transfer, is shown in Fig. 1 [5]. Each node having a randomly chosen destination is capable of transmitting at *W* bits per second over a common wireless channel. The requirements for successful transmission are described as per two interference models: i) the Protocol Model, which is a binary model, i.e., the transmission is successful if there is enough spatial separation from simultaneous transmissions of other nodes otherwise fails; and ii) the Physical Model, based on signal-to-interference ratio requirements. In such a static random ad hoc network, all the nodes are assumed to be homogeneous, i.e., all transmissions employ the same range or power, and wish to transmit at a common rate.

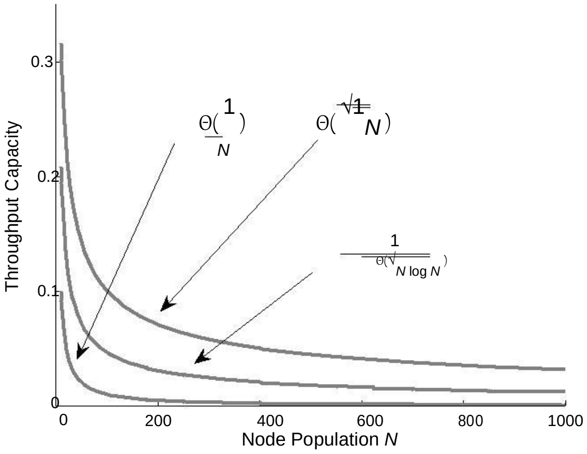


Fig. 2. Examples of showing throughput capacity trend in the order sense.

are of the same order such that there exists a sharp order estimation of the throughput capacity; for Physical Model, a throughput o f orde r Θ( ) is feasible, while Θ( )

$\sqrt{N \log N}$ $\sqrt{N}$

is not. Fig. 2 gives three examples to show the trend of throughput capacity in the order sense.

The throughput capacity is studied asymptotically, i.e., capacity scaling law results hold with high probability when the population of nodes is larger than some threshold; on the other hand, results may not hold, or hold with small probability if the population of nodes is small. The

C. Throughput Capacity of Random Networks

scaling result for random networks is pessimistic because the per-node throughput tends to zero similar to $\frac{1}{\sqrt{N \log N}}$ as the population of nodes goes to infinity, which indicates that static ad hoc networks are not feasible to scale to a large size. What causes such discouraging results? The fundamental reason is that every node in the network needs to share the channel resources or certain geo-graphic area with other nodes in proximity, which constricts the capacity. Specifically, concurrent wireless transmissions in a wireless network limit its throughput capacity, because they create mutual interference so that nodes cannot communicate as that in the wireline network where much less mutual interference exists. This interpretation also demonstrates how desirable it is to mitigate the mutual interference in wireless communications, although it is very challenging.

III. THROUGHPUT CAPACITY OF AD HOC NETWORKS

A. Strategies to Improve Throughput Capacity

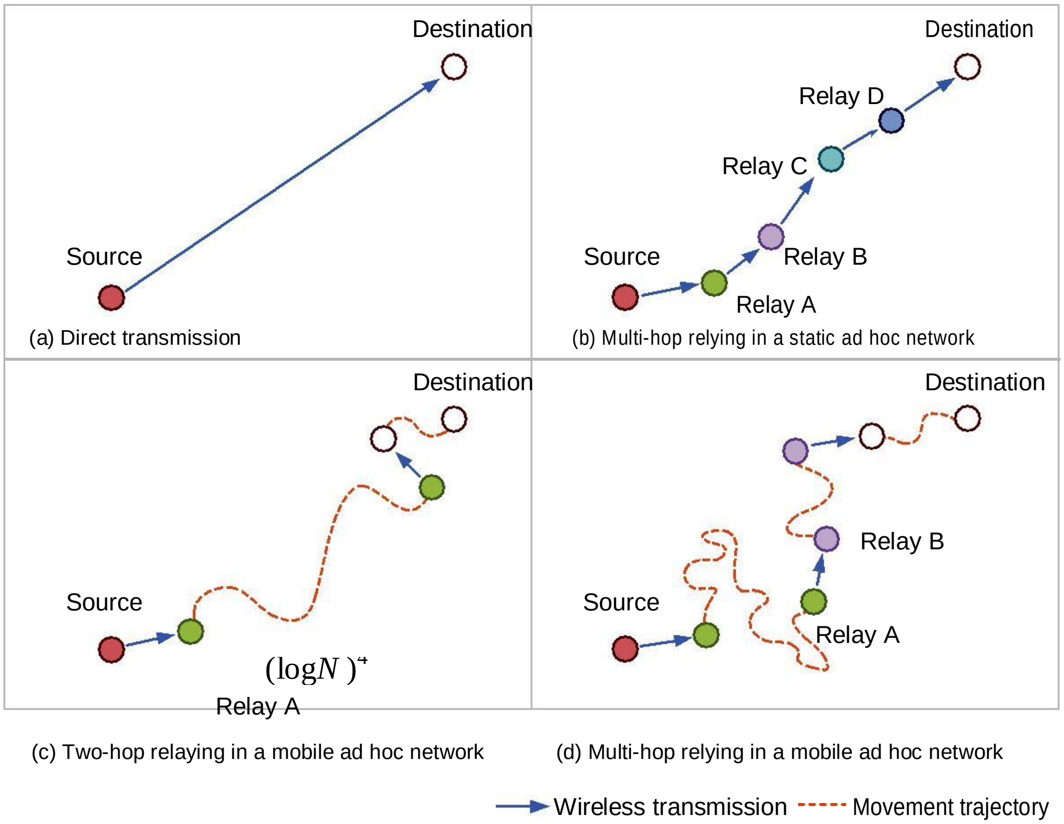
One natural question is if it is possible to improve through-put capacity of random networks by employing any ad-vanced techniques or sophisticated strategies. After significant progress that has been made to further the investigation on throughput capacity scaling, the answer is positive.

First of all, by allowing both long-distance and short-distance transmissions, the throughput capacity can be im-proved slightly to $\Theta(^{\sqrt{1}}{}_{N})$ [9]. The scheme constructed to achieve this throughput relies on multi-hop transmission, pair-wise coding and decoding at each hop, and a time-division multiple access. The gain of throughput capacity can also be achieved by employing directional antennas. Yi *et al.* in [10] considered different beamform patterns, and showed.

B. Other Factors Affecting Scaling Laws

The random network considered in [5] is a benchmark network model, in which nodes have basic communication capabilities (i.e., simple coding and decoding strategies imple-mented on the single radio), and the traffic model (symmetric unicast) and interference model (Protocol Model or Physical Model) are simplified. Besides the strategies mentioned in Section III-A to improve throughput capacity, significant re-search efforts have been made to study the impact of different modeling factors on capacity scaling laws.

Multi-channel multi-interface: In [5], it has been shownthat with a single radio mounted on each vehicle, splitting the total bandwidth W into multiple sub-channels does not change the order of



(c) Two-hop relaying in a mobile ad hoc network

(d) Multi-hop relying in a mobile ad hoc network

Fig. 3.An illustration of packet transmission strategies.

They showed that a throughput of Θ 1 ______ is achievable.

The lower bound on the capacity of wireless erasure networks was reported by Jaber and Andrews [42], in which an erasure channel model is considered, i.e., each channel is associated with an erasure probability. Such a channel model incorporates erasure events which may correspond to packet drops or temporary outages when transmission is undergoing. It is proved that the capacity lower bound scales as Θ(log N/N)and Θ($\sqrt{1}$) with independent and correlated erasure

$\overline{N \log N}$

channels, respectively.

Network topology: The shape of geographic area wherethe network is deployed has a significant impact on capac-ity scaling laws. Hu *et al.* [43] investigated the effect of various geometries, including the strip, triangle, and three-dimensional cube. The main implication from [43] is that the symmetry of the network shape plays an important role. In other words, a high throughput capacity can be achieved if the network is symmetric. In addition to two-dimensional (2-D) networks, several efforts have been put on investigation of three-dimensional (3-D) networks. In [44], a throughput

random networks under Protocol Model and Physical Model, respectively. In [45], Li *et al.* respectively derived the capacity bound for the 3-D network with regularly and heterogeneously deployed nodes.

Traffic pattern: Besides symmetric unicast, i.e., each nodeis only the source of one unicast flow and the destination of another, dissemination of information in other fashions has been extensively studied in the literature. The broadcast capacity is reported in [47]–[49], which is the maximum per-node throughput of successfully delivered broadcast packets.

For each broadcast packet, it is successfully delivered if all nodes in the network other than the source receive the packet correctly in a finite time. The multicast capacity has been widely investigated [50]–[56] considering different network settings. By employing multicast, each packet is disseminated to a subset of $N-1$ nodes which are interested in the common information from the source. Nie [57] reported a short survey on multicast capacity scaling. A unifying study was provided by Wang *et al.* [46], in which how information is disseminated is generally modeled by the (N, m, k)-casting. In this particular context, m and k denote the number of intended recipients of a source packet and the number of successful recipients, respectively. For unicast, $m = k = 1$; for multicast, $k \leq m < N$; and for broadcast, $k \leq m = N - 1$. The capacitybounds were established in [46] for each type of traffic pattern

VII. CONCLUSION

We have surveyed the existing literature for scaling laws of throughput capacity in wireless networks. A comprehensive overview of capacity-delay tradeoffs under a variety of mobility models and scaling laws for hybrid wireless networks have also been presented. In addition, recent progress in throughput capacity of emerging vehicular networks has been introduced.

We close this survey with our thoughts on future research directions in this field.The design, analysis and deployment of wireless net-works necessitate a general understanding of capacity scaling laws. Existing works often adopt different methodologies and sets of assumptions and models in developing capacity scaling laws, which may yield custom-designed solutions without universal properties that can be applied to other types of wireless networks. To better understand the impact of various settings and techniques on capacity scaling laws, it would be useful to provide a unified framework. Two research works have been performed toward this end: the study of capacity scaling laws under a generalized physical model [109] and the establishment of a simple set of criteria that can be used to determine the capacity for various physical layer technologies under the protocol model[110].The Shannon capacity was achieved by considering arbitrarily delay and vanishingly small error probability. In [2], Andrews *et al.* referred to a throughput-delay-reliability (TDR) triplet, since these quantities are interrelated. Thus, the throughput capacity of wireless networks would likely be constrained by these two fundamental quantities—delay and reliability jointly. Actually, the link reliability has been considered in studies of transmission capacity [111]–[113] which is the spatial intensity of attempted transmissions under a target outage of wireless links. The tradeoff between throughput capacity, delay, and reliability should be investigated, however this is much more challenging.

- Investigations on throughput capacity and network de-lay of emerging wireless networks are also promising. Particular characteristics of networks being studied of-ten make the problem very challenging, such as road geometry and vehicle density in vehicular networks. In addition to the aforementioned cognitive radio networks and vehicular networks, femtocell networks [114] and smart grid have also gained much interest recently, both of which have complex network architecture and heterogeneous communication devices, making the study of scaling laws a demanding task.

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