Experimentally Measuring Capacity Scaling in Wireless Mesh Networks

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Abstract

The per-node throughput capacity scaling of stationary unicast multihop wireless mesh networks is experimentally assessed. Using an Android networking testbed, we deploy wireless networks of size n = 10, 20, 30, and 40 in an office environment. We saturate each network with all-to-all Poisson traffic and calculate the network capacity as the average data reception rate per node. By fitting a least-squares power law, we find that the network capacity scales as $1/n^{0.93}$ ($R^2 = 0.84$), which is below the theoretical upper bound and better than prior experimental measurements of capacity scaling. However, this result is ultimately inconclusive due to experimental limitations, primarily the poor connectivity of the network and the linear topology imposed by the office environment. We discuss the limitations of our methodology and propose avenues for future experimentation.

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1. Introduction

1.1. Background and Motivation

Wireless mesh networks, also known as ad-hoc networks, are distributed networks in which every node cooperates in the distribution of data through the network. Distributed networks are highly robust against disconnection and surveillance because none of the constituent nodes are central. As shown in Figure 1, there are many paths between every pair of nodes, and many nodes must fail before two end nodes are totally disconnected. Centralized or decentralized, hierarchical networks (Figure 1, A and B) are vulnerable by comparison because destruction of one or two central nodes can sever communications between many peripheral nodes [1]. Because wireless mesh networks provide robust connectivity without the need for wired infrastructure, they have a broad range of potential applications, including emergency relief [2][3], municipal broadband [3], and military field operations [4]. These same properties make wireless mesh networks inexpensive to implement and maintain [5].

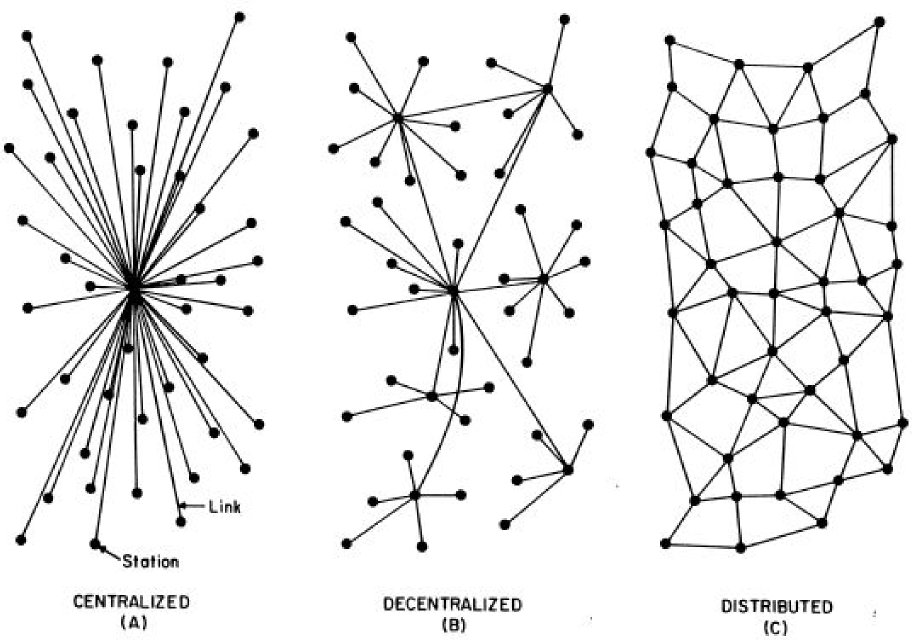

Figure 1.1.1 - Comparison of Network Topologies [1]

Nevertheless, the poor scaling properties of wireless mesh networks are a major obstacle to their development. As the network size (the number of nodes in the network) increases, the network's throughput capacity degrades significantly [4]. Substantial work in the field of communications is directed at modeling how quickly the capacity degrades (and devising strategies to mitigate it) [5]. However, there exists very little experimental work empirically characterizing the capacity degradation of wireless mesh networks.

1.2. Conceptual approach

The work described in this report addresses the experimental research gap in the scaling characteristics of wireless mesh networks. Using a networking testbed with Android smartphones as network nodes, we deploy wireless mesh networks of sizes ranging from 10 to 40 nodes and measure the per-node throughput achieved by each network. Using a least-squares power law fit, we find that the capacity scales as $1/n^{0.93}$ ($R^2 = 0.84$) where n is the number of nodes in the network. This result is ultimately inconclusive because of experimental limitations on the connectivity and topology of the network. Nevertheless, our methodology serves as a basis for further experimental research on the capacity scaling of wireless mesh networks. Experimental work and empirical models of capacity scaling provide valuable insights for communications theorists and contribute towards the greater goal of achieving feasible, large-scale mesh networks.

2. Hypothesis, Objective, and Success Criteria

2.2. Hypothesis

As the number of nodes (n, where $10 < n < 40$) in a stationary unicast multihop wireless mesh network increases, the per-node throughput capacity of the network degrades according to the power law $1/n^b$, where b lies between 0.5 and 1.68.

2.2. Objective

To assess the hypothesis, we measure the throughput of mesh networks of various sizes from $n = 10$ to $n = 40$ in an office environment. We construct mesh networks using Samsung Galaxy S4 Android smartphones. Each node in the network periodically issues packets to other nodes, generating network traffic. When the network is saturated, the capacity of the network is measured as the data reception rate of each node, averaged across all nodes in the network. We then use a least-squares power law fit to estimate b.

2.3. Success Criteria

We consider our experiment a success once we have estimated the capacity scaling law to an accuracy sufficient for assessing the hypothesis. We define this as a least-squares power law fit that estimates b with an $R^2 > 0.9$. Failure to satisfy this criteria would be evidence that the network scaling is not well-modeled by a power law.

3. Literature Review

3.1. The Capacity Problem: Theoretical Work

To situate our research, we provide a brief overview of the current state of research on wireless network capacity. The question of how much information a wireless network can theoretically transfer remains unanswered in the field of communications. A substantial amount of work is currently dedicated to the search for a solution: a fundamental theory, derived from first principles in information theory, describing the capacity of a distributed wireless network. Such a theory would not only drive insights about network science, it would motivate practical guidelines for designing architectures and protocols for distributed wireless networks [6].

In 2000, Gupta and Kumar [7] demonstrated mathematically that the achievable capacity of a wireless network cannot scale better than $1/n^{0.5}$, placing an upper bound on the network capacity. Their analytical approach models a network of n nodes placed optimally in a geographic region of one square meter. A simplified account of Gupta and Kumar's analysis states that every node can theoretically transmit simultaneously without signal interference, because the nodes are spatially distributed. The one-hop capacity of the network (the amount of data that can transmitted by all nodes in the network simultaneously) therefore scales with the number of nodes n. However, most packets will need to travel more than one hop to reach their destinations. In fact, we expect the average number of hops to scale with the diameter of the network, which scales with as $n^{0.5}$. Thus the theoretical upper bound on the capacity is proportional to $n/n^{0.5}$ for the entire network. As there are n nodes in the network, the upper bound per-node throughput capacity is proportional to $1/n^{0.5}$.

Gupta and Kumar concede that achieving $1/n^{0.5}$ scaling requires an ideal and totally optimal wireless network. This means that the physical placement, transmission range, and traffic of each node must be exactly assigned in such a way so as to use the available capacity with 100% efficiency. In practice this is unrealistic. The physical orientation and transmission ranges of each node are constrained by the environment and the specific networking hardware being used. Network traffic is never 100% efficient. In fact, efficiency depends heavily on what medium access control, routing, and congestion management techniques are implemented, and optimizing network traffic constitutes a separate research question entirely.

As an aside, Gupta and Kumar find that when nodes are placed *randomly* in a one-square-meter area (as opposed to *optimally*), and when source nodes transmit to randomly chosen target nodes, the network's per-node throughput scales only as $1/(n \log n)^{0.5}$ in the best case. In a separate model for deterministically calculating wireless network throughput based on node location, Kulkarni and Viswanath (2004) confirmed $1/(n \log n)^{0.5}$ scaling by applying their approach to

Gupta and Kumar's random node placement [8]. Though these models assume random (and therefore suboptimal) node placement, they still assume ideal network performance in all other aspects, such as medium access, routing, and congestion management. In other words, going from an optimal node placement to a random one leads to a substantial drop in network throughput, even with all other properties held constant. This result is also a strong indication that Gupta and Kumar's ideal model of $1/n^{0.5}$ scaling is unlikely to hold true in practice.

Akyildiz and Wang [5] further critique Gupta and Kumar's analytical approach for its abstraction. Gupta and Kumar's analysis examines the asymptotic case as n approaches infinity, and Akyildiz and Wang argue that this approach relies on assumptions about network size and density that don't hold true for physical network implementations (especially for small n). So although Gupta and Kumar's result provides an absolute upper bound on the capacity scaling, it is difficult to assess how closely it actually describes the capacity behavior of small-n mesh networks operating on existing, non-ideal protocols. The experimental work described in this paper directly addresses this theoretical gap by implementing physical mesh networks of small n (< 40) using currently-available medium access and routing protocols. By measuring the capacities achievable in physical networks, we can experimentally assess exactly how well theoretical models of wireless network capacity describe wireless mesh networks in practice.

3.2. Simulation and Experimentation

There does exist some work assessing Gupta and Kumar's $1/n^{0.5}$ capacity scaling law via simulation and experimentation. As discussed above, Gupta and Kumar's idealized wireless network assumes perfectly efficient routing protocols and zero interference between transmissions. In 2001, Li et al. [9] assessed how implementing the IEEE 802.11 medium access protocol alters the capacity scaling model. They simulated mesh networks of sizes n = 200, 300, 400, 500, and 600 nodes, with random node positions. Each node simulated sending packets to randomly-selected destinations using the 802.11 medium access scheduler. To isolate the effects of the 802.11 protocol, no routing protocol was used and the packets were transmitted to their destinations along predetermined routes. The simulated network capacity was found to closely match the ideal $1/n^{0.5}$ scaling model, apparently demonstrating that the 802.11 protocol approaches the maximum attainable capacity of a mesh network. Li et al. also assert that the $1/n^{0.5}$ scaling law appears to fit even for smaller networks (though the smallest network simulated was 200 nodes), providing some evidence that theoretical network models properly describe mesh networks of at least as small as 200 nodes.

That same year, Gupta, Gray, and Kumar [10] ran an experimental study on mesh network capacity scaling, using a collection of laptops communicating via 802.11. They constructed mesh networks of size n = 2, 4, 6, 8, 10, and 12 in an indoor office environment using laptops placed in adjacent offices. Every node sent 1 kilobyte UDP packets to randomly-chosen destinations, sending packets at a constant rate λ. The sending rate λ was increased from 1 kbps to 1000 kbps until the network saturated (that is, when the measured throughput at each node stopped increasing). Just as we plan to do in our experiment, they measure the network capacity as the average of the throughputs at each node at saturation. The team indicated an intent to implement a routing protocol, but faced technical obstacles and eventually hard-coded predetermined routes without implementing a routing algorithm. The experimental network configuration thus closely matches the configuration used by Li et al. in their simulations. However, the experimental results yielded a capacity scaling of only $1/n^{1.68}$, which is substantially worse than the $1/n^{0.5}$ scaling predicted by theory and observed by Li et al. in simulation.

Gupta, Gray, and Kumar's experimental setup suffers from two weaknesses. First, their experimental environment is an office building. This limits the replicability of their experiment, as the exact placement of each node is dependent on the particular office building used by Gupta et al. Second, the largest network in the experiment contained only 12 nodes, so it remains difficult to assess whether the theoretically-predicted (and simulation-confirmed) $1/n^{0.5}$ capacity scaling law usefully describes networks of less than 200 nodes, or whether the empirically-observed $1/n^{1.68}$ scaling law is a more apt model for the capacity of small-n wireless networks. Our work directly addresses the latter weakness by experimentally assessing mesh network capacities at n from 10 to 40, slightly expanding the experimental scope. Since we are also working in an office environment, our experiment does suffer from similar obstacles to generalizability and replicability. However, we adhere as closely as possible to a two-dimensional grid topology and provide floor plans of the office environment used, in the hope that similar (if not exactly replicable) experiments can still be conducted using our methods.

4. Experimental Method

4.1. Overview

Our aim is to experimentally assess how the throughput capacity of a wireless mesh network scales with the size of the network. Using smartphones, we construct wireless mesh networks of various sizes n ($10 < n < 40$) in an office environment. Conforming to the rectangular layout of the office setting, we adhere as closely as possible to a 2-by-$n/2$ grid topology for each network of size n. The specific network topology used in our experiments, superimposed on a floor plan of the office building, is available in Appendix A. Every node in the network issues 128-byte packets to every other node in the network according to a Poisson process of rate λ, where λ is the packet rate at which the network is saturated (i.e., when the amount of data being transmitted in the network is maximum).

Each node in the network records a timestamped log of every packet received and which node it came from. The per-node capacity of the network is then calculated as the transmission throughput received at each node, averaged across all nodes in the network.
Though there is no measurement error per se (in a digital system, each phone logs the bytes it sends and receives with essentially 100% accuracy), there is randomness because packets are issued according to Poisson processes, and network behavior may also be influenced by objects moving through the office building. To mitigate this error, we run each experiment over a five-minute duration to average out transient effects, and we run each experiment three times.

4.2. Equipment and Location

The experimentation platform is an existing networking testbed comprised of Samsung Galaxy S4 smartphones (Figure 4.2.1) and generously provided by MIT Lincoln Laboratory. Every phone carries identical firmware for ad-hoc wireless networking using WiFi standards. Every node is labeled with a unique ID number *N* between 1 to 40 and assigned the Internet Protocol (IP) address 10.1.1.*N*. The phones can be programmed via a central server, to which all the phones are connected via USB (or "tethered") between test runs. The server is also used to collect log data from the phones. The central server is accessible from any laptop on the Lincoln Lab internal network.

Figure 4.2.1 - Samsung Galaxy S4 smartphone [11]

To adhere to Lincoln Lab's security requirements, we cannot publish the code base used on the testbed. However, we highlight the main features of the software and networking protocols used.

Network traffic is generated using Multi-Generator (MGEN), an open-source IP networking toolset developed by the Naval Research Laboratory [12]. MGEN emulates many types of network traffic, but the features salient to this project are: the ability to issue packets to specified destinations, the ability to specify packet rates and packet sizes, the ability to issue packets according to a Poisson process, and timestamped logging of every received packet.

Our experiment uses standardized protocols from the Internet Protocol (IP) suite. Packets are specified according to User Datagram Protocol (UDP), which is known to outperform Transmission Control Protocol (TCP) in wireless settings [10]. Packets are routed according to Optimized Link State Routing Protocol (OLSR), a routing protocol designed for wireless mesh networks [13]. The 802.11 Wi-Fi specification is used for the physical layer and medium access control, and nodes in the network communicate on the 5.18 GHz band. Time on all phones is synchronized by the server using Network Time Protocol [14] before every experimental deployment.

Experiments will take place in Building B of the Lincoln Lab facility in Lexington. Building B consists of a single, straight hallway with offices on either side. The walls in Building B are metallic, which attenuates the transmission range of each node. This ensures that network traffic is truly multi-hop as it is in Gupta and Kumar's model, and that phones cannot simply transmit packets directly to their destination nodes. For a given n-node network, the rectangular layout of Building B permits an approximately 2-by-$n/2$ grid network topology with one phone per office.

4.3. Experimental Procedure

Each experimental run occurs in three phases: setup, deployment, and collection. The setup phase occurs with the phones tethered to the central server. We define an experiment in a specification file written in XML markup language. That file specifies the duration of the experiment and the IP addresses of the nodes being tested. The file also specifies an optional startup delay, giving us time to deploy all the phones in the office before the experiment begins. Additionally, a shell script is defined for every node, specifying to MGEN the types, rates, and destinations of packets to issue during the experiment.

Multiple experiments defined in this fashion can be executed in series with one deployment, without collecting and re-deploying all the phones between experiments. Specification files and shell scripts for each experiment are loaded into a file directory to form a "batch." We then load the entire batch of files onto the phones through the server.

During setup, we also pre-plan the locations of each node using a floor plan of Building B. We have already secured permission from Building B occupants for the use of their offices over the next two months. To expedite the deployment process, we visit each office in advance and lay down manila folders (labeled by node number) to mark the location of each node. The folders also act as signs for passersby, with warnings not to touch or move the phones during experiments as well as contact information for the researchers.

Before deploying the network, we execute the following checklist to verify that all phones are working as expected. Using shell scripts, this checklist takes 5-10 minutes.

1. Ping every phone and verify that every phone is responsive
2. Verify that the WiFi interface is running on every phone
3. Verify that every phone has the appropriate IP address
4. Verify that Network Time Protocol is running on every phone, and that the time on each phone is synchronized

The series of experiments is initiated with a “runBatch” command while the phones are still tethered. The runBatch command waits for the specified delay, then executes every experiment in the batch in series. During that delay, we untether the phones from the server, transport them to the Building B test environment, and deploy them in the 2-by-n/2 grid topology described above. From preliminary tests, we estimate conservatively that deployment takes 1 minute per node per person.

The duration of each experiment is strictly specified, so the runBatch command can calculate the completion time of the experimental batch. At that completion time, we collect all the phones and retether them to the server. A “collect” command is used to download the log files generated by each experiment from the phones to the server. The log files provide a timestamped accounting of every received packet, as well as the packet’s origin and size.

The incoming throughput observed by each phone can be estimated with a moving average, by taking the total number of packets received in a specified time window, multiplying by the number of bytes per packet, and dividing by the size of the time window. The measured per-node capacity of the entire network is the incoming throughput of each node, averaged across all nodes in the network. A Python script, taking the log files from each node as input, is used to streamline this calculation.

The independent variable in this experiment is the number of nodes n in the network, ranging from $n = 10$ to $n = 40$. The dependent variable is the per-node capacity achieved by the network. This is reflected in our test matrix (Table 4.3.1). For each test, nodes issue packets to all other nodes in the network according to a Poisson process with saturation rate λ, for a duration of four minutes. The saturation rate λ is determined by a series of calibration experiments at varying packet-transmission rates. The saturation rate λ is then taken to be the packet-transmission rate at which the per-node capacity stops increasing, indicating that the network is fully loaded. We execute five experimental runs for each *n*, giving us a total of 20 data points with which to assess the hypothesis. All final data is taken on the same day to control for environmental factors. Experiments are alternated so no two experiments of the same network size are sequential in time; that is, we execute the first 40-node experiment, then a 30-node experiment, then a 20-node experiment, then a 10-node experiment, followed by the second 40-node experiment, the second 30-node experiment, and so on.

Table 4.3.1 - Test Matrix

Network size *n*	**10**	**20**	**30**	**40**
Experimental run				
1				
2				
3				
4				
5				(capacity, bps)

4.4. Safety and Training

This experiment bears minimal safety requirements, as the Android testbed is composed of commercial smartphones communicating via WiFi (conditions common to everyday life). There are no experimental conditions that require special training, as there are no human subjects or hazardous environments. Our work complies with security requirements necessary for routine access to MIT Lincoln Lab, as well as a safety needs assessment proctored by David Robertson (Technical Instructor, MIT AeroAstro).

5. Results

Figure 5.1 depicts a log-log plot of the per-node throughput capacity measured in each of the 20 experiments, plotted against the number of nodes in each network. Using a least-squares best fit yields the following power law, with $R^2 = 0.84$:

$$\text{Capacity} \propto 1/n^{0.93}$$

The residual plot of the least-squares best fit is shown in Figure 5.2. Visual examination shows a slight trend in the residuals, which suggests that a power law regression may not provide the best model for this data.

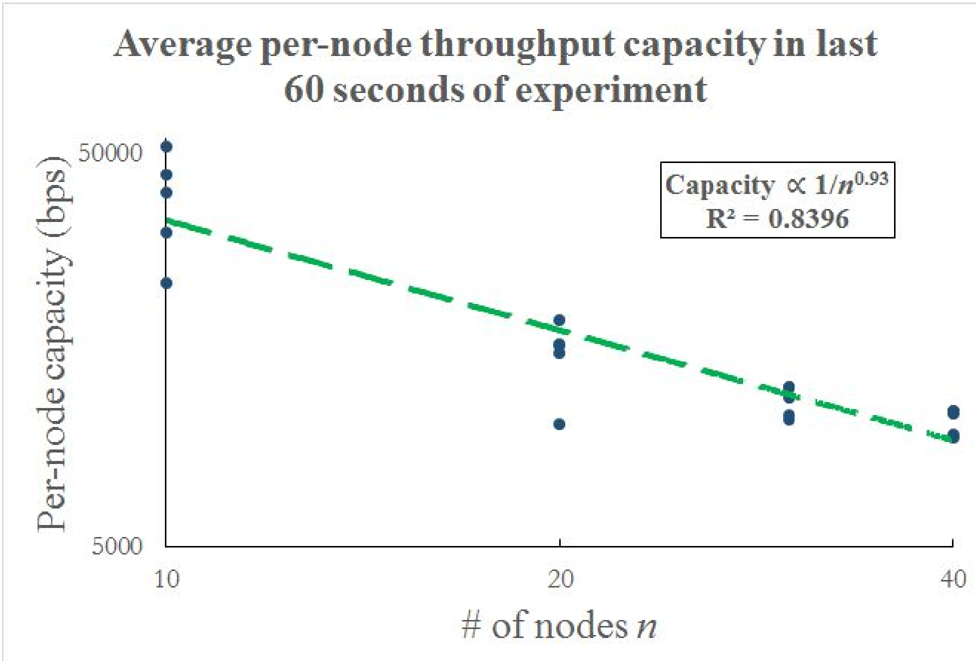

Figure 5.1 - Average per-node throughput capacity in each experiment, with best-fit power law.

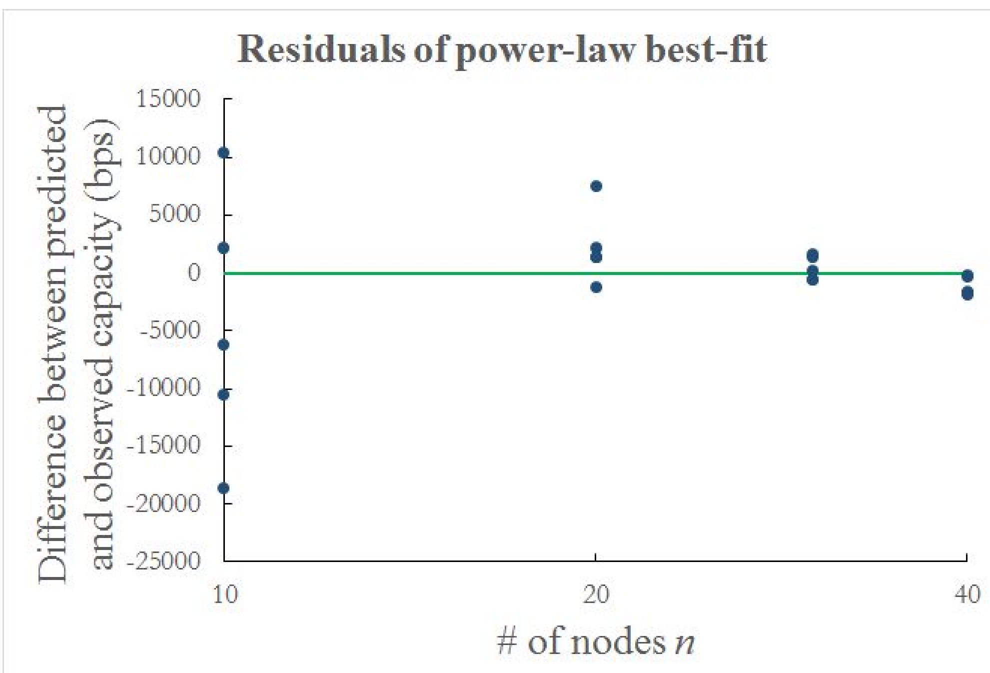

Figure 5.2 - Residuals of power law least-squares fit

The network deployment was limited by the geometry of the office building where tests were conducted. Though the test environment is a simple rectangular hallway, the network topology was only approximately grid-like because nodes could only be placed in hallways or accessible offices, and not in closets or restricted spaces. The 40-node topology is depicted in Figure 5.3. Each group of ten nodes is labeled to illustrate how smaller networks were all subgraphs of the largest network. That is, the 10-node test used nodes 1-10, the 20-node test used nodes 1-20, the 30-node test used nodes 1-30, and the 40-node test used all 40 nodes. This allowed us to run all the experiments without redeploying the network for each *n*. A larger version of this diagram, with each node labeled from 1 to 40, is available in Appendix A.

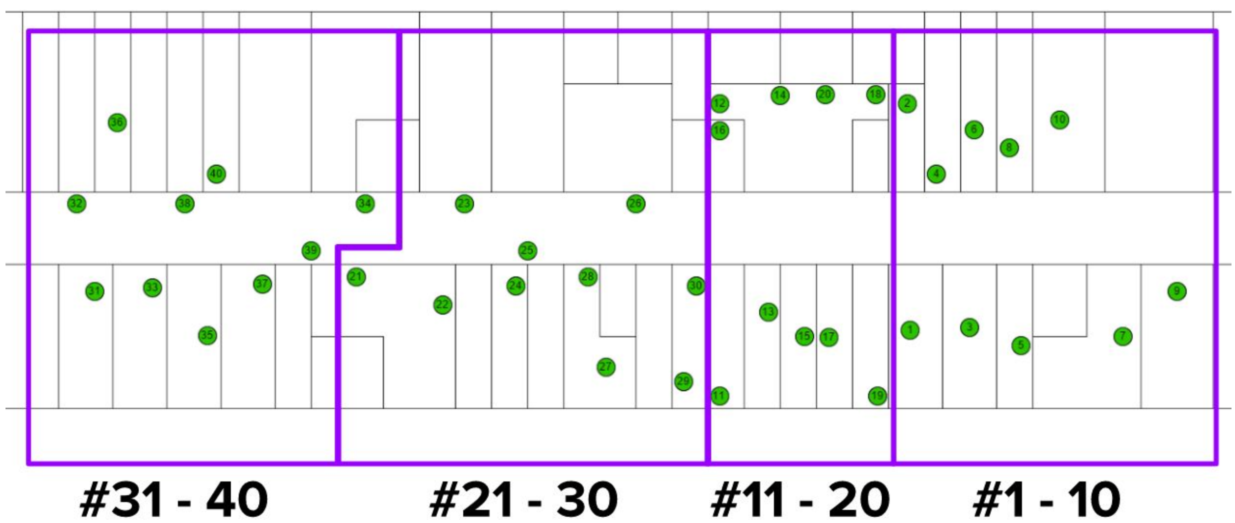

Figure 5.3 - 40-node topology of nodes in office building

We construct a connectivity matrix of the network by counting the number of packets received by each node from each other node in one of the 40-node experiments (Figure 5.4). Notice that some nodes (20, 24, 25, 26, 37) are entirely absent from the connectivity matrix. In other words, they receive no traffic, and no other nodes in the network receive traffic from them. The remaining nodes are divided into two connected components, the first consisting of nodes 1-19 and 27-30, and the second consisting of nodes 21-23, 31-36, and 38-40. As a result, the $n = 30$ and $n = 40$ experiments represent data from traffic in two separate networks, as opposed to traffic in a single large network as initially intended.

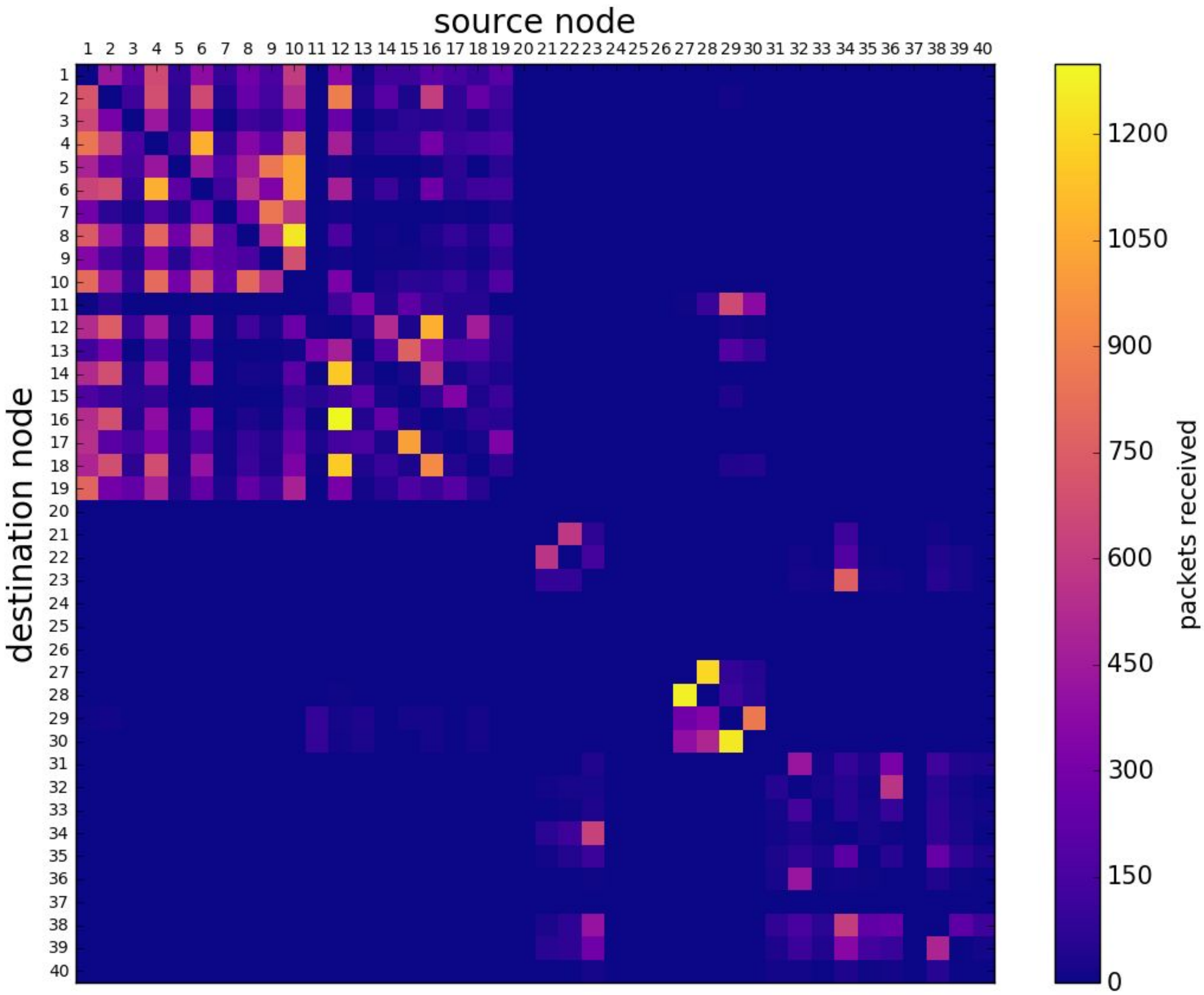

Figure 5.4 - Connectivity matrix of 40-node network

6. Discussion

As shown in Figure 5.1, experimental data shows that the per-node throughput capacity scales as $1/n^{0.93}$ according to a least-squares power law fit with $R^2 = 0.84$. This is a negative assessment of our initial hypothesis and success criteria. Although the observed capacity scaling follows a power law $1/n^b$ with $0.5 < b < 1.68$ as hypothesized, the R^2 value of the least-squares fit does not satisfy the success criteria of $R^2 > 0.9$.

Other properties of the data support a negative assessment of the hypothesis. The residual plot of the power law fit (Figure 5.2) exhibits a slight trend, suggesting that the observed throughput capacity may not be well-modeled by a power law at all. Furthermore, the connectivity matrix (Figure 5.4) indicates that the network connectivity was sparse for all networks with more than 10 nodes. For the 20-node, 30-node, and 40-node networks, no nodes successfully exchange packets with every other node in the network. Five nodes were entirely absent from the 40-node network, transmitting and receiving no packets from any other node, and the 30-node and 40-node networks were split into two disconnected components. These are deviations from the ideal experiment, where every node communicates with every other node in the network. Rather than exhibiting multi-hop traffic across the network, the connectivity matrix suggests that most nodes only exchanged data successfully with their nearest neighbors.

The office environment also introduced factors that limit the conclusiveness of our experiments. Primarily, because the network size scales by only one dimension (the hallway of the office building), we expect the average number of hops to scale approximately with n, not with $n^{0.5}$ as is assumed in prior theoretical work and simulations. It is therefore spurious to make claims that the capacity scaling in our experiment can be directly compared to Gupta and Kumar's $1/n^{0.5}$ capacity scaling model. The office environment is also a source of wireless noise from other WiFi devices and electronics in the building. Though we control for environmental noise by running multiple experiments for each network size, and taking all measurements on the same day, we cannot account for localized increases or bursts in 5.18 GHz noise. For instance, if a person in one office begins downloading a large file over WiFi during an experiment, the node in that office would suffer a decrease in connectivity. Moreover, the connectivity of each node (and therefore the overall network topology) can be affected by physical changes to the environment, such as people walking around, moving furniture, and doors opening and closing.

Though our experimental results are ultimately inconclusive, we can speculate as to some possible (albeit very weak) interpretations of our data. First, we note that our observed capacity scaling of $1/n^{0.93}$ is better than prior experimental work, namely Gupta, Gray, and Kumar's observed scaling of $1/n^{1.68}$. This could be partially due to advances in WiFi protocols and networking hardware since Gupta, Gray, and Kumar's work in 2001, but it may also provide evidence that the capacity scaling of the network correlates strongly with the network topology used in the experiment. Like in this work, Gupta, Gray, and Kumar's experiments were limited by the geometry of their office environment.

Moreover, the slight trend in the residual plot indicates that capacity scaling in this range may not adhere to a power law. A more sophisticated statistical analysis investigating other scaling laws, such as the $1/(n \log n)^b$ scaling proposed by Gupta and Kumar for networks with randomly-placed nodes, would be worthwhile. We also note that since the diameter of our network scales approximately linearly with n and not with $n^{0.5}$, we can use Gupta and Kumar's approach to argue that the theoretical per-node capacity should scale as $1/n$. This is perhaps weakly supported by the $1/n^{0.93}$ scaling that we observed, with all the caveats detailed above.

7. Conclusion

We have experimentally measured the per-node throughput capacity of wireless mesh networks between 10 and 40 nodes in an office environment. Using those measurements, we estimate that the capacity scales as $1/n^{0.93}$ according to a least-squares power law fit with $R^2 = 0.84$. This is a negative assessment of our initial hypothesis that wireless mesh network capacity scales according to a power law $1/n^b$ where b lies between 0.5 and 1.68. Although the observed power law of $b = 0.93$ does lie in the hypothesized range, the R^2 value does not pass the success criterion that the best-fit power law satisfy $R^2 > 0.9$. Other experimental flaws, primarily the sparsity of the network and the topology imposed by the office environment, prevent us from drawing strong conclusions about capacity scaling from this data.

There were a number of difficulties unique to the experimental nature of this work that bear mentioning. As discussed earlier, theoretical work on capacity scaling in wireless mesh networks often makes idealized assumptions about the network that often fail in practice. These include the assumption that nodes in the network can be placed in such a way as to make optimal use of the available spectrum, the assumption that all messages can be transmitted error-free, and the assumption that lower-level network protocols for medium access control, routing, or congestion control do not affect the overall capacity. None of these assumptions hold true in an experimental setting, making it difficult to ascertain why exactly the capacity in a physical mesh network might not scale according to theory. Future experimental work on capacity scaling in mesh networks would do well to decouple each of these assumptions, in order to assess the impact of each individual networking component on the capacity. For instance, we might investigate exactly how much the capacity is affected by routing overhead by comparing the capacity of a network using OLSR with the capacity of a network using predefined routing tables. Isolating and comparing different protocols for medium access, routing, and flow control would help pinpoint specific reasons as to why the network capacity doesn't scale in practice as it does in theory. This line of inquiry would reveal whether there are specific protocols that, if improved, would yield the largest gains in capacity scaling.

Other avenues of further research might expand on this work by implementing similar experiments in an outdoor setting (or a large indoor setting with no people). A larger space would allow for network topologies where the distance between nodes truly scales as $n^{0.5}$ as theorized by Gupta and Kumar, while mitigating the impact of environmental noise. Broadening the range of network sizes in the experiment to beyond 40 nodes would also increase the validity of any empirically observed capacity scaling laws.

8. Acknowledgments

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Appendix A: 40-Node Network Topology Map