Experimentally Measuring Capacity Scaling in Wireless Mesh Networks

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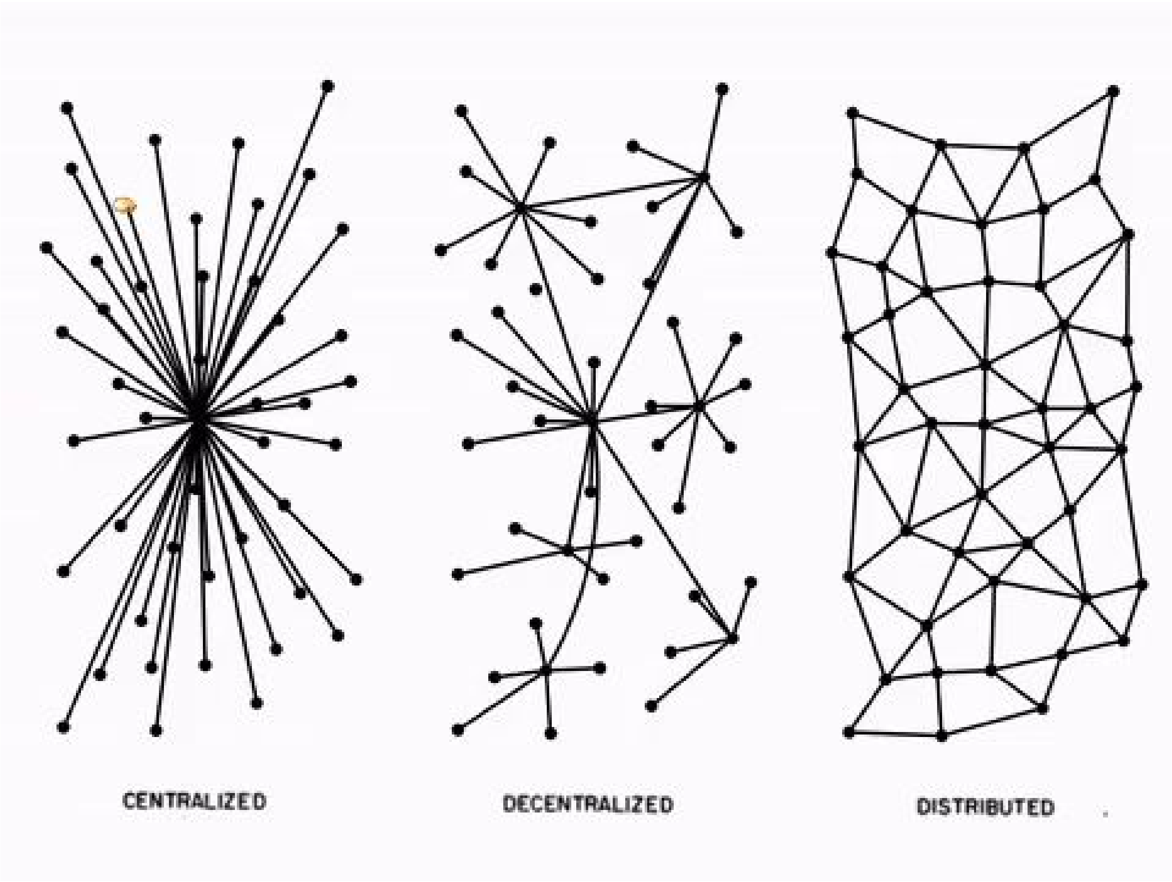
Contents

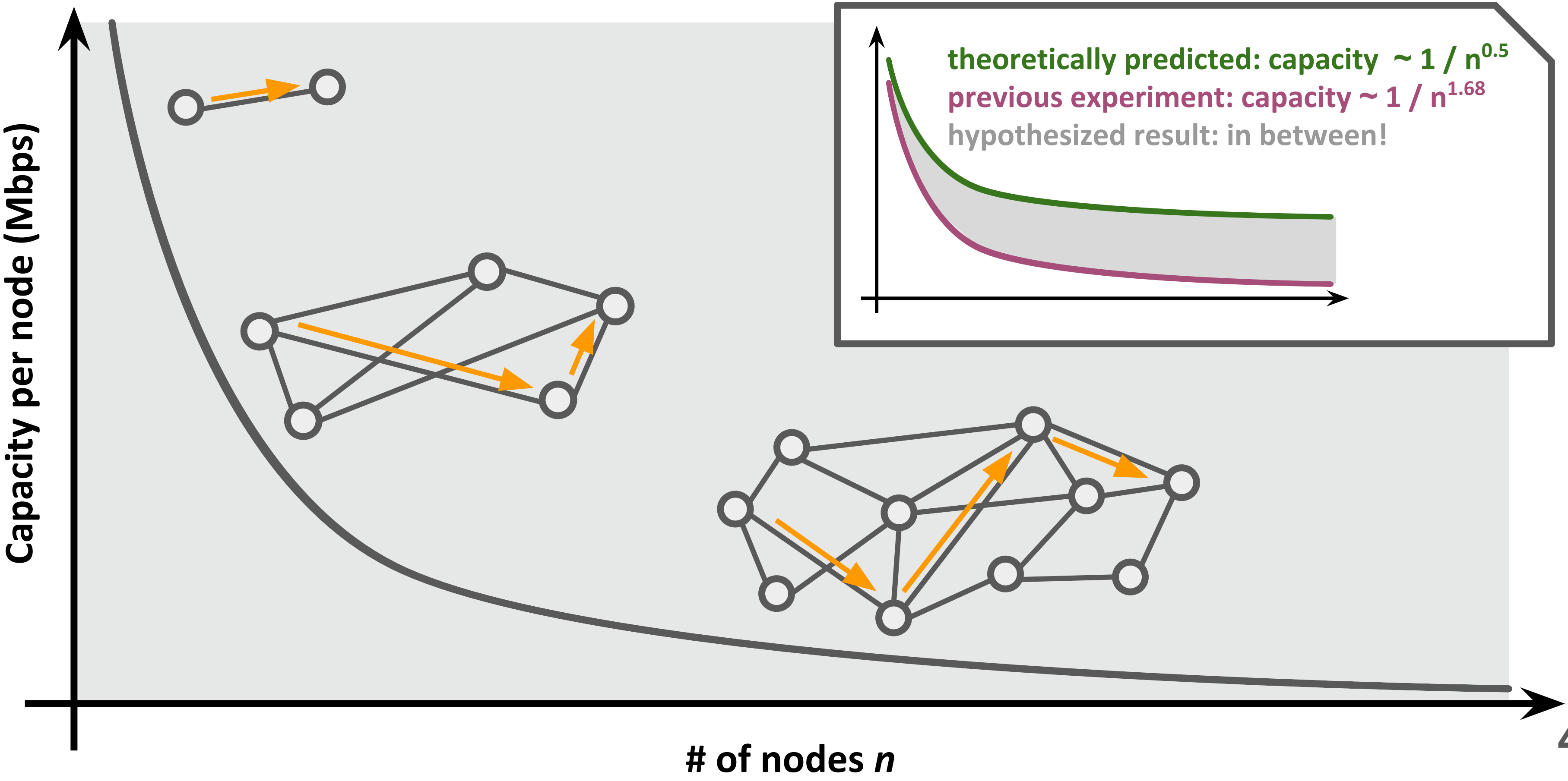
Overview



Baran, P., “On Distributed Communications: Introduction to Distributed Communications Networks,” RAND Corporation, RM-3420-PR, Santa Monica, CA, Aug. 1964.

Animated by Mushon Zer-Aviv

Overview | Capacity degrades as size increases



Overview | Summary of Approach

Goal: Experimentally measure capacity scaling law of mesh networks

Dependent variable: per-node network capacity
Independent variable: mesh network size *n* ($10 < n < 40$)

- 40 Android smartphones provided by Lincoln Lab
- Construct wireless mesh networks from 10 to 40 nodes in office environment
- Measure per-node network capacity achieved by each network
- Fit power law relating capacity to network size

Prior Work | Theory

- Gupta & Kumar (2000) found theoretical upper bound on per-node capacity scaling is $\mathbf{1/n^{0.5}}$
    - Assumes perfect node placement and perfect spatial reuse
    - Doesn’t account for protocol overhead:
        - medium access control
        - routing
        - congestion management
- Gupta & Kumar (2000) and Kulkarni & Viswanath (2004) independently found that when nodes are placed **randomly** and not **optimally**, per-node capacity scaling has an upper-bound of only $\mathbf{1/(n \log(n))^{0.5}}$

Prior Work | Simulation and Experimentation

- Li et. al. (2001) simulated network traffic in mesh networks of size ranging from $n = 200$ to $n = 600$, using 802.11 medium access protocol
- Result closely matches Gupta & Kumar's $\mathbf{1/n^{0.5}}$ scaling law

- Gupta, Gray, & Kumar (2001) experimentally measure capacity scaling using mesh networks of size $n = 2$ to $n = 12$ in office setting
- Found throughput scales as $\mathbf{1/n^{1.68}}$

- Limitations of prior work:
  - Scale
  - Lack of clear consensus
  - No prior work implements routing protocols; data is transmitted along pre-defined routes

Hypothesis, Objective, and Success Criteria

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.

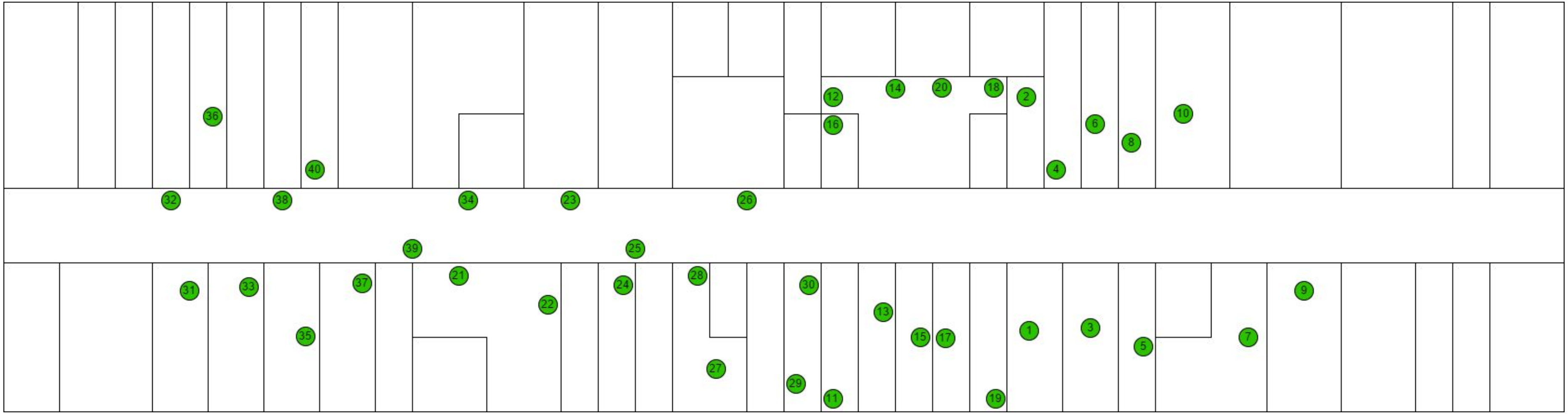
OBJECTIVE: To assess the hypothesis, we measure the throughputs of mesh networks of various sizes from $n = 10$ to $n = 40$ in an office environment. We construct mesh networks using Samsung Galaxy S4 Android smartphones (provided by MIT Lincoln Lab). Each node in the network periodically issues packets to all 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*.

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.

Experimental Procedure

1. Specify experiment definition files (scripted in Python)
    a. Experiment duration
    b. Data rate attempted for each UDP flow
2. Sync phones to server (USB connection)
    a. Load experiment code onto cell phones
    b. Run through verification checklist
3. Deploy phones out over 1 floor of an office building
    a. 2-by-*n*/2 grid topology (approximately - see next slide)
4. Cell phones attempt to transmit all-to-all Poisson traffic at saturation rate (λ)
    a. Use a “calibration experiment” to find saturation rate
    b. Can run multiple experiments with one deployment
5. Connect phones to server again; collect data
6. Reduce data (scripted in Python)

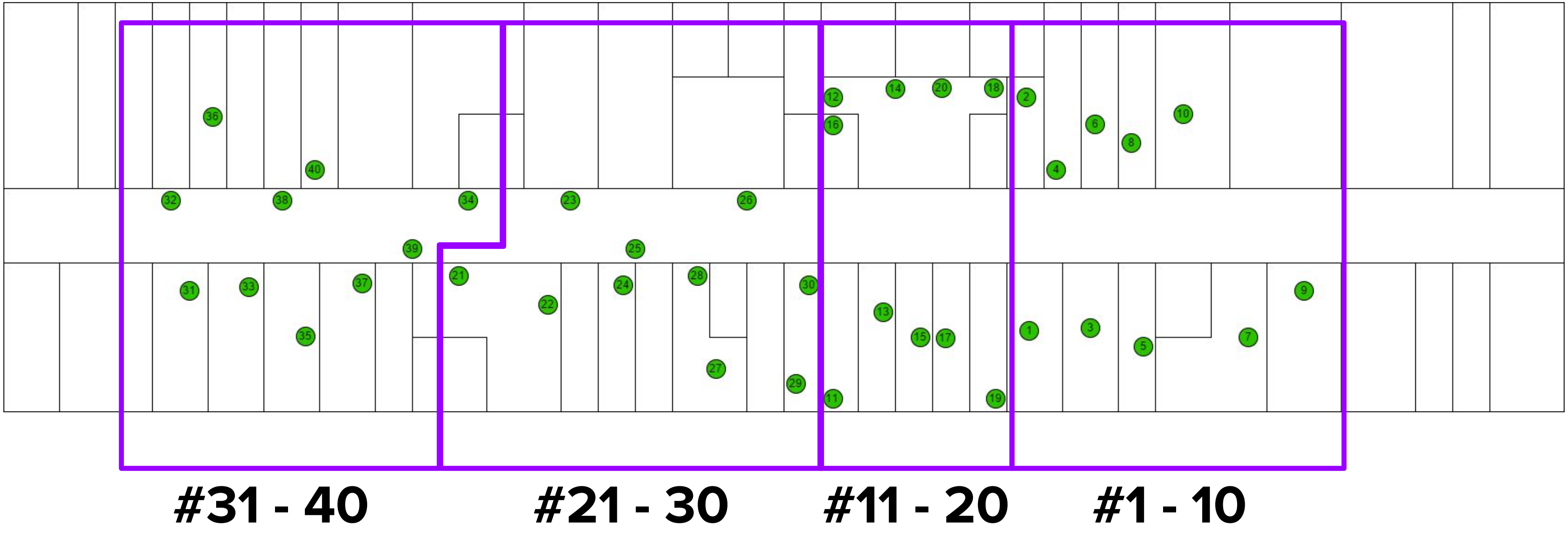
Experimental Procedure | Network Topology



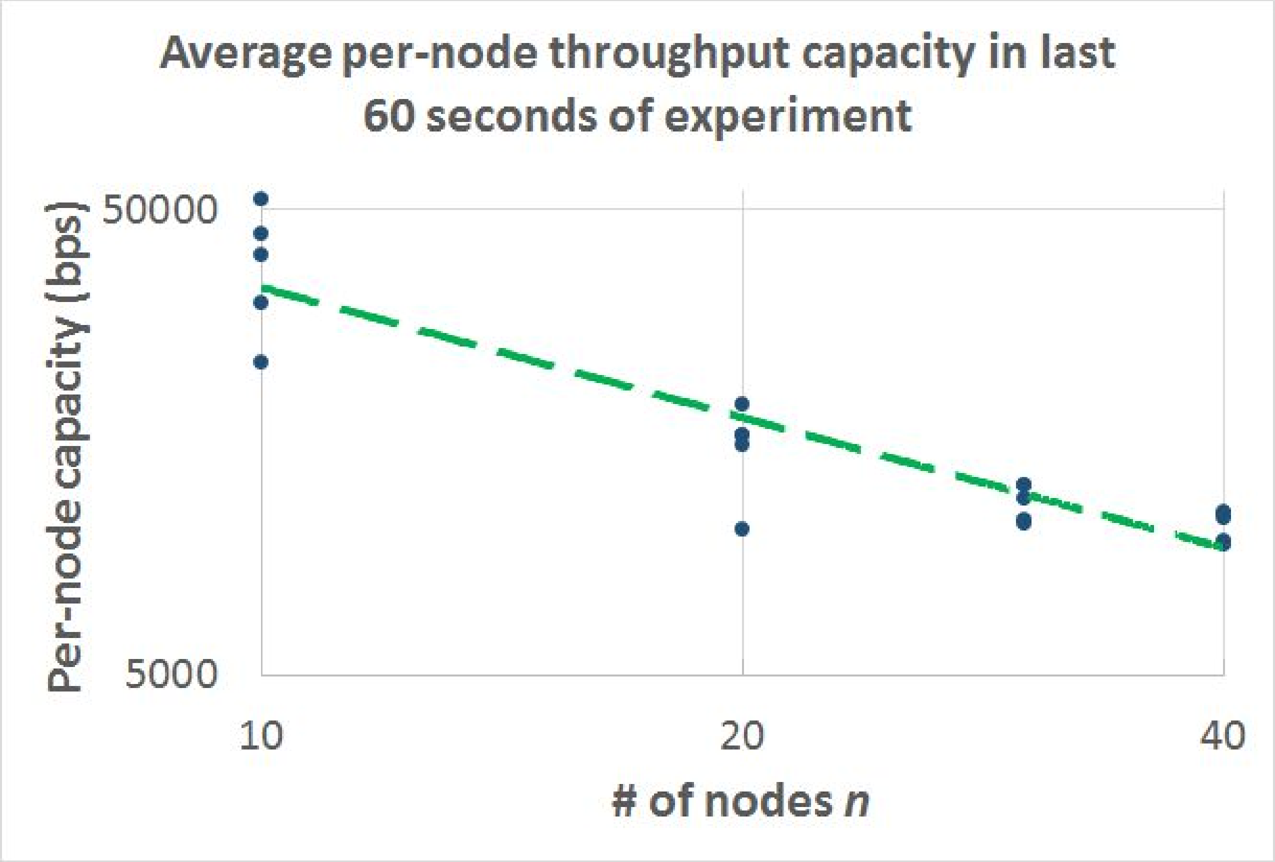
Topology limited by:

- Confidential meeting spaces/offices where phones are prohibited by policy
- Restricted lab spaces
- Closets, stairwells, bathrooms

Experimental Procedure | Network Topology



Results



Power law least-squares fit:

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

$R^2 = 0.8396$

Results | Assessment of Hypothesis/Success Criteria

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.

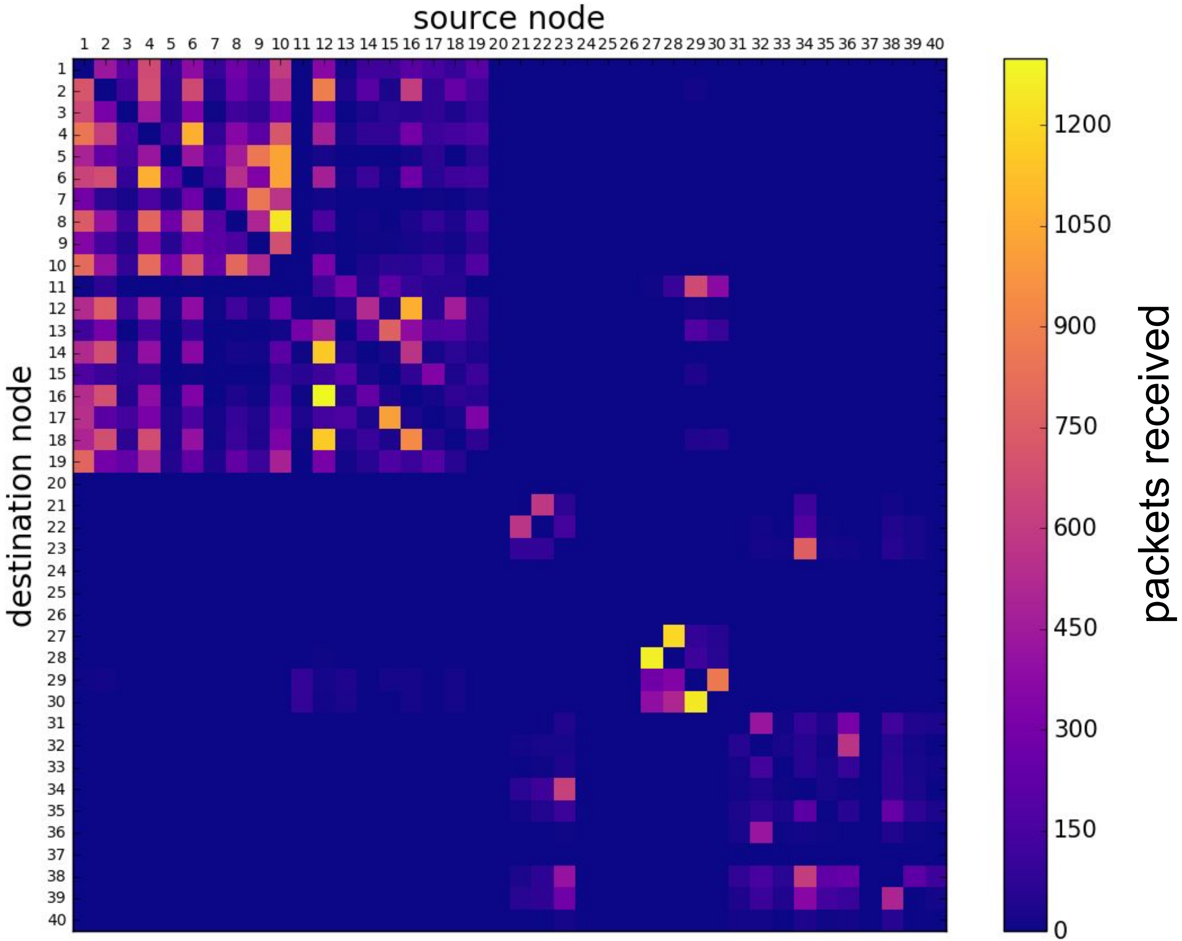
SUCCESS CRITERIA: We consider our experiment a success once we have estimated the capacity scaling law to an accuracy sufficient for assessing the hypothesis. We define this as a least-squares power law fit that estimates b with an $R^2 > 0.9$. Failure to satisfy this criteria would be evidence that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

b **= 0.93** indeed satisfies $0.5 < b < 1.68$

but $R^2 = 0.84$ does **not** satisfy $R^2 > 0.9$

So we assess our hypothesis negatively. There is **weak but inconclusive evidence** that the per-node capacity of a mesh network scales according to a power law.

Results | Connectivity

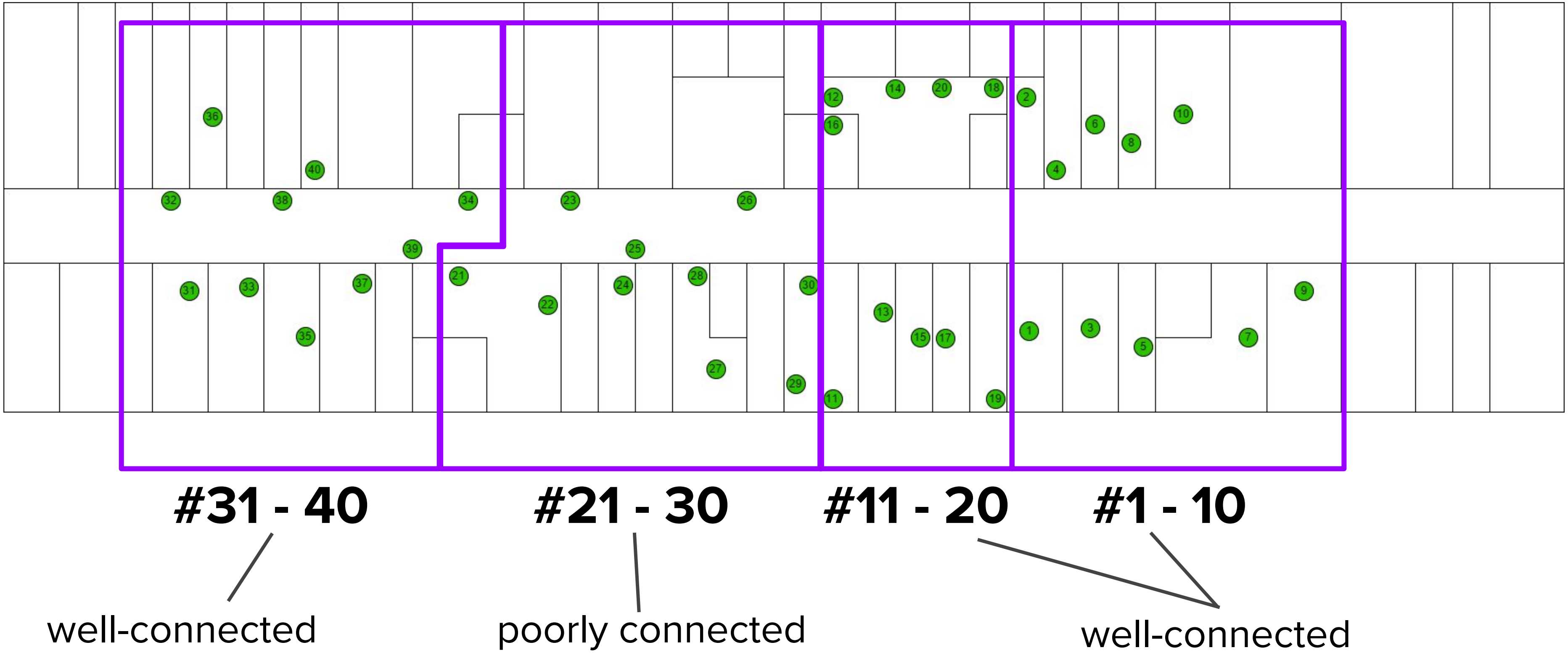


Connectivity matrix indicates that majority of traffic was one- or two-hop traffic; that is, **most nodes only communicated successfully with their nearest neighbors.**

Nodes **31-40** are entirely disconnected from nodes **1-20**

Some nodes receive no data at all

Results | Connectivity



Conclusion

- We experimentally measured the per-node throughput capacity scaling of wireless mesh networks between $n = 10$ and $n = 40$
- We found that scaling law to be $1/n^{0.93}$ with $R^2 = 0.8396$ according to a least-squares power law fit, which is a negative assessment of the hypothesis
- In other words, there is weak but inconclusive evidence supporting prior theoretical and experimental work indicating that the capacity scaling:
    - **ONE**: can be modeled as a power law
    - **TWO**: has an upper bound of $1/n^{0.5}$

Conclusion | Future Work

- More standardized test environments/topologies
- Wider range of network sizes
- Are there better ways to load the network to achieve multi-hop traffic?
  - Perhaps paired traffic between random node pairs

Questions + Discussion