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Notes on Scalability of Wireless Ad hoc Networks

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<draft-irtf-and-scalability-notes-00.txt>

http://wnl.ece.cornell.edu/Publications/ draft-irtf-ans-scalability-definition-00.txt

Problem Statement

- **Objective:** To determine a general framework to analyze the scalability of *methods* in the context of wireless ad hoc networks.
- A *method* can be anything whose scalability needs to be evaluated; e.g., a routing protocol, a MAC protocol, an algorithm, etc.
- The *scalability of a method* in an ad hoc network is a measure of its ability to maintain efficiency, as some parameters of the network increase to very large values.
- Many metrics contribute to the determination of scalability of a method with respect to a given parameter in a particular environment. For this reason, one should talk about a method's scalability with respect to a [parameter, metric, environment] triple.

Some challenging Theoretical Results when the growing parameter is the number of nodes (N)

- [1] *Piyush Gupta, P. R. Kumar, "The Capacity of Wireless Networks", IEEE Transactions on Information Theory, vol. 46, no. 2, March 2000*

  SINR threshold model: $\lambda = O\left(1/\sqrt[\gamma]{N}\right), \quad \gamma > 2$ Collision model: $\lambda = O\left(1/\sqrt{N}\right)$

- [2] *M. Grossglauser and D. Tse, "Mobility Increases the Capacity of Ad-hoc Wireless Networks", IEEE/ACM Transactions on Networking, vol. 10, no. 4, August 2002*

  SINR threshold model: $\lim_{N \to \infty} \mathrm{P}\left(\lambda \geq cW_{max}\right) = 1$

Some challenging Theoretical Results when the growing parameter is the number of nodes (N)

- [3] *O. Arpacioglu and Z. J. Haas, "On the scalability and capacity of wireless networks with omnidirectional antennas", submitted to IEEE INFOCOM'04, Hong Kong, China.*

-SINR threshold model: $\lambda = O(1/N)$

-A desired per node end-to-end throughput is not achievable as $N \rightarrow \infty$, unless the following conditions apply:

H does not exceed a constant,

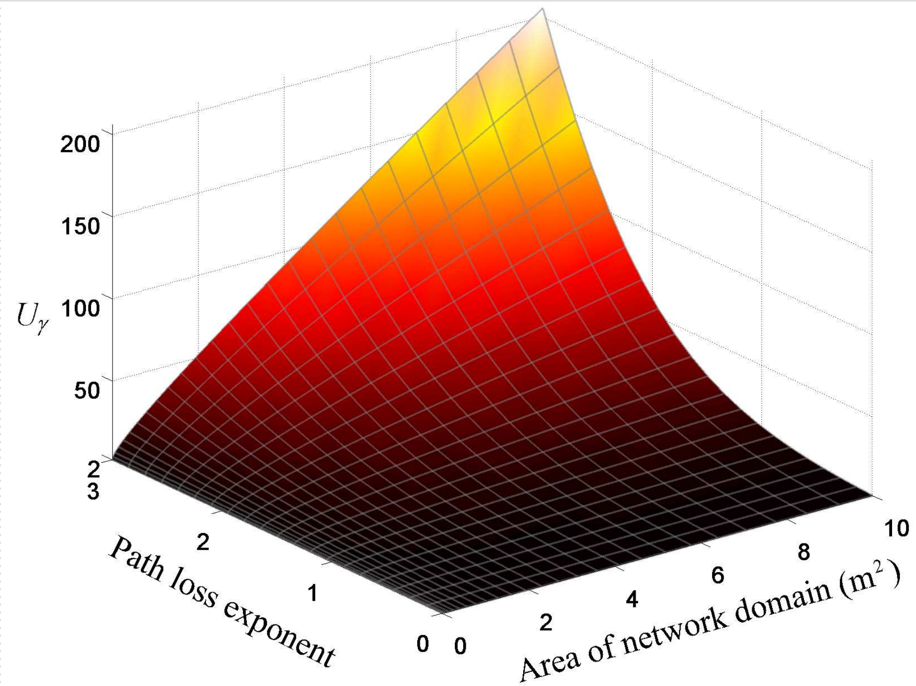
A grows with N, such that N is:

- $O(A^{\min\{\gamma/2,\,1\}})$ when $\gamma \neq 2$

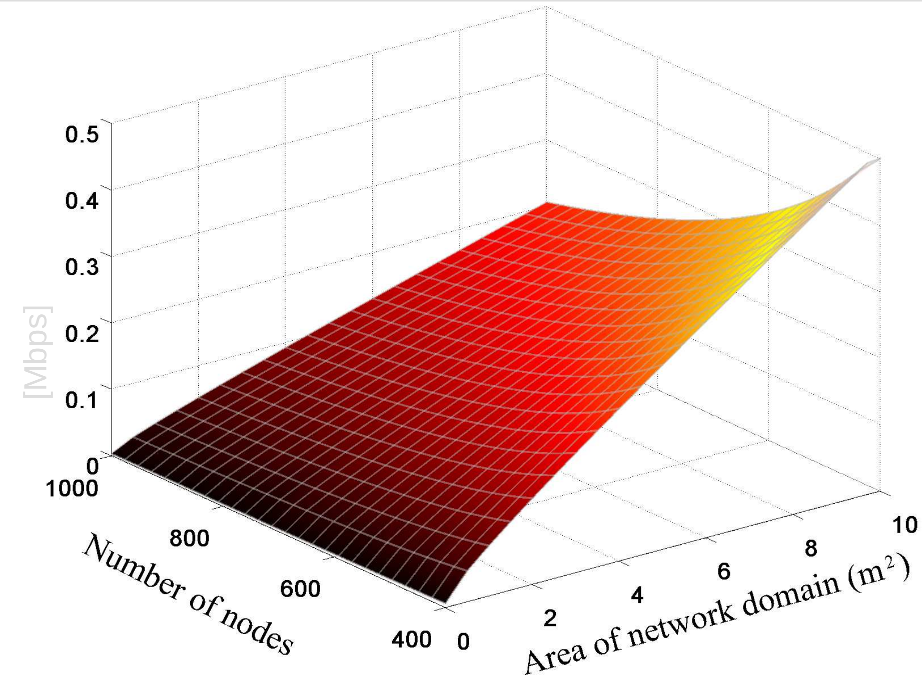
- $O(A/\log(A))$ when $\gamma = 2$

Upper bounds – An Example

- For example, when G = 10, β = 10 [dB], W_{max} = 1 [Mbps]:



Upper bound on N_t^{max} and N_t^Q



Upper bound on λ

Related Works that evaluate scalability

- Many of the studies focus on the implementation of a routing scheme that offers satisfactory performance as *N* increases.
  - Most of them developed their own set of metrics such as packet delivery ratio, throughput, end-to-end delay, routing overhead, average path length, or storage requirements.
  - Usually, evaluation of scalability has been based on simulations.
  - The main limitation of these works is the subjective choice of the metrics and other parameters used in the simulations.
- [4] C. Santivanez, B. McDonald, I. Stavrakakis, R. Ramanathan, "On the scalability of ad hoc routing protocols", IEEE INFOCOM'02, New York, June 2002.

Related Works that evaluate scalability (con't)

- First step towards developing a more objective and theoretical framework for analyzing scalability of wireless networks.
- Defines a routing protocol as scalable if the total overhead of the routing protocol does not exceed the traffic load of the network under optimal conditions, as the parameter approaches infinity.
- Compares scalabilities of routing protocols based on the relative overhead growth rates of the protocols.
- However, it (1) focuses only on the routing aspect of the problem, (2) evaluates scalability using routing overhead exclusively, and (3) chooses a specific set of environmental parameters.

Independent parameters

- INDEPENDENT PARAMETERS are aspects of the network that an evaluator of a method has the ability to change. (These parameters can be freely varied.)
- Some of such possible parameters are applicable to different types of methods are:
  - Number of nodes
  - Node density
  - Traffic load
  - Mobility
  - 1/(Physical size of nodes)
  - Accuracy (of the results of an algorithm)

Primary Metrics

- PRIMARY METRICS of the system are the dependent variables that are observed as the network is scaled with respect to an independent parameter.
- Since, most often, for a particular evaluation, an evaluator will choose more than one primary metric, the primary metrics are arranged in a SCALABILITY VECTOR. In general, scalability of individual metrics is insufficient to consider, but rather the scalability of all of the components in the vector must be simultaneously considered.
- Finite values of these metrics are necessary to ensure sufficient communication in the network.

Primary Metrics - Possible Definitions

- (1/throughput) of the network
  - Hop-by-hop throughput of a flow
  - End-to-end throughput of a flow
  - Throughput of the entire network
  - Minimum throughput over all flows
  - Average throughput over all flows
- Delay in the network
  - Maximum or average hop-by-hop delay
  - Maximum or average end-to-end delay
- Battery power required at the network nodes
- Memory/storage required at the network nodes
- Processing power required at the network nodes

Primary Metrics - Possible Definitions (con't)

- 1/(network lifetime)
  - Network dies when one of the nodes dies
  - Network dies when certain fraction of the nodes dies
  - Network dies when all of the nodes die
  - Network dies when the maximum number of possible connections decreases below a threshold value

Environmental Parameters

The following environmental parameters may affect scalability:

- Network characteristics
  - Mobility pattern of the nodes
  - Initial distribution of node locations
  - Area of the network domain
  - Existence of a wired backbone; relation between numbers of nodes and base stations
- Traffic pattern
  - Choice of destinations: random, local, etc.
  - Average number of hops between a source and a destination.

Environmental Parameters (con't)

- Routing layer
  - Method used to choose the next hop node of the received data
  - Overhead introduced to facilitate these next hop decisions
  - Method to identify nodes; e.g., uniquely identifying N nodes requires $\Theta(\log(N))$ IDs, which grows with N indefinitely
  - Response to errors and failures
  - Fairness in forwarding decisions

Environmental Parameters (cont.)

- Medium access layer
  - Reception model: collision-based, SINR threshold-based, BER-based or probability-based, adaptive rate models
  - Transmission model: ability to maintain multiple transmissions and/or receptions simultaneously
  - Scheduling of transmissions
  - Response to unsuccessful transmissions
  - Fairness in medium acquisition
- Physical layer
  - Link bandwidth
  - Transmission and reception modes: omnidirectional, directional; beamwidth, side lobes
  - Propagation model: path loss exponent, fading, shadowing

Environmental Parameters (cont.)

  - Power control, maximum transmission power, noise conditions
  - Modulation scheme: narrowband, wideband; processing gain, interference cancellation

- Node design
  - Memory/storage at nodes: maximum storage space, certain amount of buffer overflow permitted, loss is not allowed, or QoS buffering used
  - Processing power: maximum number of CPU cycles per unit time, identical allocation to all nodes, preference given to some nodes.

Absolute Scalability

- EFFICIENCY of a network is said to VANISH as an independent parameter tends to infinity if ANY of the primary metrics becomes arbitrarily large.
- A method is termed ABSOLUTELY SCALABLE with respect to a given parameter, if the efficiency of the network DOES NOT VANISH as the parameter tends to infinity.
- Example:
  - Choose the *number of nodes*, N, as the independent parameter.
  - Suppose *total overhead* and *1/throughput* are two of the primary metrics.

Absolute Scalability (con't)

- For constant average node degree, maximum path lengths increasing as $\Theta(N^{0.5})$ and other assumptions described in [4], the total overhead of HSLS (Hazy Sighted Link State Routing Protocol) is $\Theta(N^{1.5})$. Also, in the network model of [4], maximum achievable throughput of the entire network is $\Theta(N)$.
- This means that as N -> infinity, the total overhead of HSLS exceeds the amount the network can actually support, so the throughput and efficiency vanish. Thus, we say that HSLS is not absolutely scalable with respect to the triple [number of nodes; total overhead, 1/throughput; $\Theta(N^{0.5})$ maximum path lengths,…,[4]'s environmental parameters].

Relative Scalability

- A method e1 is termed MORE SCALABLE than another method e2 with respect to a given parameter p and primary metric m, if

$$\lim_{p \to \infty} \frac{m(e1)}{m(e2)} = 0$$

- If the result of this limit is a positive constant, then we say e1 and e2 are EQUALLY SCALABLE.
- Note that:
  - *without specifying the metric m, we are unable to define the relative scalability of e1 and e2 in terms of a parameter p.*
  - *e1 may be more scalable than e2 with respect to one metric, but less scalable with respect to another .*

Relative Scalability - Example

- Returning to the example from [4], again consider the number of nodes as the independent parameter, and compare HSLS total overhead with SLS (Standard Link State).
- Using all the assumptions from the previous example, the total overhead of e1 = HSLS is $\Theta(N^{1.5})$ and the total overhead of e2 = SLS is $\Theta(N^2)$. This means that

$$\lim_{N \to \infty} \frac{m(e1)}{m(e2)} = \lim_{N \to \infty} \frac{\Theta(N^{1.5})}{\Theta(N^2)} = \lim_{N \to \infty} \frac{1}{\Theta(N^{0.5})} = 0$$

- This means that <u>HSLS is more scalable than SLS with respect to the triple</u> [number of nodes; total overhead; $\Theta(N^{0.5})$ maximum path lengths,…, [4]'s environmental parameters].

Relative Weak Scalability

- It is possible that a parameter grows large in an ad hoc network, but cannot grow arbitrarily large. In particular, it might be impossible/impractical for a parameter to grow larger than some value, M.
- In this case, we consider only an interval [a, M], where a is the minimum value of the parameter and M is its maximum value.
- A method e1 is termed MORE WEAKLY SCALABLE than another method e2 with respect to a given parameter p and primary metric m over the range [a, M] , if

$$\int_a^M m`(e1)dp < \int_a^M m`(e2)dp$$

$$\Leftrightarrow \boxed{m(e1)\big|_{p=M} - m(e1)\big|_{p=a} < m(e2)\big|_{p=M} - m(e2)\big|_{p=a}}$$

Challenges in the application of the framework

- Clearly, absolute scalability, relative scalability, and relative weak scalability of a method are <u>heavily dependent on the environmental parameters</u>.
- A certain set of environmental parameters may lend itself well to one method compared to another.
  - For example, if the number of nodes is increased, then increasing the area of the network domain and keeping the node density constant could lead to good scalability patterns, while keeping the area of the network domain constant would cause the system to suffer from high node density and would not likely be scalable.
- It may be difficult to find a set of environmental parameters, which can lead to a <u>fair comparison</u> among methods.

Challenges in the application of the framework

- Furthermore, interactions among environmental parameters and between independent and environmental parameters may also affect fairness of a comparison.
  - For example, while comparing relative scalability of two routing protocols, the choice of the MAC layer protocol may change the result of the comparison.
- Consequently, standardization of a set of environmental parameters remains a challenge to achieve fair comparison among different methods.

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- [2] M. Grossglauser and D. Tse, “Mobility increases the capacity of wireless adhoc networks,” IEEE/ACM Trans. on Networking, vol. 10, no. 4, pp. 477–486, August 2002.
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