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Notes on Scalability of Wireless Ad hoc Networks

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<draft-irtf-and-scalability-notes-01.txt>,

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

[http://wnl.ece.cornell.edu/Publications/ draft-irtf-ans-scalability-definition-01.txt](http://wnl.ece.cornell.edu/Publications/draft-irtf-ans-scalability-definition-01.txt)

Updates from previous draft

NEW!

- Based on group mailing list discussions
- Added definition of optimal scalability with examples (captures idea of sufficient scalability)
- Emphasis on [environment, independent parameter, primary metric(s)] triple
- Added to environmental parameters

Thanks to all of you who provided comments!

What is Scalability?

- A measure of a method's ability to maintain efficiency, as some network parameters increase to very large values

Environment	Parameter	Metric
Only single-hop communications	Number of nodes	Required storage at each node
Random destinations	Node density	Overhead

- E.g., applicable to sensor networks

Objective

- To provide working definitions of
  - absolute scalability
  - optimal scalability
  - relative scalability
  - weak scalability

  for methods of an ad hoc network (e.g. an algorithm or protocol)

Challenging theoretical results

- [1] *P. Gupta, P. R. Kumar, "The Capacity of Wireless Networks", 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", August 2002*

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

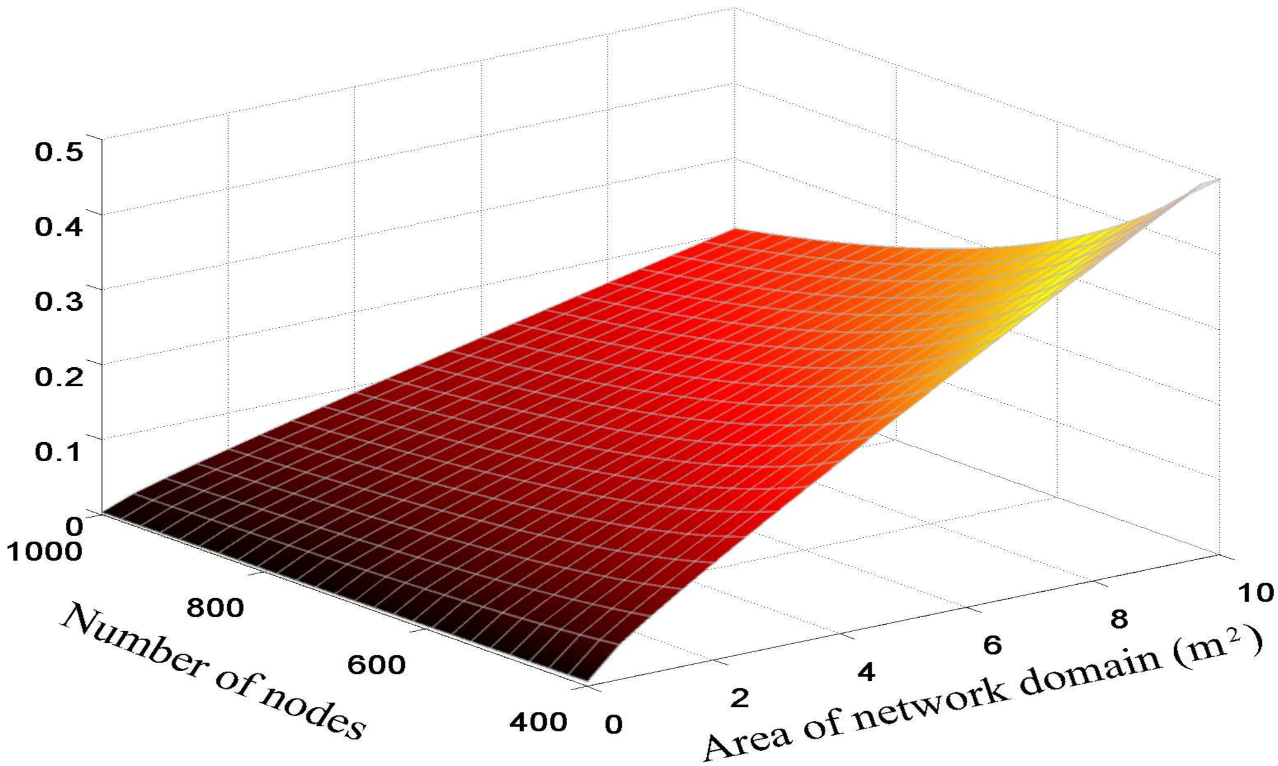
Challenging theoretical results

- [3] *O. Arpacioglu and Z. J. Haas, "On the scalability and capacity of wireless networks with omnidirectional antennas", submitted to IEEE INFOCOM'04.*
- SINR threshold model
- Desired per node end-to-end throughput *only* achievable as number of nodes $N \rightarrow \infty$ if
  - Average number of hops does not exceed a constant
  - ***Area A,*** grows with ***N*****,** such that ***N*** is:

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

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

End-to-end throughput



Upper bound on end-to-end throughput λ

Other related work

- Focus on particular implementation of protocol as number of nodes, *N*, increases
- Develop their own metrics, such as packet delivery ratio, throughput, end-to-end delay, routing overhead… (subjective)
- Evaluate based on simulations
- [4] C. Santiváñez, B. McDonald, I. Stavrakakis, R. Ramanathan, "On the scalability of ad hoc routing protocols", IEEE INFOCOM'02, New York, June 2002.

[4] "On the scalability of ad hoc routing protocols"

- First attempt for more objective, theoretical work
- Scalable if total overhead does not exceed traffic load
- Compares protocols based on growth rates
- But… - Focuses only on the routing aspect of the problem
  - Evaluates scalability using routing overhead exclusively
  - Chooses a specific set of environmental parameters

Independent parameters

- Can be freely varied by the user
- Define scalability as these approach ∞
- E.g.
  - Number of Nodes
  - Node density
  - Traffic load
  - Mobility
  - 1/(physical size of nodes)
  - Accuracy (of an algorithm)

Primary Metrics

- dependent variables that are observed as the network is scaled w.r.t. an independent parameter (We hope $\not\to \infty$!)
- E.g.
  - (1/throughput) of the network
  - Delay in the network
  - Battery power consumed at nodes
  - Memory/storage at nodes
  - Processing load at nodes
  - 1/(network lifetime)

Environmental Parameters

- Aspects of environment and technological choices affect scalability

Network characteristics	Mobility, existence of wired backbone, area
Traffic pattern	Choice of destinations (random or local)
Routing layer	Labeling of nodes, overhead for decision making
Medium Access layer	Reception model, transmission model, scheduling
Physical layer	Link bandwidth, path loss, modulation
Node design	buffer size, CPU cycles/time

Absolute scalability

- Scalable with respect to a triple *[E,p,m]*
- *e1* absolutely scalable if the efficiency of the network does not vanish as the *p* tends to ∞

Efficiency vanishes if *any* primary metric becomes arbitrarily large

Absolute scalability - example

- Consider: method HSLS (Hazy Sighted Link State) *p* = number of nodes, *m* = 1/(throughput), in environment *E*, path lengths are $\Theta(N^{0.5})$, other assumptions in [4], so total overhead is $\Theta(N^{1.5})$. Maximum achievable throughput of network is $\Theta(N)$.

- Overhead exceeds amount network can support $\Rightarrow$ efficiency vanishes

- HSLS not absolutely scalable w.r.t. *[E,p,m]*

Relative scalability

- Scalable with respect to a triple *[E,p,m]*
- *e1* more scalable than *e2* if

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

- *e1* equally scalable to *e2* if

$$\lim_{p \to \infty} \frac{m(e1)}{m(e2)} = k > 0, \text{ k is finite}$$

Note: e1 may be more scalable than e2 with respect to one metric, but less scalable with respect to another

Relative scalability - example

- Consider: e1 = HSLS, e2 = SLS
  p = *N* (number of nodes), *m* = total overhead, environment *E* from [4], so *e1* has overhead of $\Theta(N^{1.5})$, *e2* has overhead of $\Theta(N^2)$.

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

- HSLS is more scalable than SLS w.r.t. [*E* from [4], *N*, total overhead]

Optimal scalability

- *e1* optimally scalable w.r.t. *[E,p,m]*, if **no** other method is *more scalable* w.r.t. *[E,p,m]*
- Useful to consider, especially if absolute scalability is impossible w.r.t. *[E,p,m]*

Optimal scalability - example

- Consider: *p = N* (number of nodes), *m1* = bandwidth consumed, *m2* = overhead, *E:* traffic of $\Theta(N^{2.5})$.
  Like the previous example, *e1* has overhead $\Theta(N^{1.5})$, *e2* has overhead $\Theta(N^2)$.

- Both *e1*, *e2* are optimally scalable w.r.t. *[E, N,* bandwidth*]*, since no method can perform better than $\Theta(N^{2.5})$.
- *e2* is not optimally scalable w.r.t. *[E, N,* overhead*]*, since *e1* is more scalable.

Relative weak scalability

- *e1* more weakly scalable than *e2* over range *[a, M]* w.r.t. *[E,p,m]* if

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

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

- Considers only a finite interval *[a, M]*
- Useful if *p* in *[E,p,m]* must be contained in some *[min, max]* range

Challenges in application

- Some environments *E* might lend themselves well to certain types of applications
- Parameters of *E* may interact
- Difficult to find *E* for fair comparison

Main challenge: Find a standard set of environments for meaningful comparison

References (1)

- [1] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” IEEE Trans. on Info. Theory, vol. 46, no.2, pp. 388–404, March 2000.
- [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.
- [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.
- [4] C. Santivanez, B. McDonald, I. Stavrakakis, R. Ramanathan, “On the scalability of ad hoc routing protocols”, IEEE INFOCOM'02, New York, June 2002.

References (2)

- [5] A. Iwata, C. Chiang, G. Pei, M. Gerla, T. Chen, “Scalable routing strategies for ad hoc wireless networks”, IEEE Journal on Selected Areas in Communications, vol. 17, issue: 8, August 1999, pp: 1369 -1379.
- [6] C. Santivanez, R. Ramanathan, I. Stavrakakis, “Making link-state routing scale for ad hoc networks”, MobiHoc 2001, Long Beach, CA, USA, Oct. 4-5, 2001.
- [7] X. Hong, M. Gerla, Y. Yi, K. Xu, and T. Kwon, “Scalable ad hoc routing in large, dense wireless networks using passive clustering and landmarks”, Proceedings of ICC 2002, NY, April 2002.

References (3)

- [8] I. D. Aron, S. K. S. Gupta, “On the scalability of on-demand routing protocols for mobile ad hoc networks: an analytical study”, Journal of Interconnection Networks, vol. 2, No. 1, pp: 5-29, 2001.
- [9] J. Li, J. Jannotti, D. S. J. De Couto, D. R. Karger, R. Morris, “A scalable location service for geographic ad hoc routing”, Proceedings of the 6th ACM MobiCom, 2000.