MASS’05 Keynote Speech on

On Some Choices in Design for QoS in Ad Hoc and Sensor Networks

Prof. Zygmunt J. Haas
Wireless Networks Laboratory
Cornell University
Ithaca, NY 14853, U.S.A

E-mail: haas@ece.cornell.edu
URL: wnl.ece.cornell.edu

The Wireless Networks Laboratory (WNL) @ Cornell - Our Charter

Research in our lab is focussed on the effect of:

Mobility in wireless networks, and

Lack of infrastructure (ad hoc technology) on the design and implementation of networking protocols

One of the key question that we are studying:

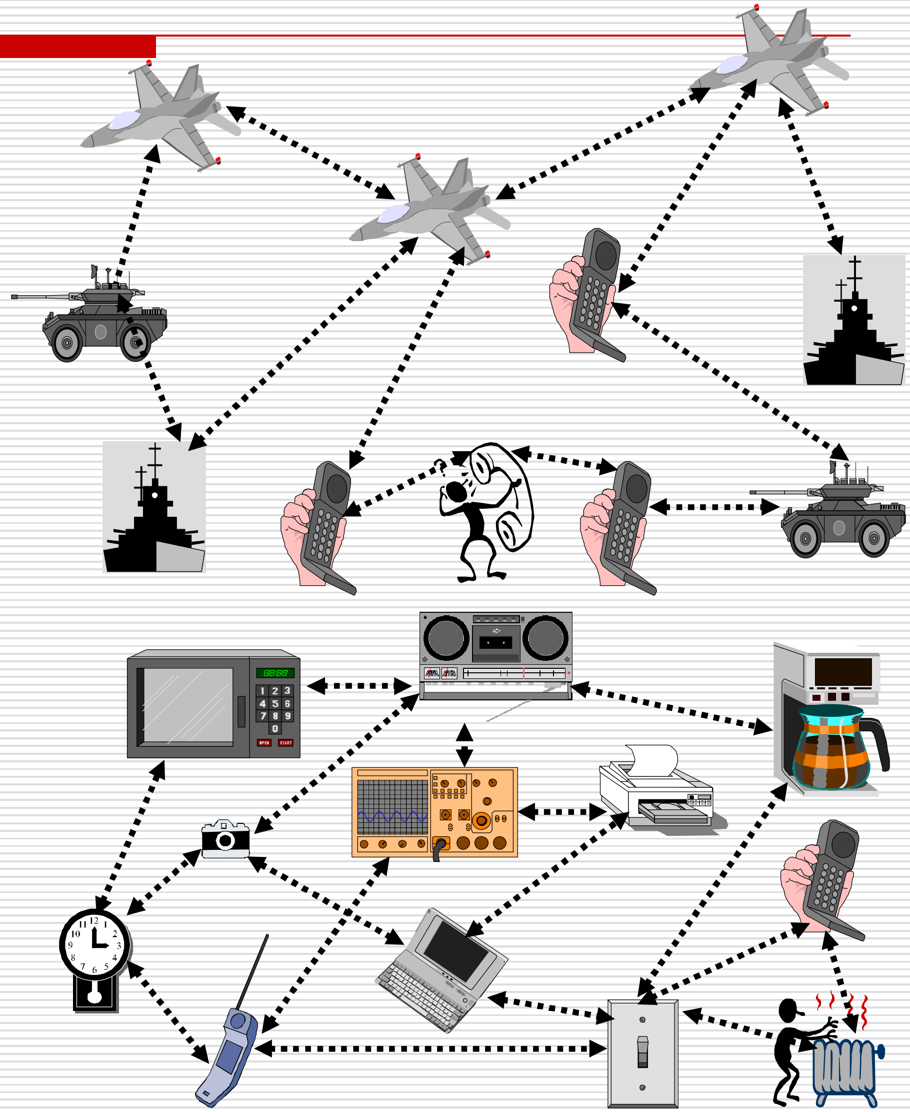
what are the limitations of the ad hoc and sensor networks in delivering real-time, secure, and manageable communication, and

how to overcome those limitations using practical technical solutions

Ad-Hoc Networks: Definition

Some Salient Features of Ad Hoc Networks:

✓ fast deployable
✓ infrastructure-less network
✓ rapidly and frequently reconfigurable topologies
✓ self-adaptable to changing networking parameters (e.g., traffic patterns) and communication environment (e.g., propagation conditions)
✓ adaptable to different and differing (in time) users' mobility patterns
✓ allows quality of service provisioning
✓ supports various media traffics (e.g., "best effort", (limited) real-time, etc)
✓ hybrid technologies (e.g., RF, optics)cc



Challenges of Ad-Hoc Networks

[Z.J. Haas and S. Tabrizi, "On Some Challenges and Design Choices in Ad-Hoc Communications," IEEE MILCOM'98]

- ***The challenges in the design of Mobile Ad-Hoc Networks (MANETs) stem from their following attributes:***
  - **the lack of centralized entity ⇒ the need for self-organizing and distributed protocols**
  - **the possibility of rapid platform movements; i.e., highly versatile network topology ⇒ fast convergent and adaptive protocols**
  - **<u>all</u> communications are carried over the wireless medium ⇒ efficient and robust protocols**

Commercial Ad-Hoc Networks?

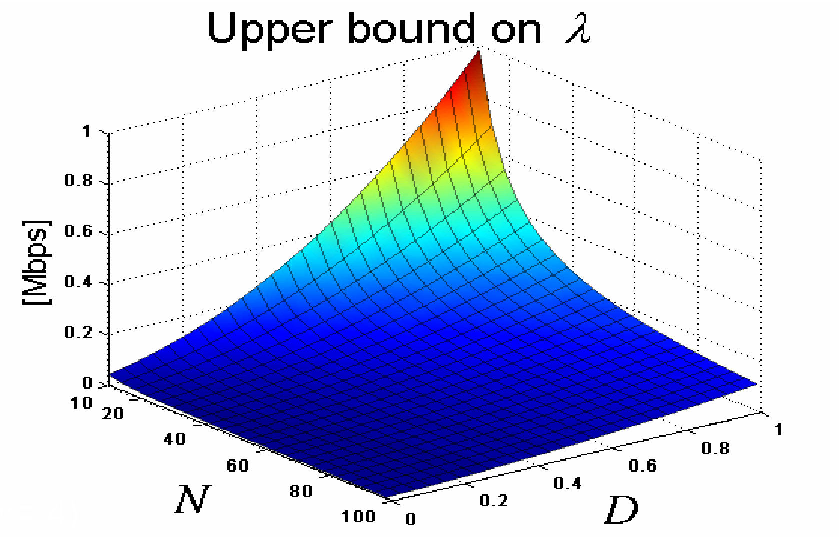
- ***Technology***
  - **Is multihop technology commercializable?**

    (Note that the commercial environment is not necessarily collaborative)
- ***Application***
  - **Which applications would benefit (or even require) this technology?**
- ***Design/Implementation***
  - **Is reliable, manageable, survivable, and secure implementation feasible?**
- ***Operational/Business-related***
  - **How to manage/maintain the network, how to bill for services ?**

Sensor Networks: Definition

Differing Features of Sensor Networks:

- ✓ unattended operation
- ✓ many-to-one communication patterns
- ✓ more stringent energy limitations
- ✓ topology usually static (or limited mobility)
- ✓ massive deployment (thousands to tens of thousands devices)
- ✓ individual nodes are not addressable
  - ➢ geographically dependent info.
- ✓ single nodes are unreliable
  - ➢ but, overall, highly reliable network
- ✓ energy-depleted nodes die; network lifetime should be maximized
- ✓ usually single and constant traffic type and traffic patterns
- ✓ low network utilization

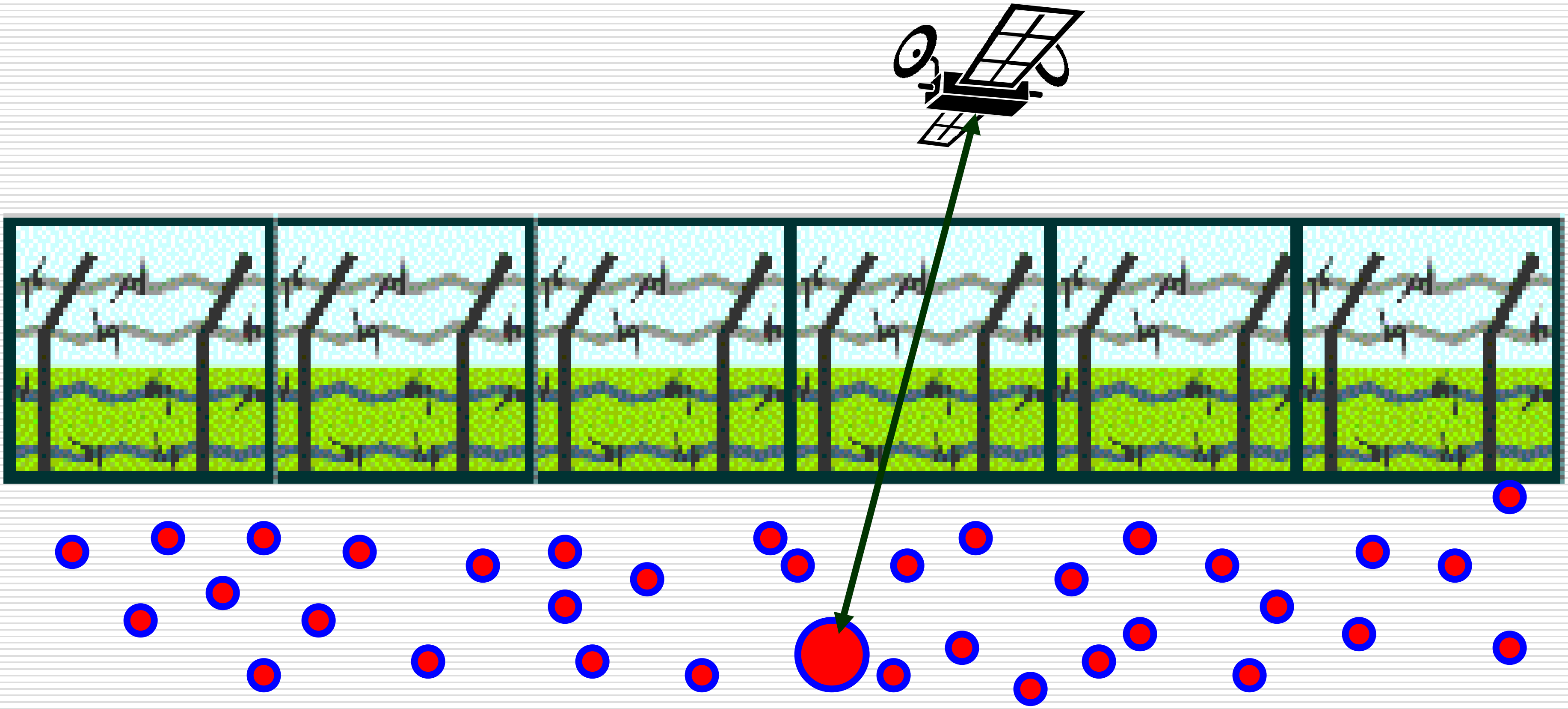


An example of our research project:

There are severe limitations on how dense a massively deployed network could be.

We study these limitations, as to understand what are the <u>scalability</u> bounds and feasible <u>growability</u> patterns of such networks

Sensor Networks



Ad Hoc vs. Sensor Networks

Some Salient Features of Ad Hoc Networks:

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- ✓ infrastructure-less network
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communication environment (e.g., propagation conditions)

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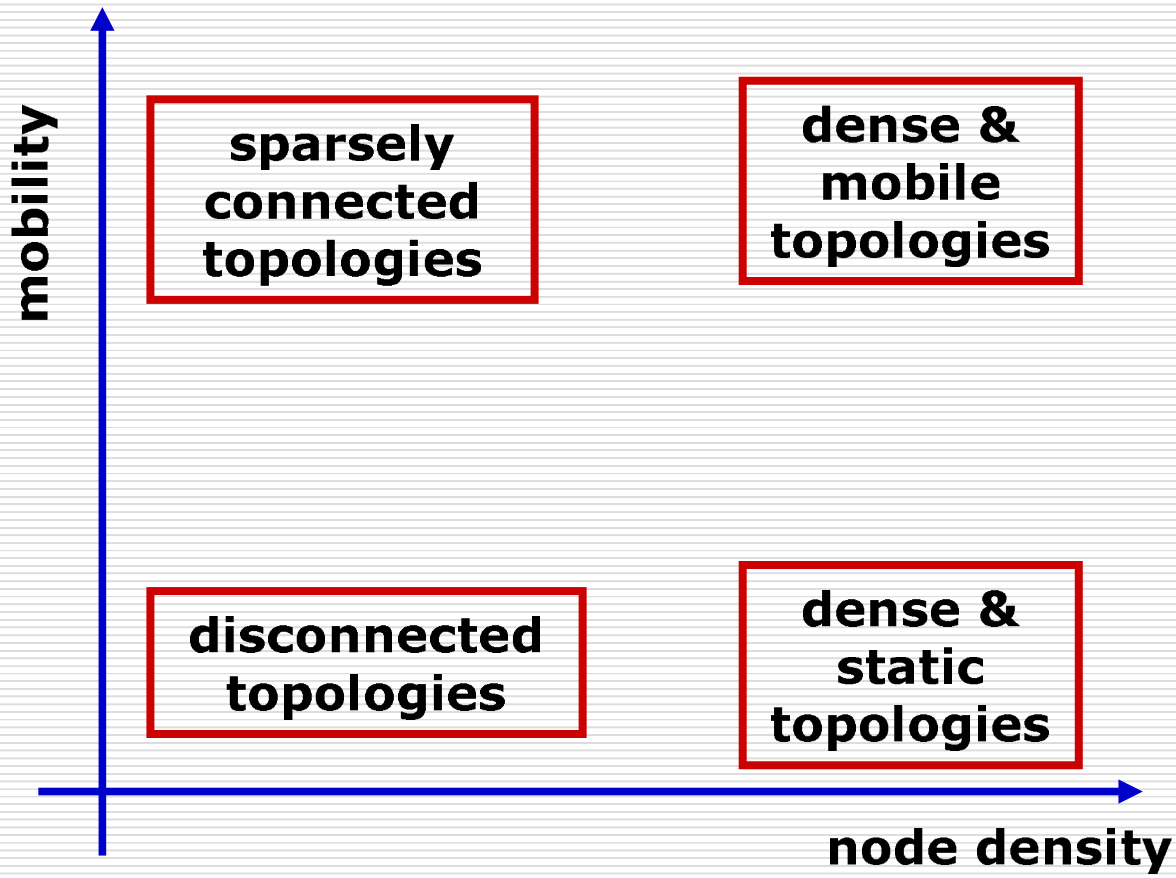
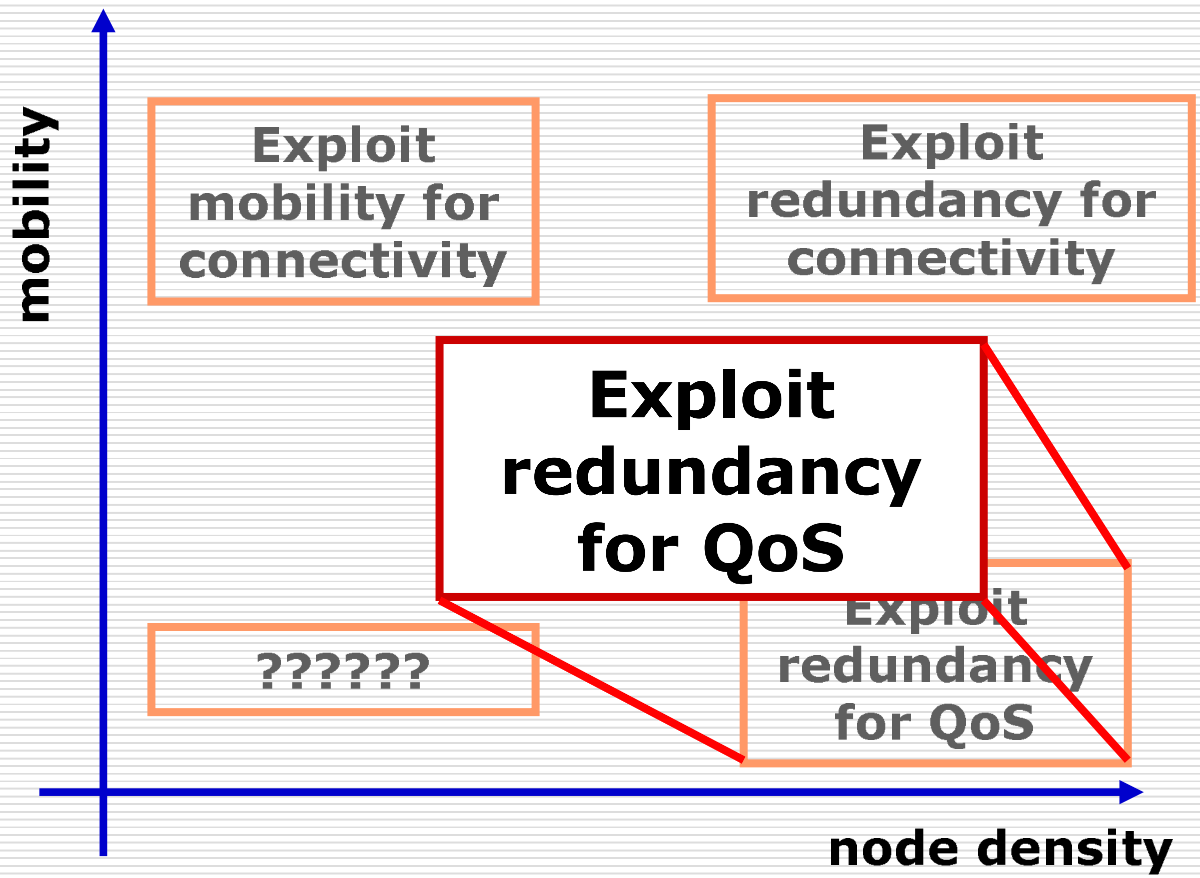
Ad Hoc Networks have small number of typically mobile nodes

Sensor Networks have massive number of typically static nodes

Some Architectural Design Choices



Some Architectural Design Choices



P. Papadimitratos and Z.J. Haas,
"Secure Message Transmission in Mobile Ad Hoc Networks,"
***Elsevier Ad Hoc Networks Journal*, vol. 1, no. 1, Jan/Feb/March 2003**

P. Papadimitratos and Z.J. Haas,
"Securing Mobile Ad Hoc Networks,"
***The Handbook of Ad Hoc Wireless Networks,* CRC Press 2003**

P. Papadimitratos and Z.J. Haas,
"Securing Data Communication in Mobile Ad Hoc Networks,"
accepted for publication in the *IEEE Journal on Selected Areas in Communications,* special issue on "Security in Wireless Ad Hoc Networks," 2006

Secure Communication in Ad hoc Networks

- The Goal: Maintain end-to-end connectivity in the presence of adversaries across an unknown, frequently changing multi-hop wireless network
- The Solution: Security for route discovery and data forwarding stages
- Design principles
  - No restrictive assumptions on the network trust, membership and size
  - Single end-to-end security association per source-destination pair
  - Limited cryptographic overhead

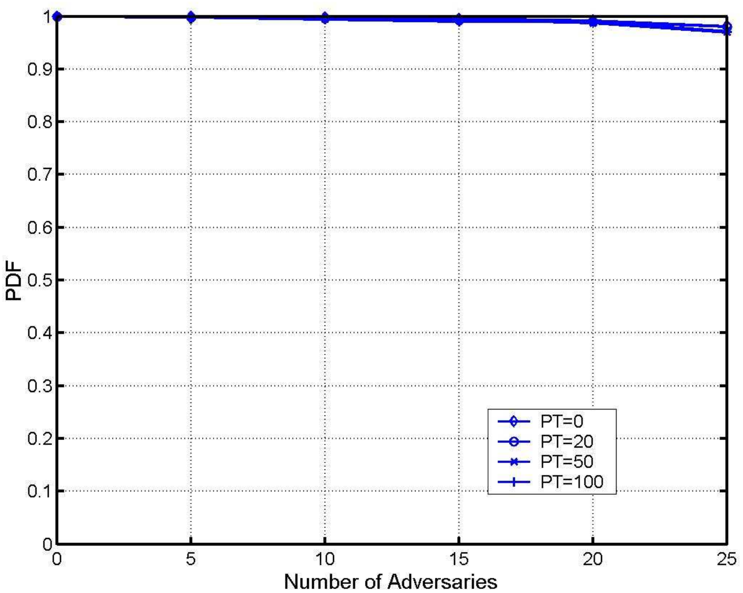
Secure Message Transmission (SMT)

- ***Correct Route ≠ Secure Route***
- ***Deliver data in the presence of adversaries***
  - **Detect and avoid compromised routes**
  - **Tolerate malicious and benign faults**
  - **Low delay, limited overhead**
- ***Basic Elements***
  - **End-to-end secure and robust feedback**
  - **Dispersion of the transmitted data**
  - **Simultaneous usage of multiple paths**
  - **Adaptation to the network conditions**

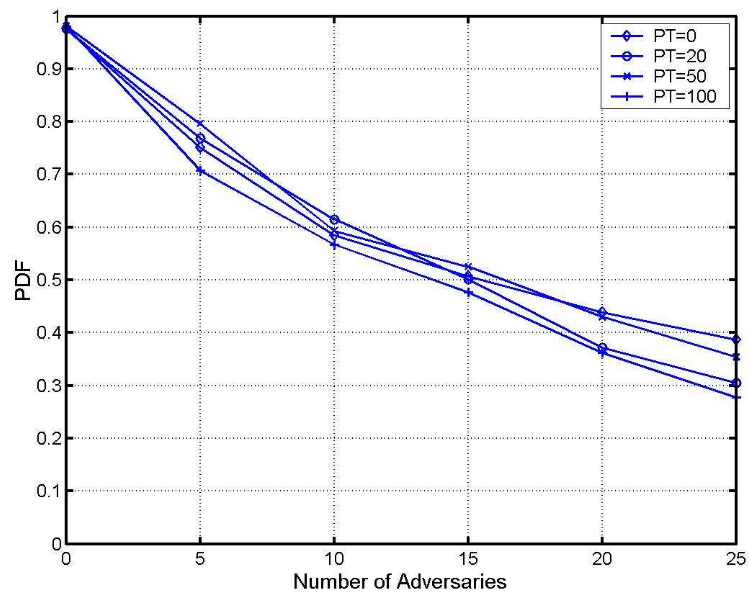
SMT Performance Evaluation

Packet Delivery Fraction

SMT



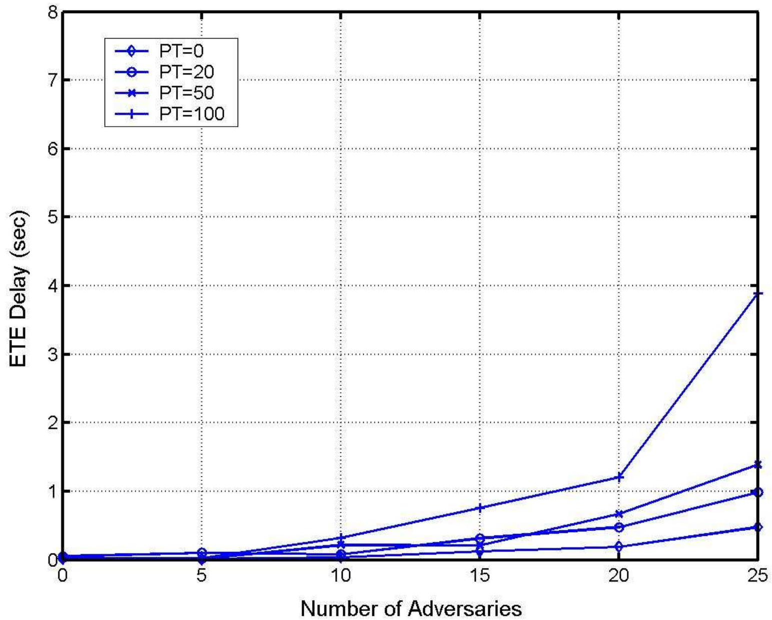
No data security



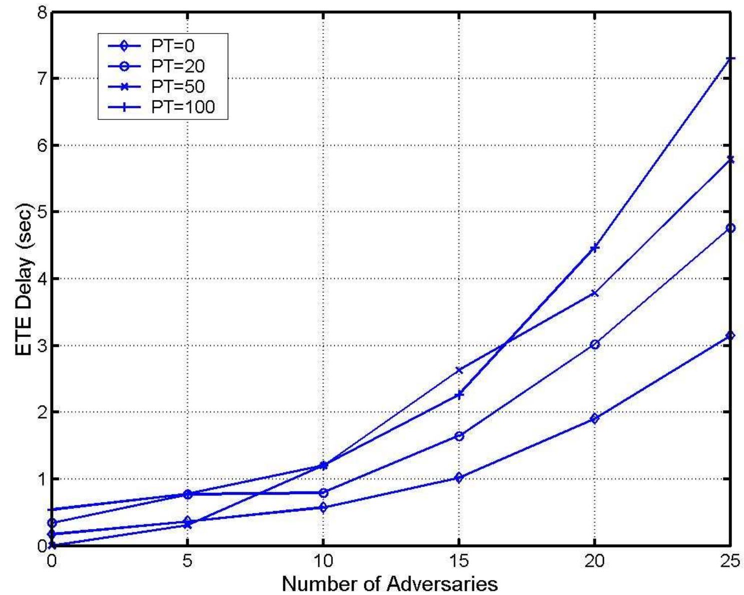
SMT Performance Evaluation (cont'd)

End-to-End Message Delay

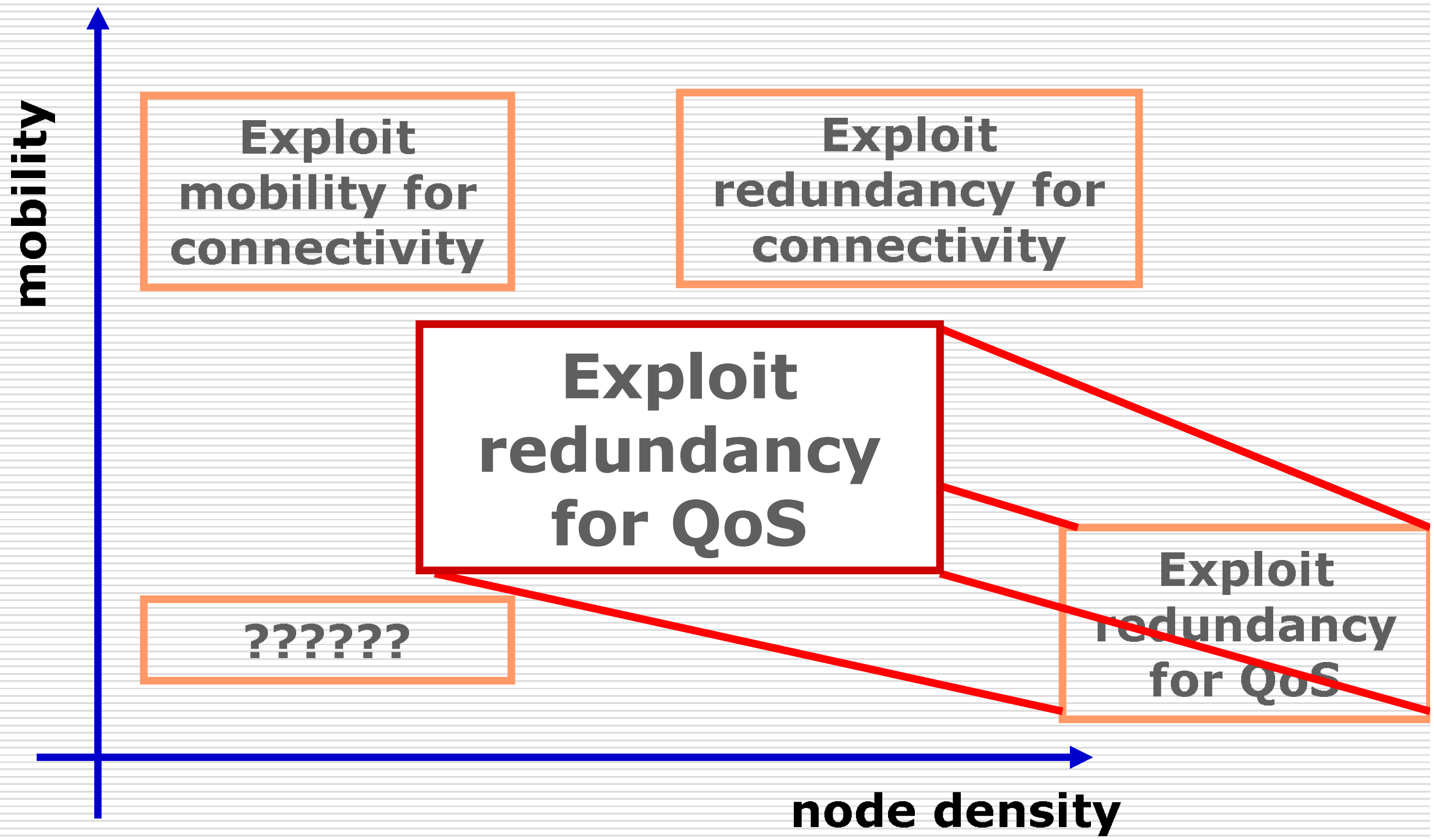
SMT



Single-Path Secure Data Forwarding



Some Architectural Design Choices



O. Arpacioglu and Z.J. Haas,
"On the Scalability and Capacity of Single-User-Detection Based Wireless Networks with Isotropic Antennas,"
accepted for publication in the *IEEE Transactions on Wireless Communications,* 2006

O. Arpacioglu and Z.J. Haas,
"On the Scalability and Capacity of Planar Wireless Networks with Omnidirectional Antennas,"
Wireless Communications and Mobile Computing journal, 2004; 4:1-18

O. Arpacioglu and Z.J. Haas,
"On the Capacity of Wireless Sensor Networks with Omnidirectional Antennas,"
accepted for publication in the Journal of the Brazilian Telecommunications Society, special issue on "Sensors and Ad Hoc Networks," 2005

Problem Statement

- **Objective:** To determine the required conditions for the scalability of wireless networks with the number of nodes.

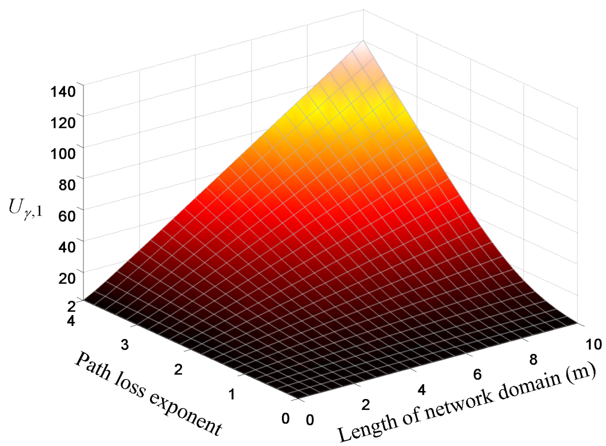
- Main requirement for scalability : Per node end-to-end throughput capacity (λ) should not approach zero as the number of nodes in the network becomes large.

- So, we should understand how λ depends on various parameters of the system, such as:
  - Number of nodes, N
  - Volume of the network domain, V
  - Path loss exponent, γ
  - Processing gain, G
  - Threshold SINR, β

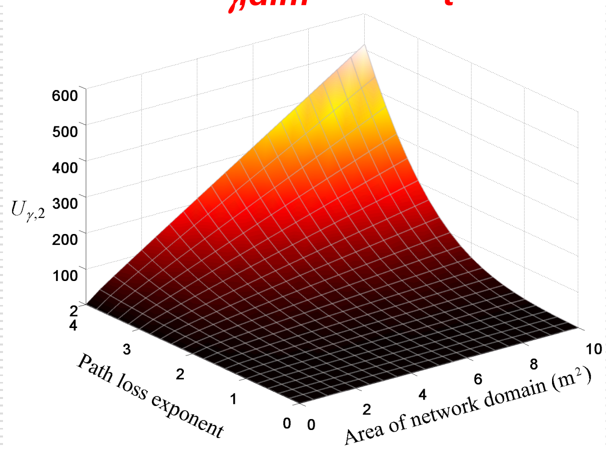
Results from the Analysis of the Upper Bounds

- N_t^Q is:
  - $O(V^{\min\{\gamma / \dim, 1\}})$ when $\gamma \neq \dim$
  - $O(V / \log(V))$ when $\gamma = \dim$
  - $O(\gamma^{\dim})$
  - $O(G / \beta)$
- N_t^{max} and λ are:
  - $O(1)$ w.r.t. V and γ
  - $O(\min\{G / \beta, s\})$ w.r.t. G / β
- ***If $\gamma \to 0$ or $V \to 0$, $N_t^Q \leq N_t^{max} \leq 1 + G / \beta$. This conforms with the intuitive expectation that lack of attenuation is equivalent to lack of space.***

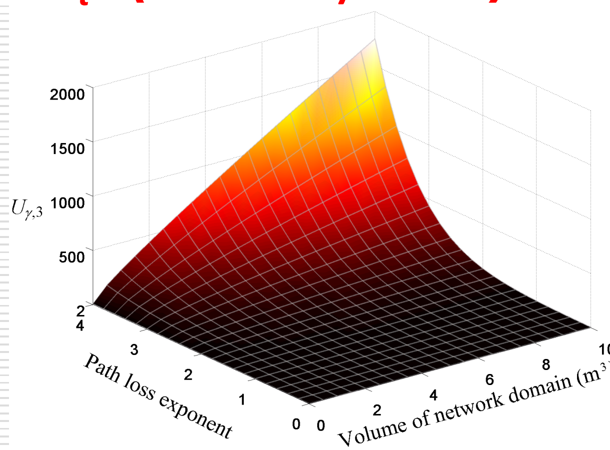
The common upper bound $U_{\gamma,\dim}$ on N_t^{max} and N_t^Q ($G = 10$, $\beta = 10$)



Q is a line



Q is a circle



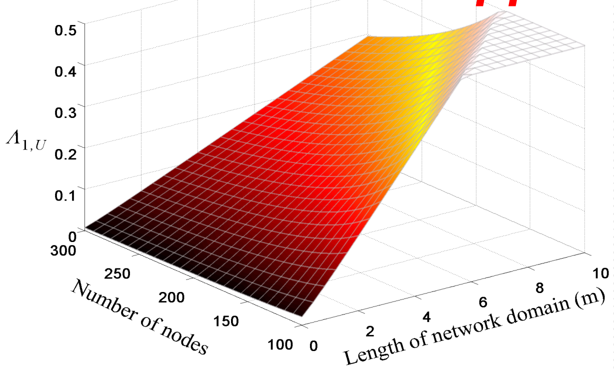
Q is a sphere

Results from the Analysis of the Upper Bounds (cont.)

- λ is O (1/N) and O (1/H) even when the
  - mobility pattern of the nodes,
  - spatial-temporal transmission scheduling policy,
  - temporal variation of transmission powers,
  - source-destination pairs,
  - possibly multi-path routes between them

  are <u>optimally chosen</u>, and even when the
  - nodes maintains multiple simultaneous trans. And recept.
  - bandwidth is divided into smaller sub-channels

The normalized upper bound on λ ($G = 10$, $\beta = 10$, $\gamma = 3.2$, $H=1$, $s=1$, $c=1/2$)



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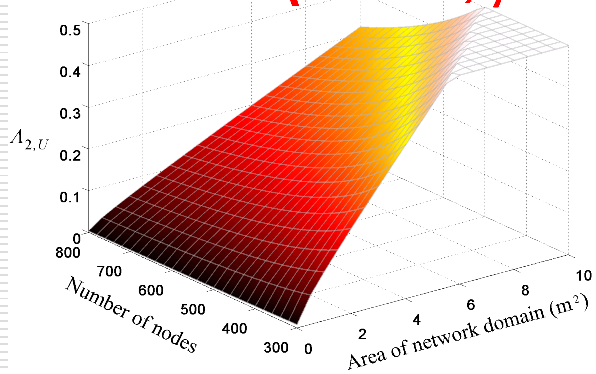

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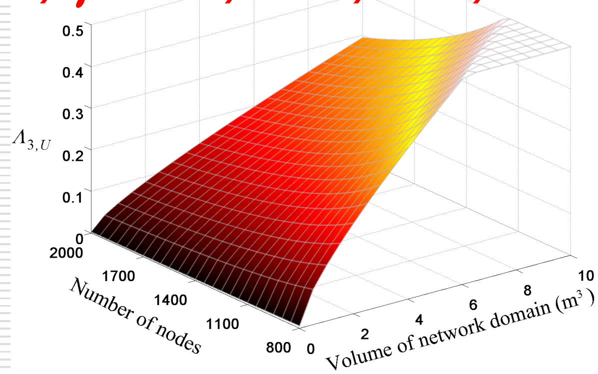
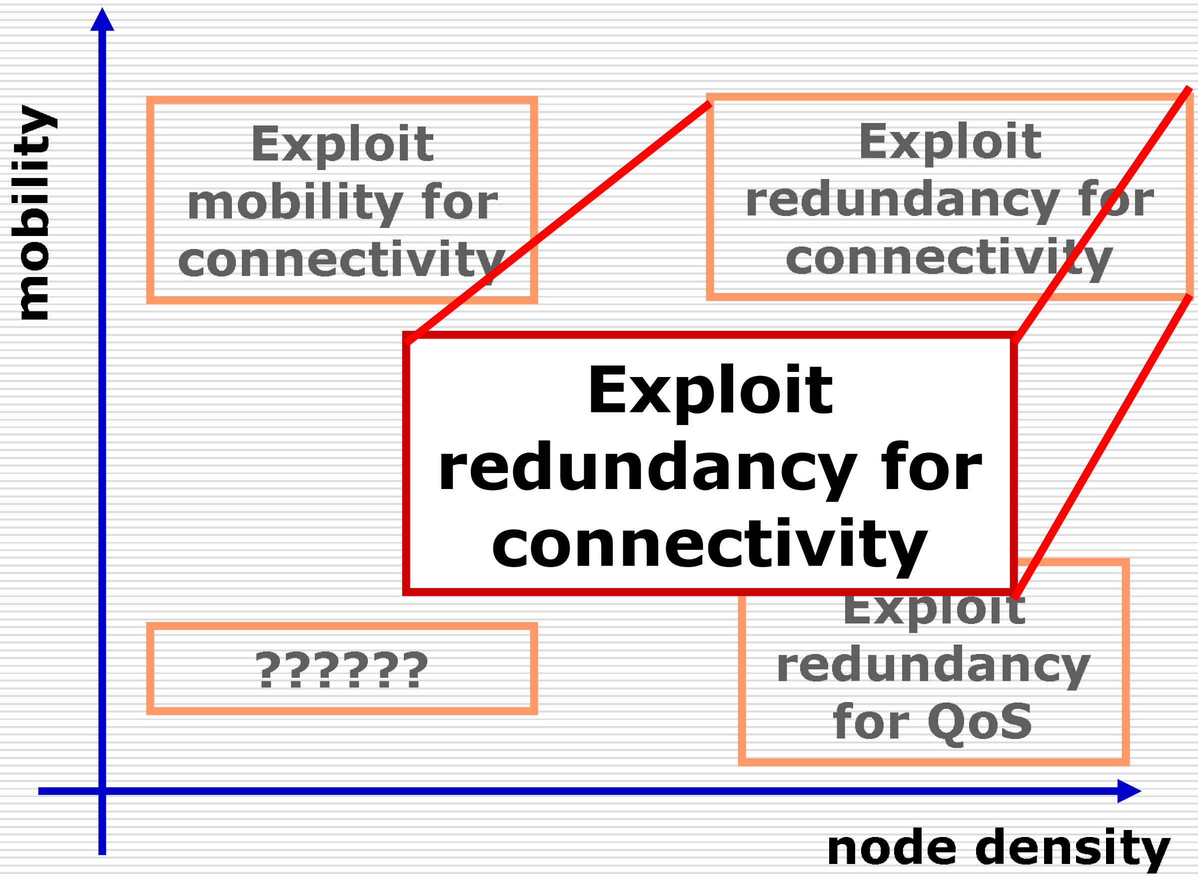


Q is a sphere

Conclusions

- ***The capacity results of previous models were extended by:***
  - **using a bounded propagation model,**
  - **finding results on λ without restricting the mobility pattern,**
  - **considering the situation when the nodes can maintain multiple simultaneous transmissions and/or receptions,**
  - **addressing how λ depends on V, γ, G and β as well as N.**
- ***Regarding scalability, to prevent the vanishing of λ as N grows,***
  - **keeping H bounded,**
  - **increasing the volume of the network domain at an appropriate rate are found to be essential.**

Some Architectural Design Choices



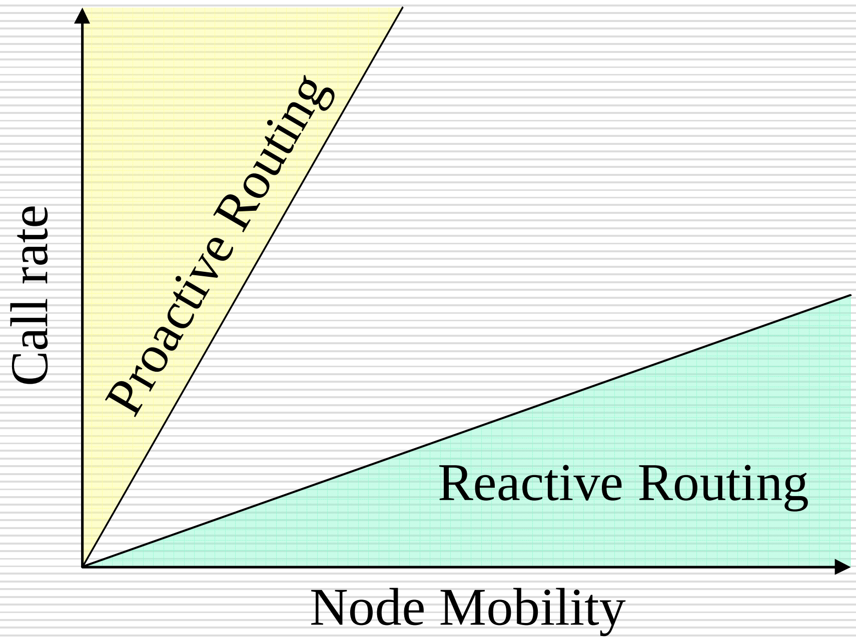
Hybrid Routing to Ad Hoc Networks

M.R. Pearlman and Z.J. Haas,
"Determining the Optimal Configuration of for the Zone Routing Protocol,"
IEEE JSAC, special issue on Ad-Hoc Networks, vol. 17, no.8, August 1999

Z.J. Haas and M.R. Pearlman,
"The Perforamnce of Query Control Schemes for the Zone Routing Protocol,"
ACM/IEEE Transactions on Networking, vol. 9, no. 4, pp. 427-438, August 2001

P. Samar, M.R. Pearlman, and Z.J. Haas,
"Hybrid Routing: The Pursuit of an Adaptable and Scalable Routing Framework for Ad Hoc Networks,"
The Handbook of Ad Hoc Wireless Networks, CRC Press 2003

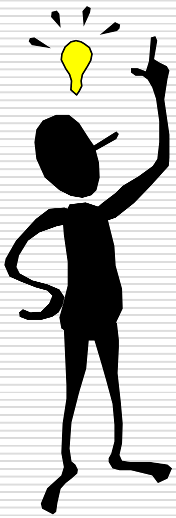
Applicability of Hybrid Routing to Ad Hoc Networks



- MANET routing protocols could be classified either as Proactive (e.g, OLSR, TBRF) or Reactive(e.g., DSR, AODV).
- Proactive or Reactive protocols perform well only at the "edges" of ad hoc network design space.

- Two <u>main</u> parameters determine whether the environment would be better served by a proactive or reactive protocol; Call Rate and Mobility

Proactive Vs. Reactive Routing

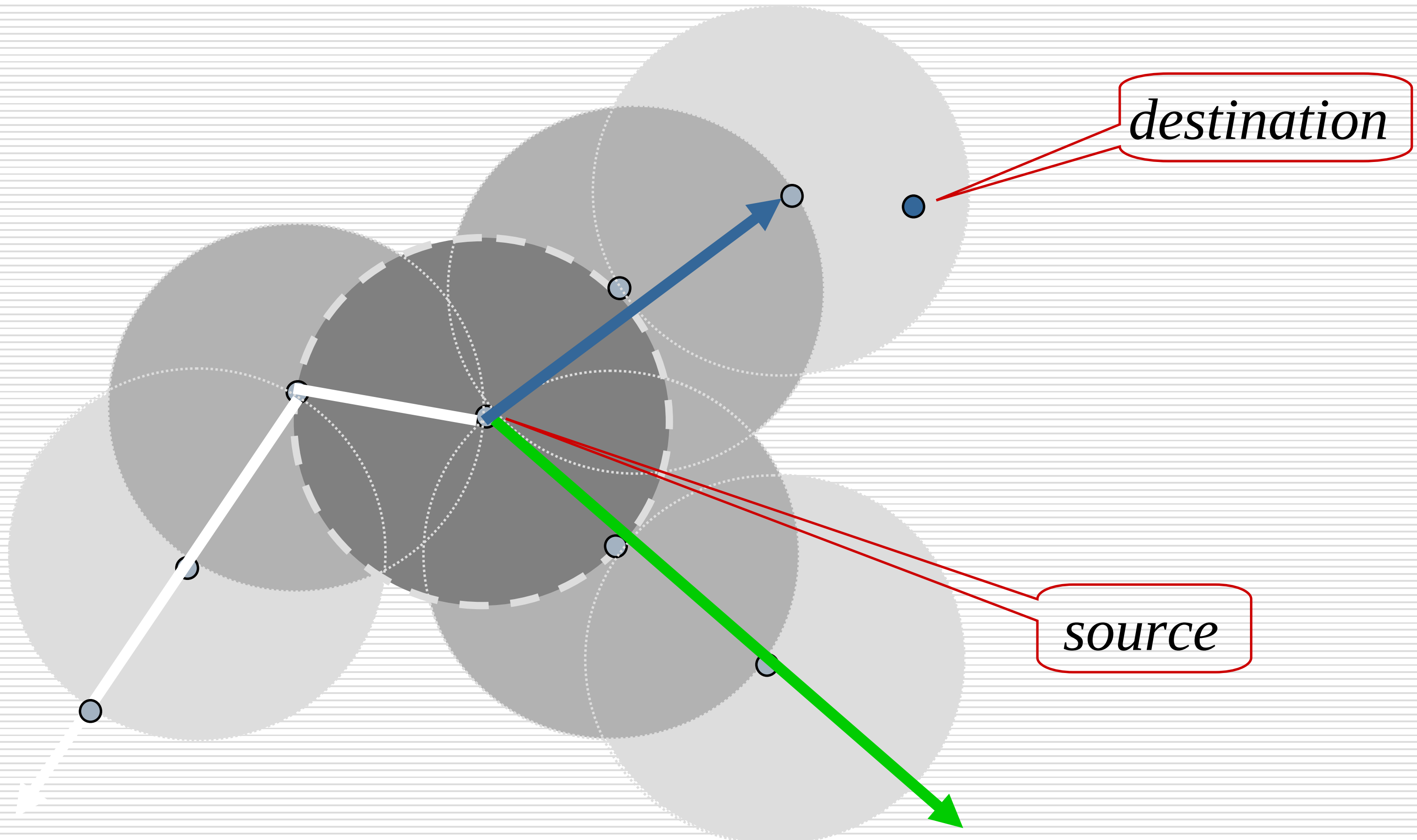


A hybrid protocol incorporates the advantages of the proactive schemes (fast route determination) with the advantages of the reactive schemes (low volume of control traffic)

An example:

The Zone Routing Protocol (ZRP)

The Zone Routing Protocol (ZRP)



Introduction to the Zone Routing Protocol (ZRP)

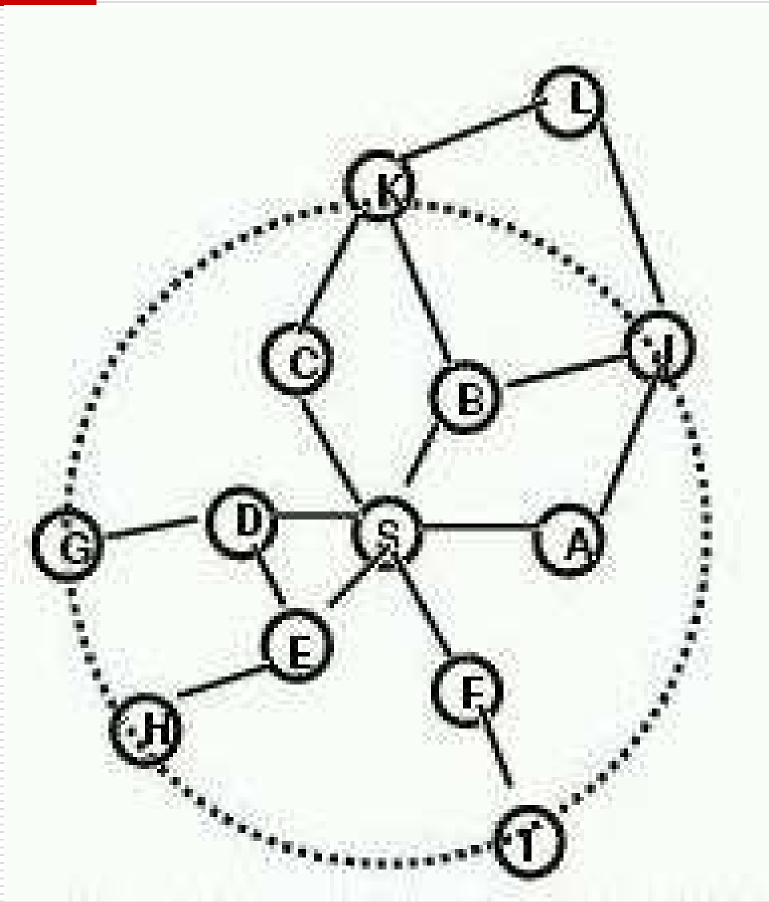
- **The Zone Routing Protocol (ZRP) is specifically designed for Ad Hoc Networks. It is a hybrid of the reactive and proactive protocols and works on the concept of *routing zones* to efficiently route the query to the destination.**

- **In ZRP, a node proactively maintains routes to destinations within a local neighborhood, called the routing zone, using a table-driven protocol, called the *IntrAzone Routing Protocol (IARP).***

- **The *IntErzone Routing Protocol (IERP),* an on-demand protocol, reactively discovers routes to destinations located beyond a node's routing zone.**

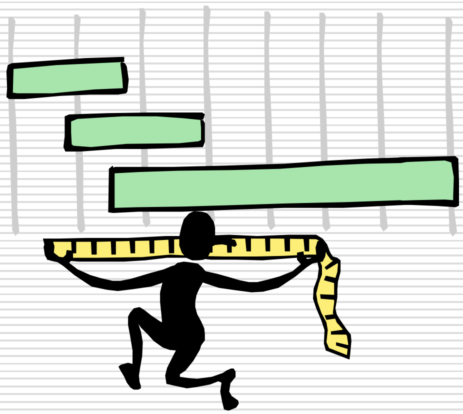
The Notion of a Routing Zone

A ***routing zone*** is defined for each node and includes the nodes whose **minimum** distance **in hops** from the node in question is **at most** some predefined number, which is referred to here as the ***zone radius***.

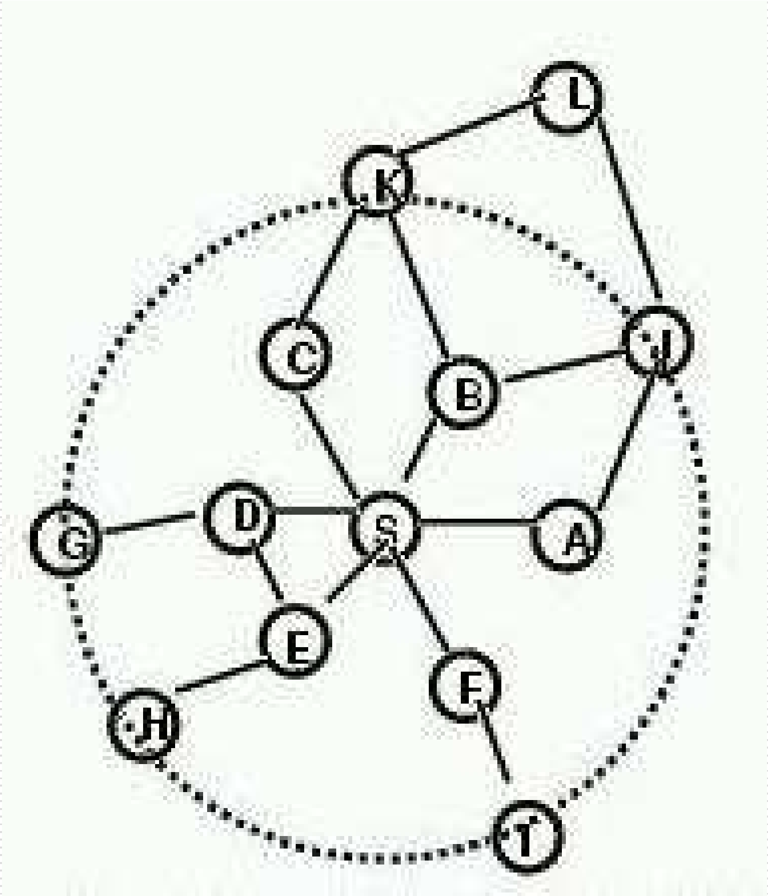


Routing Zone radius of 2 hops

The Notion of Peripheral Nodes



Nodes, whose minimum distance from the node in question is <u>exactly equal</u> to the zone radius are referred to as *peripheral nodes*.

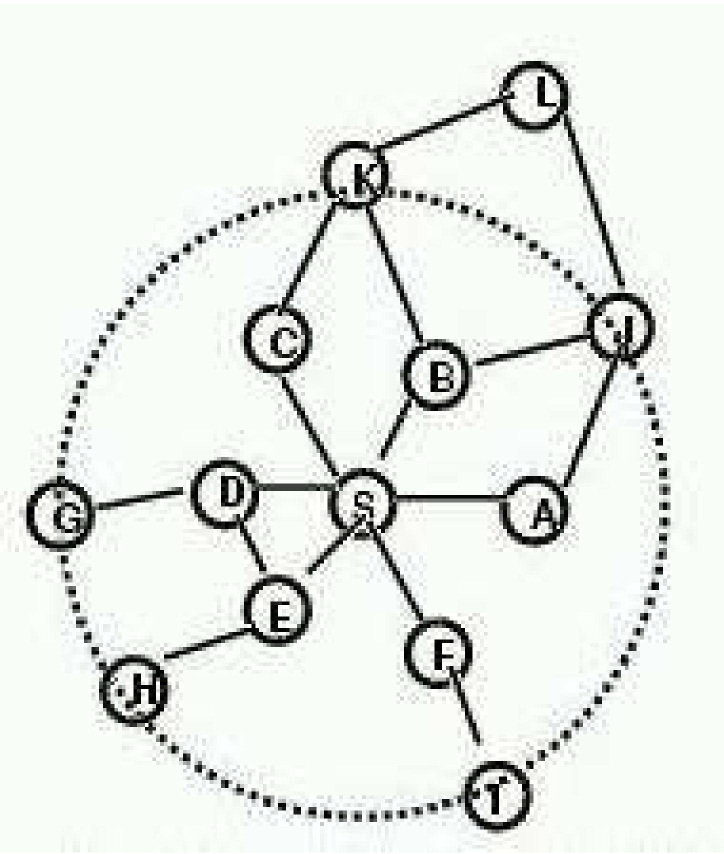


Routing Zone radius of 2 hops

The Zone Routing Protocol (ZRP) (con't)

- The source of a query uses *Bordercasting Protocol (BRP)* to deliver messages to the peripheral nodes of its routing zone, if it does not have a route to the destination.

- The peripheral nodes, in turn, *bordercast* the query to their own peripheral nodes if they do not have a route to the destination.



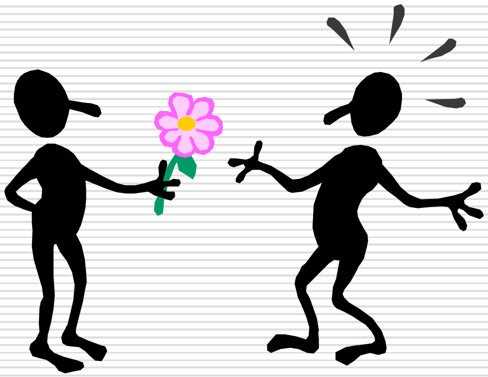
Routing Zone radius of 2 hops

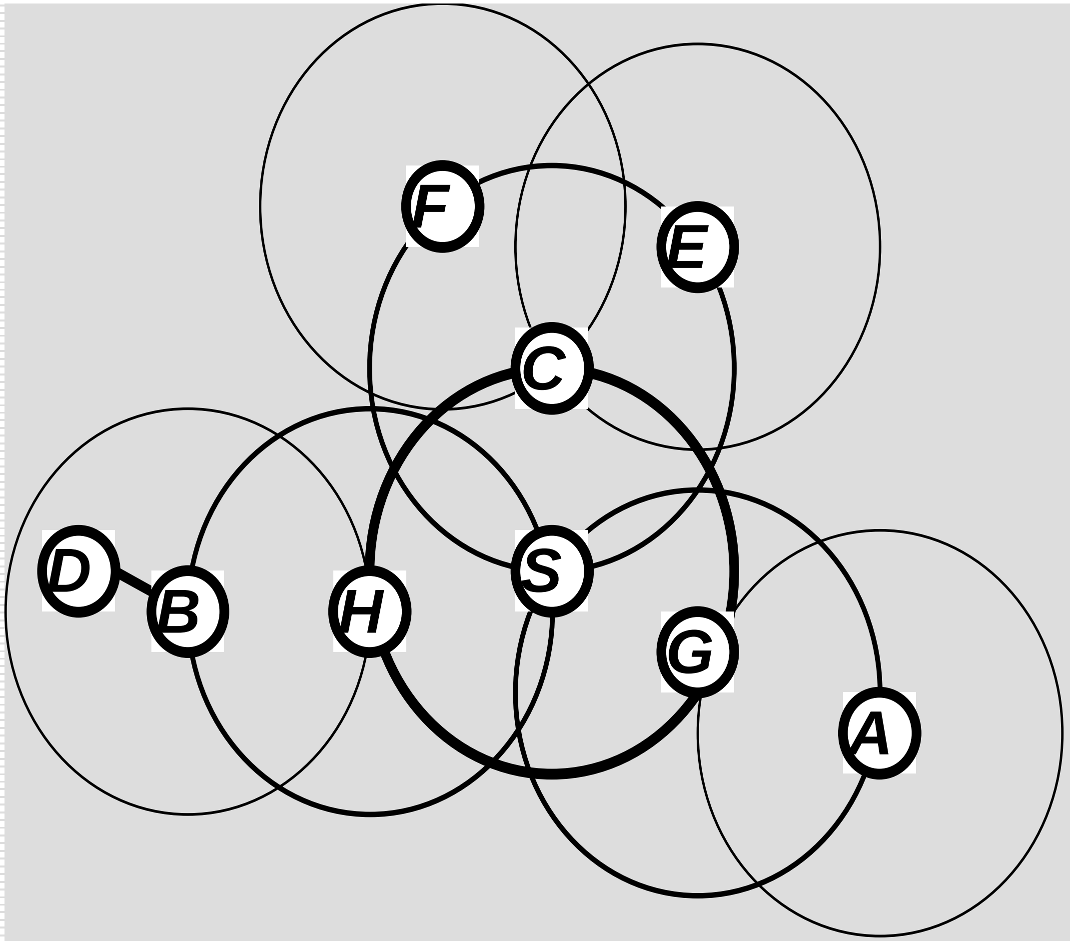
The Operation of ZRP

- *Zone Routing Protocol (ZRP):*
  - **Each node proactively maintains topology information about its *routing zone* - nodes within a constant *zone radius* number of hops.**
  - **A node reactively queries for routes to destinations lying beyond its routing zone through *bordercasting,* which effectively utilizes the available routing zone topology information.**
  - **An optimal value of zone radius exists for the network (dependent on average network characteristics) that leads to least routing overhead.**

M.R. Pearlman and Z.J. Haas, "Determining the Optimal Configuration of for the Zone Routing Protocol," IEEE JSAC, special issue on Ad-Hoc Networks, vol. 17, no.8, August 1999

The Operation of the ZRP

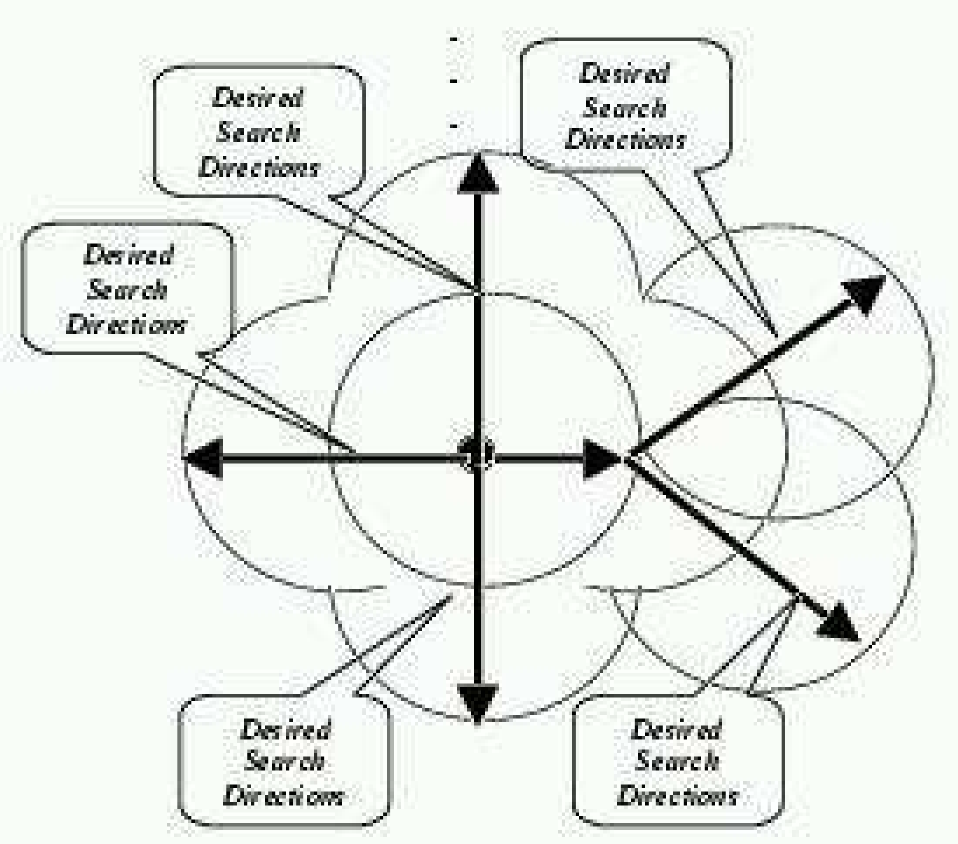




An example of IERP operation

Zone Routing Protocol (ZRP) (con't)

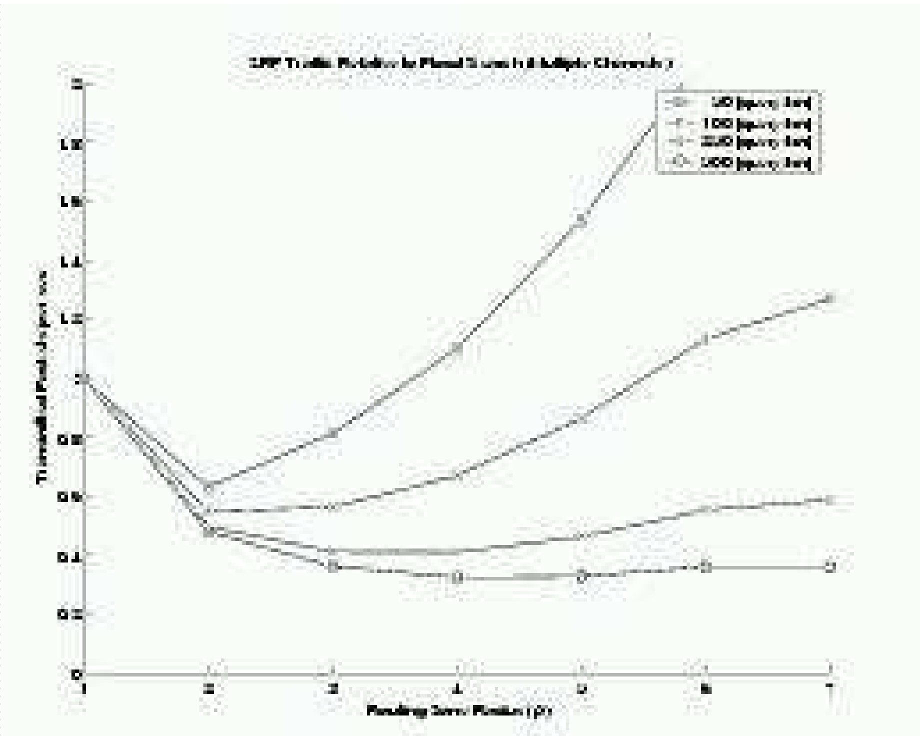
Query Detection (QD) & Early Termination (ET) are used to efficiently query the network, thus reducing the control traffic.



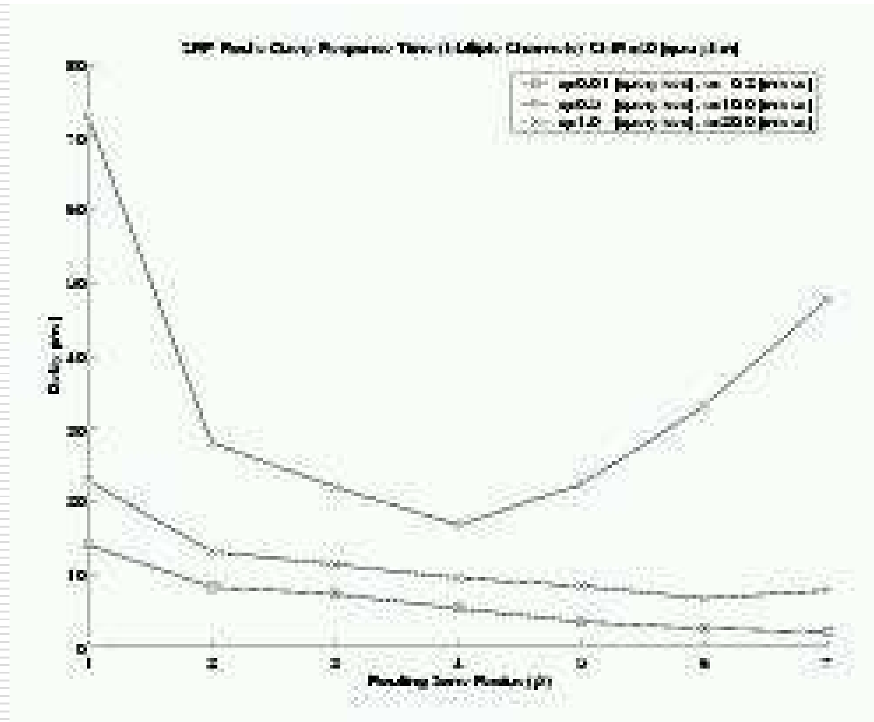
Guiding the search in desirable directions using QD & ET

Z.J. Haas and M.R. Pearlman, "The Peforamnce of Query Control Schemes for the Zone Routing Protocol," ACM/IEEE Transactions on Networking, vol. 9, no. 4, pp. 427-438, August 2001

Some Representative ZRP Performance Results



ZRP traffic relative to flood search vs routing zone radius



ZRP route query response time vs routing zone radius

From ZRP to IZR

- The Independent Zone Routing (IZR) Variance
  - In ZRP, all nodes have the same zone radius, whose optimal value (i.e., that minimizes the amount of control traffic as part of a route discovery process) is determined by a pair of parameters: the call rate and the node mobility.
  - The values of these parameters can change (both temporarily, as well as spatially); the optimal value needs to be (continuously) adapted.
  - In Independent Zone Routing (IZR), each network node maintains (and updates) its own settings of the zone radius, settings which are suitable to the particular operational conditions of the node.

P. Samar, M.R. Pearlman, Z.J. Haas, "Hybrid Routing: The Pursuit of an Adaptable and Scalable Routing Framework for Ad Hoc Networks," Chapter 14, Handbook of Ad Hoc Wireless Networks, CRC Press, Dec. 2002

IZR Properties

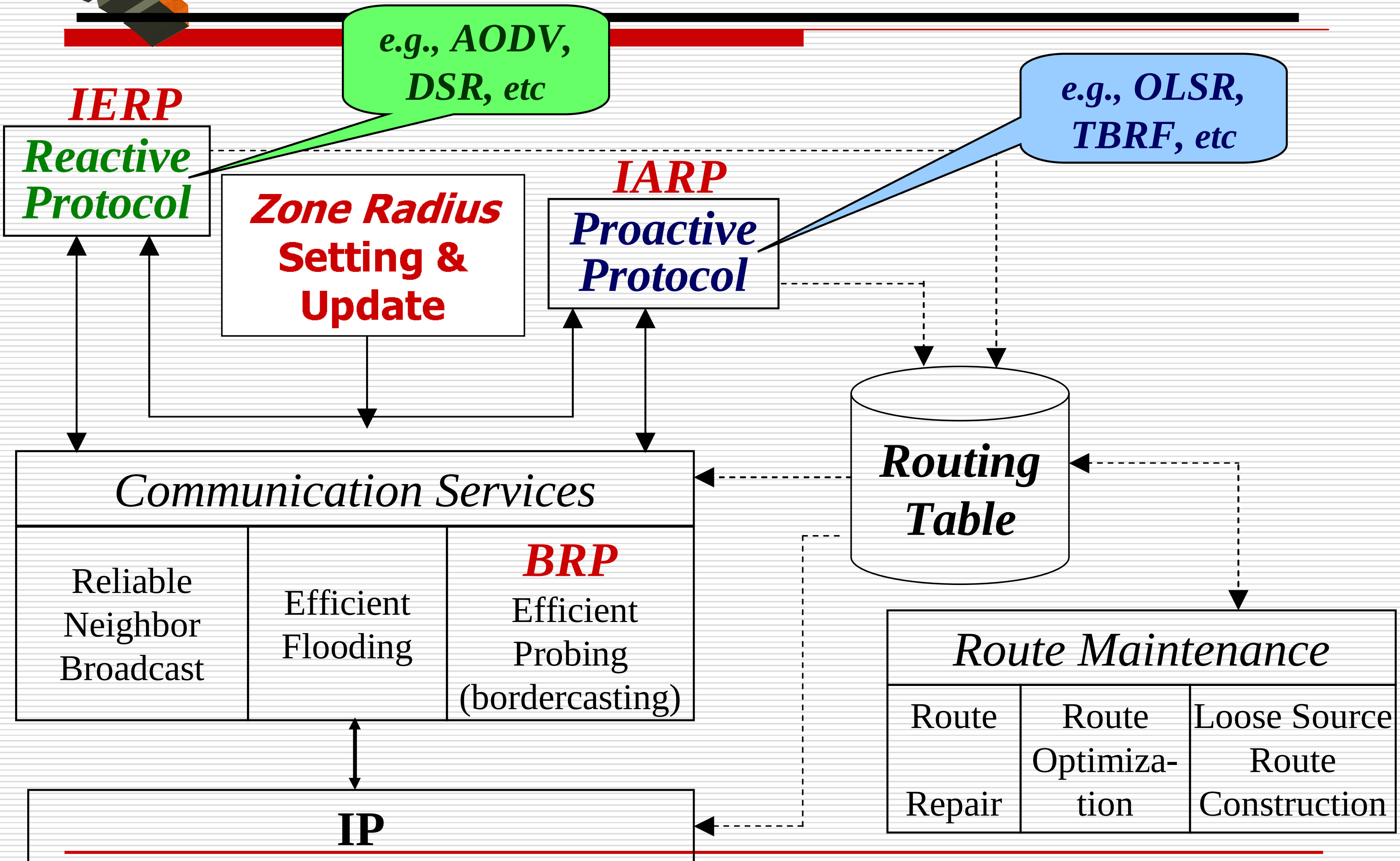
- Different parts of a network may have different characteristics, implying different optimal zone radii.
  - *High mobility and/or low call rates favor smaller zone radius (more reactive routing).*
  - *Low mobility and/or high call rates favor larger zone radius (more proactive routing).*
- IZR enables each node to independently configure its optimal zone radius in a distributed fashion.
- IZR quickly adapts a node’s configuration as the local network conditions change.
- Allows self organizing network, with nodes free to join or leave at any time, without any external configuration.

Efficiency of IZR and its Scalability

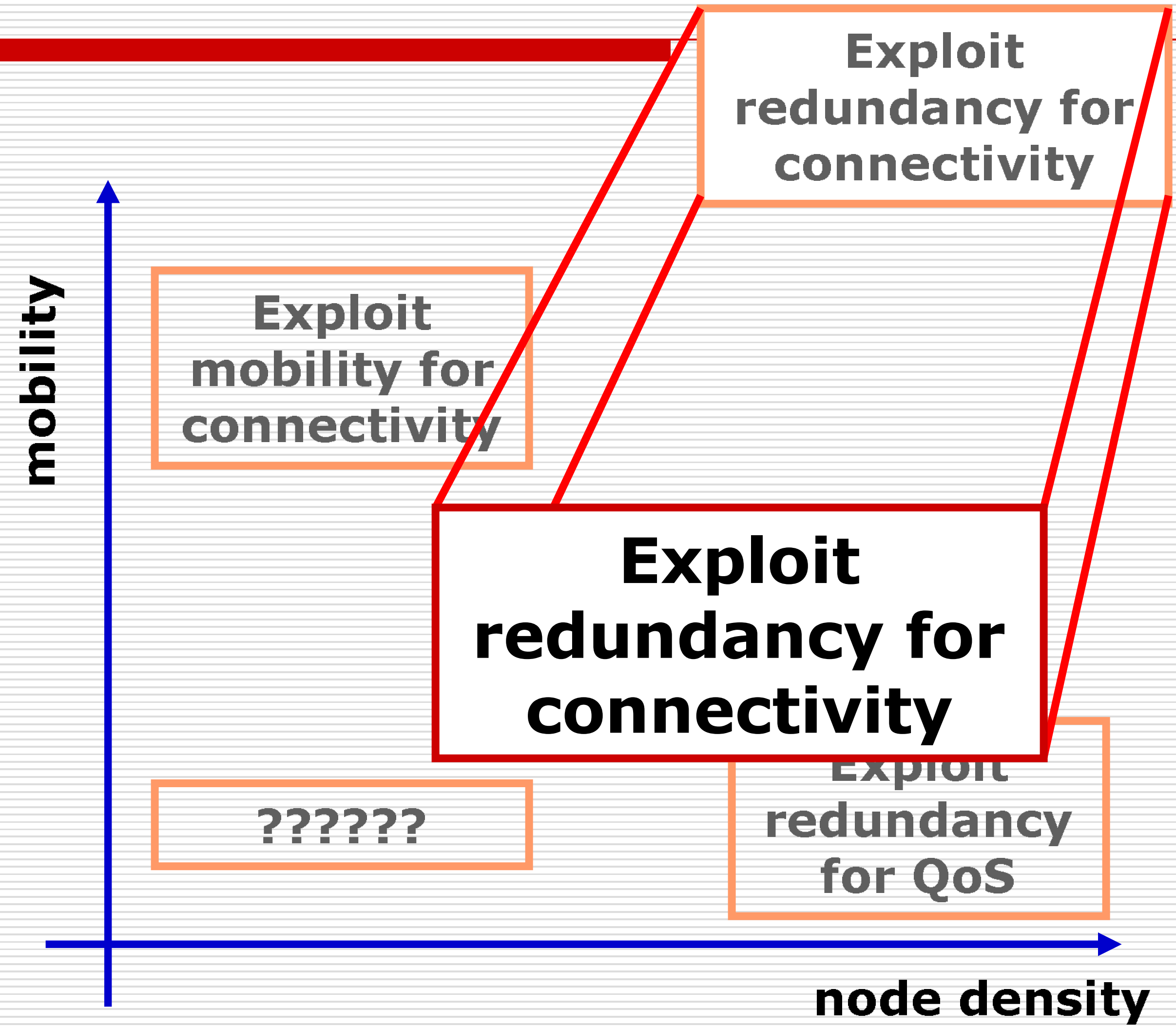
- **The hybrid IZR fine-tunes the framework to specific local network characteristics, improving efficiency; i.e., it substantially reduces the amount of network control traffic for the route discovery operation.**
- **Hybridization enables optimal balance of proactive and reactive routing components:**
  - **Only a subset of network nodes need to be queried**
  - **Lesser global route queries initiated**
- **IZR adaptively reconfigures the framework, making it robust to changes in network characteristics with time.**
- **Adaptivity, efficiency, robustness and hybridization lead to scalable routing for ad hoc networks.**

(For best results, IZR should be implemented using the Cross Layer Design approach.)

ZRP (IZR) Architecture



Some Architectural Design Choices



Z.J. Haas and R. Barr,
"Density-independent, Scalable Ad Hoc Network Route Discovery," **invited paper,**
IEEE 16th International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC'05), **Berlin, Germany, September 11-14, 2005**

R. Barr, Z.J. Haas, and R. van Renesse,
"Scalable Wireless Ad Hoc Network Simulation,"
Handbook on Theoretical and Algorithmic Aspects of Sensor, Ad Hoc Wireless, and Peer-to-Peer Networks, Jie Wu, Editor, chapter 19, pp. 297 -- 311, CRC Press, 2005

Route Discovery in Ad Hoc Networks

- **Many ad hoc wireless network routing protocols (AODV, DSR, OLSR, TBRPF, ZRP, etc)**
- **many differences, but some shared attributes**
  - discover a route, if it exists
  - at some point, protocol must query the network
    - because route to destination is not locally known
    - due to changes, limited cache sizes, or arrival of a new query
    - therefore, query must be propagated;
      in the worst case: to the entire network
- **network-wide query propagation is:**
  - frequent
  - expensive.

Naïve Query Propagation

- **flooding**
  - simplest query propagation protocol
  - rebroadcast query upon hearing it for the *first* time
  - add jitter to avoid broadcast collisions
  - at each node, query received at least once
  - inefficient: at each node, query transmitted exactly once

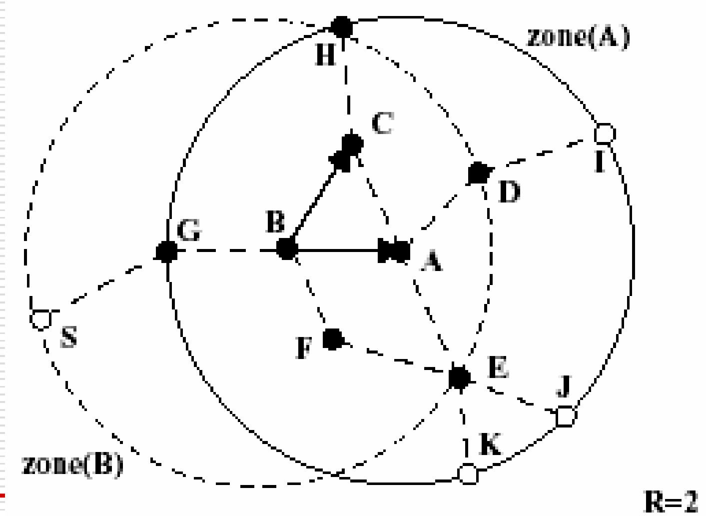
```
state
  local: address
  processed: set of query

RECEIVE-FLOOD(q: query):
  PROCESS-QUERY(q)
  sleep JITTER-TIME()
  if q ∉ processed then
    processed ← processed ∪ q
    BROADCAST(q)

FLOOD(q: query):
  RECEIVE-FLOOD(q)
```

Cost of Optimal Propagation

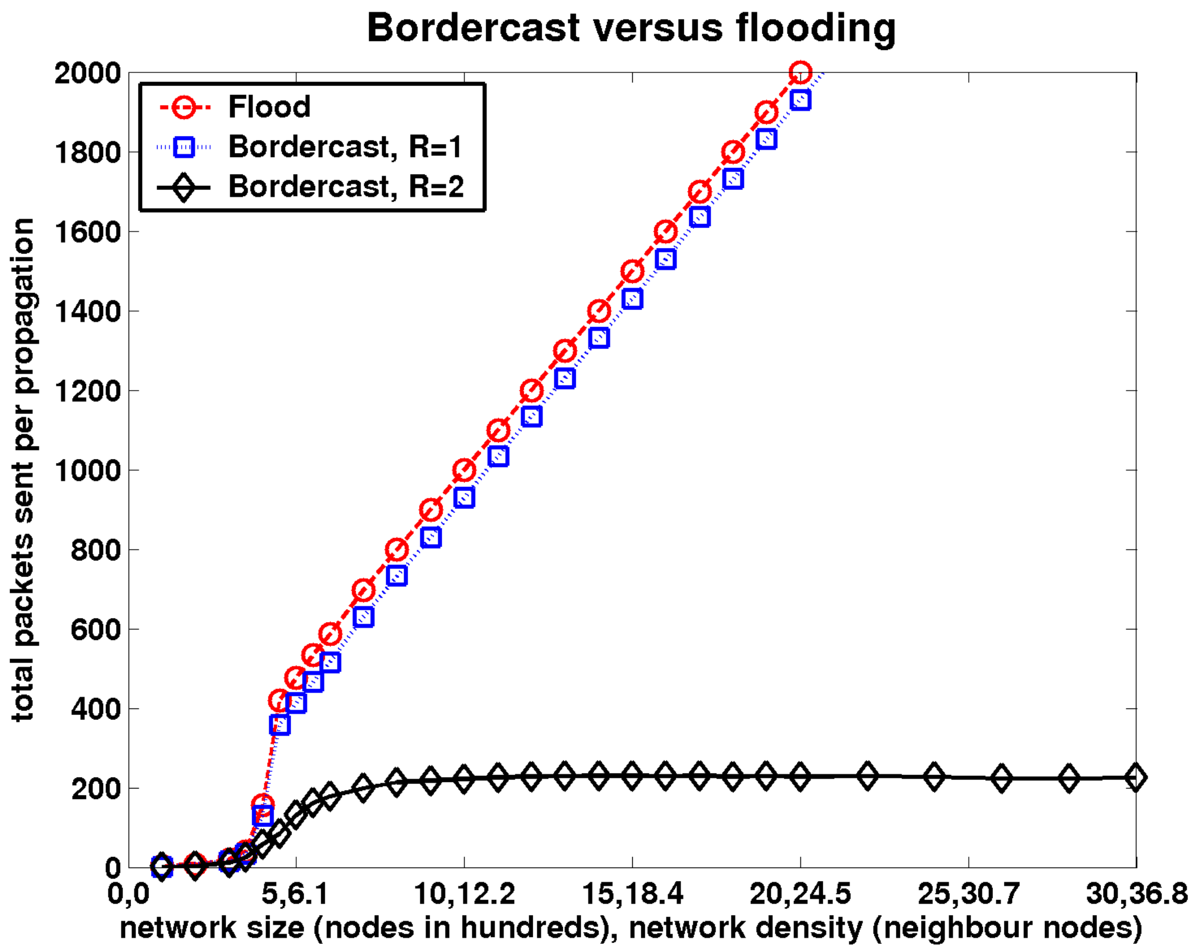
- **Number of transmissions required to optimally propagate a query is:**
  - proportional to the area of the network
  - independent of the number of network nodes or, equivalently, independent of the network density.
- **but, not realistic: NP-complete, missing topology information**
- **use heuristic: bordercast**

Bordercast Query Propagation

- **bordercast**
  - an efficient propagation protocol
  - part of the Zone Routing Protocol (ZRP)
  - can replace flooding within other routing protocols
- **definitions**
  - zone: set of nodes within *R* network hops
  - border: set of nodes at exactly *R* network hops
  - node covered iff query received by any of its zone members
- **basic idea**
  - cover all nodes in the network by iteratively relaying query towards uncovered *border* nodes.
  - *not all neighbors need to relay the query, especially in dense networks*

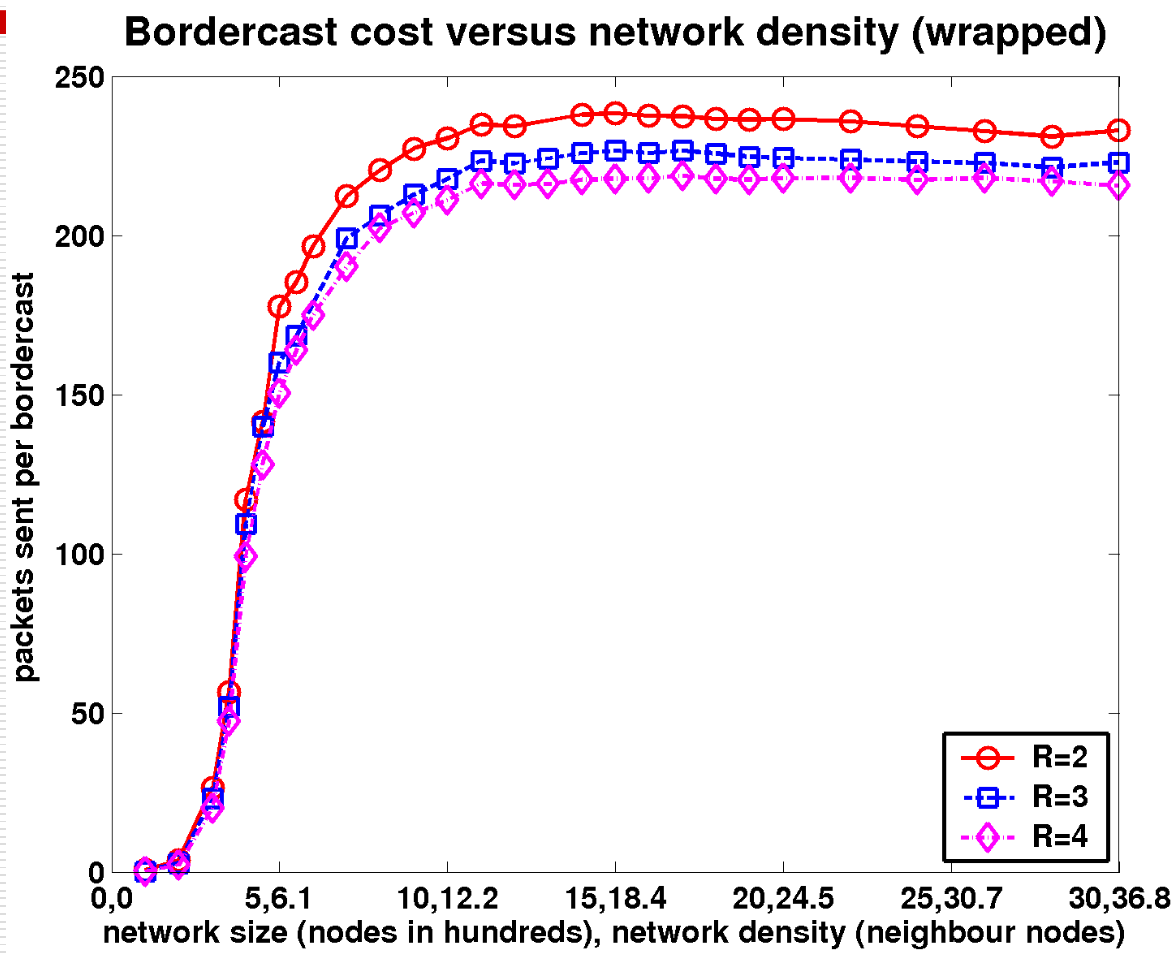


Results



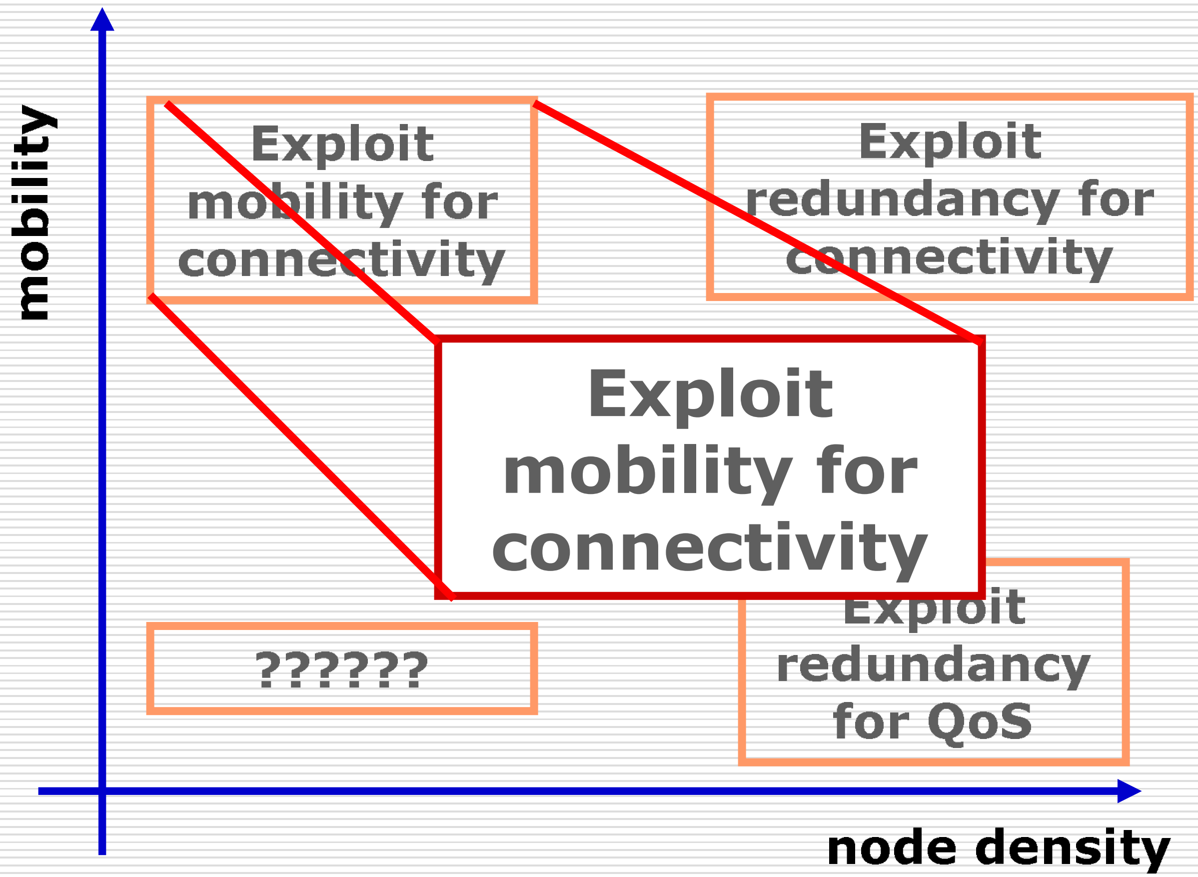
Bordercast exhibits density-independent query propagation.

Results (con't)



Zone radius of *R* = 2 is sufficient

Some Architectural Design Choices



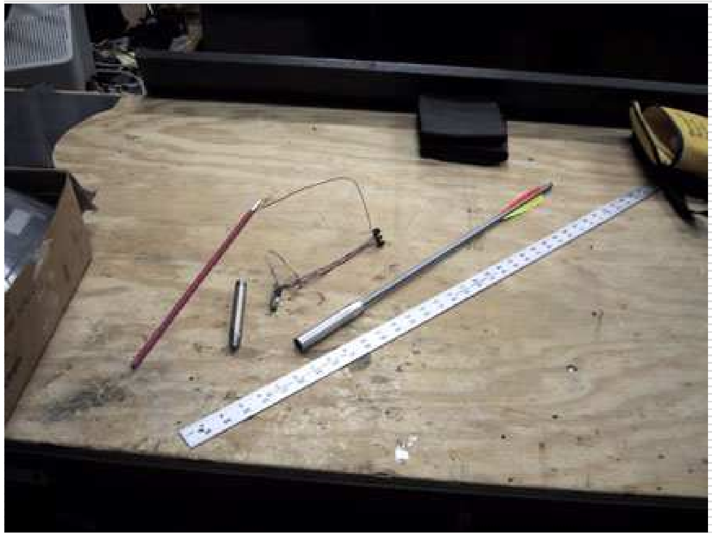
T. Small and Z.J. Haas,
"The Shared Wireless Infostation Model -- A New Ad Hoc Networking Paradigm (or Where there is a Whale, there is a Way),"
ACM MOBIHOC'03, Annapolis, Maryland, June 1-3, 2003

T. Small, Z.J. Haas, A. Purgue, and K. Fristrup,
"A Sensor Network for Biological Data Acquisition,"
Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems, M. Ilyas and I. Mahgoub, editors, CRC Press, 2005, pp. 11-1 -- 11-17

Z.J. Haas and T. Small,
"Trading Storage for Delay: Evaluation of a New Communication Model for Ad Hoc Networks,"
accepted for publication in the ACM/IEEE Transactions on Networking, 2006

A Network of Whale Tags

* Bottle-sized radio tags can be injected into whales (by means of a crossbow)
* Tags collect data about whale and environment
* Noise exposure to marine mammals (Navy tests force beluga whales to flee for 2-3 days)
* Wildlife preservation (Beaked whales are "rarest of the rare" and we want to avoid them on shipping routes)



* General biological knowledge (more knowledge of whales and the ocean for biologists and oceanographers)
* More general (3 month data storage): depth, water temperature, ambient sound level, ambient light level, summaries of heart rate information
* More specific (perhaps 24 hour data storage): details of movements, orientation, heart rate

Data Recovery from Radio Tags

- RF tags in the whales get rejected from the body in approximately 3 months
- Need a way to retrieve data from whale without collecting the tag:
  - Satellite tags (ARGOS – ~720 bits/second links)
  - Stations on the surface of the water or on shore
  - Other animals???
- *Radio tags on whales transmit information only when the whale is surfacing (periodically)*
- Packets from these devices are not extremely delay-sensitive, but some reasonable delay is needed.
- Packets may be large
- Additional information; e.g., mobility of whales, feeding locations, etc

***Infostations** are an option for data retrieval*

SWIM:
A Shared Wireless Infostation Model

- *Shared Wireless Infostation Model (SWIM)*
- *Extends the Infostation concept by sharing data between nodes*
- *Applied to our biological information acquisition system:*
  - Whales periodically generate data packets and when whales surface near any Infostation, they upload the data at high bit rate
  - Whales also share data if they come in contact with each other, so one whale has stored data for multiple whales

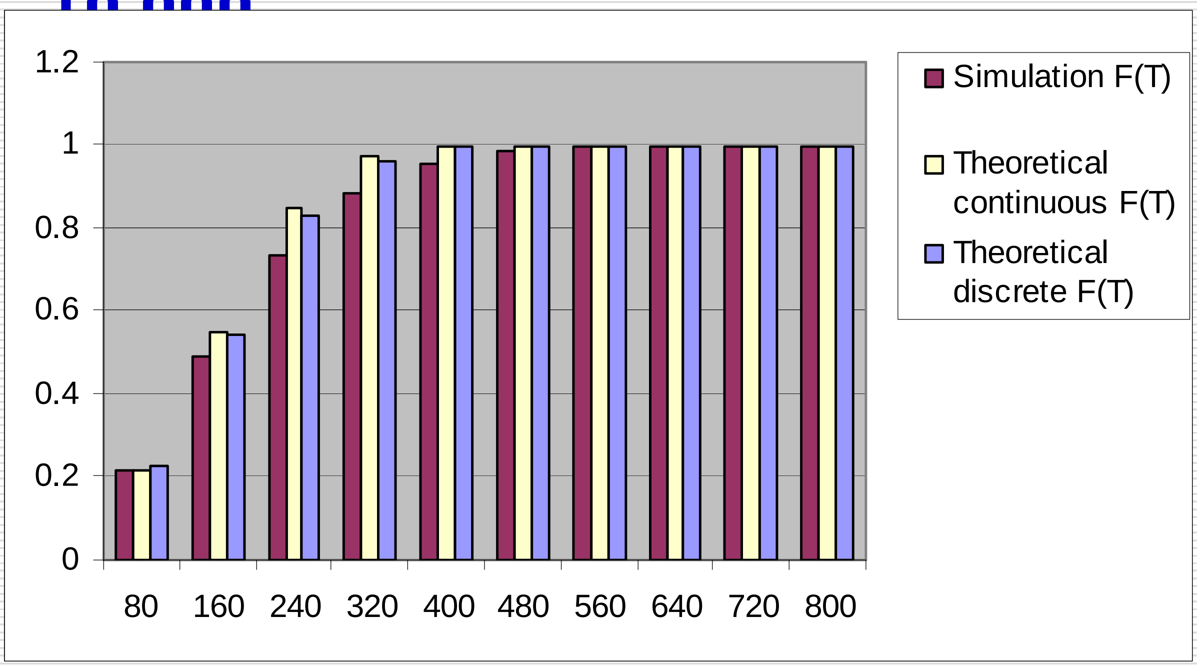
Price: Need more storage space on the nodes

SWIM storage

- The storage space is made for new packets by expiring and purging older packets from the system:
  - Packet is "expired" if there is some probability P_{thresh} of being uploaded to a station already
- To engineer the system, find the cumulative distribution F(T) where T is the time from packet creation until $P_{threshld}$ probability of being uploaded
- Using F(T), we find the expected time necessary to wait until uploading with $P_{threshld}$
- Expiration is implemented through the *TTL* field
- Global clock is not needed since each packet TTL field contains remaining time-to-live.

Simulation Results for Random Midway Mobility

- For 10 bins, χ^2 must be < 1.15 to be 99.9% sure that these are the same distribution.
- $\chi^2_{cont} = 0.037156$, $\chi^2_{disc} = 0.028055$, $\beta = 0.000608$, $\gamma M = 0.001812$, number of samples = 10,000



***** tx=20, 300*300, 20 whales, 2 buoys and whales always surfacing***

Solution for F(T)

Using the conditions that $F(0) = \dfrac{\pi\, tx_{SWIM}^{2}\, M}{\text{Grid area}}$

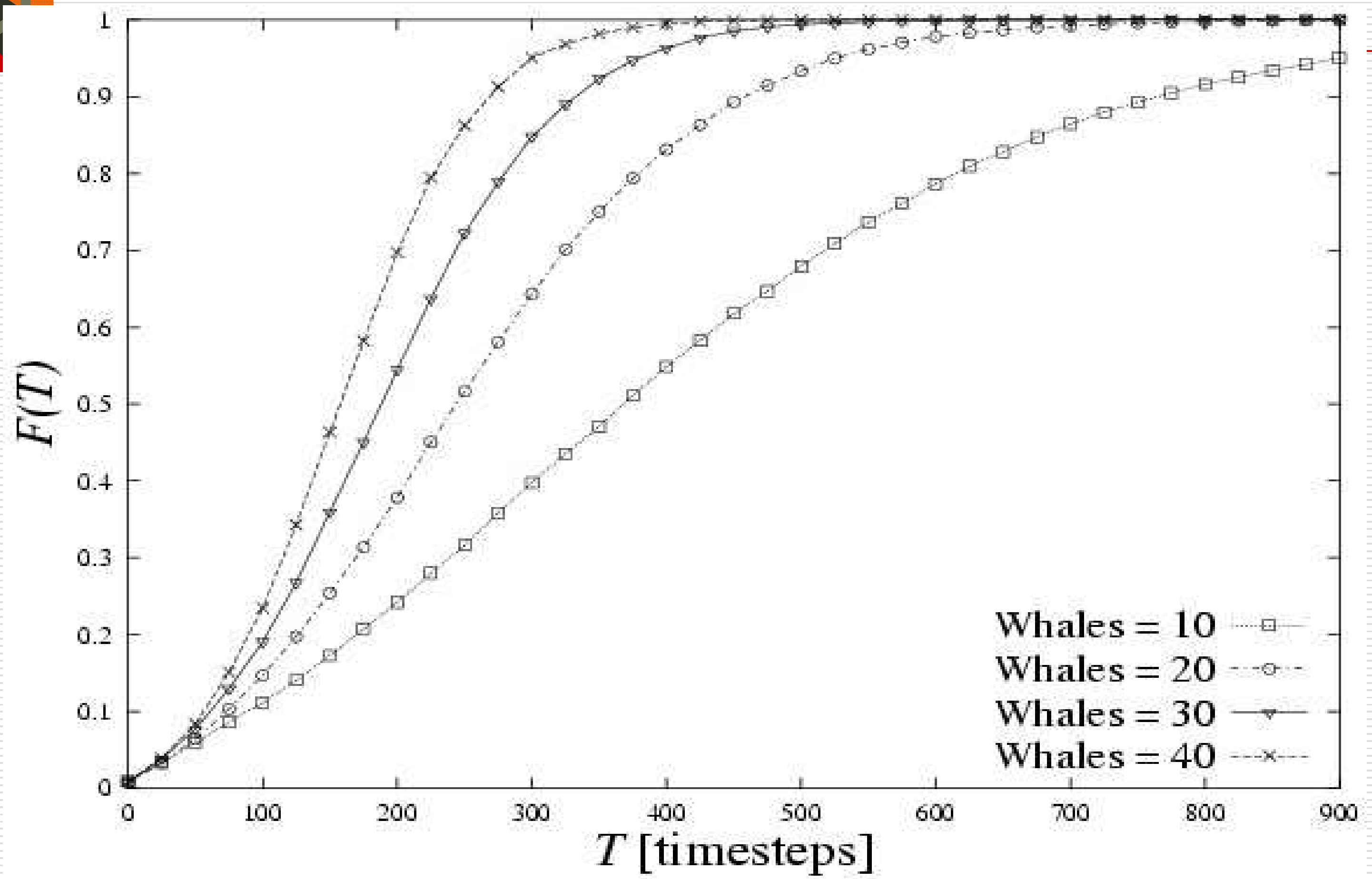
and $\lim_{T \to \infty} F(T) = 1$, we obtain that:

$$F(T) = 1 - K\left(\frac{N-1}{e^{\beta NT} + N - 1}\right)^{\gamma/\beta}$$

where $K = \left(\dfrac{N-1}{N}\right)^{-\gamma/\beta}\left(1 - \dfrac{\pi\, tx_{SWIM}^{2}\, M}{\text{Grid area}}\right)$

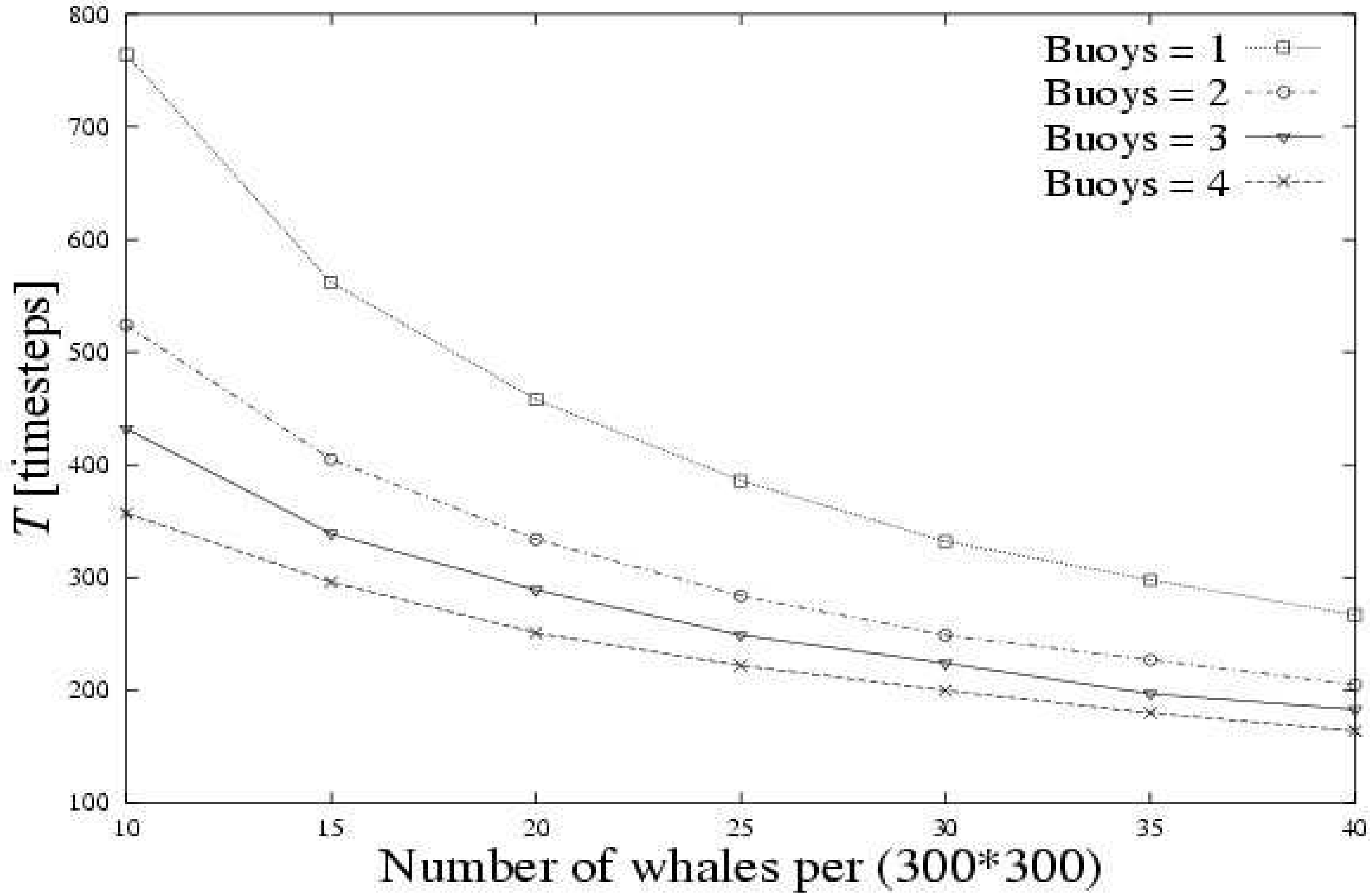
and M is the number of SWIM stations

How to Set Up the TTL?



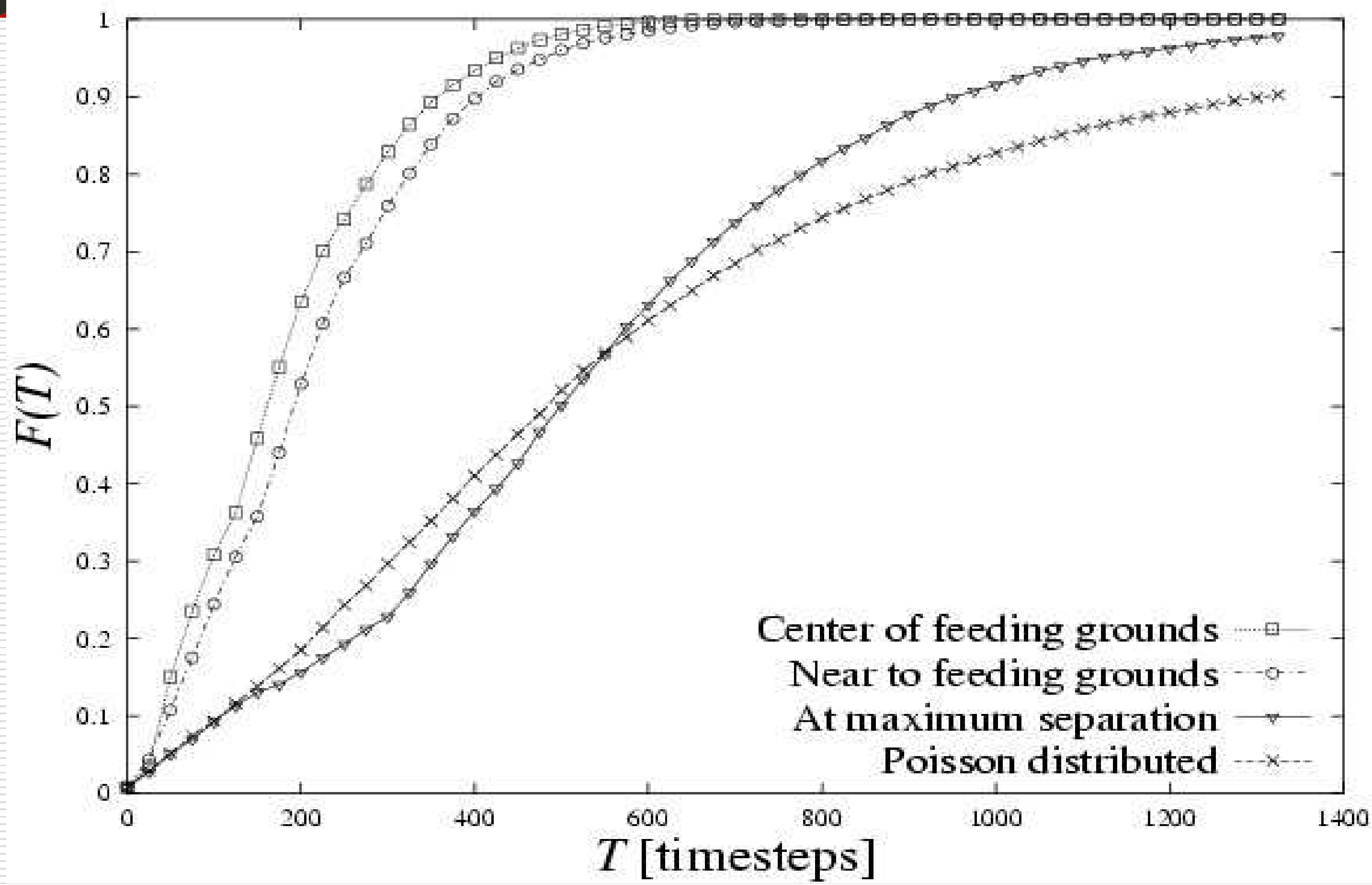
Cumulative distributions of T, the time from packet creation until offloading, for different numbers of whales in the system

Average Delay



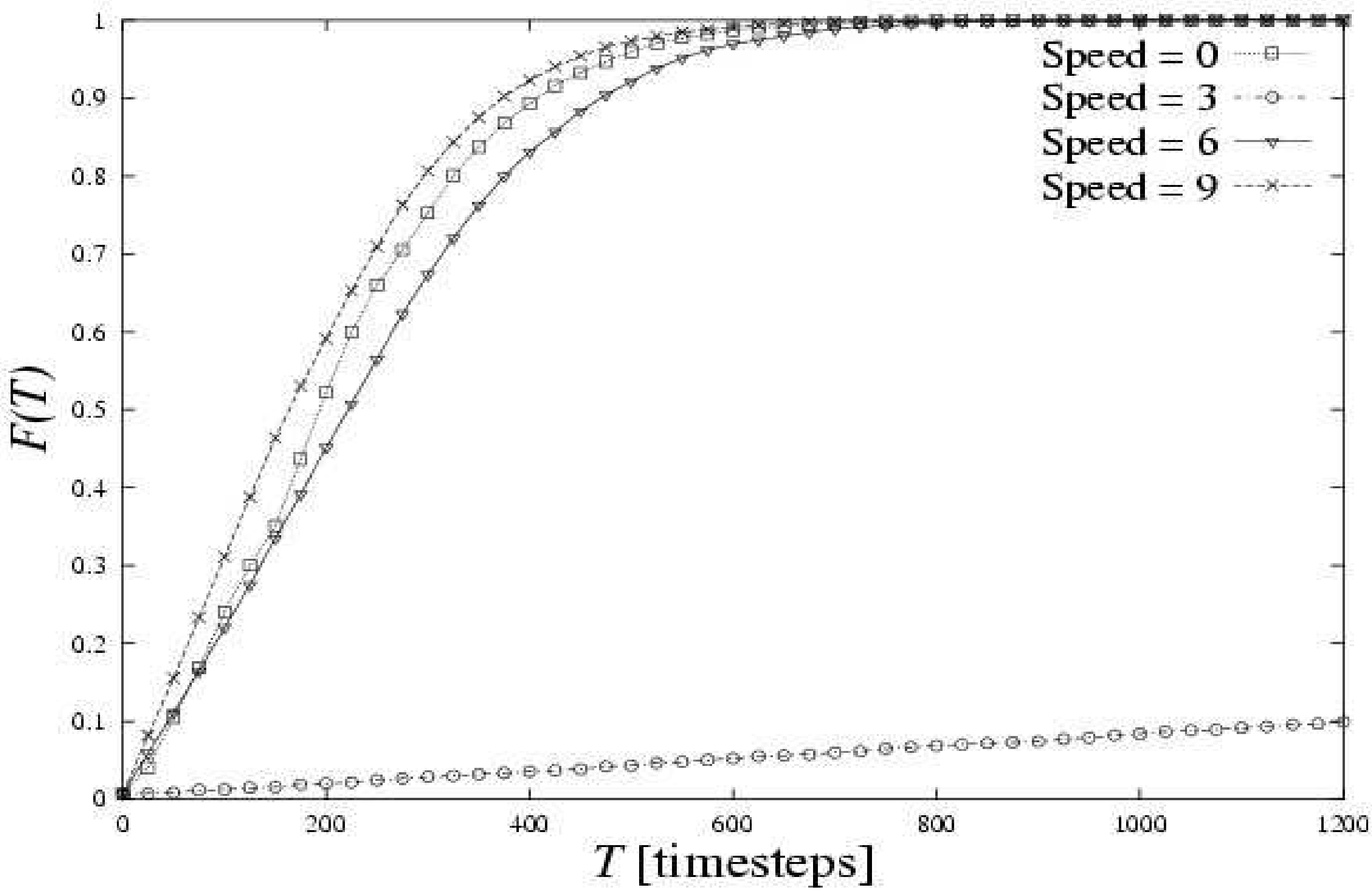
Average delay T until the packet is offloaded with probability 0.9

SWIM station locations



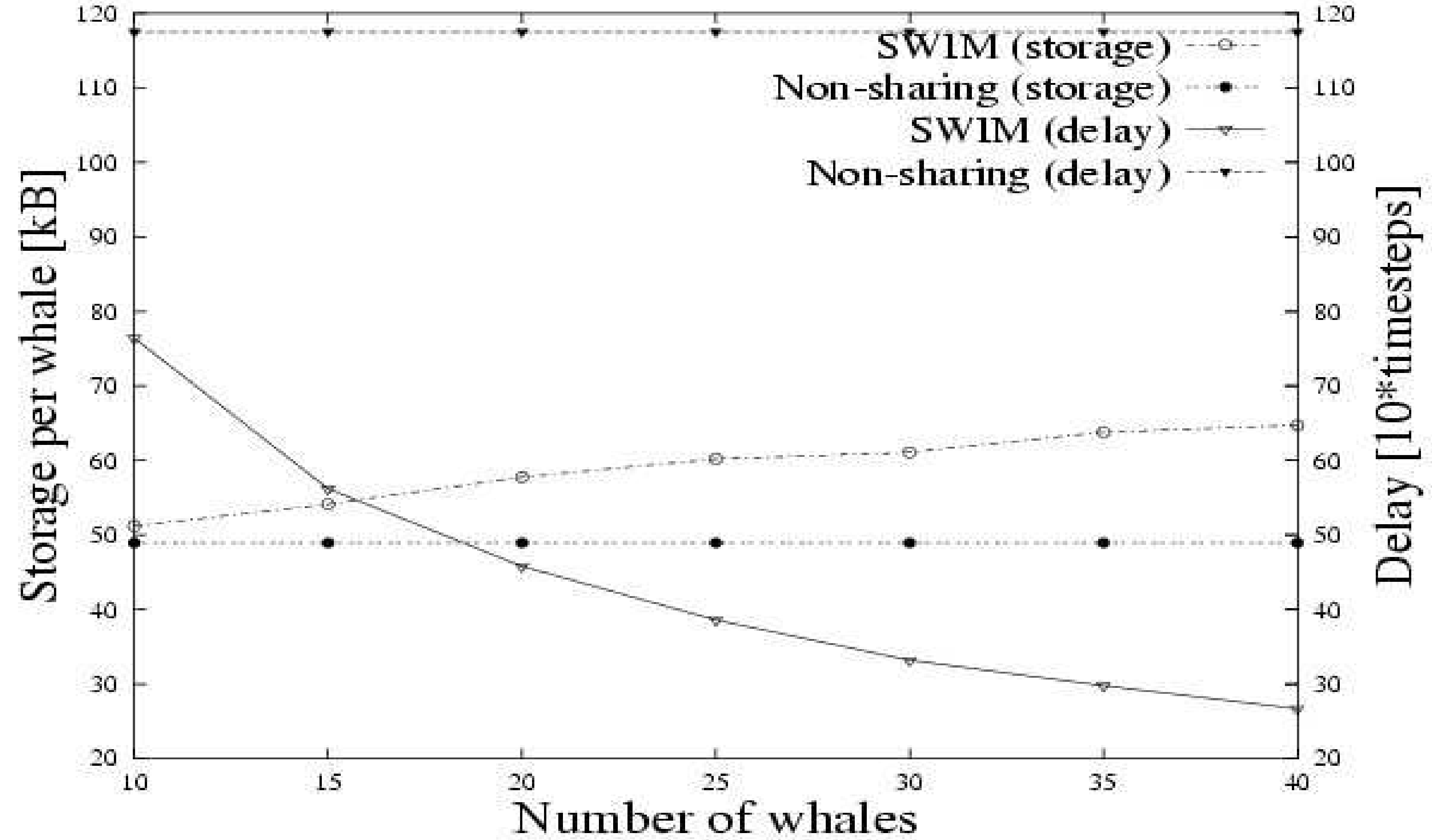
Effect of different buoys arrangements on the cumulative distribution of T

Moving stations



Allowing SWIM stations to move can accelerate the offloading to the stations, as shown by the cumulative distribution curves with varying speeds

Storage requirements



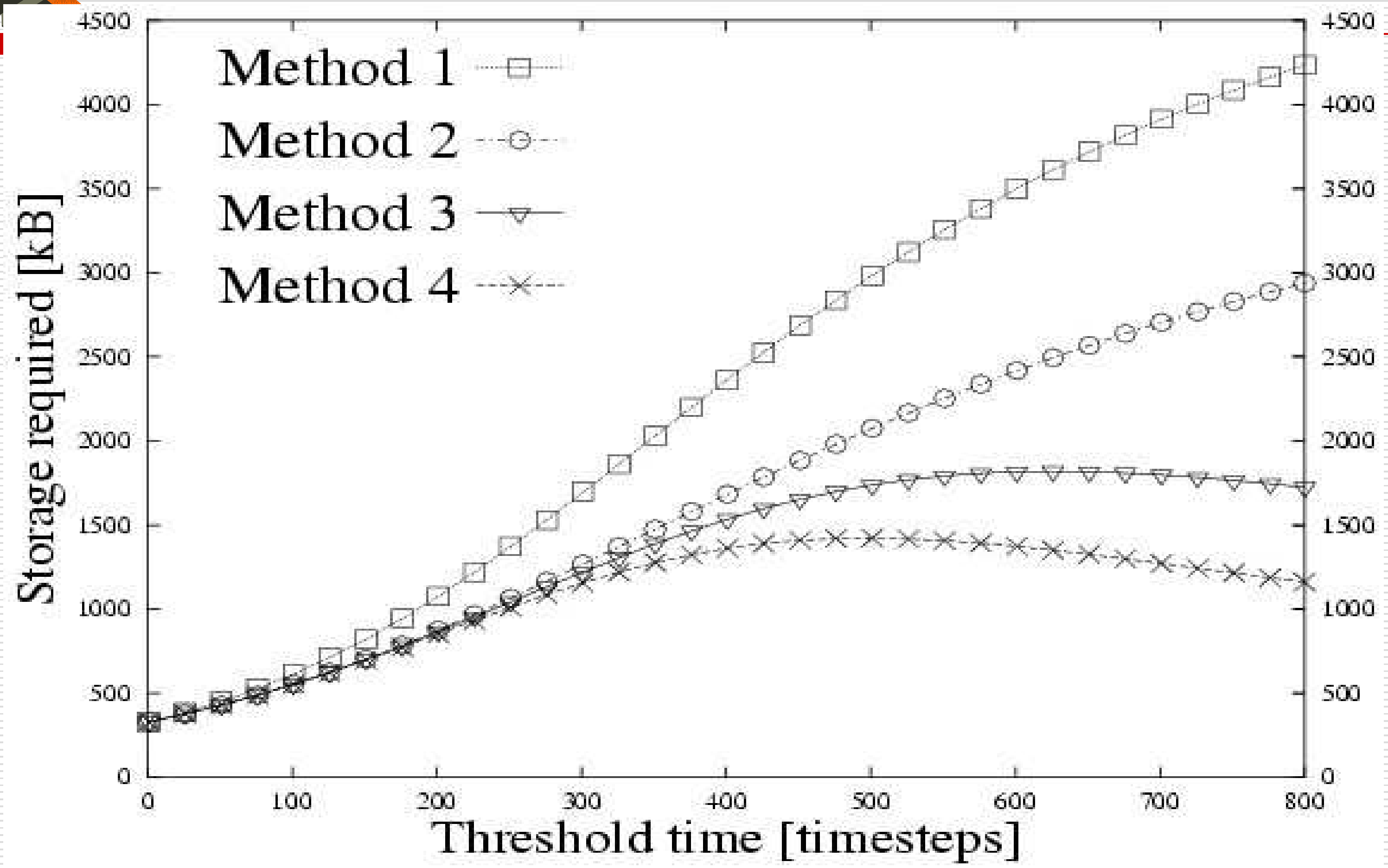
Necessary storage requirements and expected delays using SWIM vs the non-sharing model

Different Antipacket Methods

Storage and energy consumption improved without impacting delay

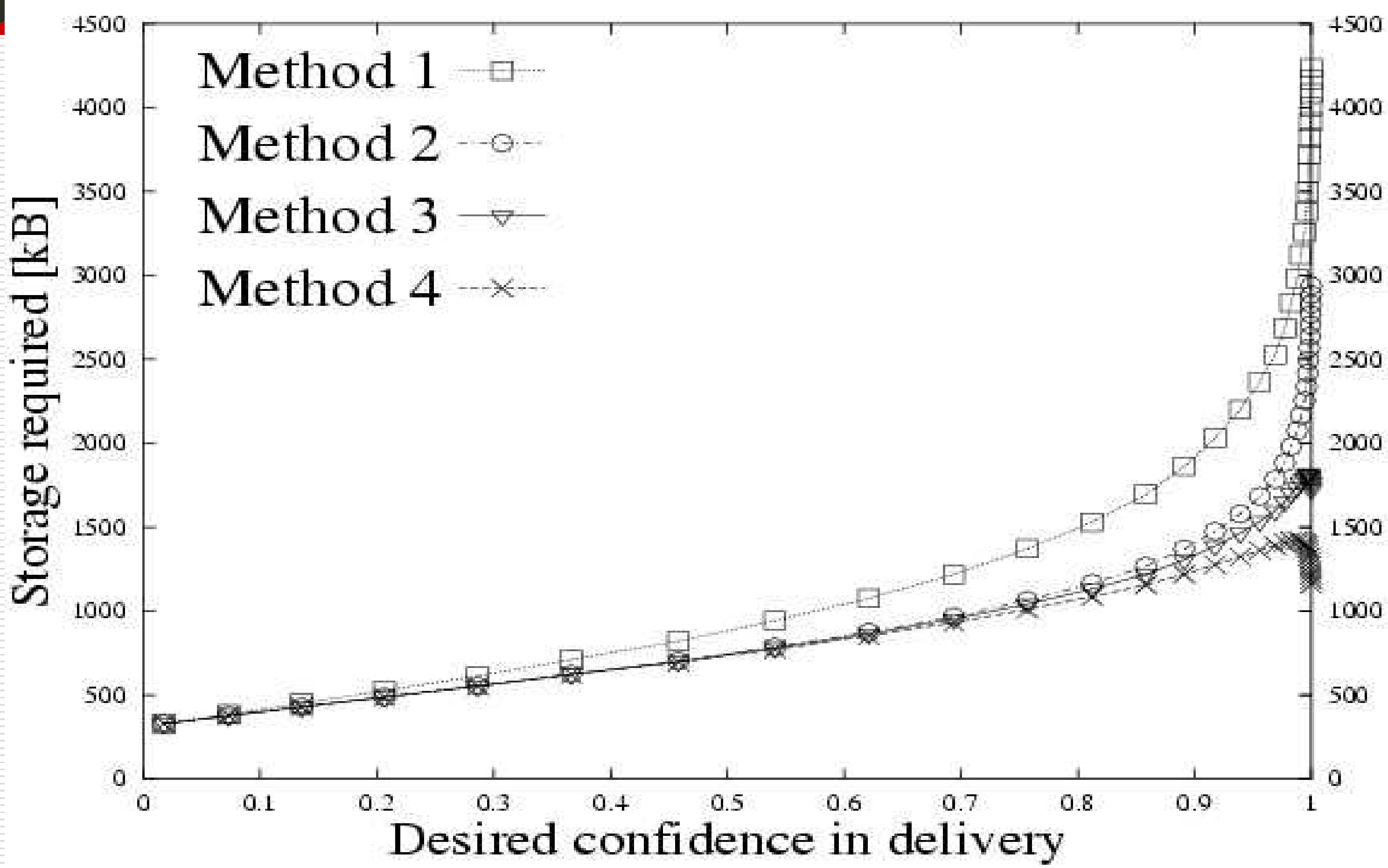
	Expires at TTL	Erased after offloading	Antipacket identifier retained	Antipacket identifier back-propagated to other whales
JUST_TTL	Yes	No	No	No
FULL_ERASE	Yes	Yes	No	No
IMMUNE	Yes	Yes	Yes	No
IMMUNE_TX	Yes	Yes	Yes	Only if packet stored previously
VACCINE	Yes	Yes	Yes	Always

Storage requirements (1)



Average amount of storage required on each whale for different delays

Storage requirements (2)



Average amount of storage required on each whale for different desired confidence levels

Conclusions

✱ Ad Hoc Networks and Sensor Networks are new technologies with a lot of potential, little of which has been realized as of yet.

✱ As the conditions are different than the traditional wireless networks, there are many unsolved problems, for which the conventional solutions are not applicable.

✱ Mobility and node density could be used to compensate for some of the restricting characteristics of Ad Hoc and Sensor Networks.

✱ In particular, richness of paths (as a result of large node density) can be used to improve reliability and security.

✱ Mobility could be used to create virtual links in sparse network, thus improving connectivity.

Conclusions (con't)

✱ However, too large density and large mobility are limitations and may adversely impact the performance of such networks.

✱ When the nodes' mobility is high, a variant of flooding may need to be used for routing.

- optimal query propagation proportional to network area, not network density
- bordercast is density-independent
- use bordercast in place of flooding

✱ When the number of nodes increases, the end-to-end capacity is reduced; particular growability patterns need to be employed.

Thank you for listening