The Wireless Networks Laboratory (WNL) at Cornell University

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The Wireless Networks Laboratory
Our Charter

- **General framework of our research:**

Support of multimedia communication by mobile and wireless networks

- **In particular, to support the Quality-Of-Service:**
  - **for different media (voice, video, data, image, …)**
  - **on various mobility platforms (stationary, pedestrian, vehicular, …)**
  - **in diverse network operation conditions (wireless and wireline)**
  - **with limited network and mobile-terminal resources.**

Some information about WNL

- **Students:**
  - **8 Ph.D/MS students**
  - **2 student associate members**
  - **6 M.Eng students**
  - **3 undergraduates**
  - **2 postdocs**
- **Funding:**
  - **NSF (including an ITR grant with Polytechnic Univ)**
  - **Air Force Rome Labs (through SBIR)**
  - **Industry: Nortel, AT&T, Motorola, MITRE, GTE**
  - **Subcontracts: SCIRES Corporation**
  - **DoD: MURI**

WNL - Summary of Current Projects (con't)

Our Projects

- ***Predictive Distance-Based Mobility Management for PCS Networks***
- ***Application of the Bluetooth technology***
- ***A Decision-Theoretic Framework to Admission Control in Wireless Networks***
- ***Multicast Flow Control for Heterogeneous Receivers***
- ***Asymmetric mobile-centric protocols (Mobile TCP)***
- ***Reliable Multicasting Schemes***

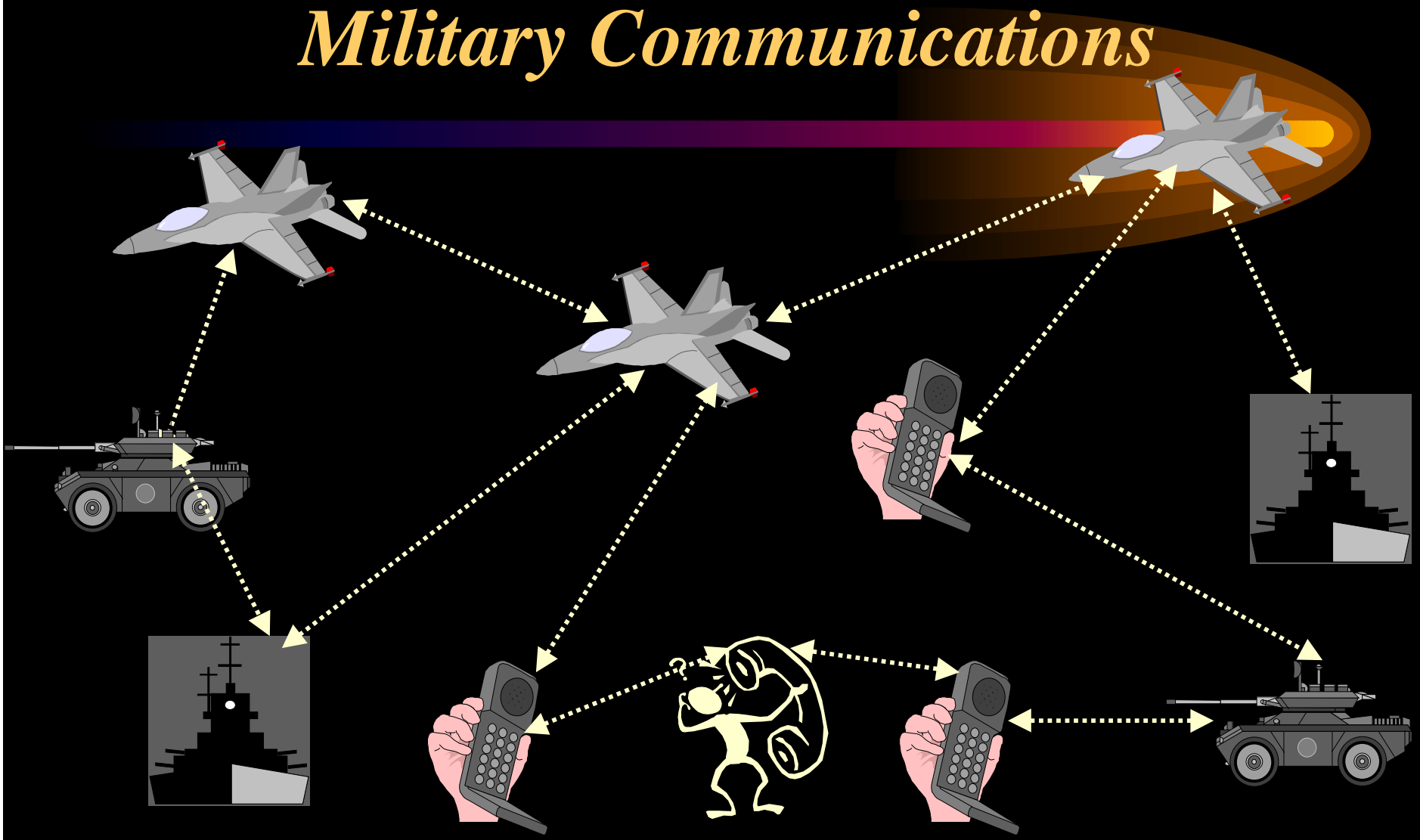
WNL - Summary of Current Projects

Our biggest project: Ad Hoc Networks

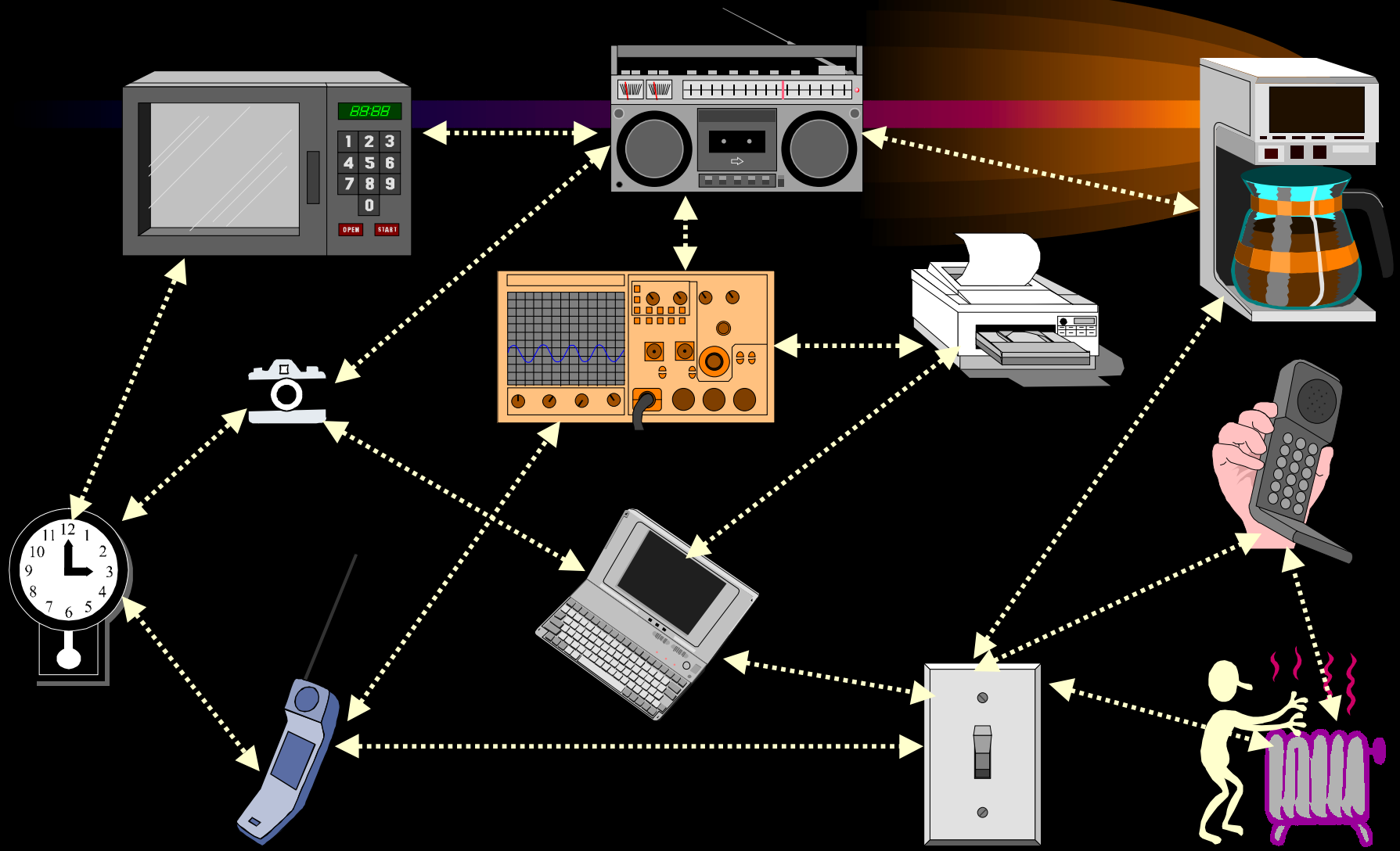
Introduction to Ad-Hoc Networks ?

- **Ad-hoc networks are network architecture:**
  - **that can be rapidly deployed**
  - **that do not rely on pre-existing infrastructure**
  - **whose set of nodes is continuously changing**
  - **which self-adapts to the connectivity and propagation patterns, and**
  - **which adapts to the traffic and mobility patterns**
- **Establishment of the *IEFT* MANET Working Group to study IP-based routing in ad-hoc networks**

Use of the Ad-Hoc Technology for Military Communications



Ubiquitous networking



Applications of the Ad-Hoc Networking Technology

- **Application of the ad-hoc network technology is appropriate when a network needs to be rapidly deployed without prior planning and to provide reliable communication in harsh propagation conditions.**
- **Example of applications:**
  - **military: for tactical communications**
  - **national security: in times of natural disaster or global war**
  - **rescue missions: in lieu of adequate wireless coverage**
  - **law enforcement: similar to tactical communications**
  - **commercial use: for setting up sales presentations**
  - **education: wall-free (virtual) classrooms**
  - **Local Area Networks (LANs): for limited-coverage communication**
  - **Sensor Networks**

WNL - Summary of Current Projects in Ad Hoc Networking Technology

1. Routing

- *Zone Routing Protocol (ZRP) for Mobile Ad hoc Networks*
- *QoS-based Routing in Ad Hoc Networks (e.g., energy-efficient)*
- *Alternate Routing Strategies for Ad Hoc Networks*
- *Alternate Path Routing (APR) in Ad Hoc Networks*
- *Multicasting in Ad hoc Networks*

2. MAC protocols

Dual Busy Tone Multiple Access - A MAC for Ad-hoc Networks

WNL - Summary of Current Projects
Ad Hoc Networking Technology (con't)

3. Topology and Network Maintenance

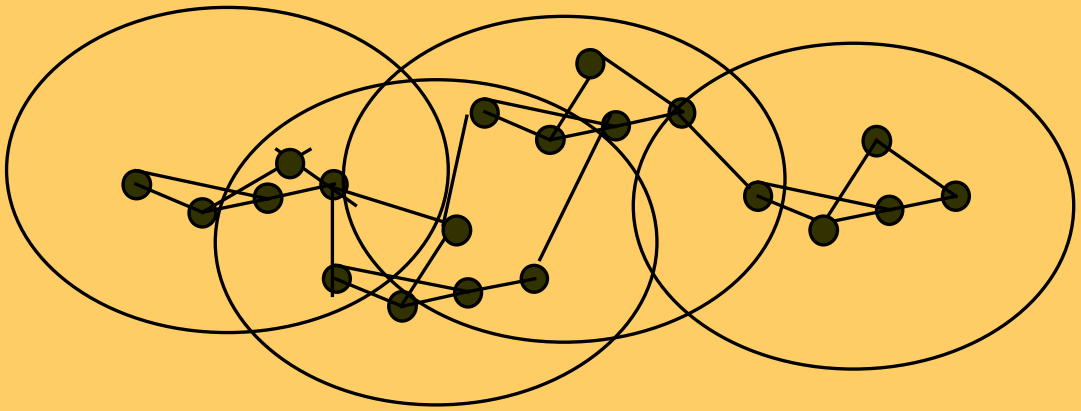
- ***Ad Hoc Mobility Management with Uniform Quorum Systems***
- ***Virtual Backbone Generation and Maintenance for Ad Hoc Mobility Management***

4. Security and Reliability

- ***Security of Ad-Hoc Networks***
- ***End-to-End Reliability of Ad Hoc Networks***

The Ad-Hoc Networks Design Choices

The *Flat* Network Architecture



A Flat Ad-Hoc Network

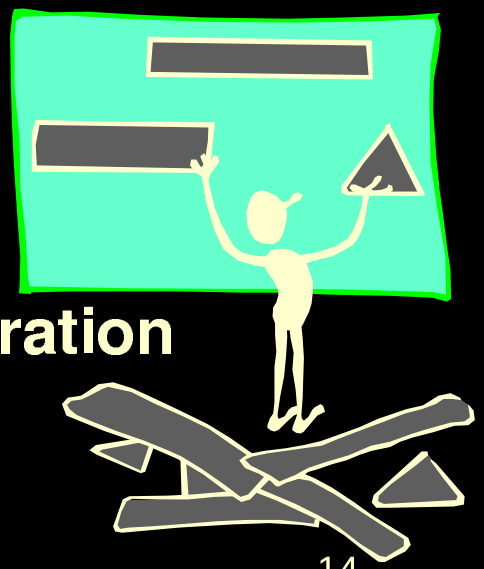
An Introduction to Ad-Hoc Networks

- **The distinctive differences between ad-hoc networks and cellular networks are:**
  - **no fixed infrastructure is present**
  - ***multi-hop routing* (network diameter >> node transmission range)**
  - **peer-to-peer operation**
  - **frequent changes of associations**

- **The challenges of the ad-hoc networks stem from two characteristics:**
  - **Lack of centralized entity ⇒ self-organizing and distributed protocols**
  - **Highly versatile network topology ⇒ efficient and robust protocols**

An Introduction to Ad-Hoc Networks

- **Selected examples of ad-hoc architectural choices:**
  - **flat vs. hierarchical (multi-tiered) network**
  - **degree of globalization in topological changes**
  - **frequency of communication of topological changes**
  - **criteria for route selection / max route determination**
  - **sizing of nodal transmission radius**
  - **synchronized vs. unsynchronized operation**



Challenges of Ad-Hoc Networks - does it have a future?

- **Application/Market penetration**
  - **is multihop technology commercializable?**
- **Design/Implementation**
  - **reliable, manageable, survivable, and secure**
- **Operational/Business-related**
  - **how to manage the network? how to bill for services?**

Technical challenges in Ad-Hoc Networks

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

- **Technical challenges in the design of Ad-Hoc networks stem from the following facts:**
  - **the lack of centralized entity**
  - **the possibility of rapid platform movements**
  - **<u>all</u> communication is carried over the wireless medium**
- **Compare these attributes with the fixed (cellular) networks ...**

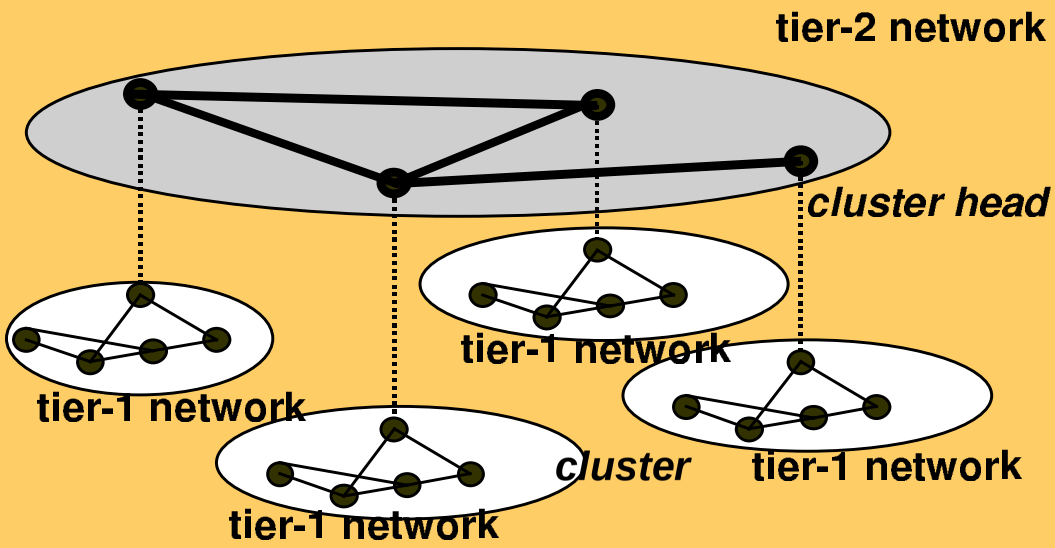
Ad-Hoc Architectural Design Choices

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

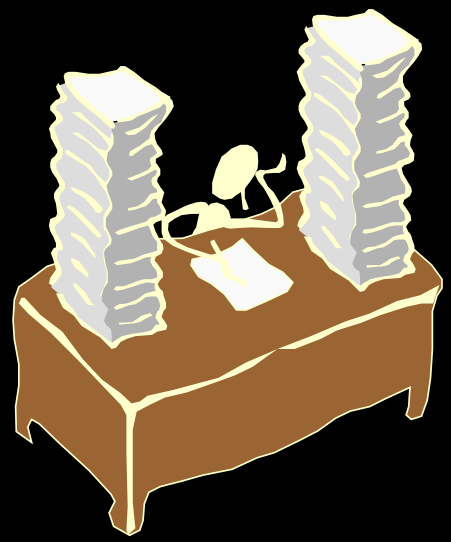
- ***Architecture: Flat vs. Hierarchical Network Architecture***
- ***Routing/Mobility Management: Proactive vs. Reactive Routing Protocol***
- ***Medium Access Control:"To Sense or Not to Sense, this is a question!"***
- ***Security: Authentication without Certification Authority***
- ***Support for real-time traffic: does the network scale for real-time traffic communication***
- ***Multicasting: Is multicast routing feasible, given the frequenly changing topology?***

The Ad-Hoc Networks Design Choices

Hierarchical Ad-Hoc Network Architecture

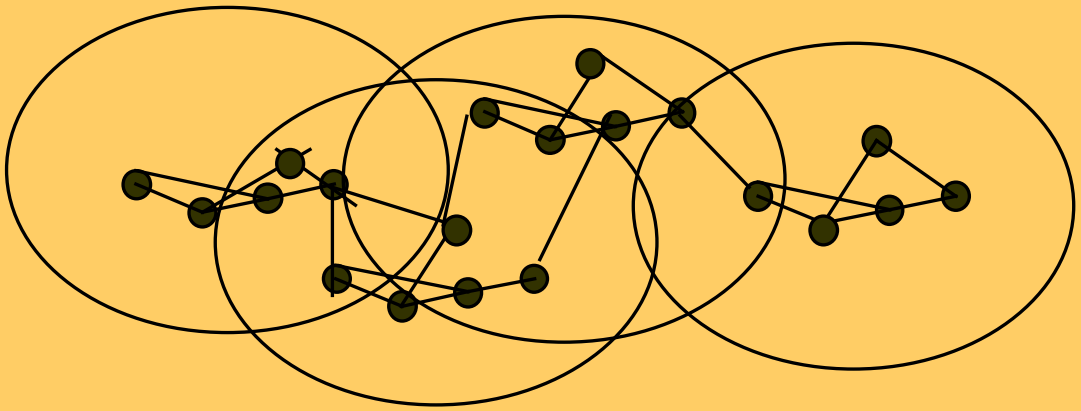


A Two-Tier Ad-Hoc Network



The Ad-Hoc Networks Design Choices

The *Flat* Network Architecture



A Flat Ad-Hoc Network

Flat vs. Hierarchical Comparison: Advantages of the Flat architecture

- **Increased reliability/survivability**
  - **no "single point of failure"**
  - **alternative routes in the network**
- **More "optimal" routing**
- **Reduced use of the wireless resources (better coverage)**
- **Better load balancing property(route diversity)**
- **Lower energy consumption**
- **Better security through low-power operation: LPD/LPI**
- **Possible QOS-based routing**
- **All nodes are of one type of equipment**
- **...**

Flat vs. Hierarchical Comparison:
Advantages of the Hierarchical architecture

- **Easier Mobility Management procedures (just ask the cluster-head)**
- **Better manageability**

An Introduction to Ad-Hoc Networks

However note that:

logical hierarchy can be implemented on top of physical, flat-routed networks;

i.e., security (authorization and authentication) can (and should) be separated from the actual routing decisions

Virtual Backbone

Ben Liang

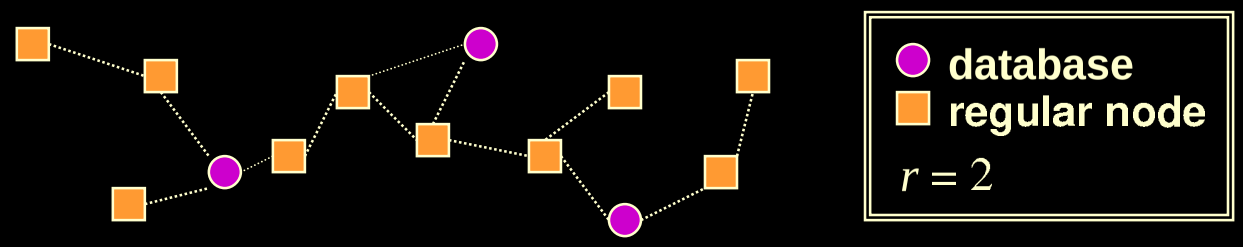
Representative publications:

- *B. Liang and Z.J. Haas, "Virtual Backbone Generation and Maintenance for Ad Hoc Mobility Management," IEEE INFOCOM'2000, Tel Aviv, Israel, March 26-30, 2000*

The Virtual Backbone

Virtual backbone **- mobile nodes containing location databases:**

- **Supports ad hoc mobility management.**
- **Every regular node is at most r hops from a database.**



- **Databases are connected through multi-hop paths.**
- **Needs to be dynamically maintained as network topology changes.**

The Virtual Backbone (con't)

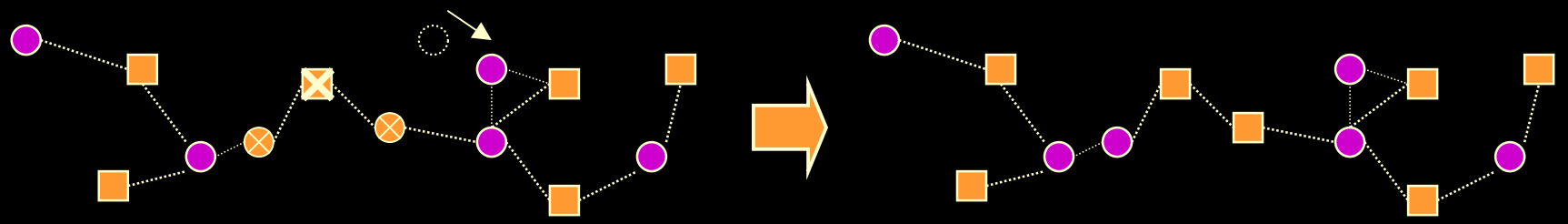
- **The current backbone (*clusterhead*, *core*) construction schemes in LCA, CBRP, CEDAR, etc, only allow $r=1$.**

- **Given any value of r, the Distributed Database Coverage Heuristic (DDCH) dynamically generates and maintains the virtual backbone.**

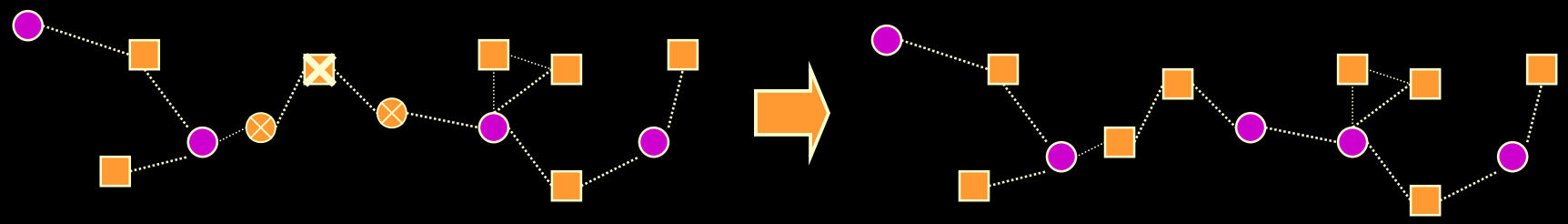
Distributed Database Coverage Heuristic

The DDCH generates the same VB as that generated by a centralized greedy algorithm.

Dynamic DDCH maintains VB coverage as network topology changes:



Database merging maintains steady-state VB size:



Virtual Backbone - Some Results

The optimized (over r) VB maintenance cost has message overhead $O(N^{1.5})$.

Comparison with (simple) full-network link-state routing:

# neighbors	4	6	8
VB	8.3×10^4	1.7×10^5	2.0×10^5
link-state	7.5×10^5	1.6×10^6	2.8×10^6

velocity std	0.05	0.2	0.8
VB	5.9×10^4	1.7×10^5	2.4×10^5
link-state	4.1×10^5	1.6×10^6	5.5×10^6

Ad-Hoc Architectural Design Choices

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

- ***Architecture: Flat vs. Hierarchical Network Architecture***
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Proactive Vs. Reactive Routing

- ***Proactive Protocols***
  - ***continuously update the "reachability" information at all the network nodes***
  - ***when a route is requested, it is immediately available***
  - ***examples of proactive protocols are: Distance-Vector (DV), Shortest Path First (SPF), Open Shortest Path First (OSPF)***
- ***Proactive protocols are inappropriate for the ad-hoc networking environment as <u>they waste too much wireless resources</u>, especially for large, highly mobile network.***

Proactive Vs. Reactive Routing

- ***Reactive Protocols***
  - *discover routes <u>only</u> upon demand*
  - *involve some sort of "global search"*
  - *there may be a significant delay associated with the route discovery*
  - *examples of reactive protocols are the family of flooding protocols*
- ***Reactive protocols are inappropriate for the ad-hoc networking environment as they are too slow and consume too much network resources, especially for large, highly mobile network.***

Ad Hoc Routing - an Overview

Ad hoc routing protocols can be classified as:

- ***<u>Reactive Routing</u> or On-demand routing invoke a route determination procedure only on demand; e.g., AODV, TORA, DSR etc. Some drawbacks are:***
  - ***- delays***
  - ***- significant control traffic***
- ***<u>Proactive Routing</u> or Table-driven routing attempt to continuously evaluate the routes to all the destinations in the network. eg. DSDV, OLSR, TBRPF etc. Drawbacks:***
  - ***- wastage of resources***
  - ***- significant control traffic***

Proactive Vs. Reactive Routing

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

⇓

The Zone Routing Protocol (ZRP)

The Zone Routing Protocol (ZRP)

Marc Pearlman and Prince Samar

Representative publications:

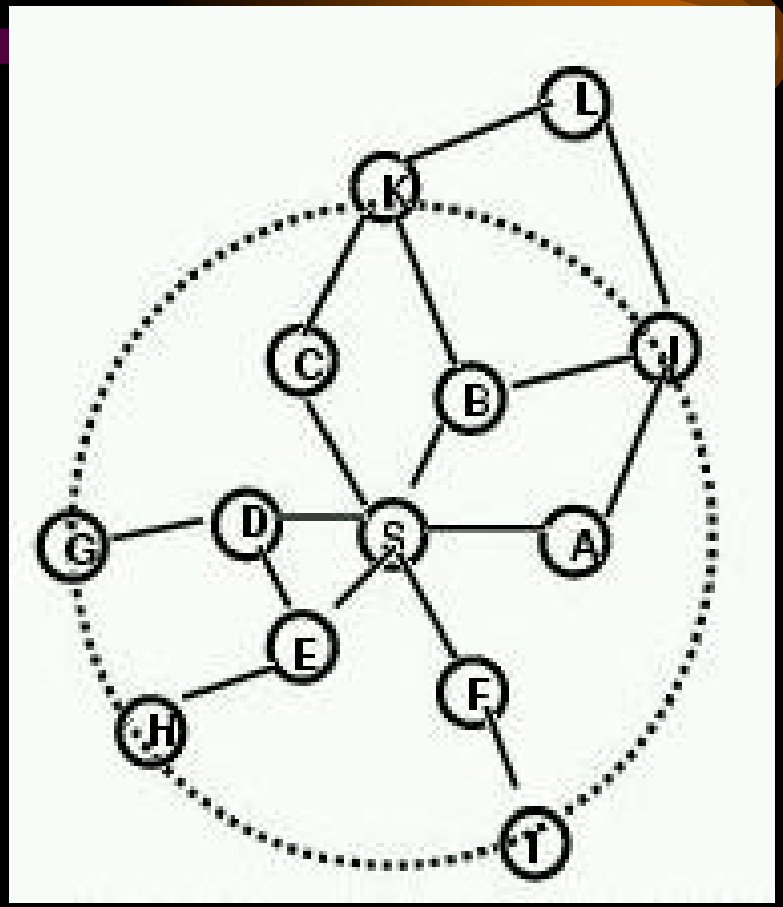
- *draft-ietf-manet-zone-zrp-3.txt*
- *M.R.Pearlman and Z.J. Haas, "Determining the Optimal Configuration of the Zone Routing Protocol," JSAC vol. 17. No. 8, Aug. 1999*
- *Z.J. Haas and M.R. Pearlman, "Providing Ad Hoc Connectivity with the Reconfigurable Wireless Networks," in Ad Hoc Networks, Charles Perkins, ed., Addison Wesley Longman, 2000*

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.

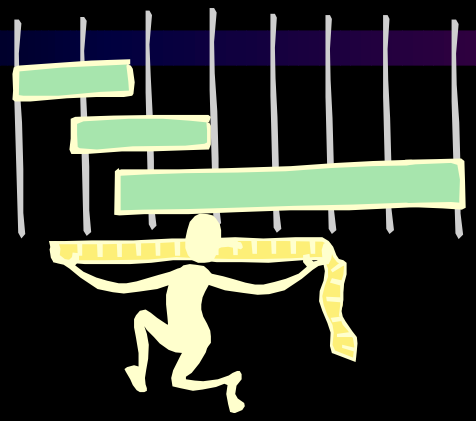
The Notion of a Routing Zone

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

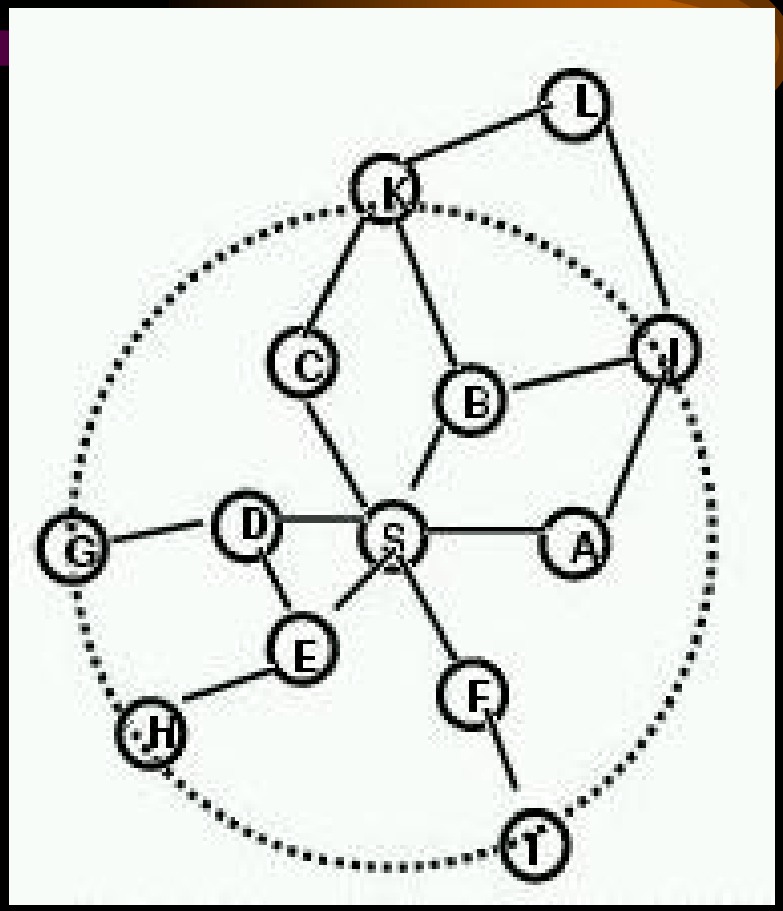


Routing Zone radius of 2 hops

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.*

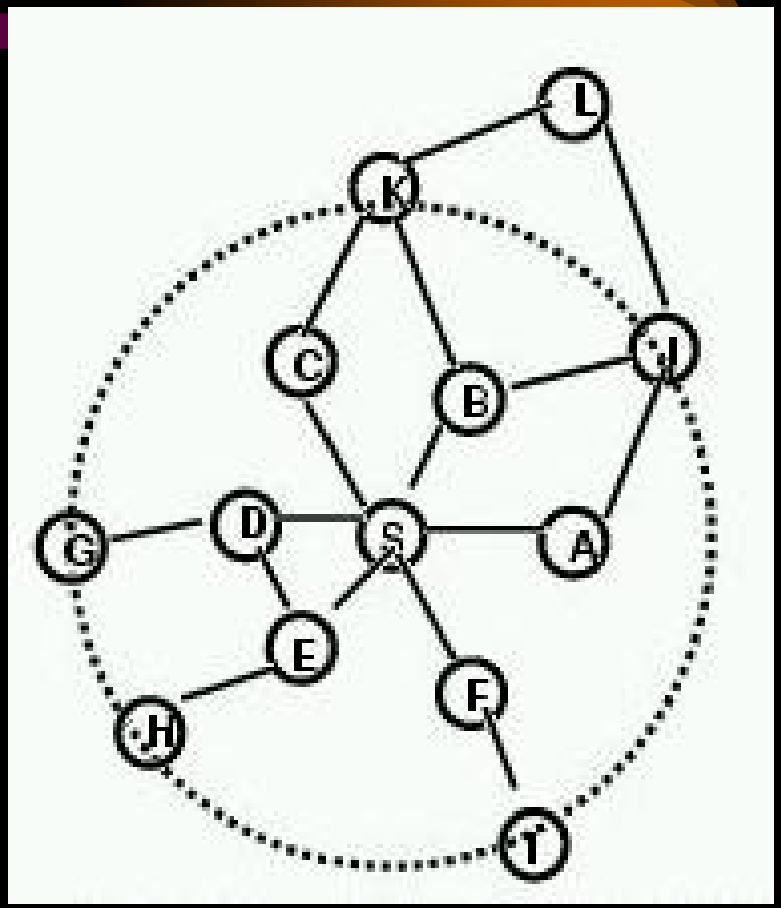


Routing Zone radius of 2 hops

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

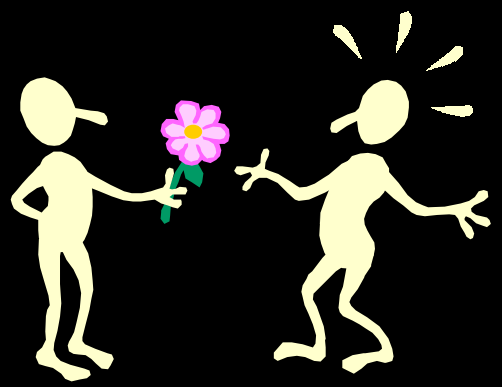
- The source of a query uses *Bordercasting Protocol (BRP)* to deliver messages to the peripheral nodes of its routing zone, if it does not have a route to the destination.

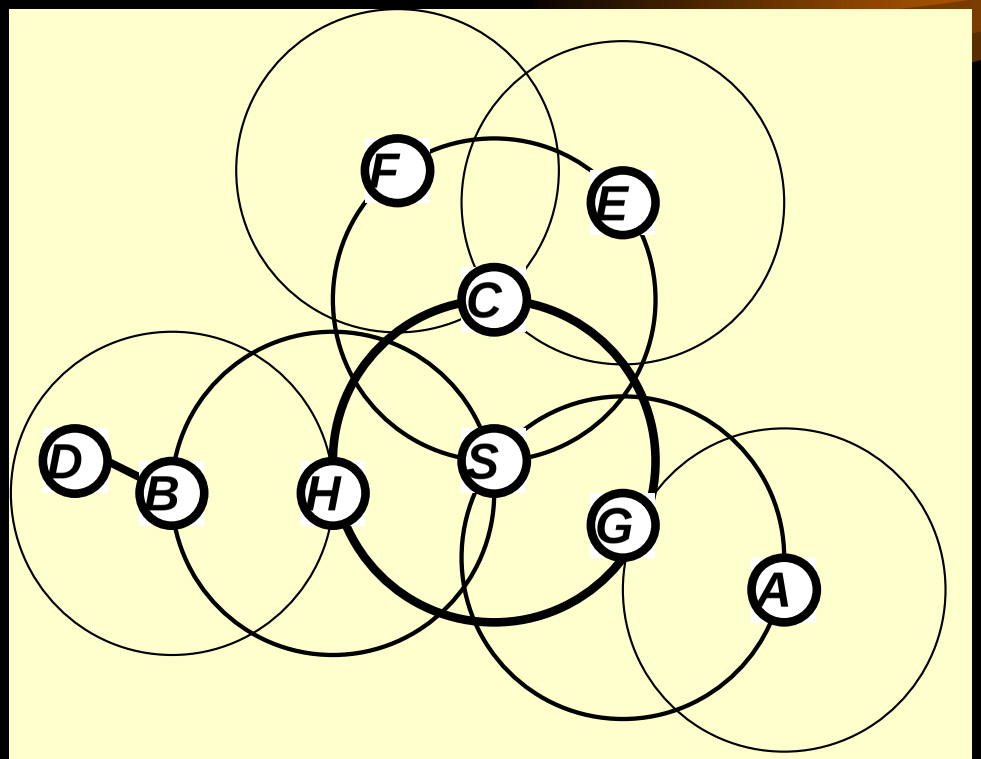
- The peripheral nodes, in turn, *bordercast* the query to their own peripheral nodes if they do not have a route to the destination.



ZRP with routing zone radius 2 hops

The Operation of the ZRP

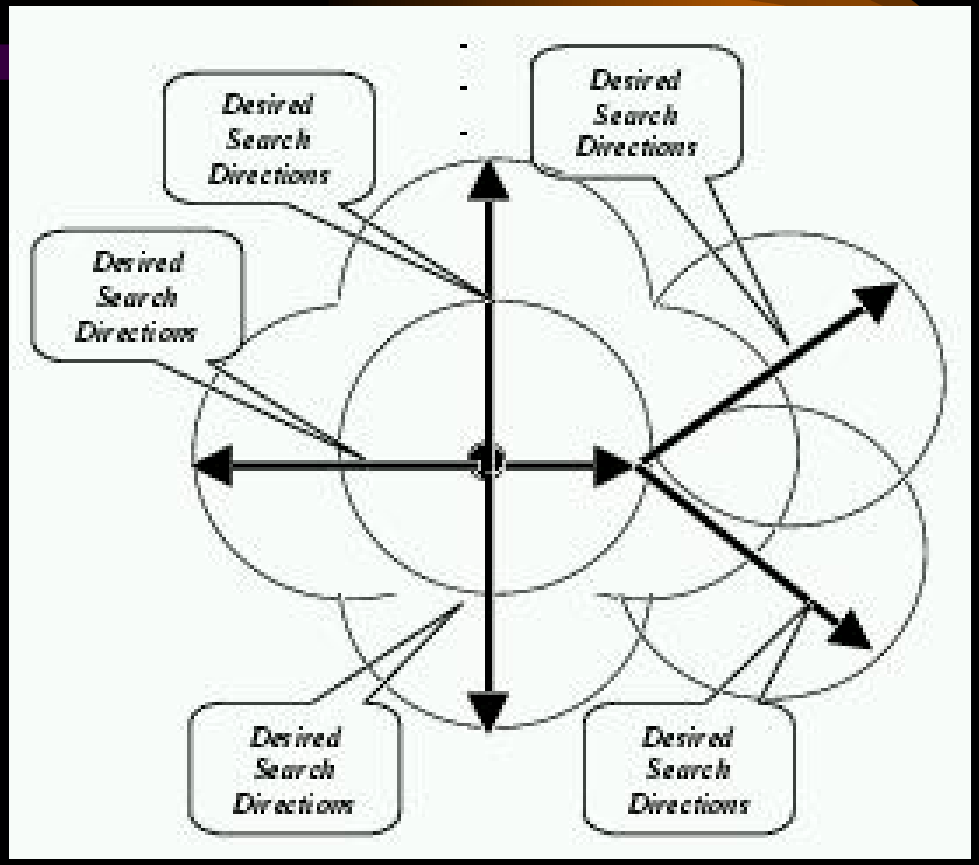




An example of IERP operation

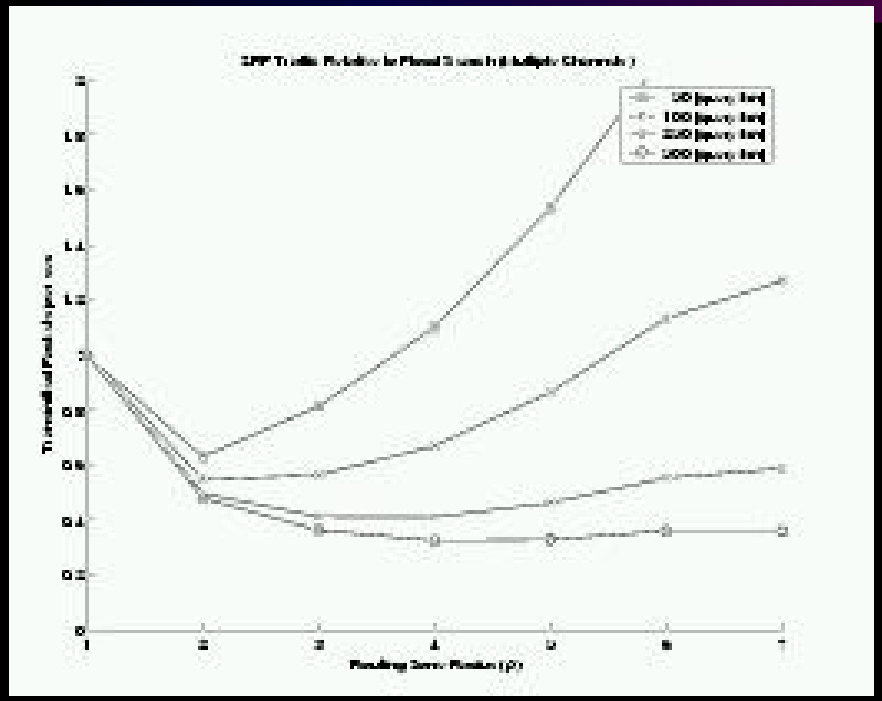
Zone Routing Protocol (ZRP) (con't)

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

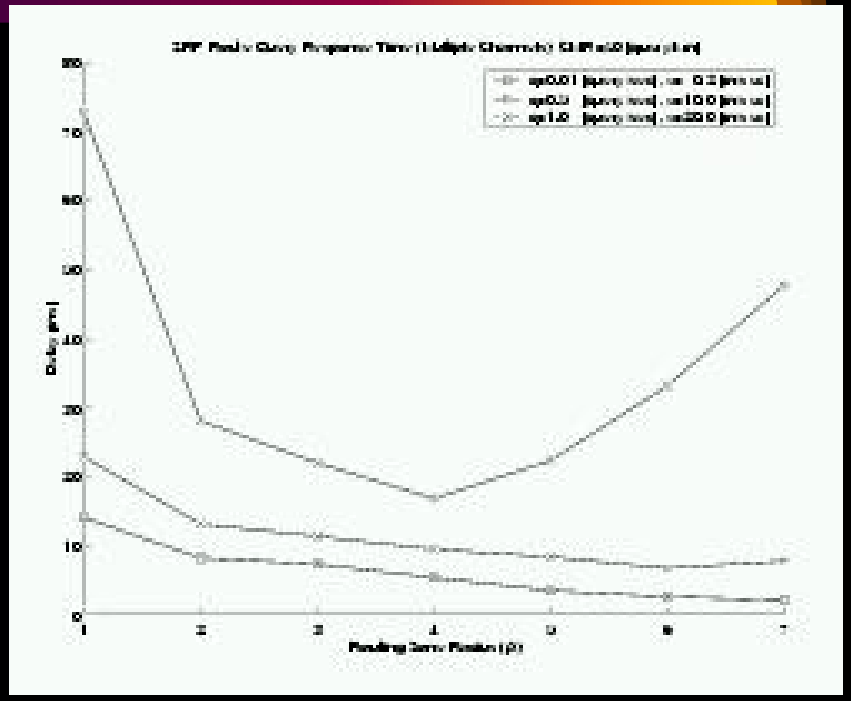


Guiding the search in desirable directions using QD & ET

Some Representative ZRP Performance Results



ZRP traffic relative to flood search vs routing zone radius



ZRP route query response time vs routing zone radius

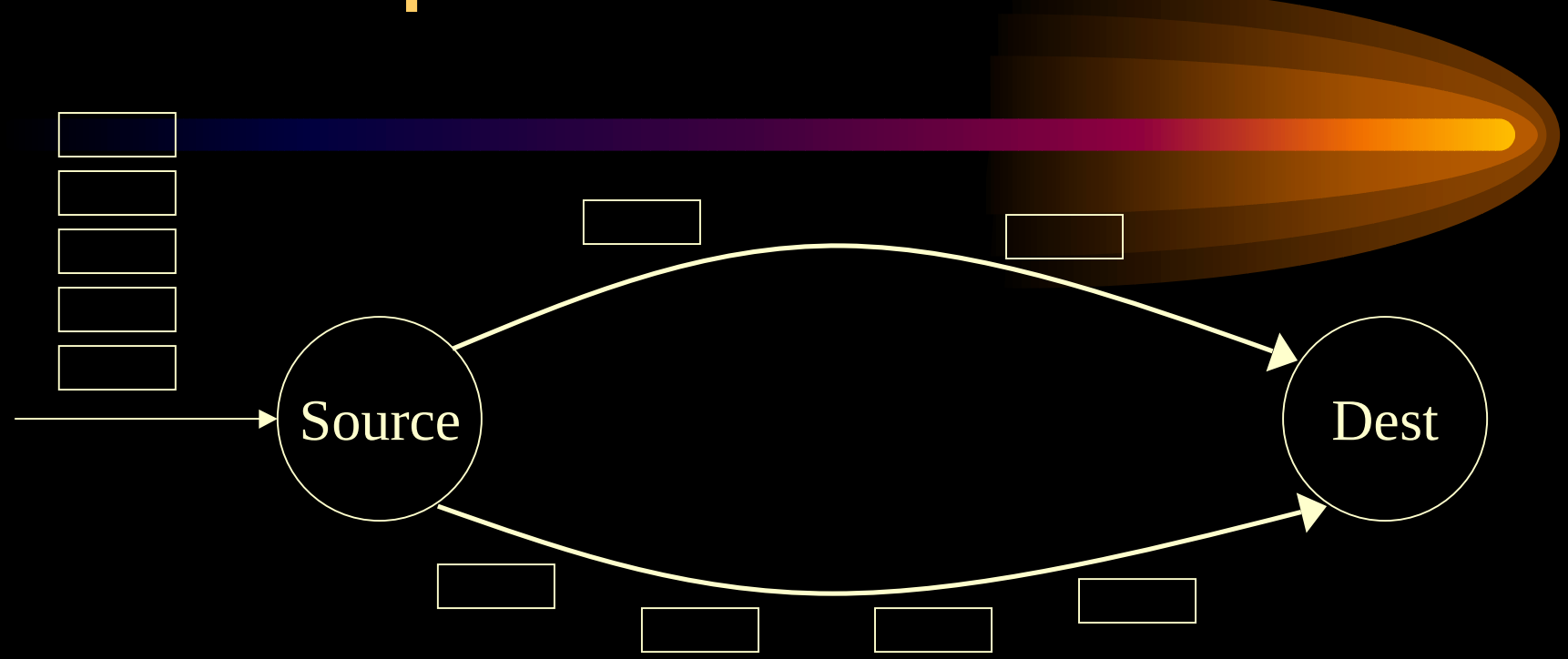
Alternate Path Routing (APR) for Load Balancing in Ad Hoc Networks

Marc Pearlman

Representative publications:

- *M.R. Pearlman, Z.J. Haas, p. Sholander, and S. Tabrizi, "On the Impact of Alternate Path Routing for Load Balancing in Mobile Ad Hoc Networks," MobiHoc'2000, Boston, MA, August 11, 2000*

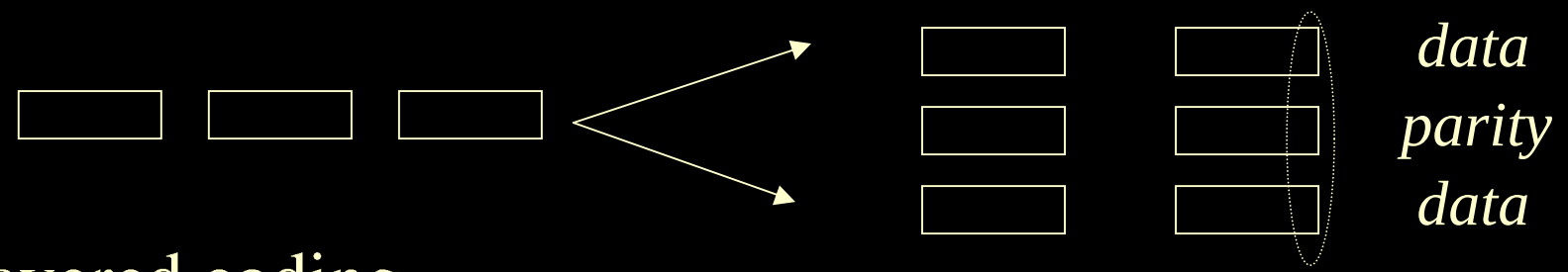
Alternate Path Routing (APR) to address MANET Spectrum and Power Limitations



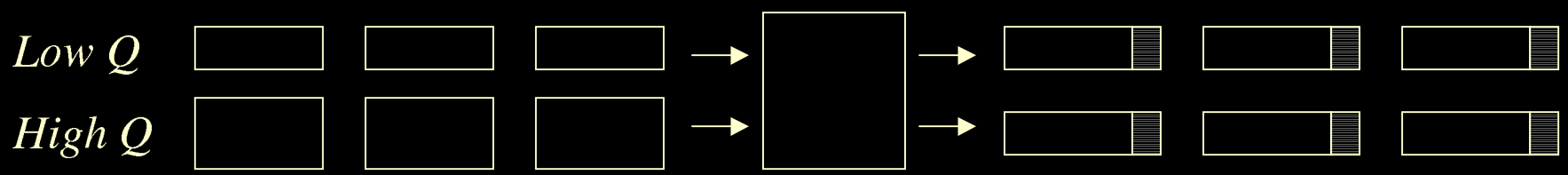
- Lowest cost path used until the onset of congestion
- Traffic should be equally divided among equal cost paths
- Fine APR granularity provides best control

Alternate Path Routing (APR) to address MANET frequent link failures

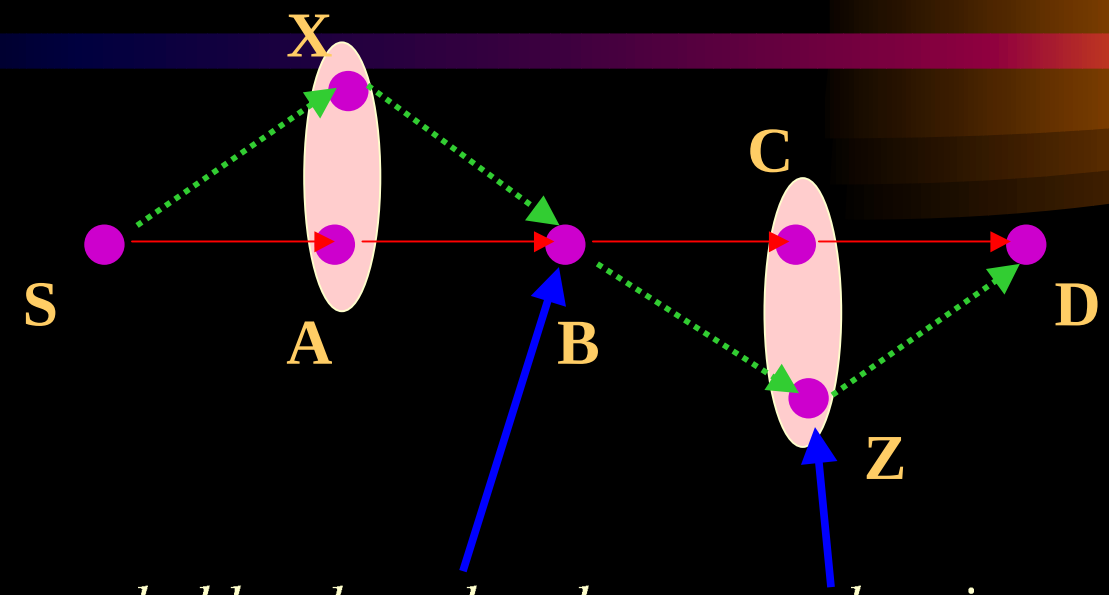
- backup routes (used sequentially)
- diversity routing (erasure coding across streams)



- layered coding

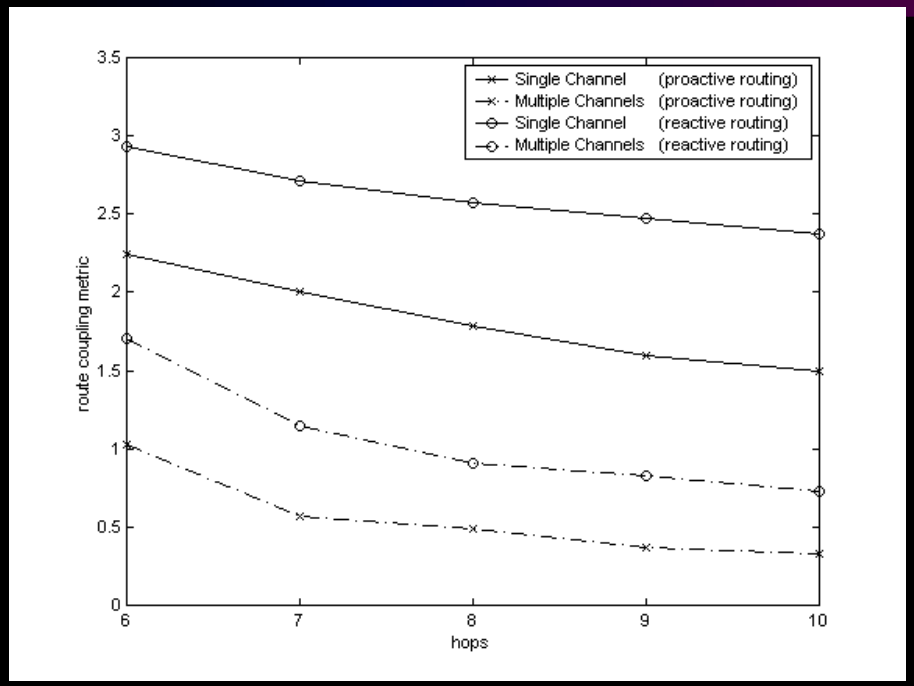


Problem: Routes are Not Independent: Route Coupling

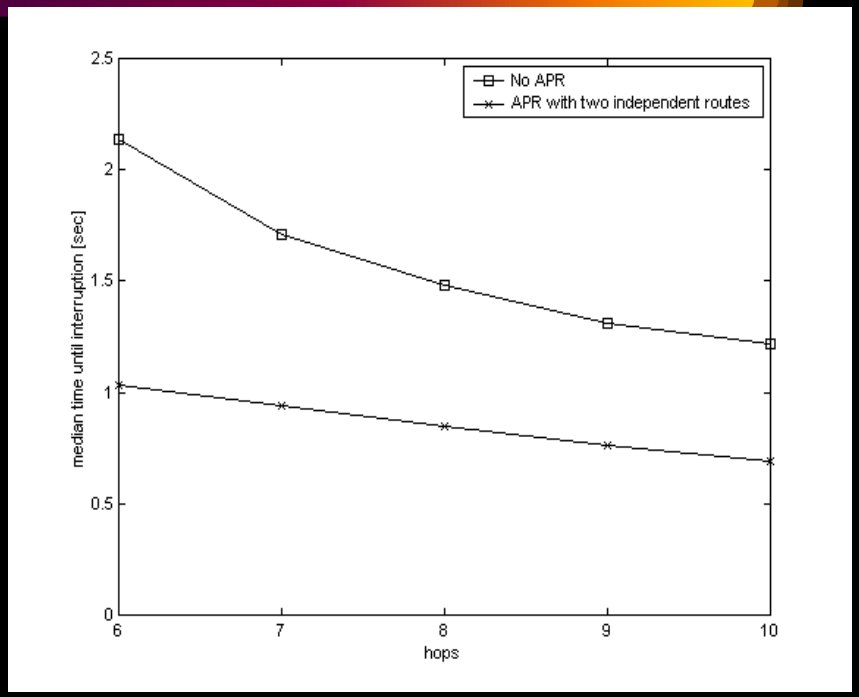


- *Routes coupled by shared nodes or overlapping radio coverage*
- *Transmission along one route blocks or degrades reception along nearby alternate routes*
- ***Route coupling is the rule, not the exception !***

APR Performance



Route Coupling



Time to Service Disruption

Conclusions

- **Tradeoff between path length and diversity.**
- **Route coupling limits APR's ability to improve end-to-end throughput and delay, *especially for single channel networks*.**
- **APR load balancing most effective with bursty traffic and fine route allocation granularity**
- **Distributing traffic across multiple paths increases exposure to link failures.**

Ad Hoc Mobility Management with Uniform Quorum Systems

Ben Liang

Representative publications:

- *Z.J. Haas and B. Liang, "Ad Hoc Location Management Using Quorum Systems," ACM/IEEE Transactions on Networking, April 1999*
- *Z. J. Haas and B. Liang, "Ad Hoc Location Management Using Randomized Database Groups," ICC'99, Vancouver, BC, Canada, June 6-10, 1999*

Mobility Management in Ad Hoc Networks

Uniform Protocols:

Each node has the same responsibilities in routing

Proactive: Destination Sequenced Distance Vector (DSDV)

Global State Routing (GSR)

Optimized Link State Routing (OLSR) ……

Reactive: Ad hoc On-demand Distance Vector (AODV)

Associatively Based Routing (ABR)

Dynamic Source Routing (DSR)

Temporally Ordered Routing Algorithm (TORA) ……

Hybrid: Zone Routing Protocol (ZRP) ……

Mobility Management in Ad Hoc Networks (con't)

Hierarchical Protocols:

Nodes take on distinguished roles in routing

Linked Cluster Architecture (LCA)

- **Cluster Based Routing Protocol (CBRP)**
- **Core-Extraction Distributed Ad hoc Routing (CEDAR)**
- **Zone-based Hierarchical Link State (ZHLS)**
- **Landmark Ad Hoc Routing (LANMAR)**

Mobility management deals with the problem of updating and tracking the location of mobile hosts.

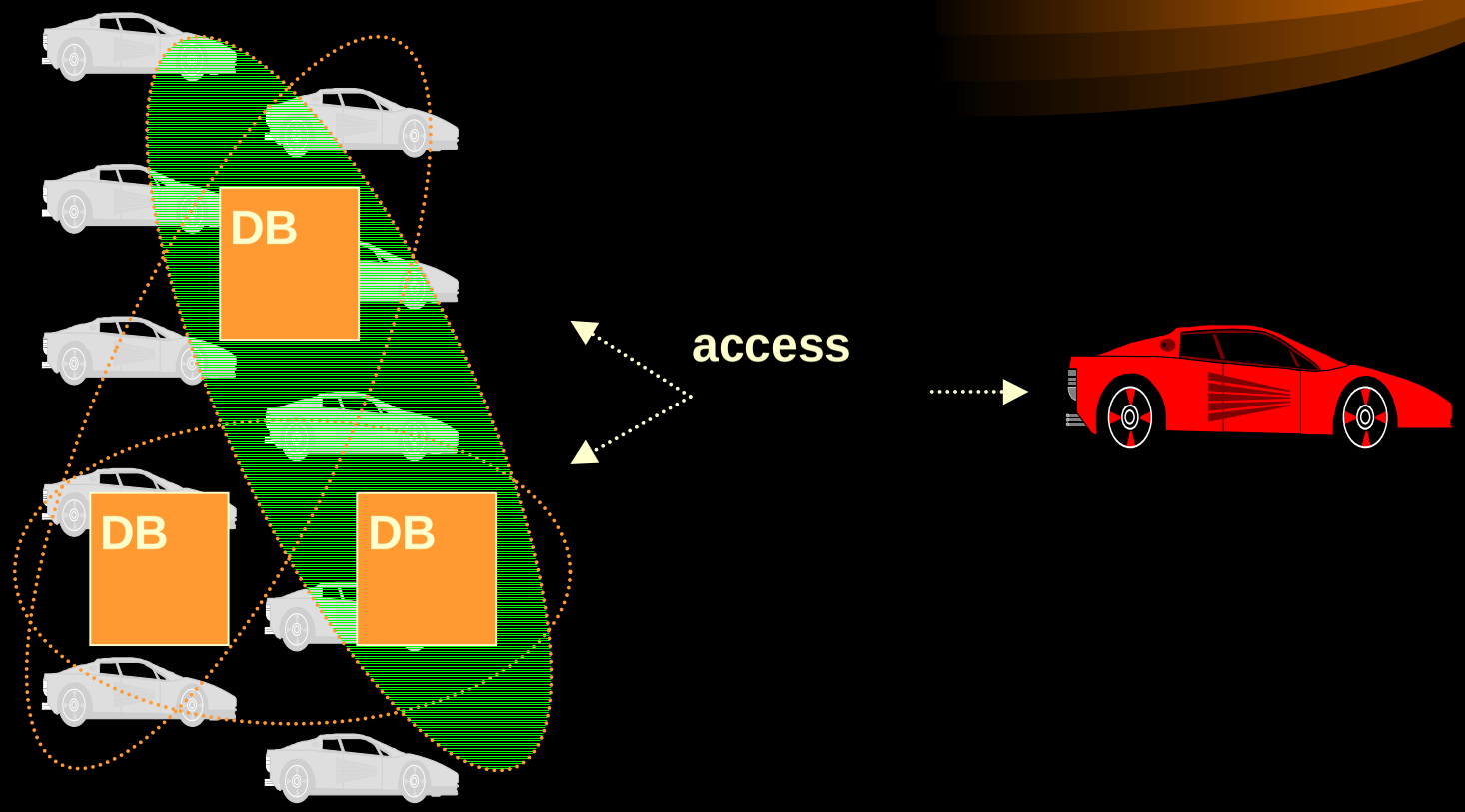
Mobility Management Using Uniform Quorum Systems (con't)

The HLR/VLR scheme is not suitable due to the lack of stability in ad hoc networks.

Ad hoc mobility management using Uniform Quorum Systems (UQS):

- **Databases reside in dynamically selected mobile nodes.**
- **Databases are logically grouped into Uniform Quorums.**
- **Location storage and location query use all databases in an *independently* and *randomly* chosen quorum.**
- **The overlapped databases provide the sought location information.**
- **Provides doubly-distributed data duplication.**

Mobility Management Using Uniform Quorum Systems (con't)



Mobility Management Using Uniform Quorum Systems (con't)

In a Uniform Quorum System:

- **Every quorum contains the same number of databases.**
- **Every database appears in the same number of quorums.**
- **Every two quorums intersect at the same number of databases.**

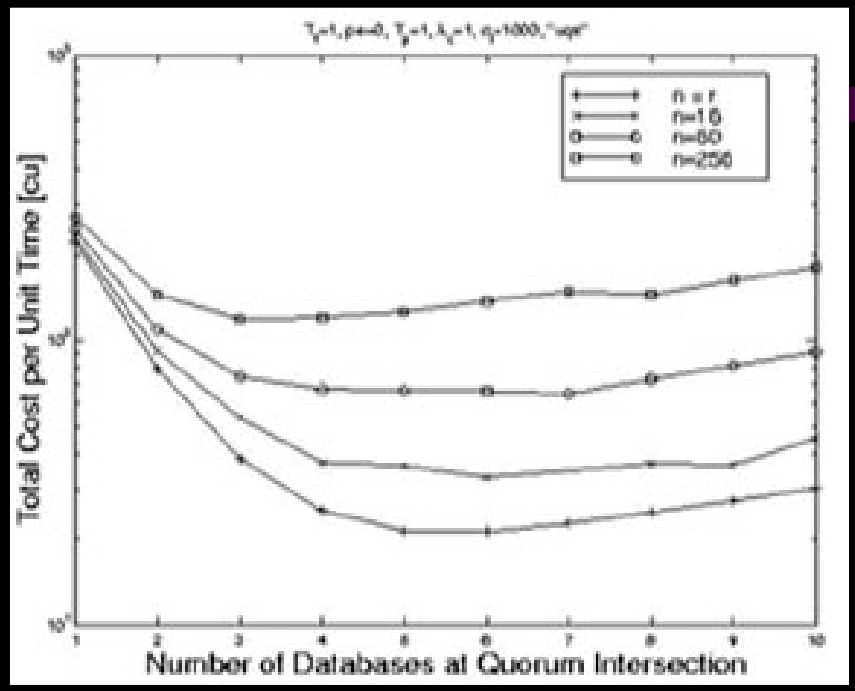
A UQS can be constructed as the dual form of a Balanced Incomplete Block (BIB) design.

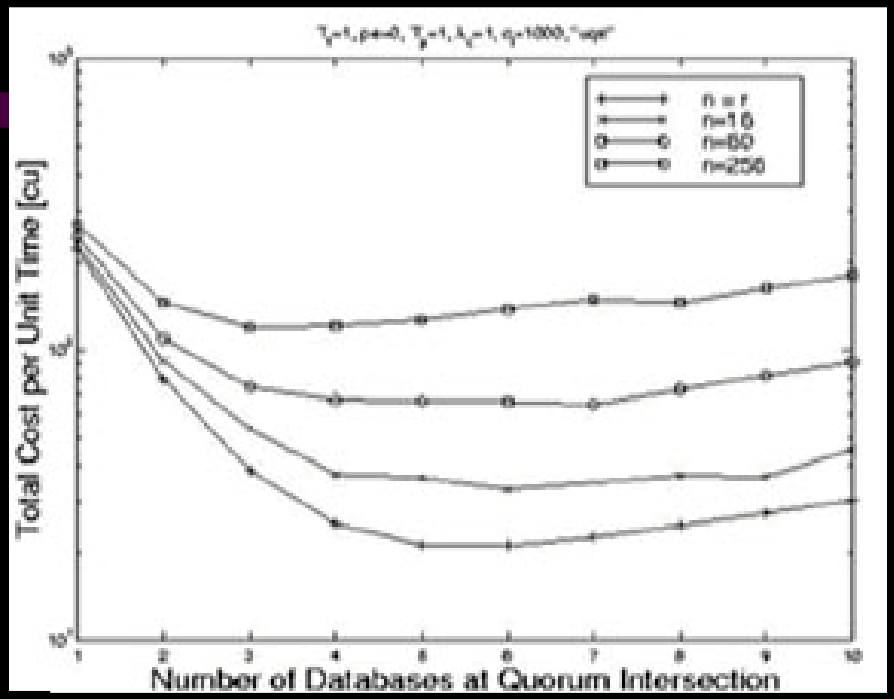
- **Hanani's BIB design**
- **Sprott's BIB design**
- **Maekawa's BIB design ……**

Numerical analysis is performed to study the joint optimization of:

- **total number of databases**
- **size of quorum intersection**
- **frequency of location updating by a mobile node**

Optimization over the total number of databases, *n*, and the size of quorum intersection, *r* :





Databases are available all the time

Databases are available *99.5%* of the time

The UQS scheme out-performs the "multiple virtual HLR" scheme (*n*=*r*) when the databases are not available all the time.

Ad-Hoc Architectural Design Choices

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

- ***Architecture: Flat vs. Hierarchical Network Architecture***
- ***Routing/Mobility Management: Proactive vs. Reactive Routing Protocol***
- ***Medium Access Control:"To Sense or Not to Sense, this is a question!"***
- ***Security: Authentication without Certification Authority***
- ***Support for real-time traffic: does the network scale for real-time traffic communication***
- ***Multicasting: Is multicast routing feasible, given the frequenly changing topology?***

The Dual Busy Tone Multiple Access protocol (DBTMA)

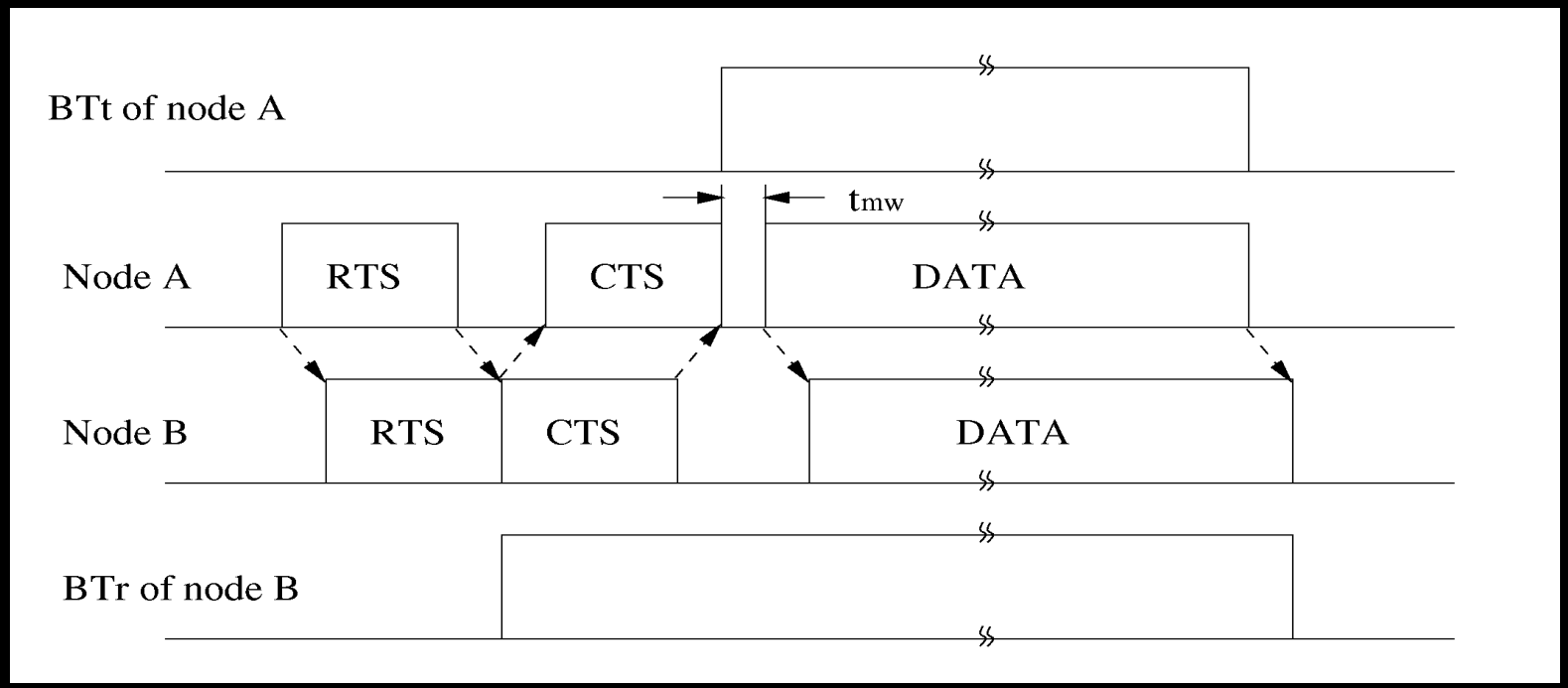
Jing Deng

Representative publications:

- *Z. J. Haas and J. Deng, "Dual Busy Tone Multiple Access (DBTMA): A Medium Access Control Scheme for Multihop Networks," WCNC'99, New Orleans, LA, September 21-24, 1999*
- *Z.J. Haas, J. Deng, and S. Tabrizi, "A Collision Free Medium Access Control Scheme for Ad Hoc Networks," MILCOM'99, Atlantic City, NJ, Oct. 31 - Nov. 3, 1999*

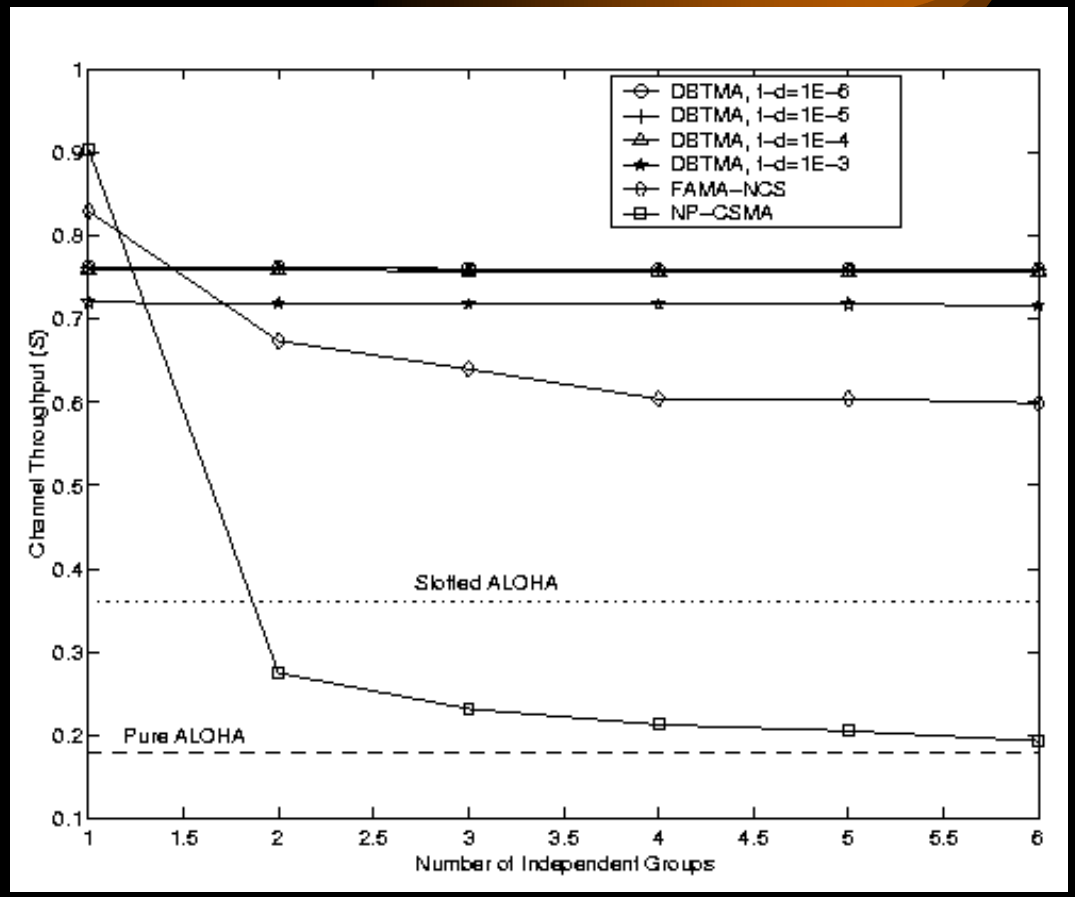
Dual Busy Tone Multiple Access (DBTMA)

- ***Use two busy tones:***
  - ***BTr set up by receiver, protecting data packets***
  - ***BTt set up by transmitter, notifying neighbor nodes***
  - ***Nodes sensing these tones need to defer***



DBTMA achieves better performance

- *Nodes in N independent groups competing to send to a common receiver*
- *Each group contains large number of nodes*
- *Comparing the performance of DBTMA with different busy tone sensing delay and other schemes*



Sensing Back-off Algorithm (SBA)

- *After collisions, all nodes back-off randomly.*
- *Duration of back-off is controlled by the length of the back-off interval (B)*
- *In Binary Exponential Back-off (BEB):*

$$f_c(x) = 2x \qquad f_s(x) = B_{\min}$$

- *In Multiple Increase Linear Decrease (MILD):*

$$f_c(x) = 1.5x \qquad f_s(x) = x - 1$$

Copy mechanism

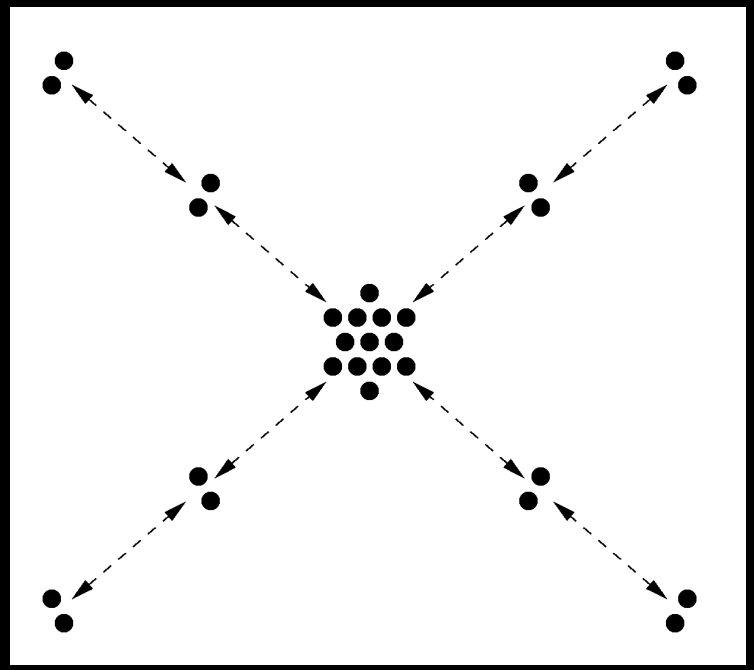
- *We propose SBA:*

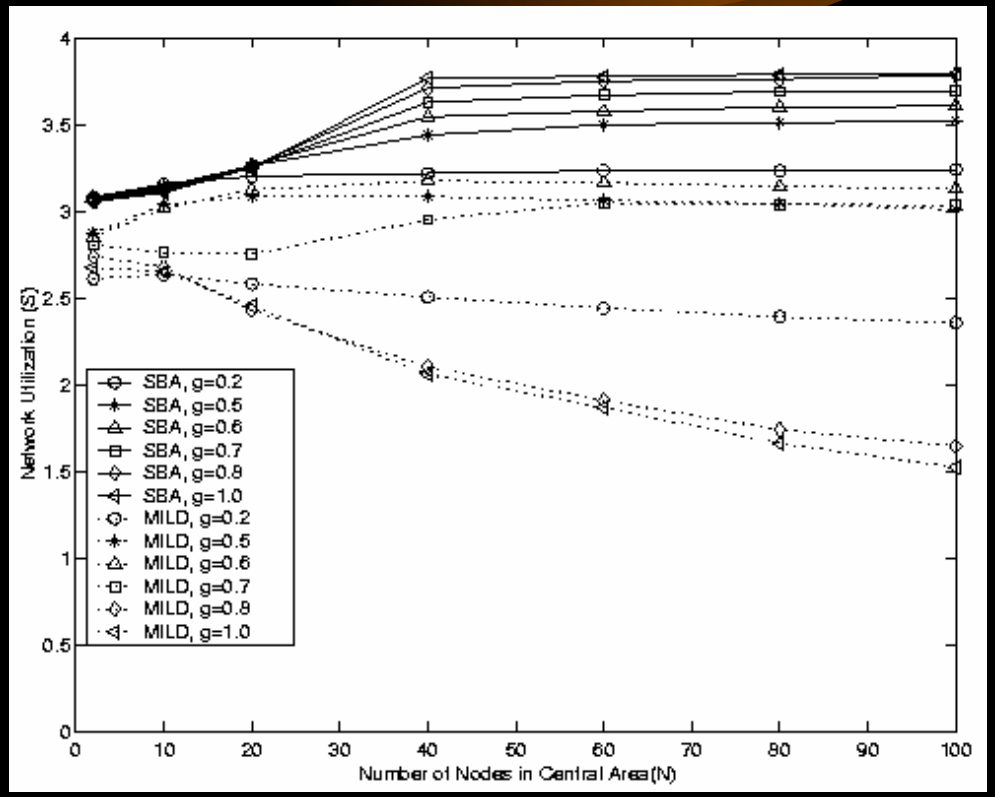
$$f_c(x) = \alpha \cdot x \qquad f_s(x) = x - \beta$$

Sensing mechanism

SBA Offers Better Network Utilization Than MILD

Heterogeneous network with different traffic load





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Securing Ad Hoc Networks

Lidong Zhou

Representative publications:

- *L. Zhou and Z.J. Haas, "Securing Ad Hoc Networks," IEEE Network Magazine, vol. 13, no.6, Nov/Dec 1999*

Securing Ad-Hoc Networks

- Secure lower layers (e.g., MAC)
- Secure routing
- <u>Secure high-level communication</u>
  - Availability
  - Authentication
  - Integrity
  - Confidentiality
  - Nonrepudiation

} Public Key Infrastructure

Securing Ad-Hoc Networks(con't)

- Security is important for many ad hoc networks application; e.g., military communications, but it's also a tough problem
- The main problems in securing ad hoc communications are:
  - **lack of a central element; e.g., no CA**
  - **frequent changes of topology; trust relations are change frequently as well**
  - **vulnerable wireless transmission medium; e.g., easy eavesdropping, denial of service, impersonation, replay, etc, attacks**
  - **scalability to large networks is required**

Securing Ad-Hoc Networks(con't)

- **Our approach is to rely on two principles:**
  - **(1) high degree of redundancy in the network topology**
  - **(2) distribution of trust among many network nodes, rather than relying on a single or small set of nodes**
- **(2) assumes that if the probability of having *t* nodes being compromised at any point in time is small, distributing the trust among *t+1* nodes suffices to ensure sufficient level of security**

Securing Ad-Hoc Networks(con't)

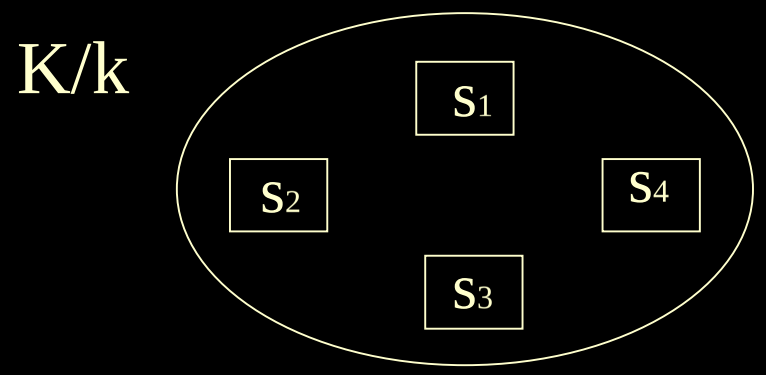
- **The routing is vulnerable, because an attacker can inject outdated control information.**
- **Secure routing can be achieved through, for instance, *Diversity Coding,* which exploit the redundancy in path discovery process.**
  - **Use *n* paths for transmission of data over *n-r* paths and redundancy information over *r* paths**
- **We implement the *Distribution of Trust* through *Threshold Cryptography.***
  - **We use *Share Refreshing* to cope with *Mobile Adversaries.***

Existing Key Management Approaches

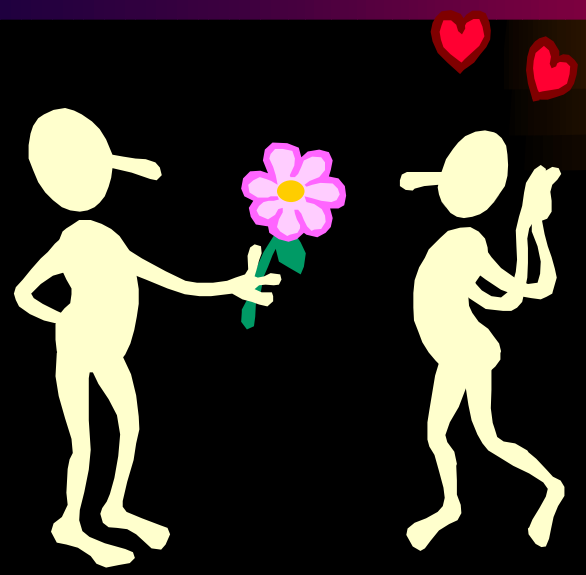
- **Offline Certification Authority**
  - **Problem: Cannot promptly reflect changes**
- **Centralized Authority**
  - **Problem: Single Point of Failure**

Distributed Key Management

- **Replication for Fault Tolerance**
- **Threshold Cryptography for Security**
- **Proactive Protocol for Adaptability**



Some final thoughts ...

- Although the ad hoc networking technology is an exciting new direction … do not tear down your cellular infrastructure yet … ☺
- The hot topics in studying the ad hoc networking technology are (still):
  - **<u>scalable</u> routing, including mobility management**
  - **multicasting**
  - **access control**
  - **security**
- The next few years will show whether this technology is commercializable.

Thank you for listening!