Message Ferrying and Other Short Stories:
Mobility-Assisted Data Delivery in Wireless Networks

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Outline

- Intermittently-Connected Networks
- Message Ferrying
- The Space of Wireless and Mobile Networks

The "Traditional" MANET Wireless Paradigm

- The Network is "Connected"
  - There exists a (possibly multi-hop) path from any source to any destination
  - The path exists for a long-enough period of time to allow meaningful communication
  - If the path is disrupted it can be repaired in short order

A Brief History of Wireless Nets

- Wireless networks are as old as the Internet itself
  - DARPA PRnet
  - Initial motivation for some protocol functions (e.g., IP-layer fragmentation)
- PRnet -> SURANet -> Mobile Ad-hoc Net (MANET)
  - Latest MANET wave coincided with 802.11 activities
  - Most wireless today is base-station oriented (not mobile, nor ad-hoc)
- My conclusion: attempt to emulate wired net model for MANET has led to failure to achieve wide deployment

The Rise of Intermittently-Connected Networks

Intermittently-Connected Wireless Networks

- Disconnected
  - By Necessity
  - By Design (e.g. for power considerations)
- Mobile
  - With enough mobility to allow for some connectivity over time
  - Data paths may not exist at any one point in time but do exist *over time*

Mobility-Assisted Data Delivery: A New Communication Paradigm

- Mobility used for connectivity
- ***New Forwarding Paradigm***

Store

Carry for a while

forward

- Special nodes: Transport entities that are not sources or destinations

Also Known As

- Delay-Tolerant Networks
- Disruption-Tolerant Networks
- Sparse Networks
- Opportunistic Networks

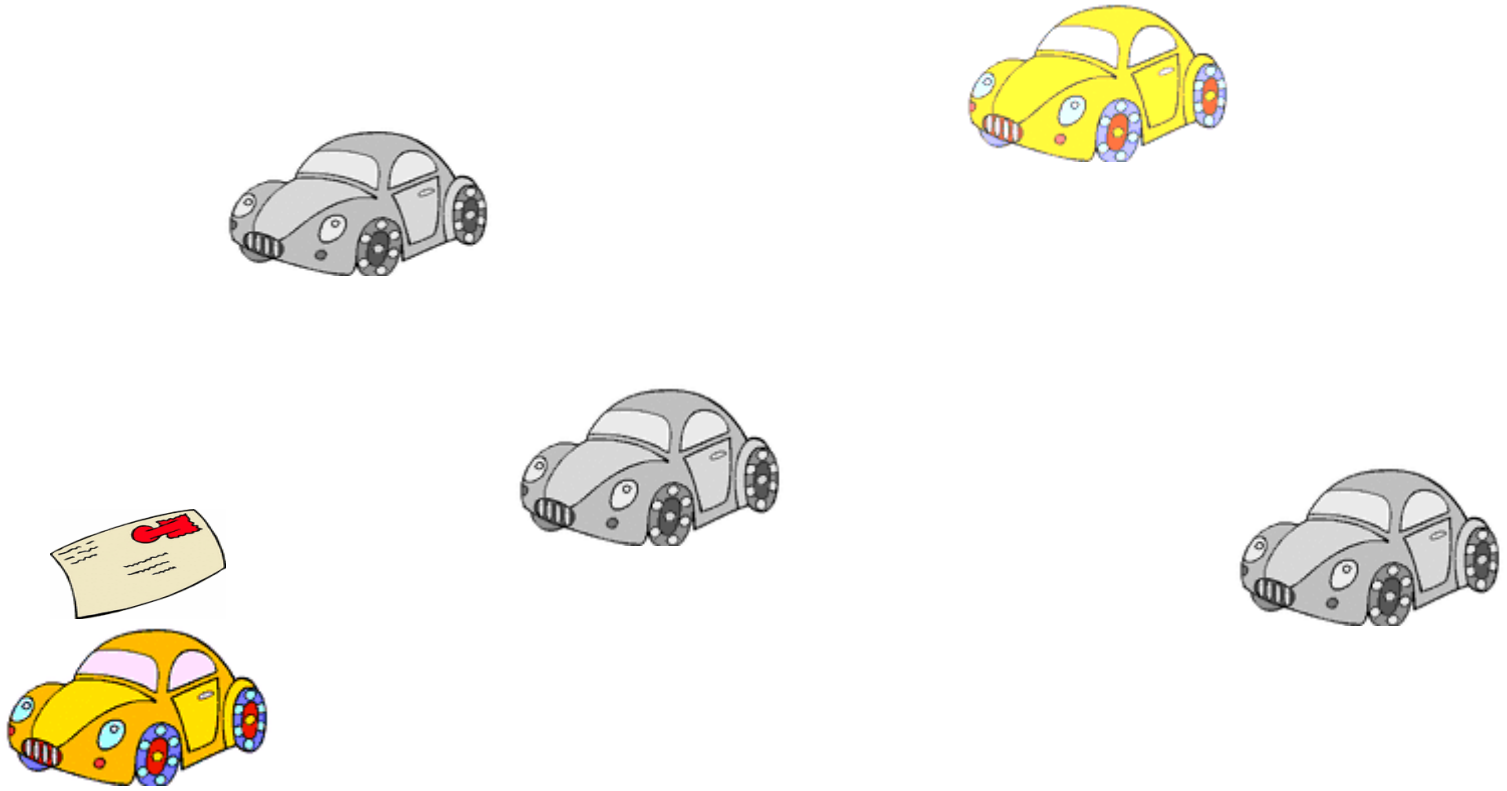
Data Applications

- Nicely suitable for Message-Switching
- Delay tolerance … but can work at multiple time scale

Epidemic Routing

- Vahdat and Becker
- Utilize physical motion of devices to transport data
- *Store-carry-forward* paradigm
  - Nodes buffer and carry data when disconnected
  - Nodes exchange data when met
  - data is replicated throughout the network
- Robust to disconnections
- Scalability and resource usage problems

Epidemic Routing



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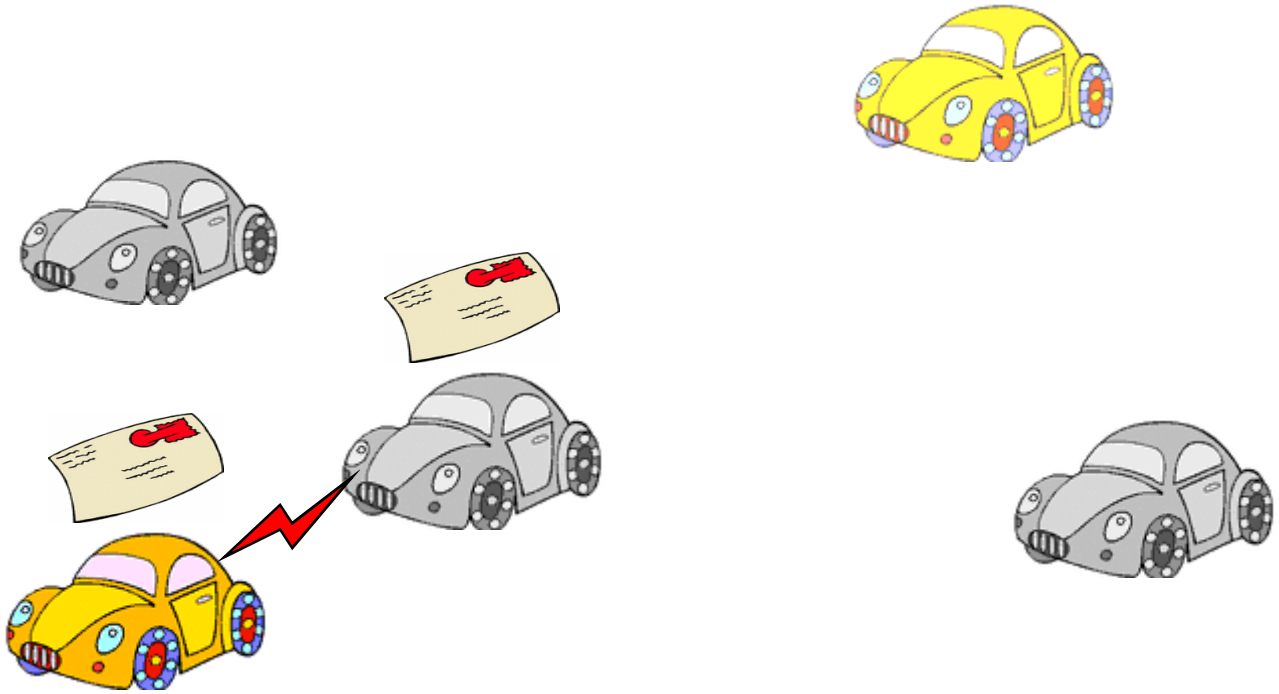

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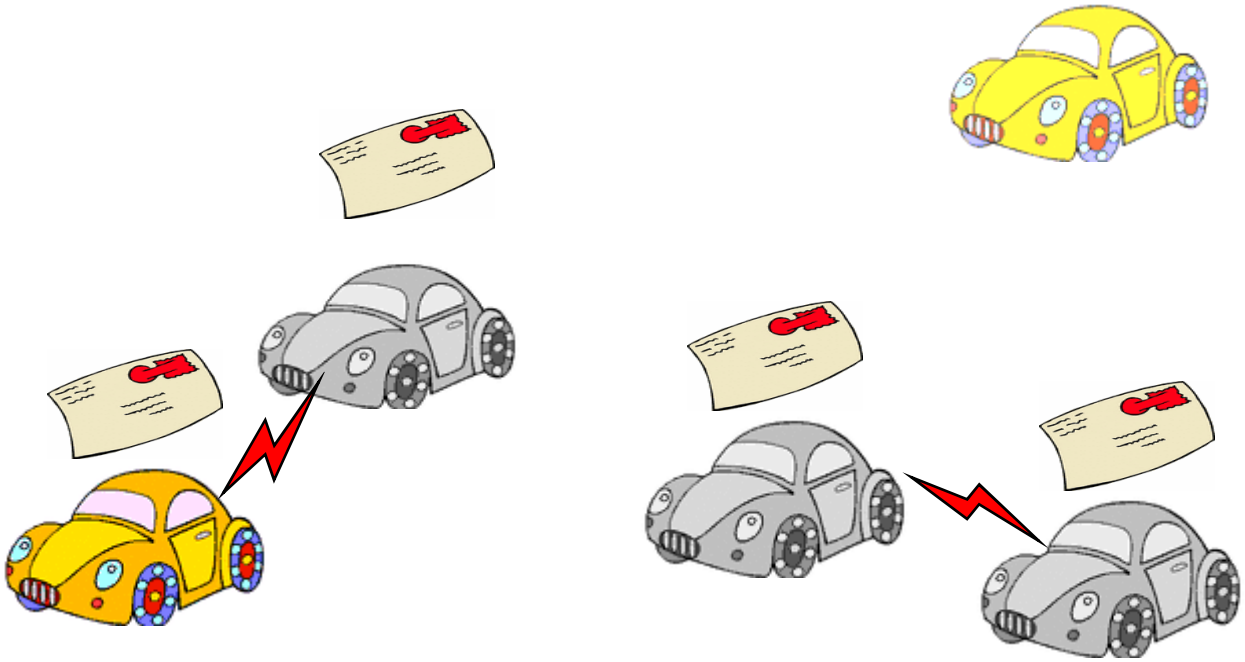

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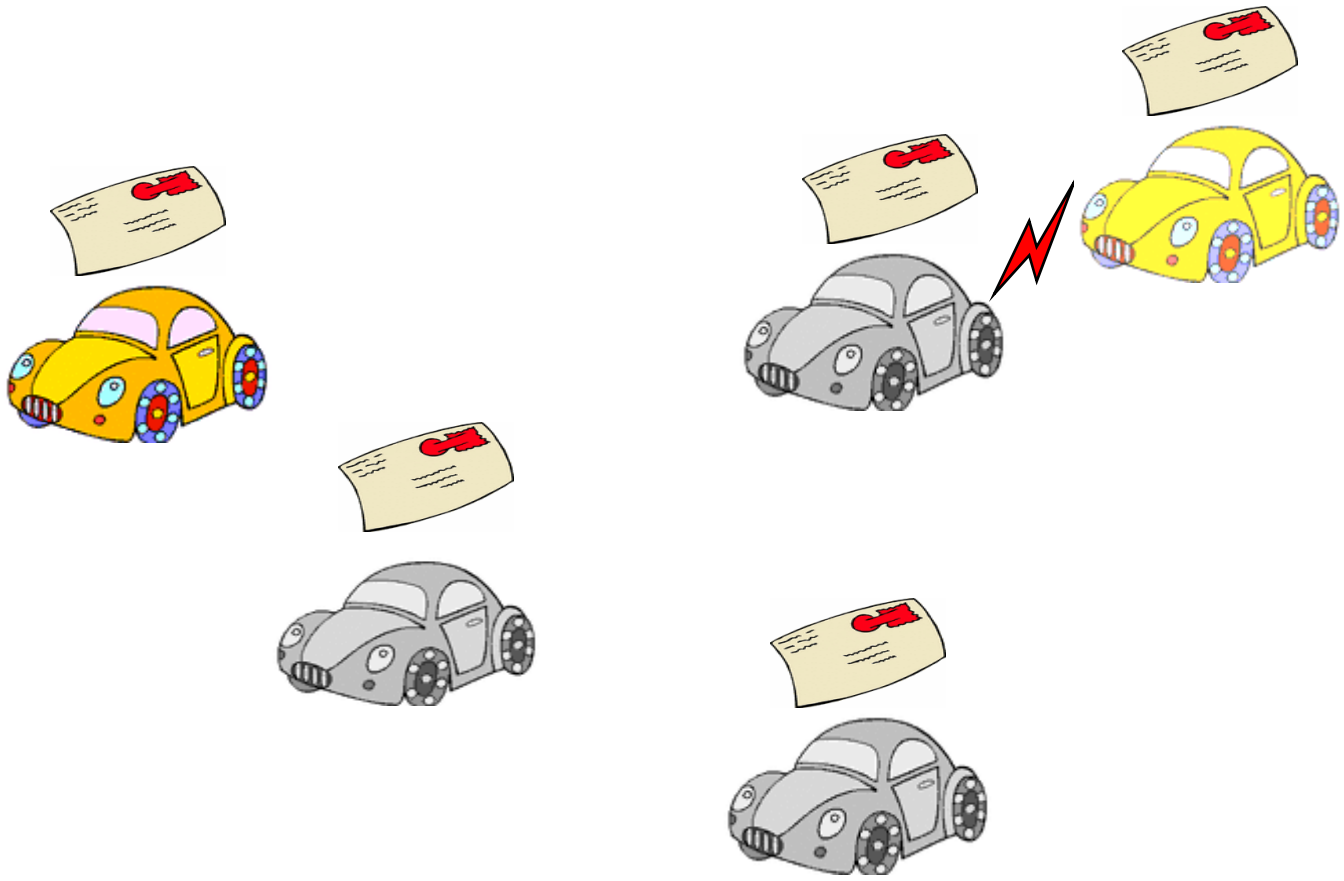


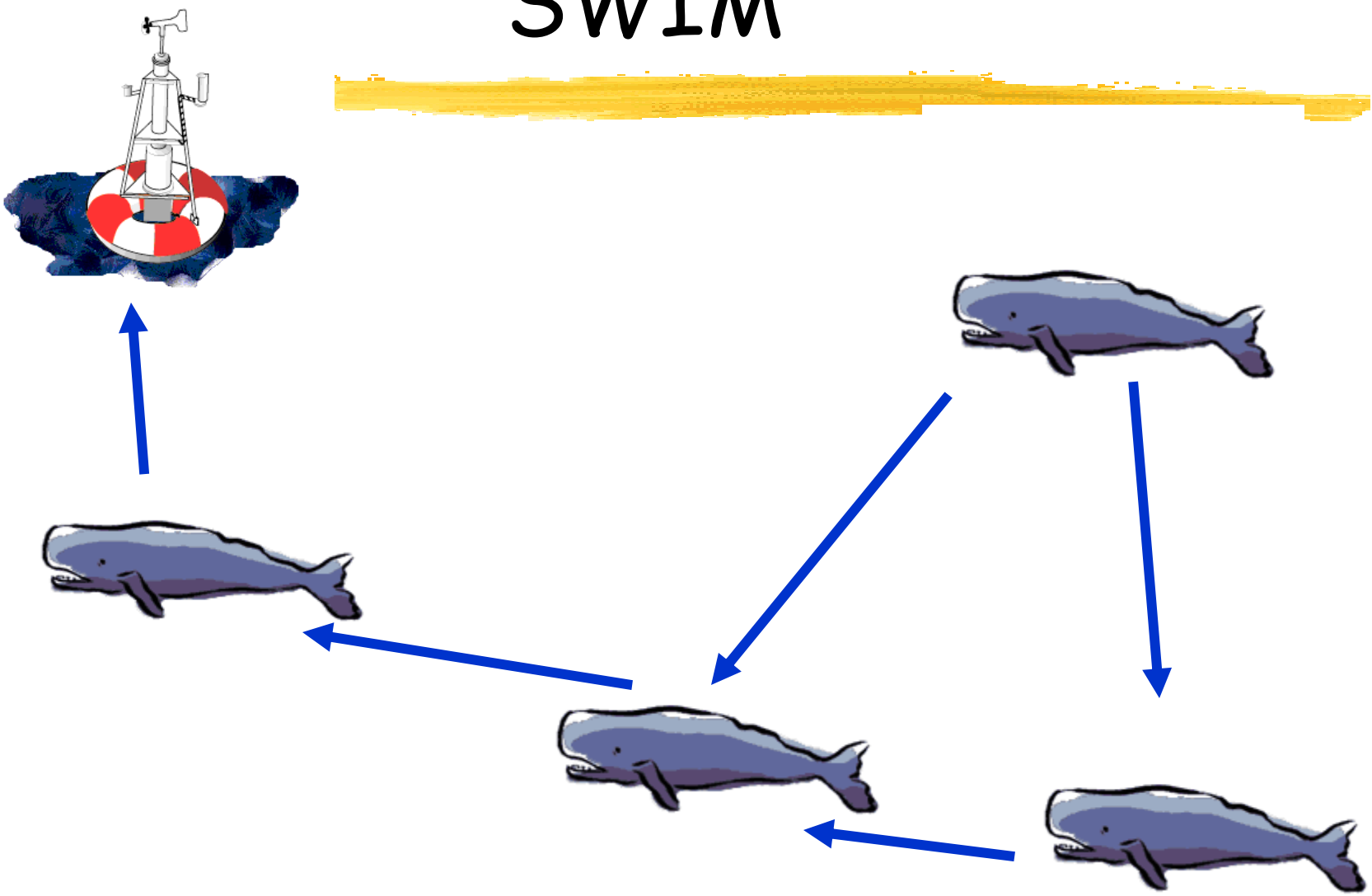
The Trouble with ER

- Potentially high-failure rate
- Message duplication consumes nodal resources
- Some mobility patterns can cause disconnection
- Can be improved with contact probability information - Levine et al

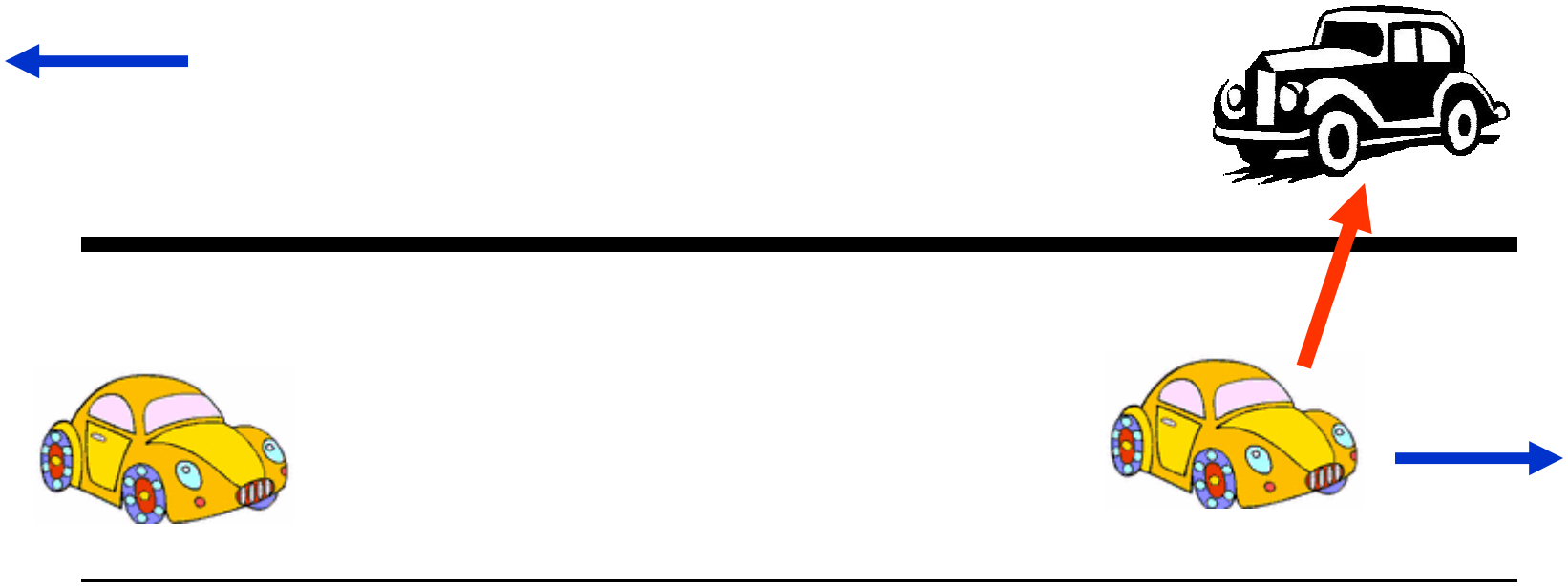
Other "Original" Systems

- ZebraNet and SWIM
- Data MULE and Smart-Tags
- Vehicle-to-Vehicle Communication
- Message Ferrying
- DakNet

SWIM



Vehicles on Highways Networks



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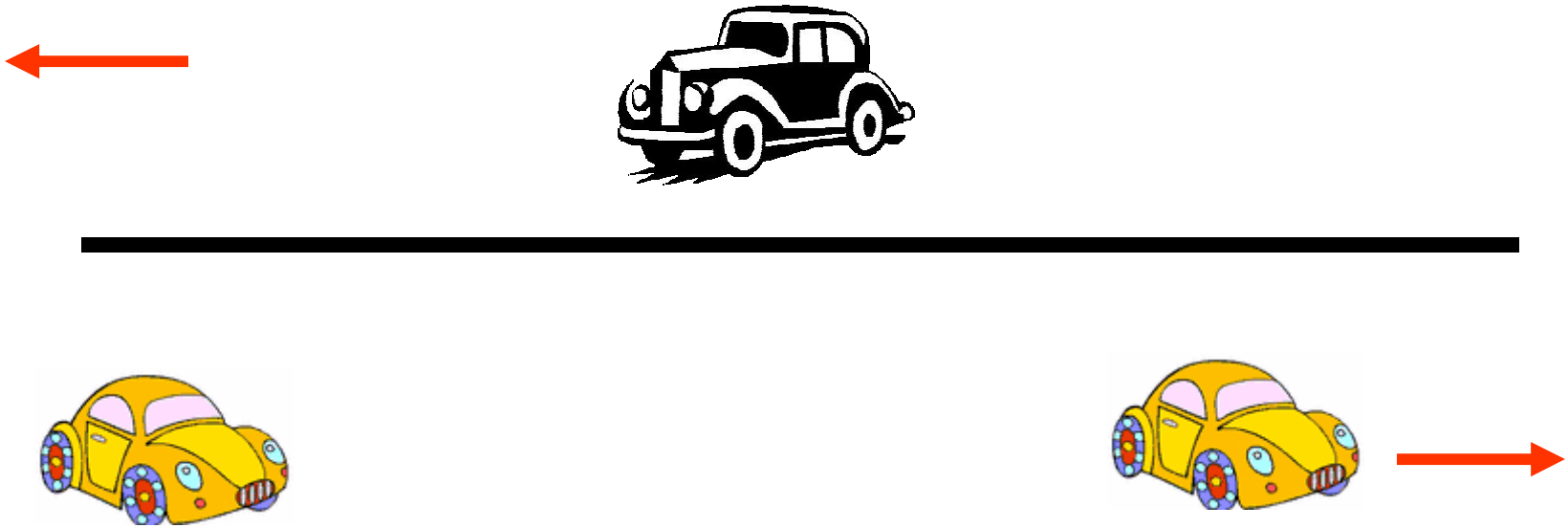

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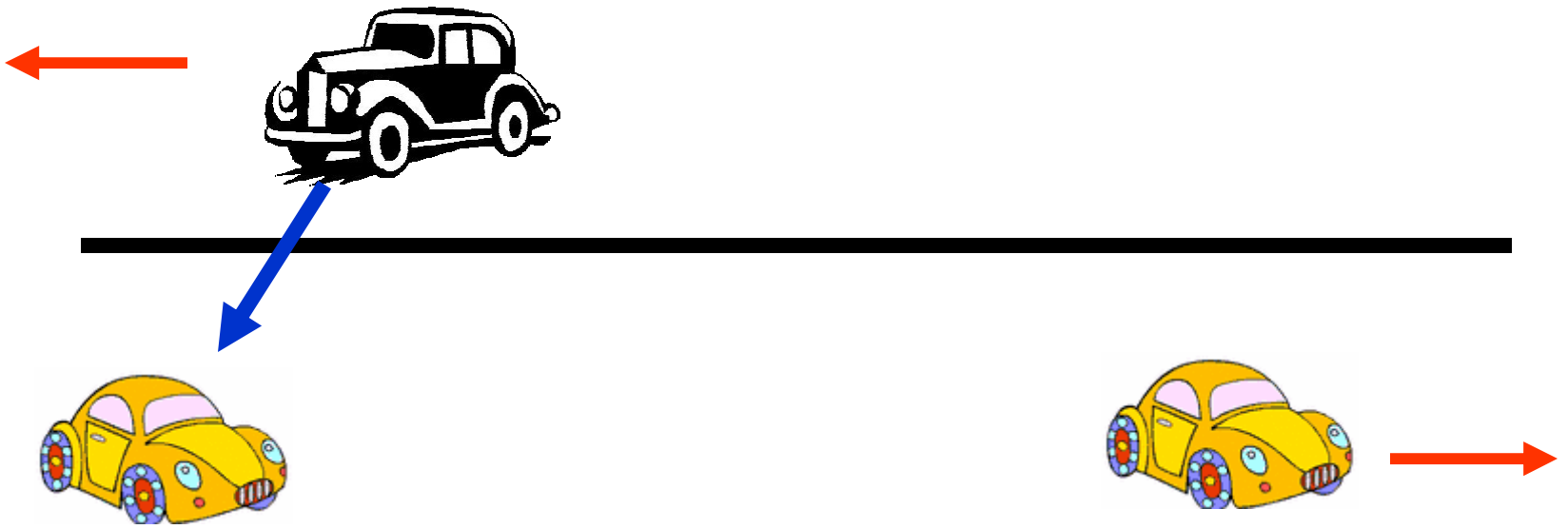
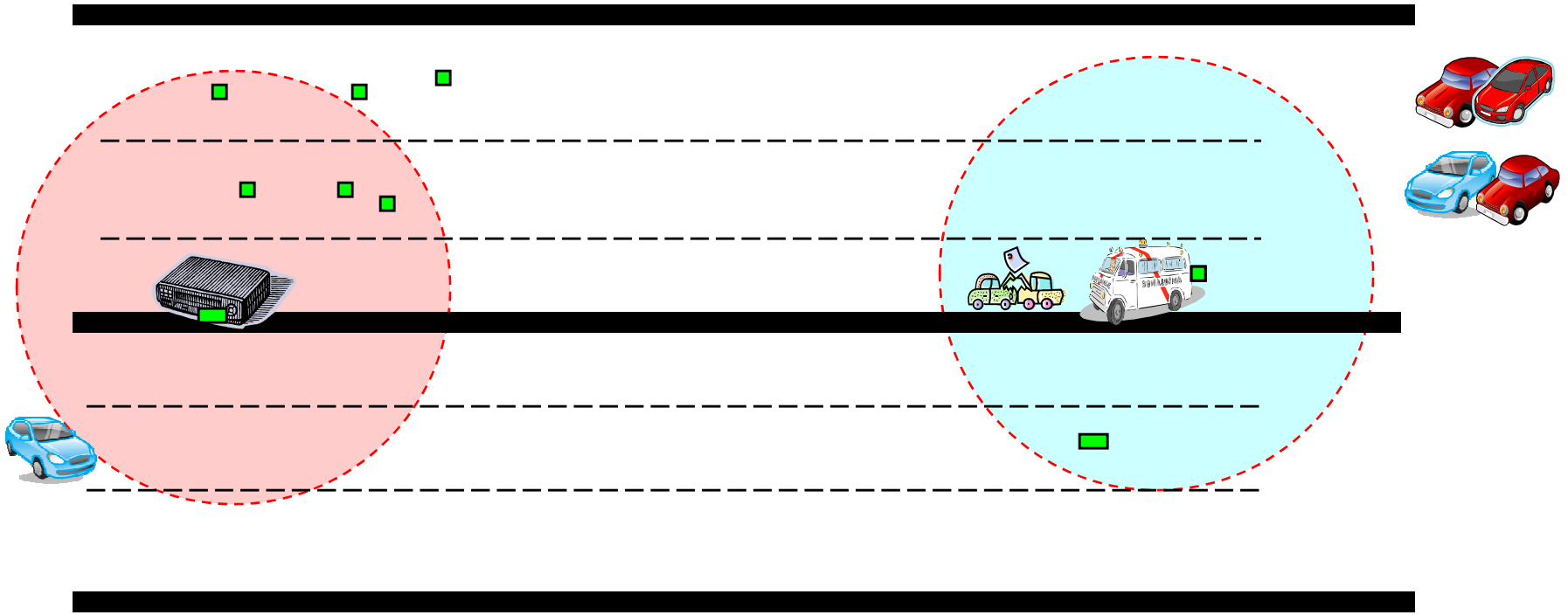
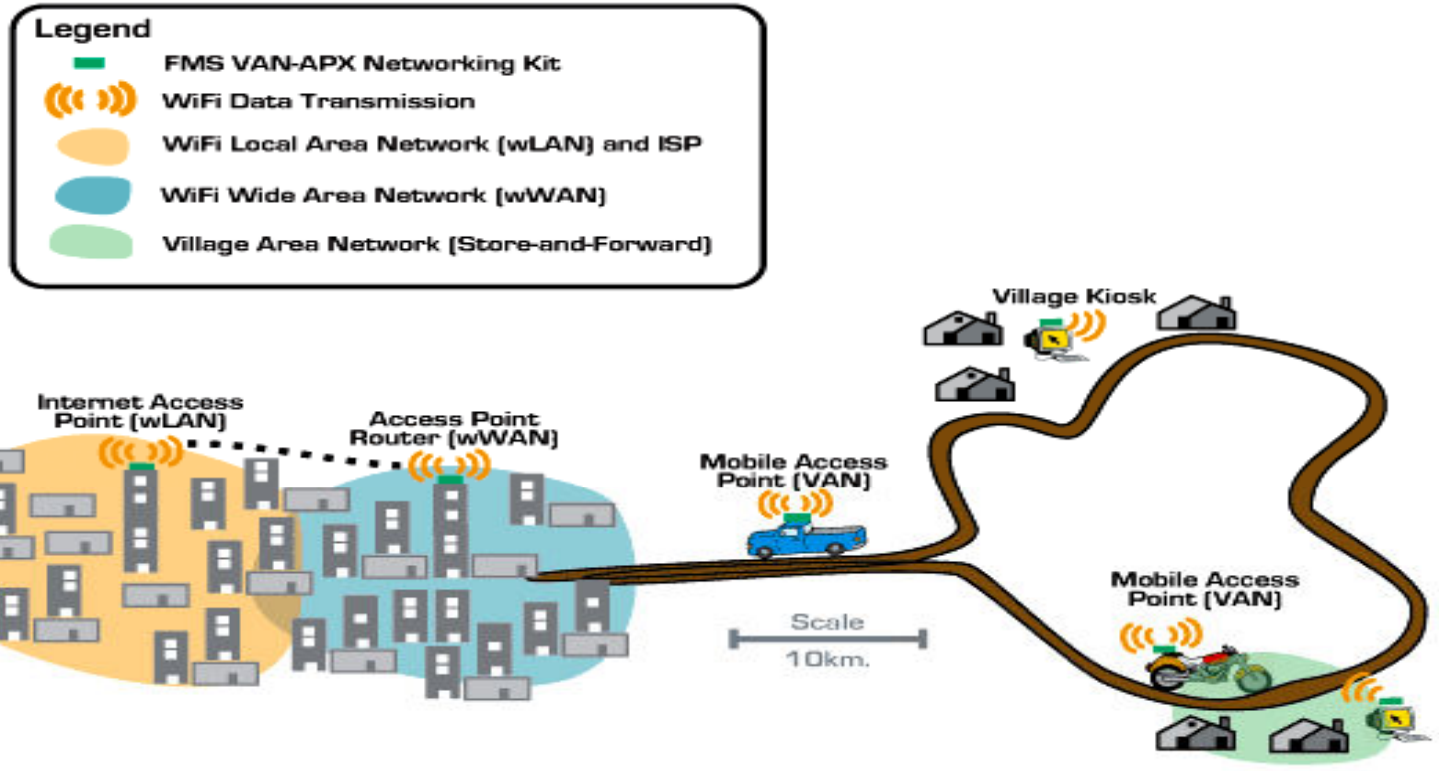


Roadside-to-Roadside Relaying



DakNet

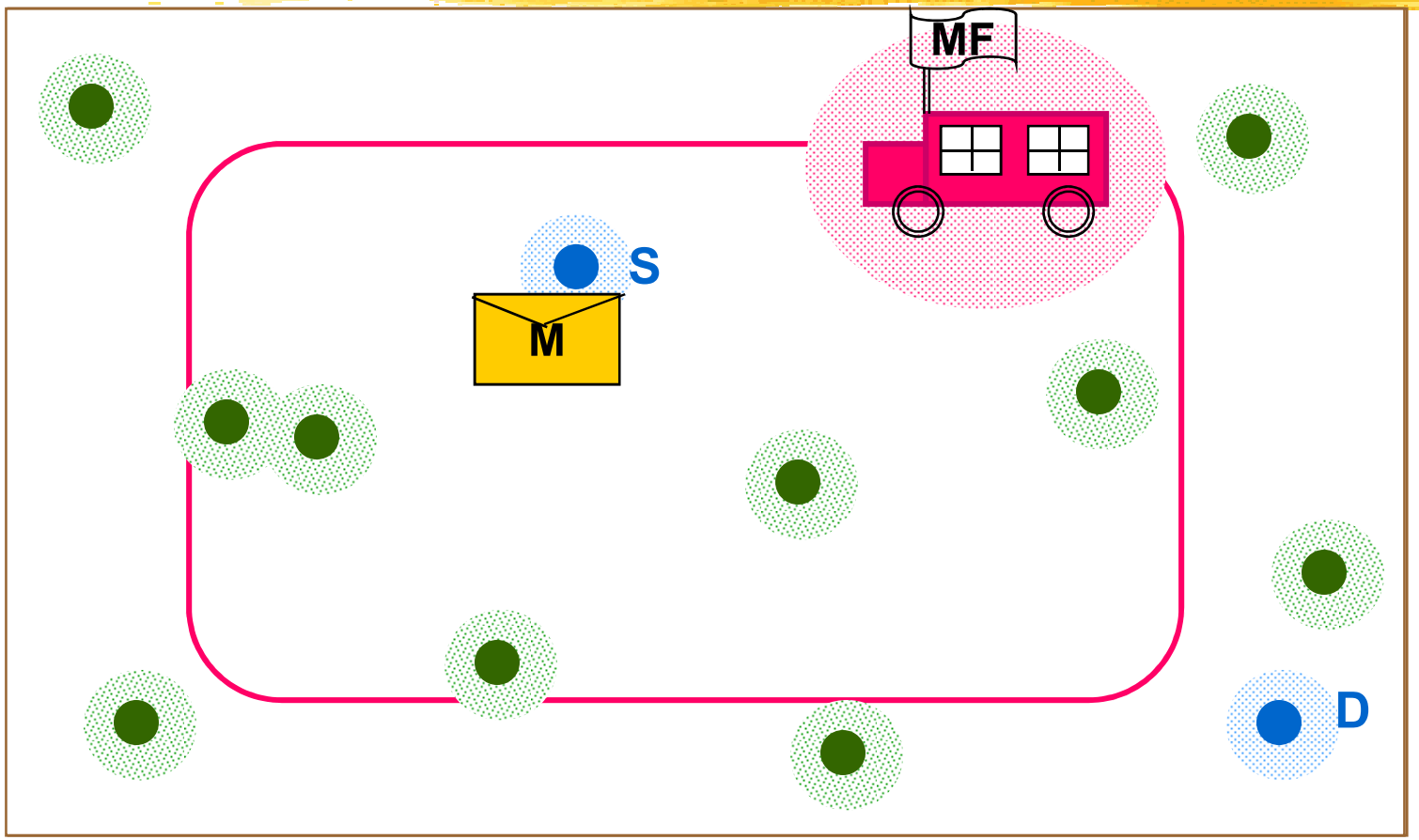
(Pentland, Fletcher, and Hasson)



Message Ferrying (MF) @ GT

- Zhao and Ammar
- Exploit *non-randomness* in device movement to deliver data
  - A set of nodes called *ferries* responsible for carrying data for all nodes in the network
  - Store-carry-forward paradigm to accommodate disconnections
- Ferries act as a moving communication infrastructure for the network

Message Ferrying System (cont.)



Putting It All Together

- Common Features:
  - Intermittent Connectivity
  - Store, carry and forward
- Other dimensions where they may differ
  - Special Nodes?
  - Source/Destination Mobile?
  - Potential for controlling mobility for data transport purposes?
  - Data Communication Pattern

More on Message Ferrying

MF Variations

- Ferry Mobility
  - Task-oriented, e.g., bus movement
  - Messaging-oriented, e.g., robot movement
- Regular Node Mobility
  - Stationary
  - Mobile: task-oriented or messaging-oriented
- Number of ferries and level of coordination
- Level of regular node coordination
- Ferry designation
  - Switching roles as ferry or regular node

Target Environments

- Needed for networks where
  - Sparse network with no node contacts
  - Not enough node contacts
- Also usable in other networks

A Taste of Message Ferrying

- Ferry Route Design Problem
  - Single Ferry
  - Multiple Ferries
- MF with Mobile Nodes
- MF in MANETs!!

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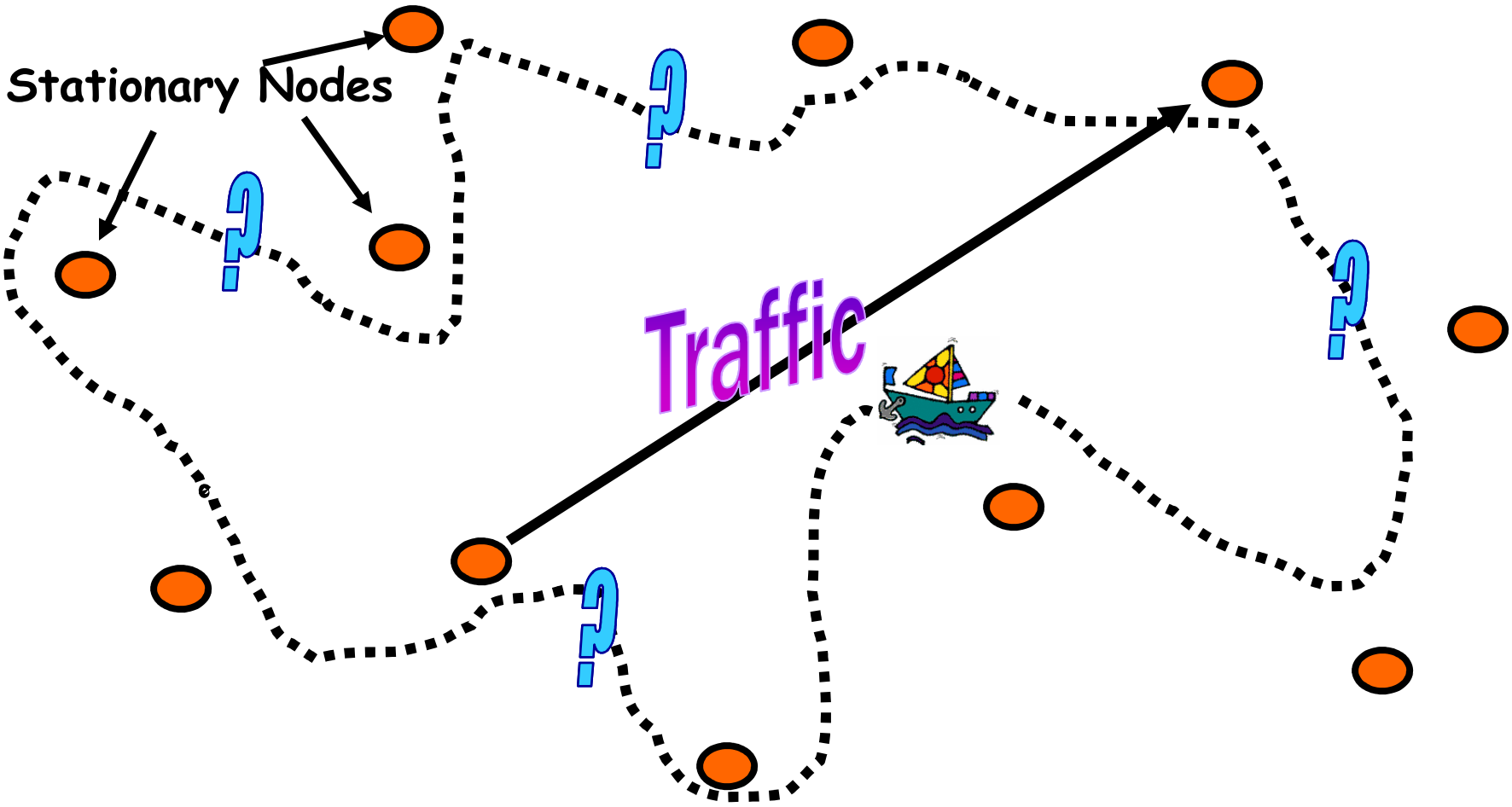
Ferry Route Design



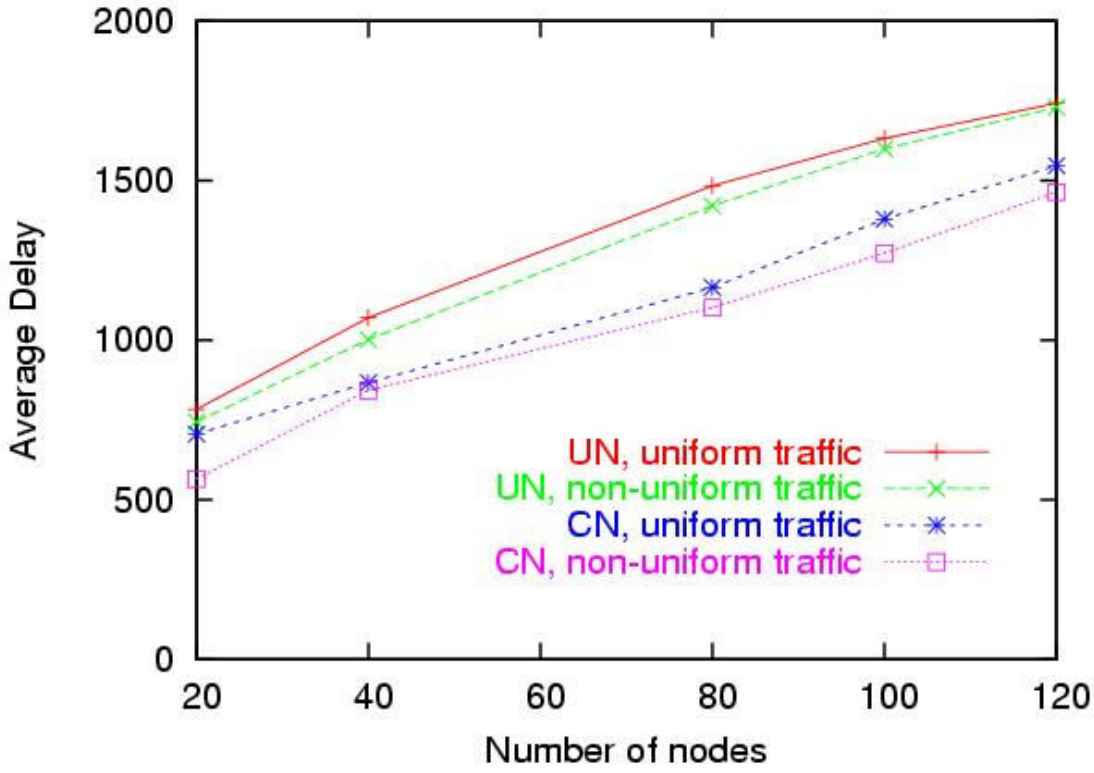
Route Design - Stationary Nodes

- Ferry route problem
  - Given node locations and expected traffic between nodes, find ferry route such that *ferry* visits all nodes, meets traffic requirements and minimizes average message delay
- Solution
  - A generalization of Traveling Salesman Problem

Numerical Results

- Experiment settings
  - *n* nodes in 4km x 4km area
  - A single ferry moving at speed 20m/s
- Node distributions
  - Random uniform node distribution (UN)
  - Random clustered node distribution (CN)
- Traffic models
  - Uniform traffic
  - Non-uniform traffic

Impact of Network Size



- MF provides reasonable performance
- For 40 nodes, each node can send at 10Kbps with 1070s delay.

A Taste Message Ferrying

- **Ferry Route Design Problem**
  - Single Ferry
  - **Multiple Ferries**
- MF with Mobile Nodes
- MF in MANETs!!

Multiple Ferry Route Design

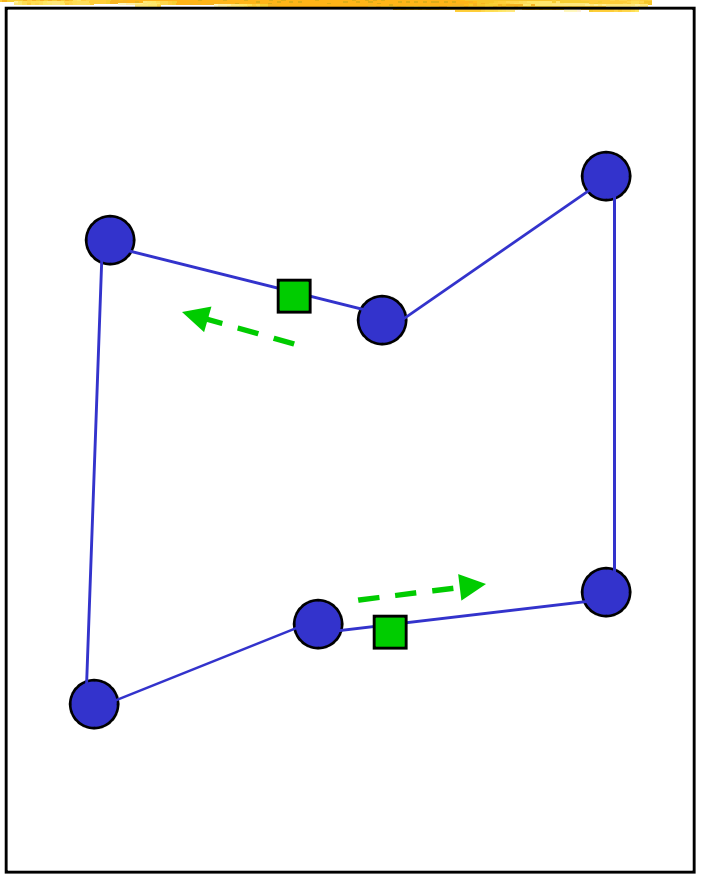
- Why multiple ferries?
  - Data transport capacity
  - Fault tolerance
- Multiple ferries introduce new problems
  - Which ferry serves which node?
  - Interaction between ferries
  - Tradeoff between number of ferries and performance improvement

Multiple Ferry Route Design Problem

- Networks with *n* stationary nodes and *m* ferries
  - Ferries move at a constant speed and follow periodic routes
- Bandwidth requirements are known
  - e.g., node A sends to node B at 10kbps
- Problem: ***find optimal ferry routes such that bandwidth requirements are met and average delay is minimized***
- NP-hard problem

Algorithms

- Single Route Algorithm (SIRA)
  - All ferries follow the same route
  - No interaction between ferries
- Multiple Route Algorithm (MURA)
  - Ferries can follow different routes
  - No interaction between ferries
- Node Relaying Algorithm (NRA)
  - Nodes relay data between ferries
- Ferry Relaying Algorithm (FRA)
  - Data exchange between ferries



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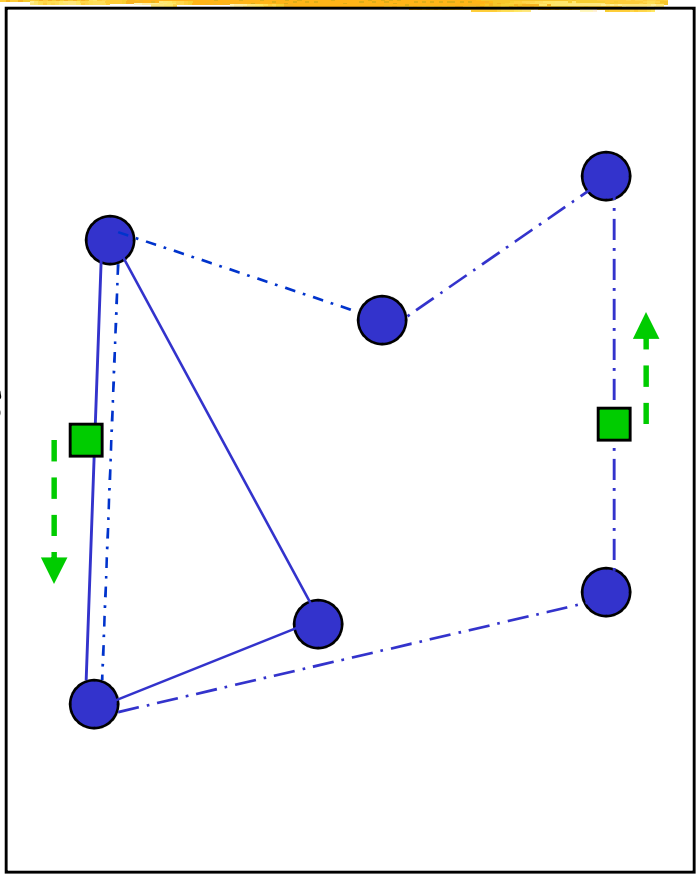

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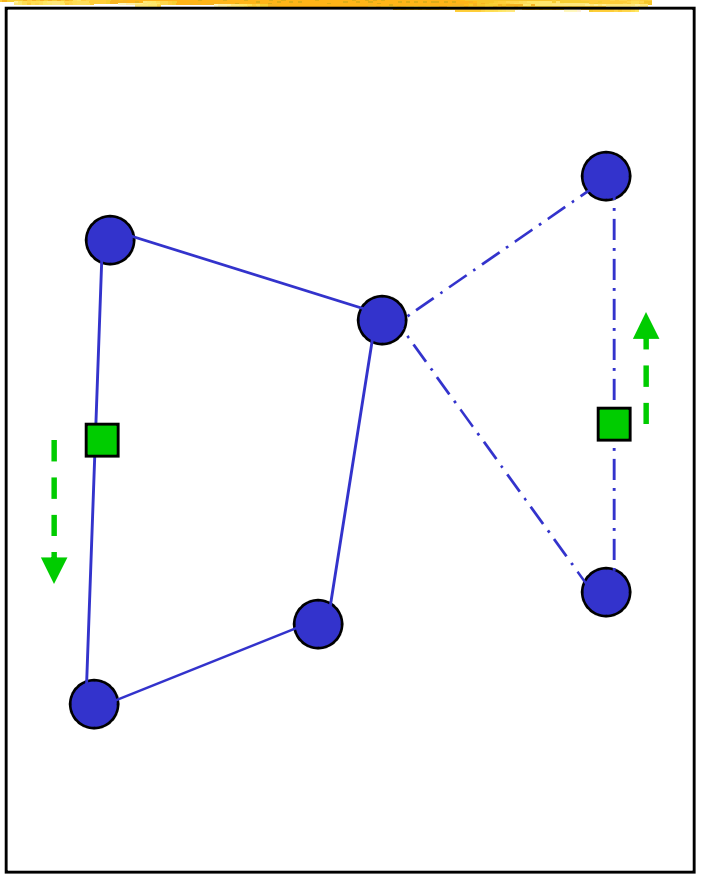

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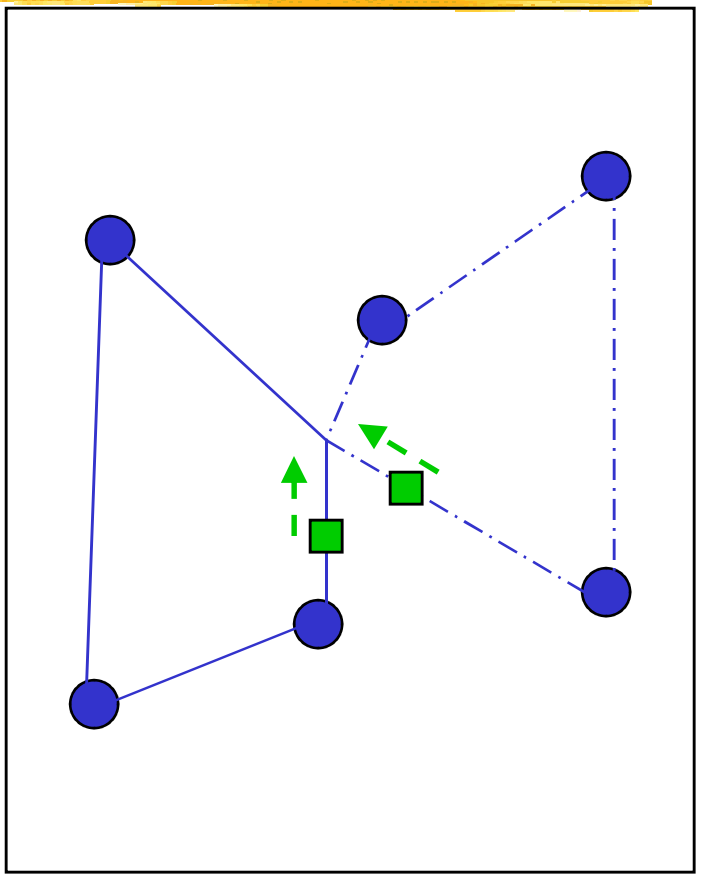
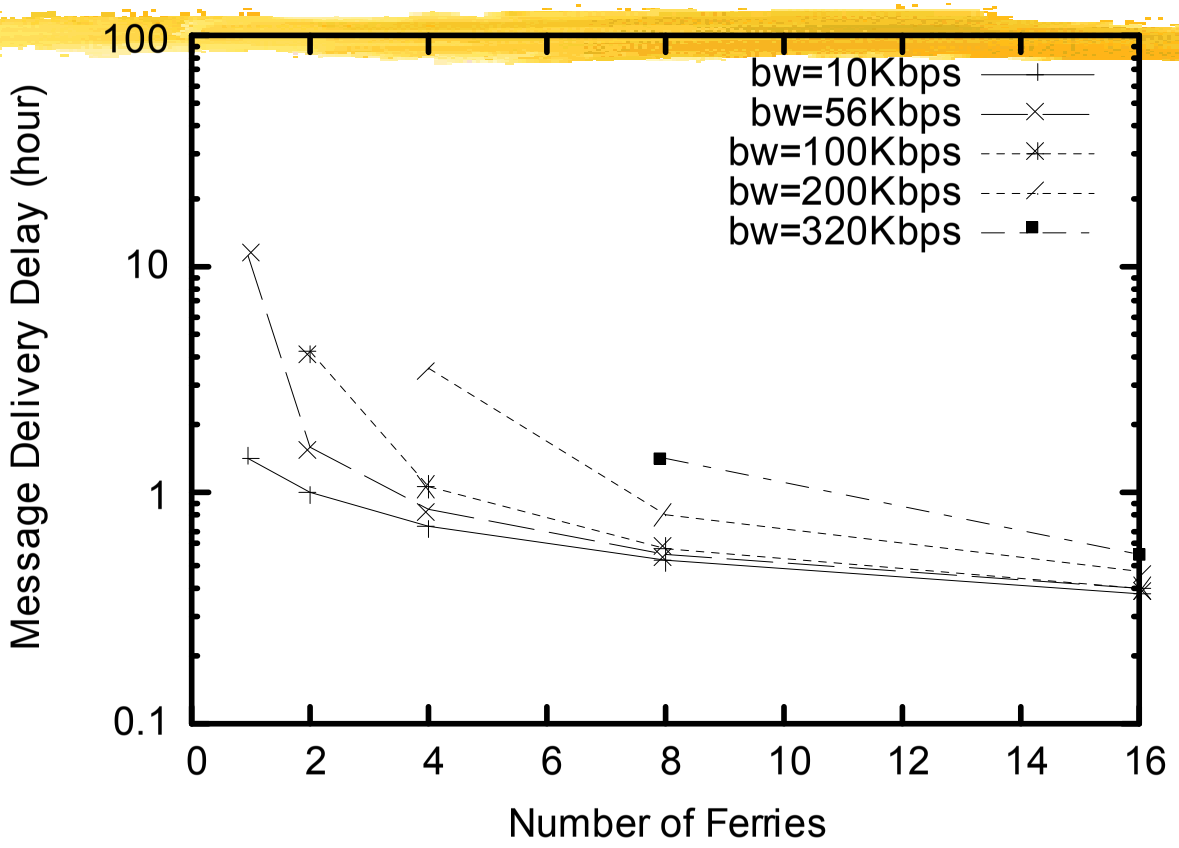


Simulation Results

- Settings
  - 5km x 5km area, 40 nodes, ferry speed: 10m/s
  - Radio range: 100m, data rate: 10mbps
  - Nodes send to random destinations
- Comparison of algorithms
  - All algorithms achieve similar delay when number of ferries is small or traffic load is high
  - MURA performs best

Impact of Number of Ferries



- The use of more ferries reduces message delay and improves total transport capacity
- Scalability can be achieved by adding more ferries

A Taste Message Ferrying

- Ferry Route Design Problem
  - Single Ferry
  - Multiple Ferries
- **MF with Mobile Nodes**
- MF in MANETs!!

MF for Networks with Mobile Nodes

- Nodes are mobile and limited in resources, e.g., buffer, energy
- Single ferry is used
  - Not limited in buffer or energy
- Data communication in messages
  - Application layer data unit
  - Message timeout

Four Approaches

- Non-Proactive (= Messaging-Specific) mobility
  - Ferrying without Epidemic Routing
  - Ferrying with Epidemic Routing
- Proactive Routing Schemes
  - Node-Initiated MF
    - Nodes move to meet ferry
  - Ferry-Initiated MF
    - Ferry moves to meet nodes

Four Approaches

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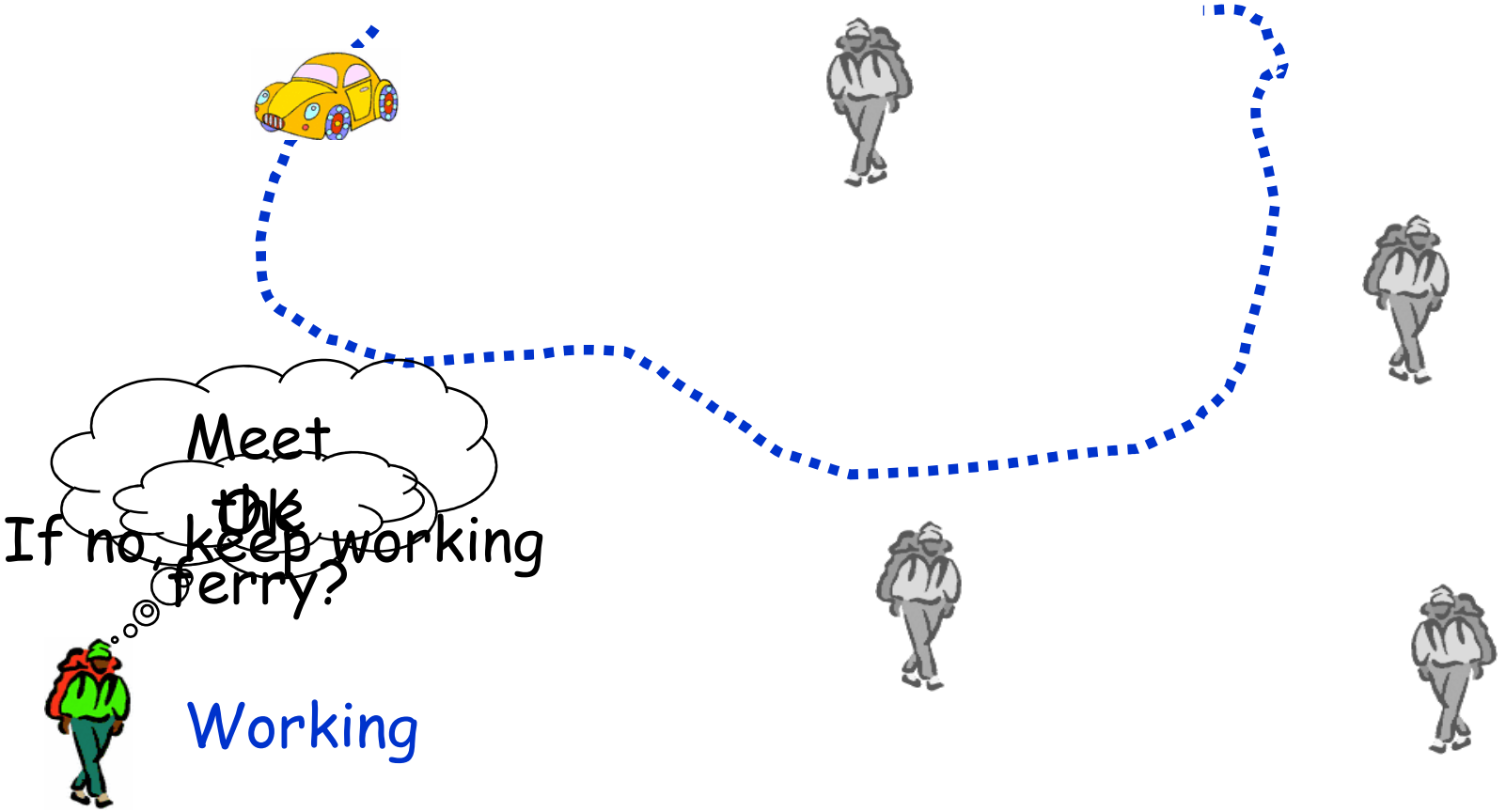
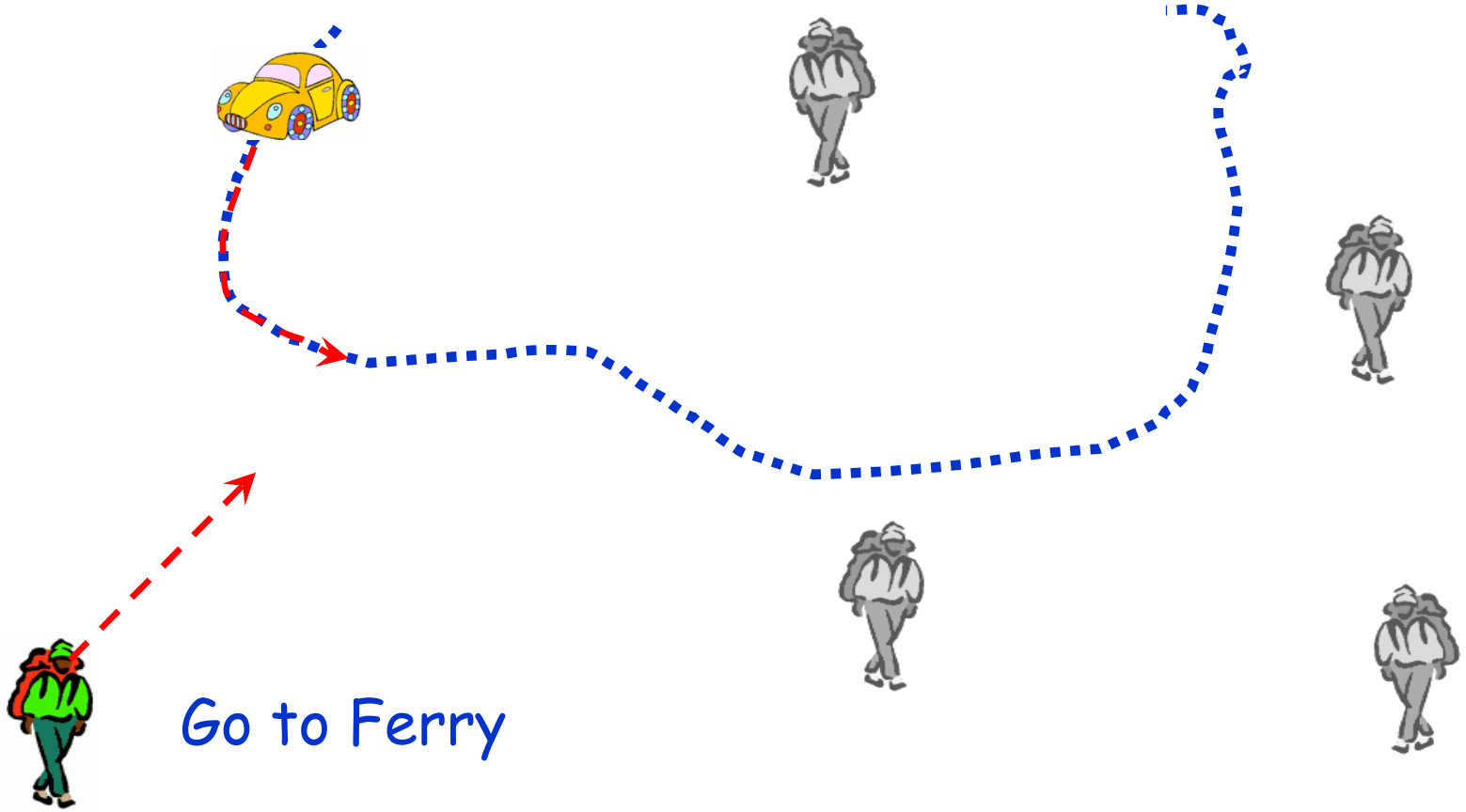
Node-Initiated Message Ferrying



Node-Initiated Message Ferrying



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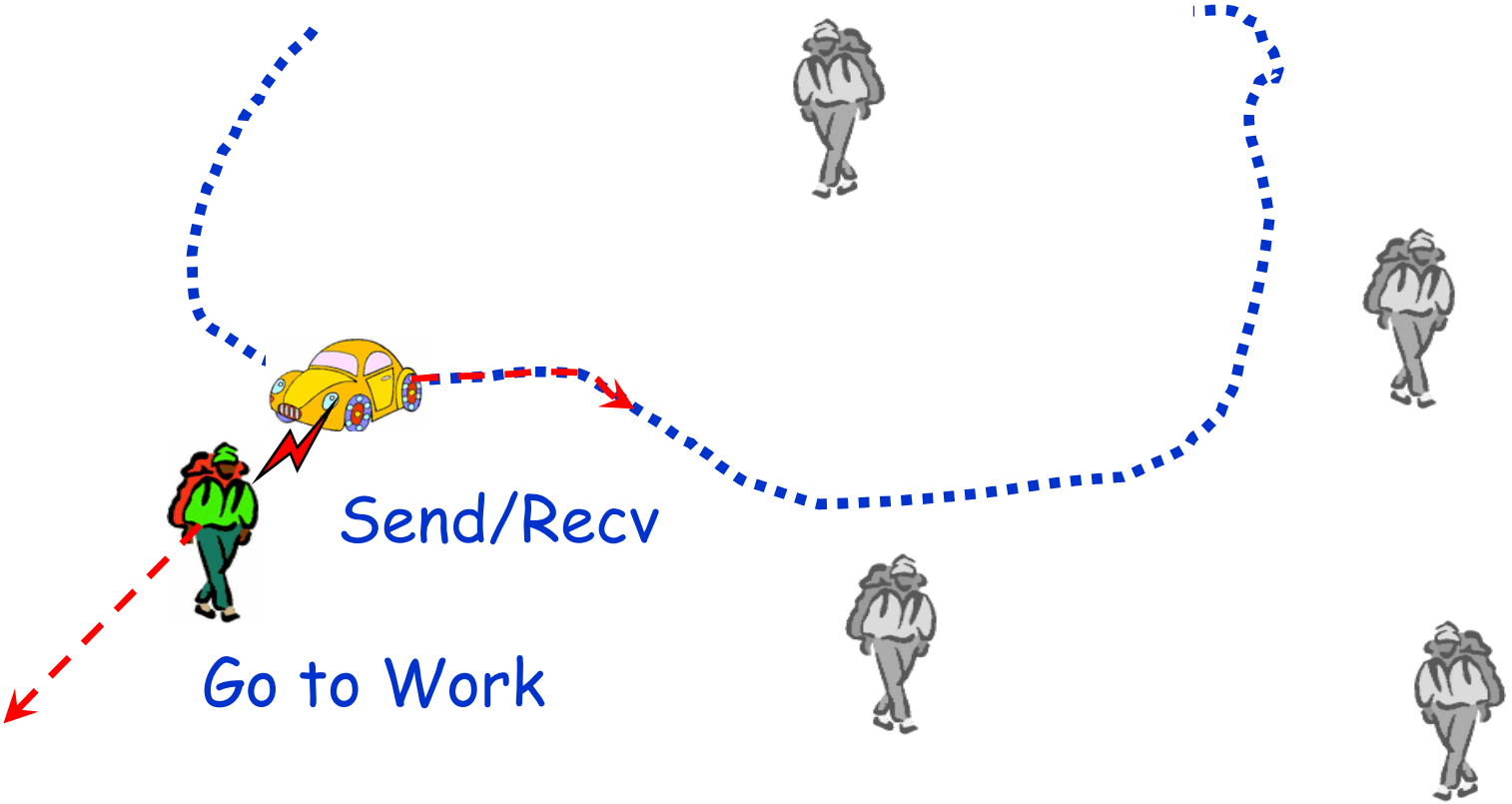

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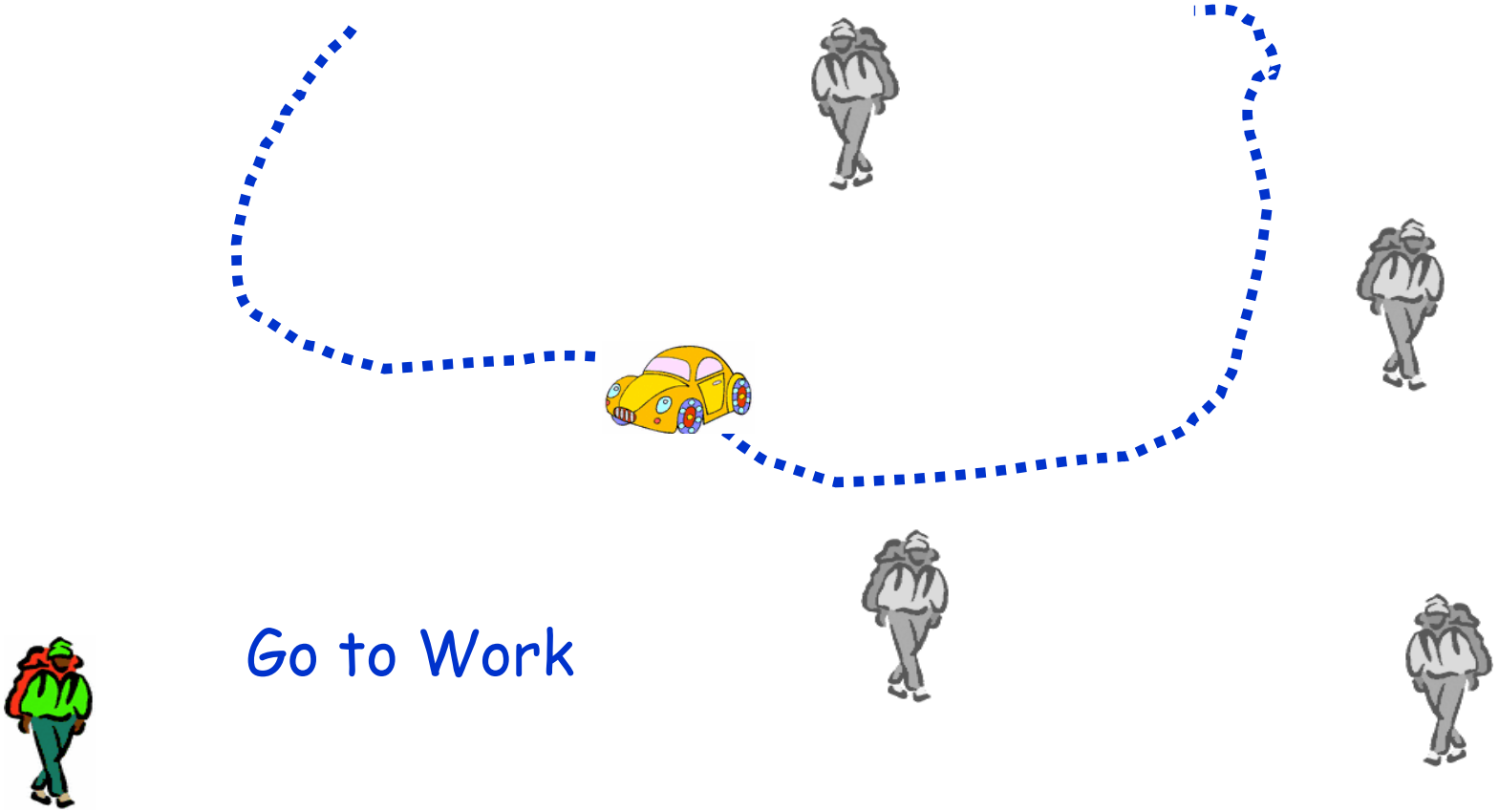


Node Trajectory Control

- Whether node should move to meet the ferry
- Goal: minimize message drops and reduce proactive movement
- Go to ferry if
  - Work-time percentage > threshold
  - and
  - Estimated message drop percentage > threshold

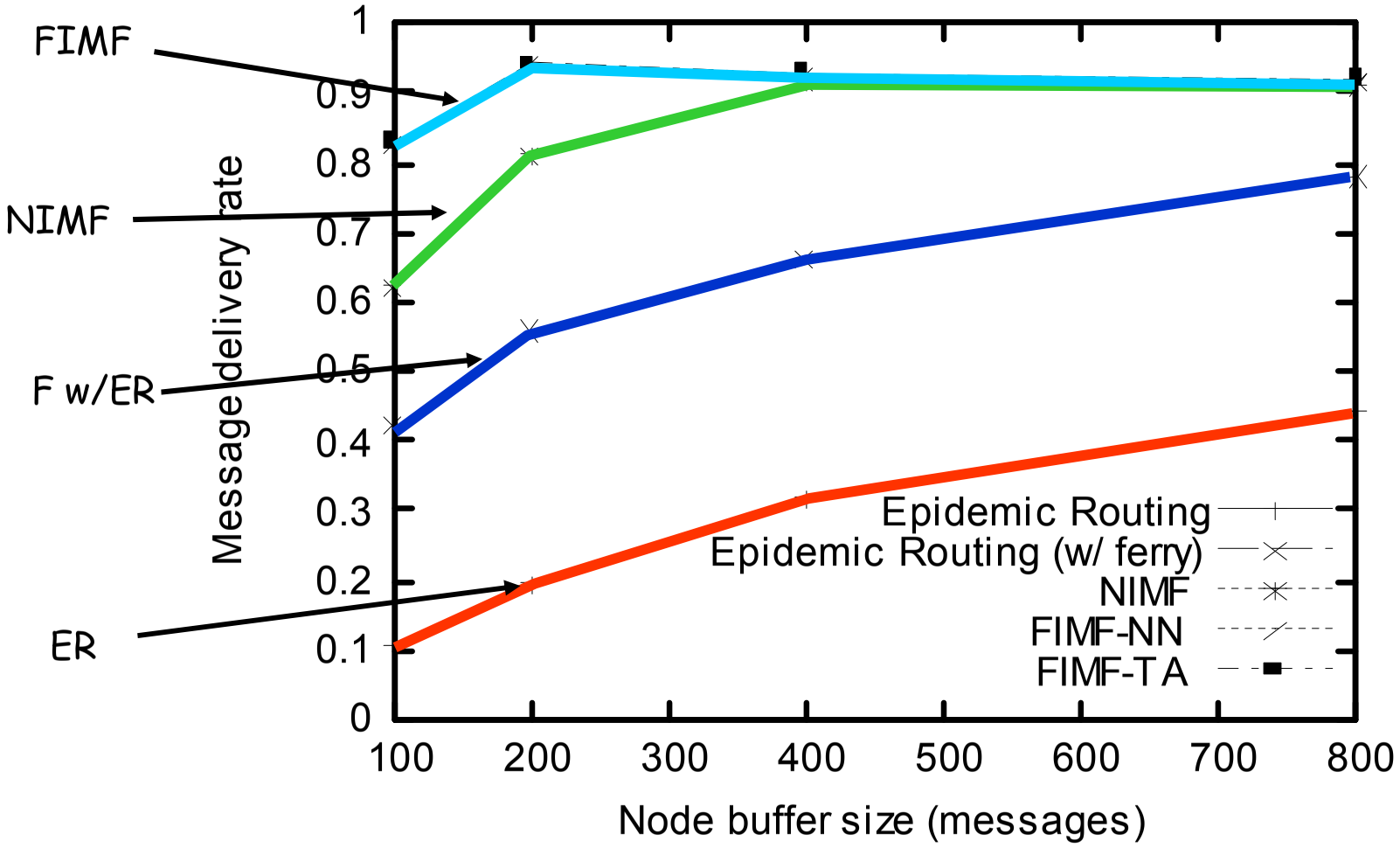
Simulations

- Ns simulations using 802.11 MAC and default energy model
- 40 nodes in 5km x 5km area
- 25 random (source, destination) pairs
- Node mobility
  - random-waypoint with max speed 5m/s
- Message timeout: 8000 sec
- Single ferry with speed 15m/s
  - Rectangle ferry route

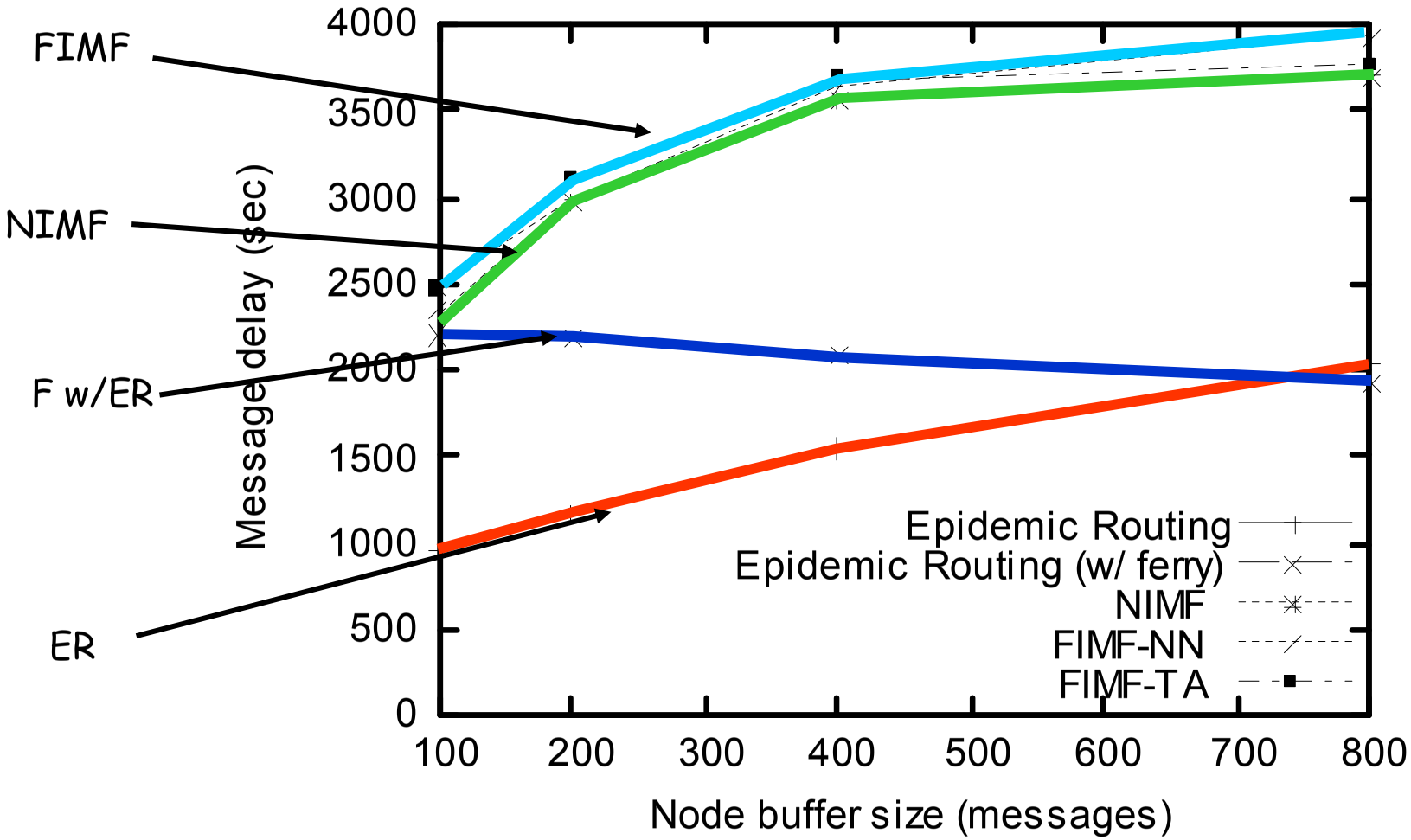
Performance Metrics

- Message delivery rate
- Message Delay
- Number of delivered messages per unit energy
  - Only count transmission energy in regular nodes

Message Delivery Rate



Message Delay



A Taste Message Ferrying

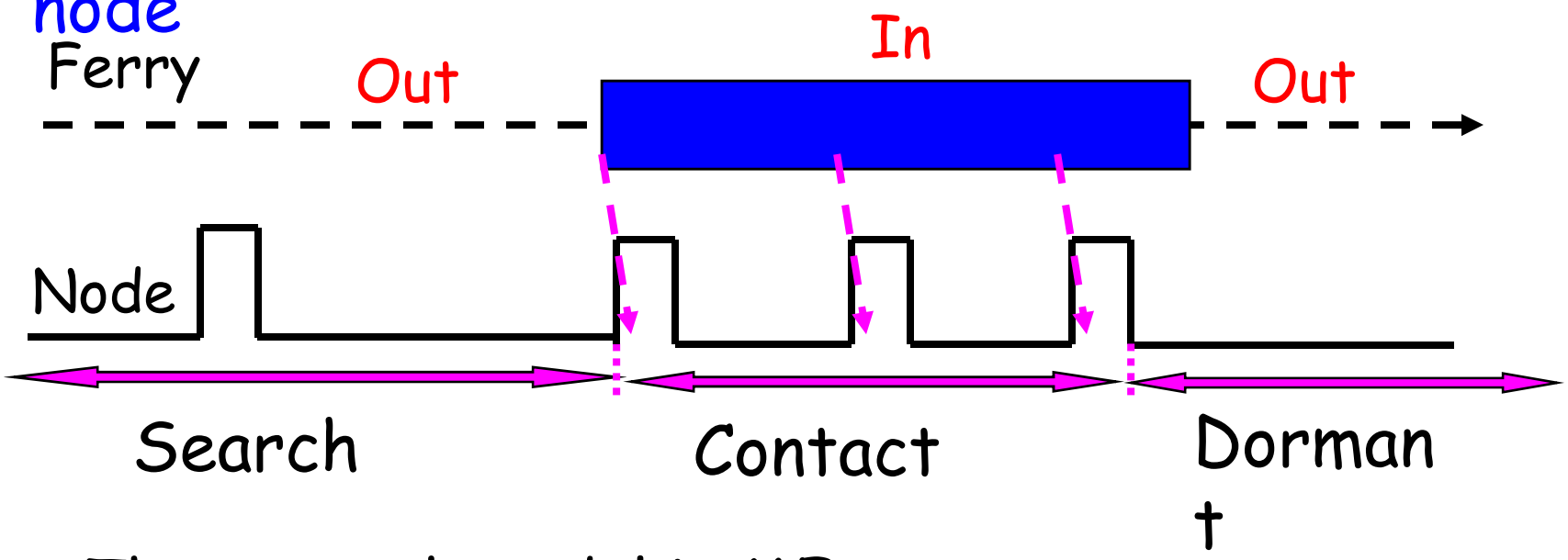
- Ferry Route Design Problem
  - Single Ferry
  - Multiple Ferries
- MF with Mobile Nodes
- **MF in MANETs!!**

MF as a Power-Management Device in MANETs

- Introducing a MF in a well-connected MANET can help organize power-management activities
- Nodes can sleep when MF is out of range.
- Can this improve on delay/power tradeoff

Power Management in MF

Ferry location in terms of the radio range of a node



- The network model in MF
  - A single ferry and multiple nodes
  - Location and time: known by each node, e.g., using GPS

Sleeping Time Estimation

- How long to sleep in the dormant mode?
- Based on the predicted location of the ferry
- Movement scenarios

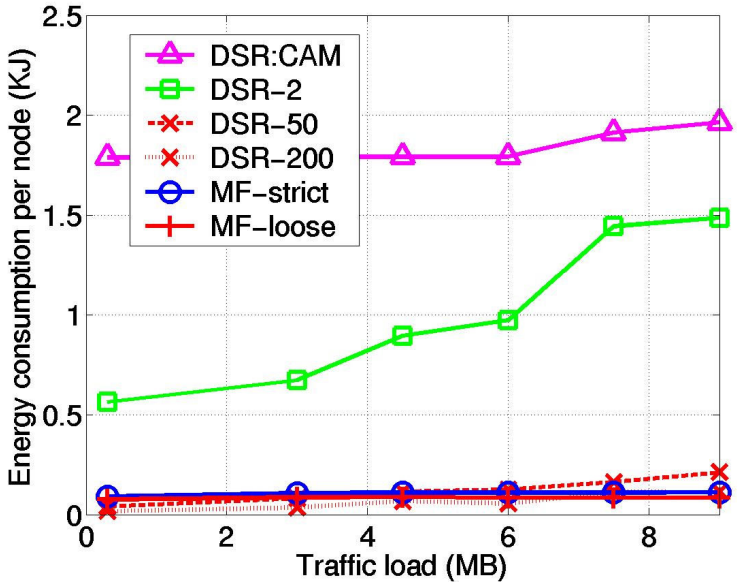
Ferry \ Node	Stationary nodes	Mobile nodes
Strictly scheduled	1	3
Loosely scheduled	2	4

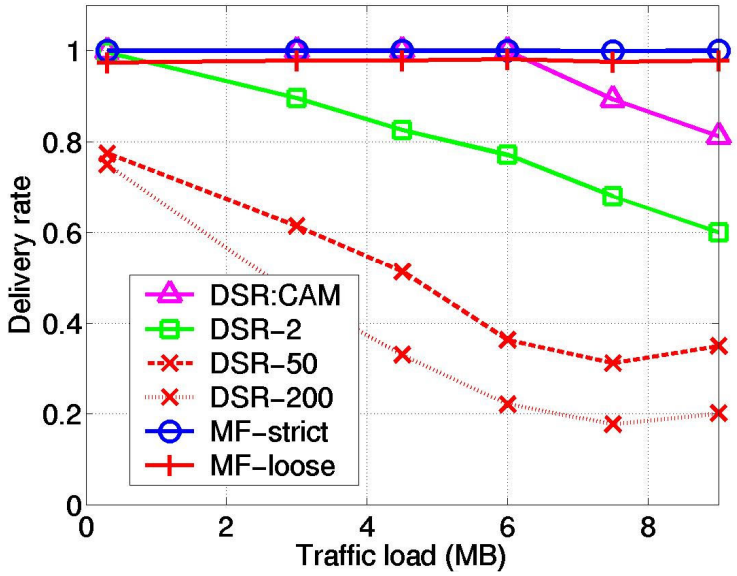
Increasing randomness

Performance Evaluation

- Ns-2 simulation with 802.11 MAC protocol
- 50 nodes in 2000m x 500m and a ferry
- Capacity of node buffer: 700 messages
- Dynamic source routing (DSR) with a synchronous wake-up mechanism
  - DSR-x: wake-up interval of x seconds
  - DSR:CAM: continuous aware mechanism
- How to sleep (i.e., disabling or turning off): decided based on the expected sleep time

Impact of Traffic Load on Stationary Nodes





- DSR with large wake-up intervals and MF:
  Low energy consumption and high delivery delay

A Fundamental Question

- What is the relationship of MF nets with MANETs and with other DTNs?

Understanding theWireless and Mobile Network Space

[CHANTS 07]

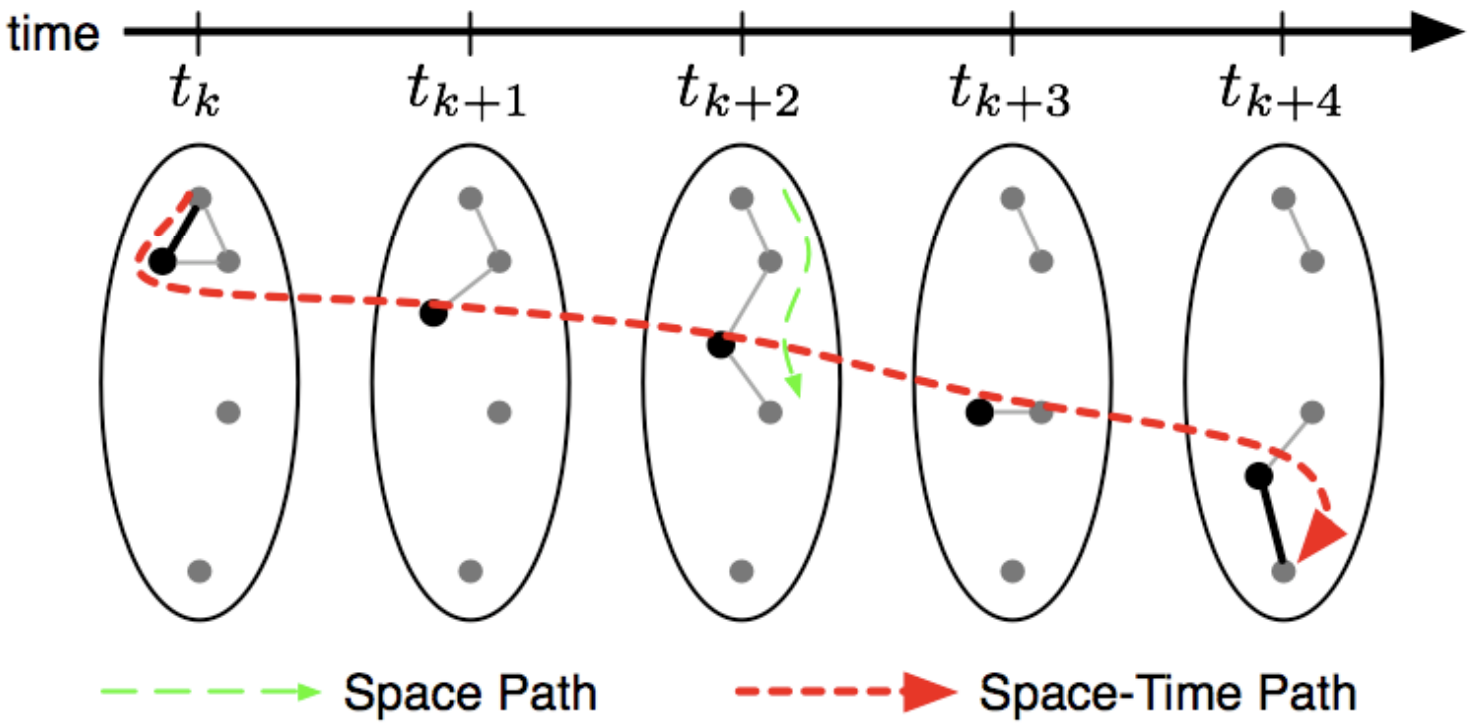
Background

- Different Types of Wireless and Mobile (WAM) Networks
  - MANETS -> MANET Routing (AODV,DSR,…)
  - DTNs (opportunistic,…) -> DTN routing (flooding, MaxProp, Prophet, …)
  - Sparse, Disconnected Nets -> Message Ferries, Data Mules, Throwboxes, …
- Questions:
  - What's the relationship among these classes?
  - How can one tell to which of these classes a particular network belongs?

Some Terminology

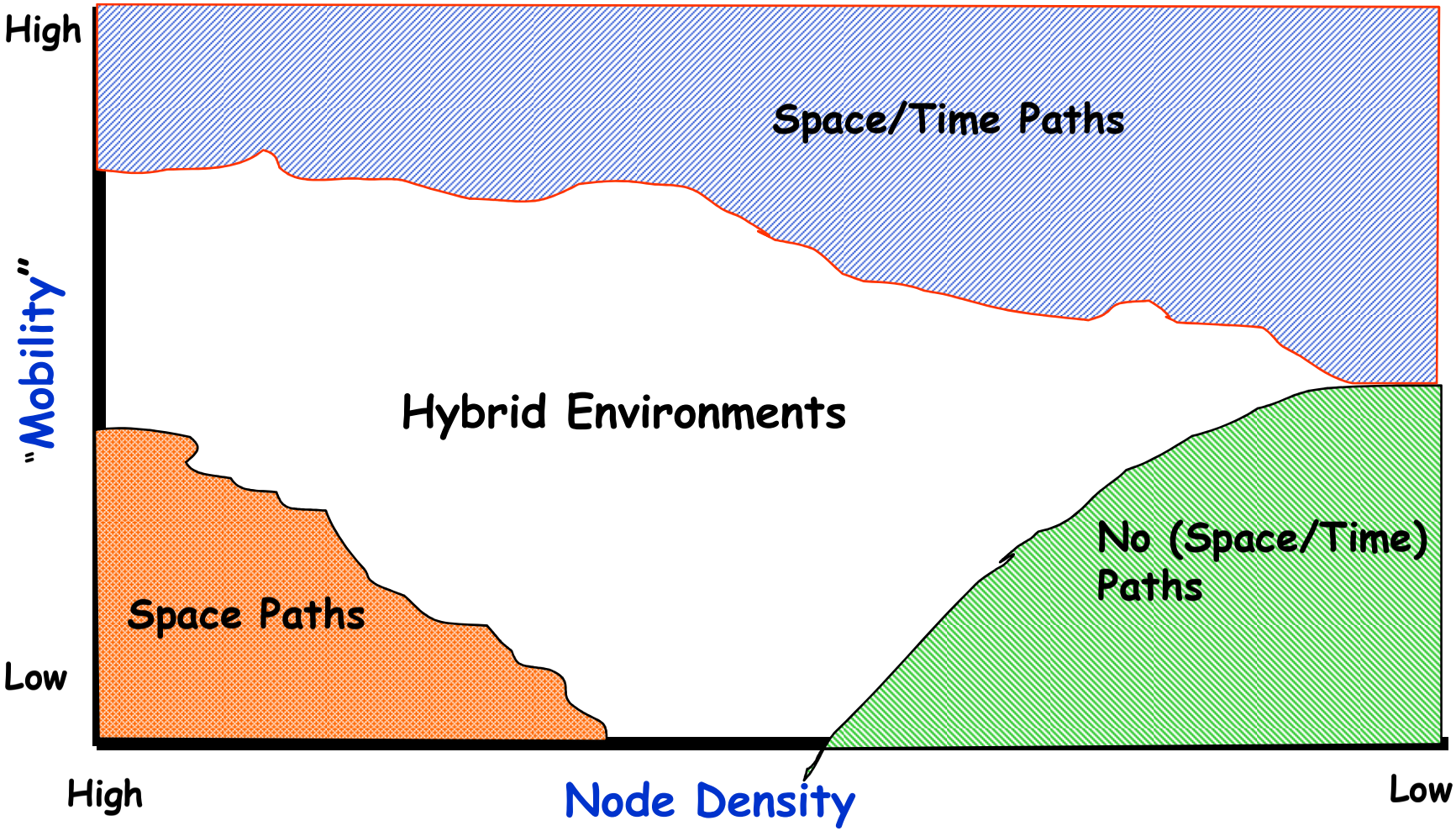
- A Space Path: A multi-hop path where all the links are active at the same time
- A Space/Time Path: A multi-hop path that exists over time
- NOTE: S path is a special case of S/T path

Space/Space-Time Paths

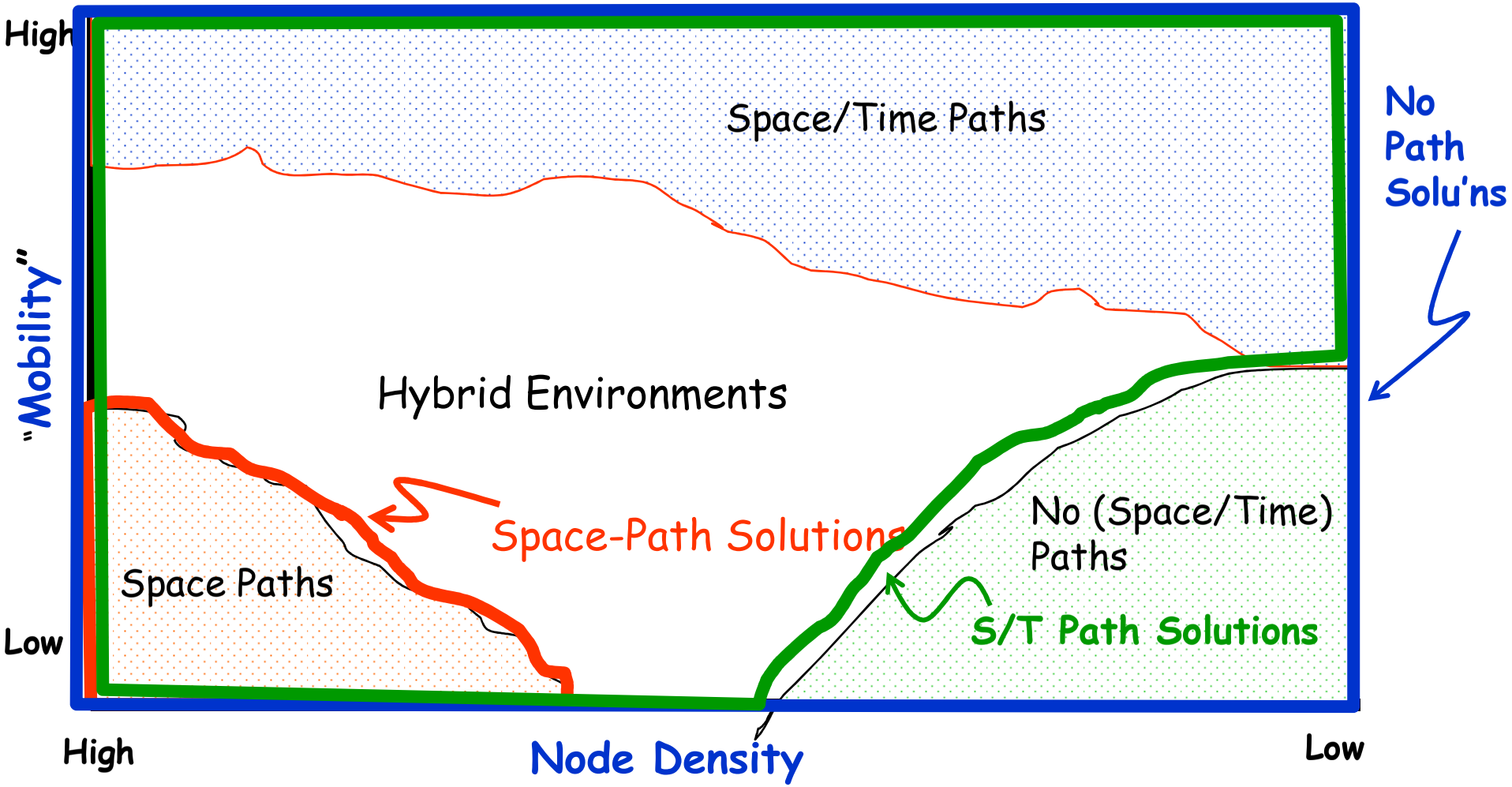


The Wireless and Mobile (WAM) Space

(my panel presentation at WDTN 2005)



Mapping Routing Solutions to Space



Classifying WAMs

- Goal:

  Provide a framework for WAM classification that provides guidance about the deployment of routing approaches

- Starting point: Theory of Evolving Graphs

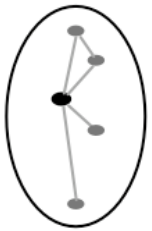
Evolving Graph (EG)*

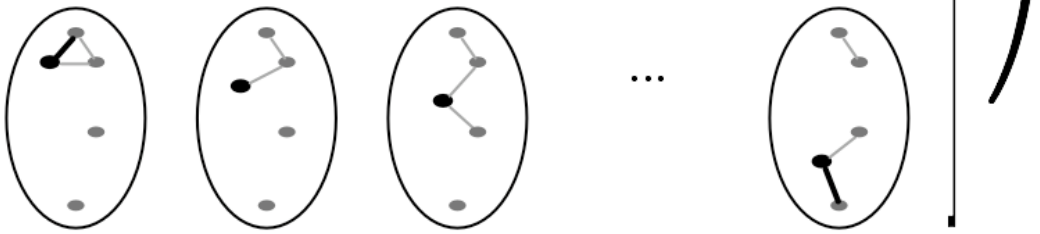
*A. Ferreira. Building a reference combinatorial model for MANETS. IEEE Network, 18(5):24–29, Set 2004.

- Is a graph with edges that turn "on" and "off" over time
- Made up of a sequence of subgraphs
- Two variations: of EGs
  - Finite-Duration
  - Infinite Duration (our definition)
- Journey = Space-Time Path:
  - Min-hop, foremost, shortest

WAMs as Evolving Graphs

$$\mathcal{G} = \left(\begin{array}{l} G = \\ S_T = [\ t_0 \quad t_1 \quad t_2 \quad \cdots \quad t_{\mathcal{T}}\ ] \\ S_G = \left[\begin{array}{ccccc} G_0 & G_1 & G_2 & & G_{\mathcal{T}} \\ \end{array} \right. \end{array} \right)$$



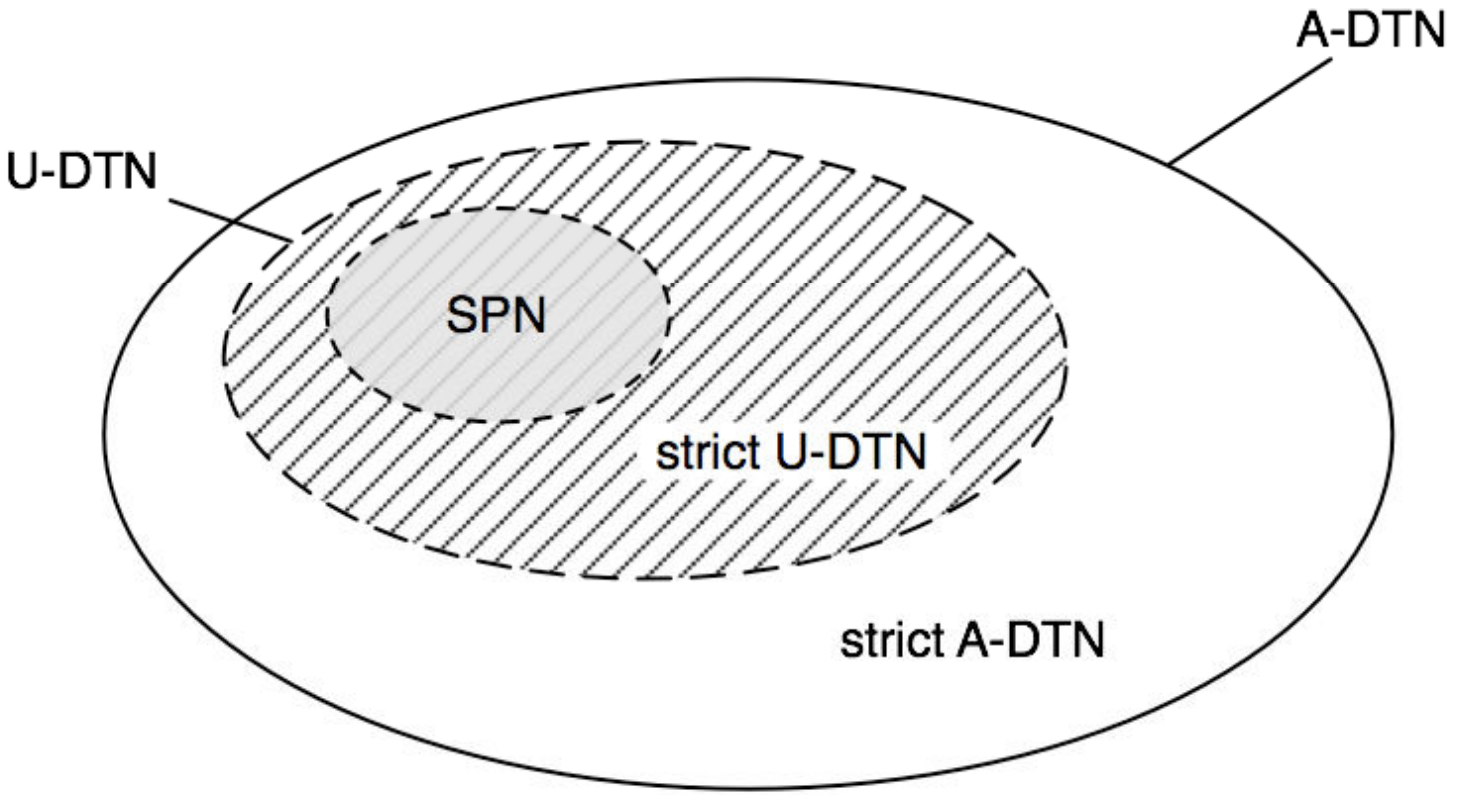


Our Classification – The idealized version

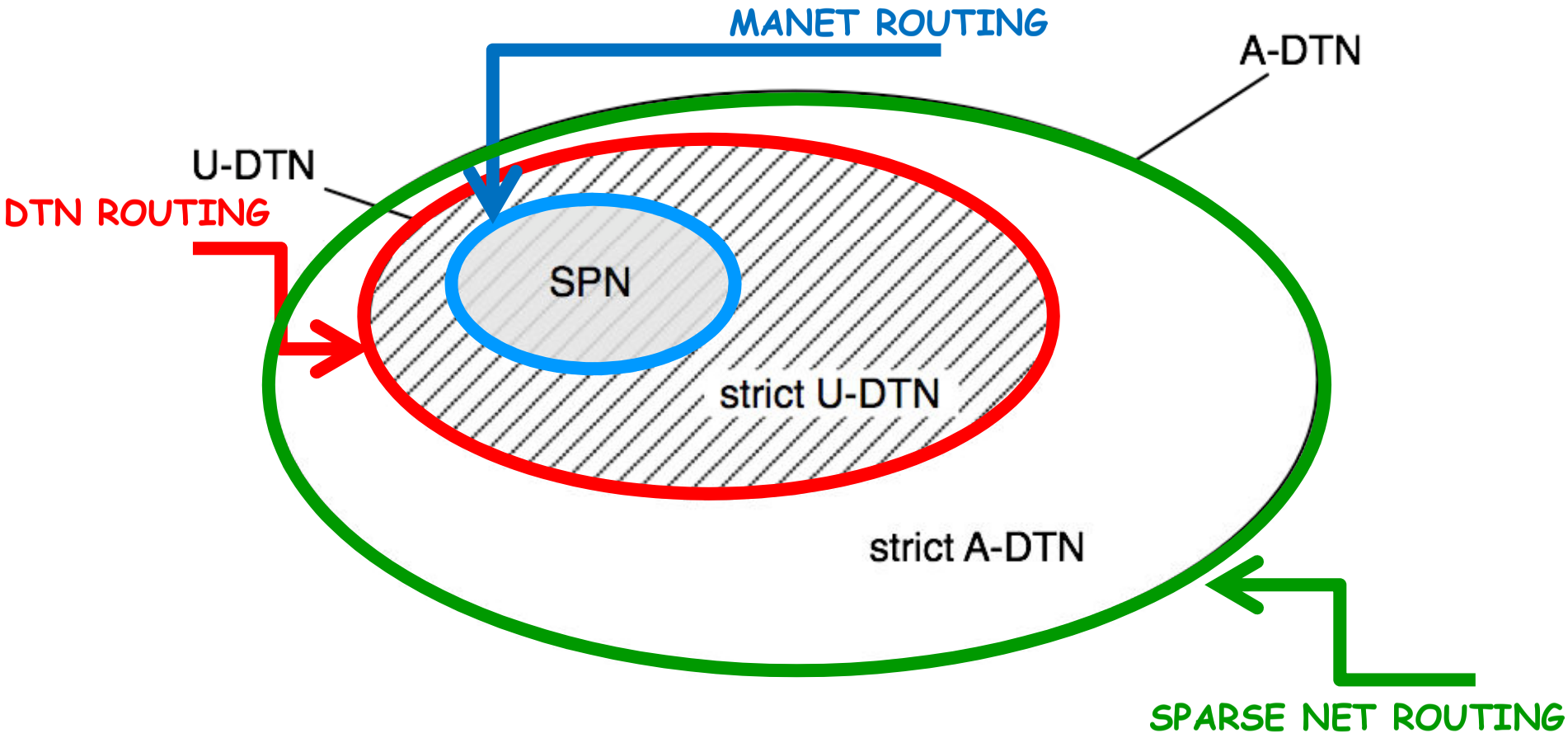
For Infinite-duration graphs

- Ideal Space-Path Networks (SPNs):
  An infinite evolving graph where all subgraphs are connected
- Ideal Unassisted DTNs (U-DTN):
  For all t and for all (i, j) there is a journey from i to j after t
- Ideal Assistance-needed DTN (A-DTN):
  Everything else

SPNs, U-DTNs, A-DTNs



Mapping Routing Families WAM Classes

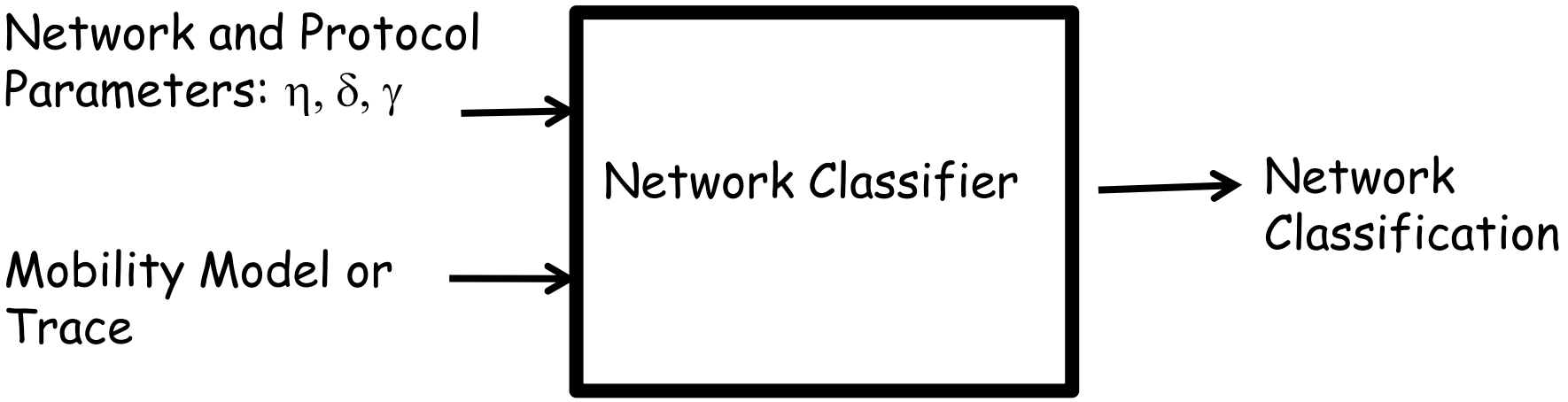


An "Practical" Classification

- Intuition: Boundary between classes is not "crisp".
- Additional Considerations:
  - Finite-duration EGs
  - Practical routing considerations, e.g., it takes time for a MANET routing protocol to discover routes.
- Many ways to do this – See CHANTS07 for one approach

Classifying Networks From Network Traces

- Goal



Network Classification

- Objective: Percentage of time spent in each network class.

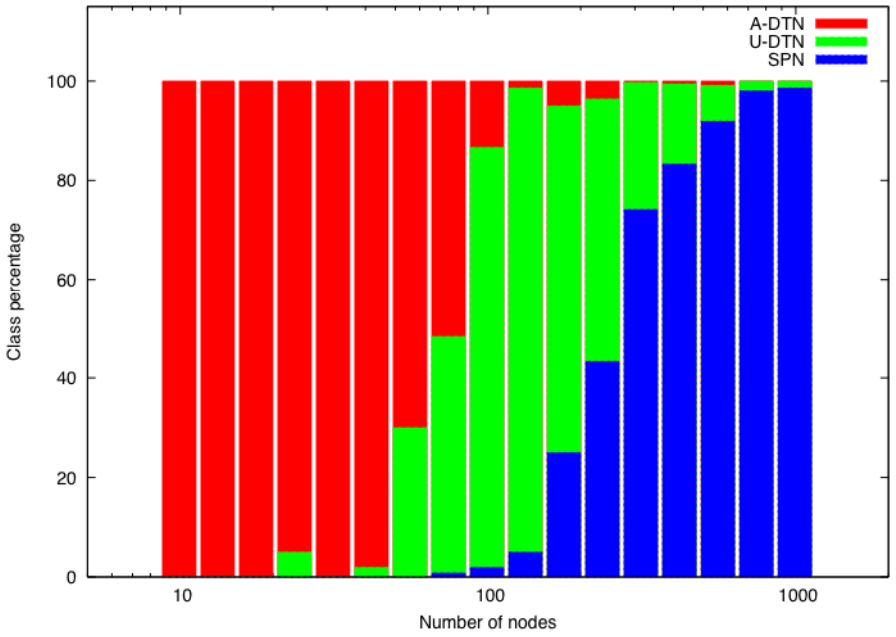
  X% SPN, Y% U-DTN, Z% A-DTN

- Informally:
  - SPN: Network connected for long enough period and with high link resilience
  - U-DTN: Long enough in U-DTN class and path-less time is < γ
  - A-DTN otherwise

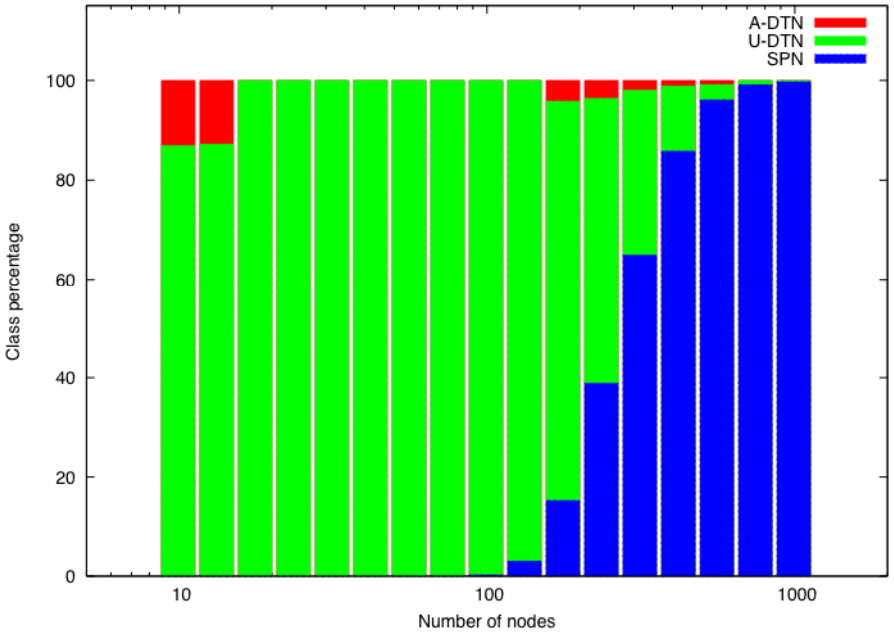
Illustrative Examples

- RWP and RW mobility models
- 2km x 2km, 250m radio range, 3hrs
- Pedestrian (avg 1.5m/s) and vehicular (15m/s) speeds
- Goal: to illustrate classification outcome from our approach

Effect of Speed

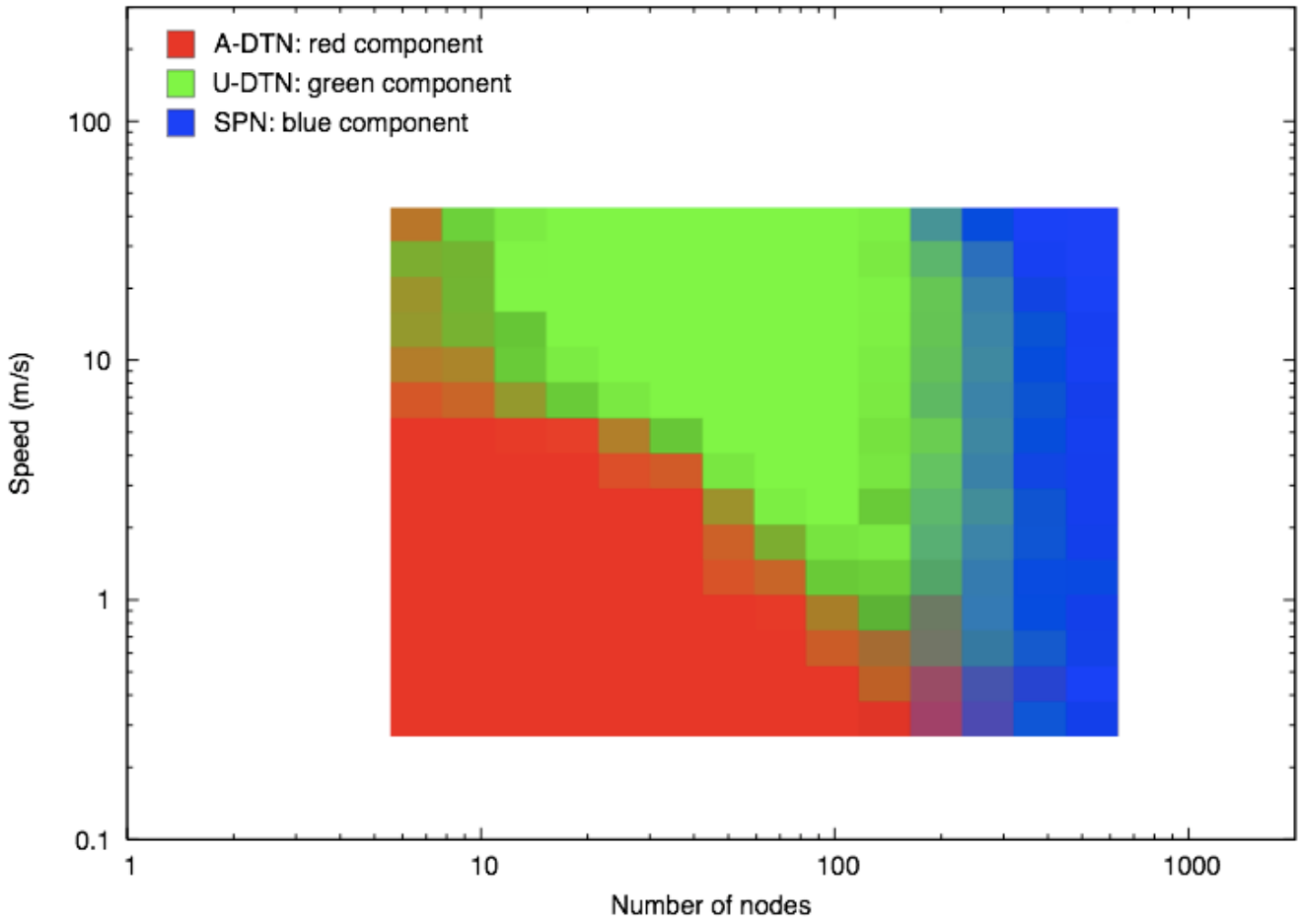


RWP – Pedestrian Speed



RWP – Vehicular Speed

Joint Density/Speed: RWP



Remaining Issues

- Transformations between classes
- Partial classification (e.g., per S-D pair)
- More on practical parametric classification – direct analysis of routing
- Experience using classification

Concluding Remarks

- FINALLY! A realistic mobile wireless network paradigm
- Within this new paradigm:
  - Everything looks familiar but this is a truly different environment
  - Techniques developed have wide applicability
  - Fertile Ground for both networking problems and novel application paradigms
- Essential to understand entire WAM space

Concluding Remarks

- Mobility can be your friend
- Now the rest of the ICEBERG is visible
  - MANETs are just a special case
- So many networks so little time
  - Can be solved by unified treatment of entire WAM space

Questions?