Life in the WAM Continuum:
Investigating Fundamental Properties of Wireless and Mobile Networks

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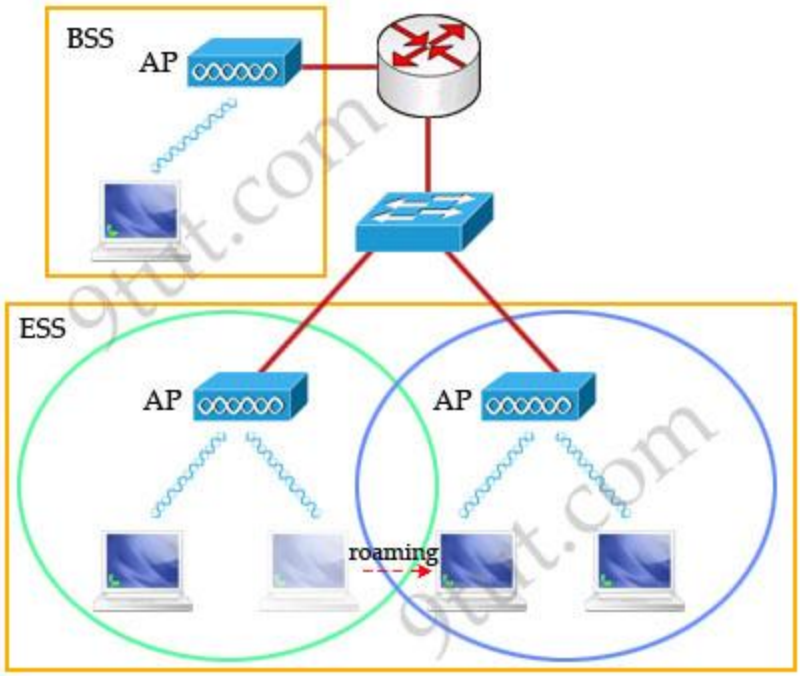
Funding: NSF, DARPA, Cisco

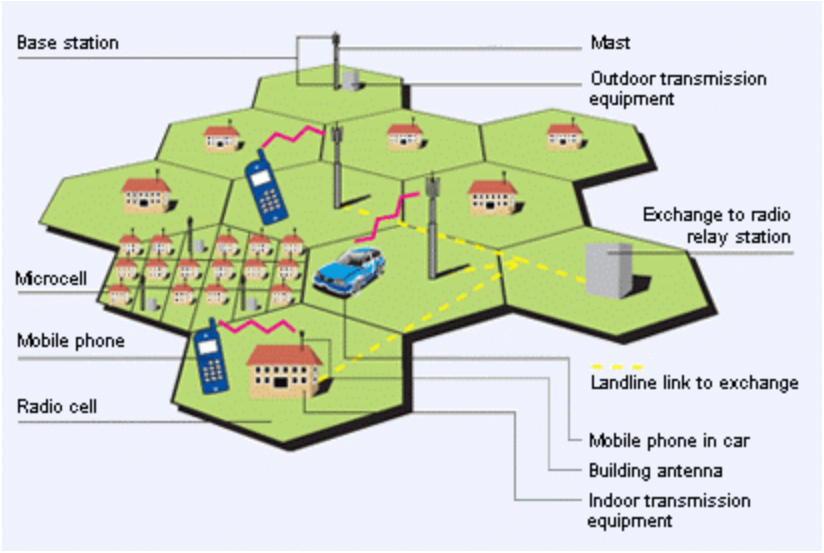
Background/Motivation

- The Mobility Revolution
- Infrastructure-based networks
- Infrastructure-less mobile networks

Connectivity on the go!

Wireless Infrastructure





But Sometimes we don't have infrastructure

Infrastructure overloaded and overpriced

Thursday, January 19, 2012 As of 12:00 AM New York 52°|33°

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By GREG BE

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"Data usage

to give customers more data upfront."

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By JENNA WORTHAM

Published: September 2, 2009

Slim and sleek as it is, the iPhone is really the Hummer of cellphones.

Home / News & Blogs / Between the Lines

International data roaming rates: You're being robbed

By Larry Dignan | March 29, 2011, 2:00am PDT

International data roaming charges remain a big issue for travelers and many respondents to a ZDNet survey noted that the billing process wasn't transparent enough. The only edge you have is Wi-Fi.

Horror stories about data roaming stories were everywhere. It's not surprising that the wide majority of ZDNet readers around the globe thought international data roaming rates were a rip-off. To wit:

TWITTER

LINKEDIN

COMMENTS (322)

Outline

- **Three classes** of mobile networks
- Understanding Mobile Networks
  - When is a mobile network connected?
  - Does a mobile network have a backbone?
  - Why are mobile networks hard to measure and characterize?
  - Can mobile networks compute?

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Infrastructure-less mobile networks

- As old as the Internet
- Focused on wrong mobility paradigm
- Only a slight deviation from wired networks

Mobility

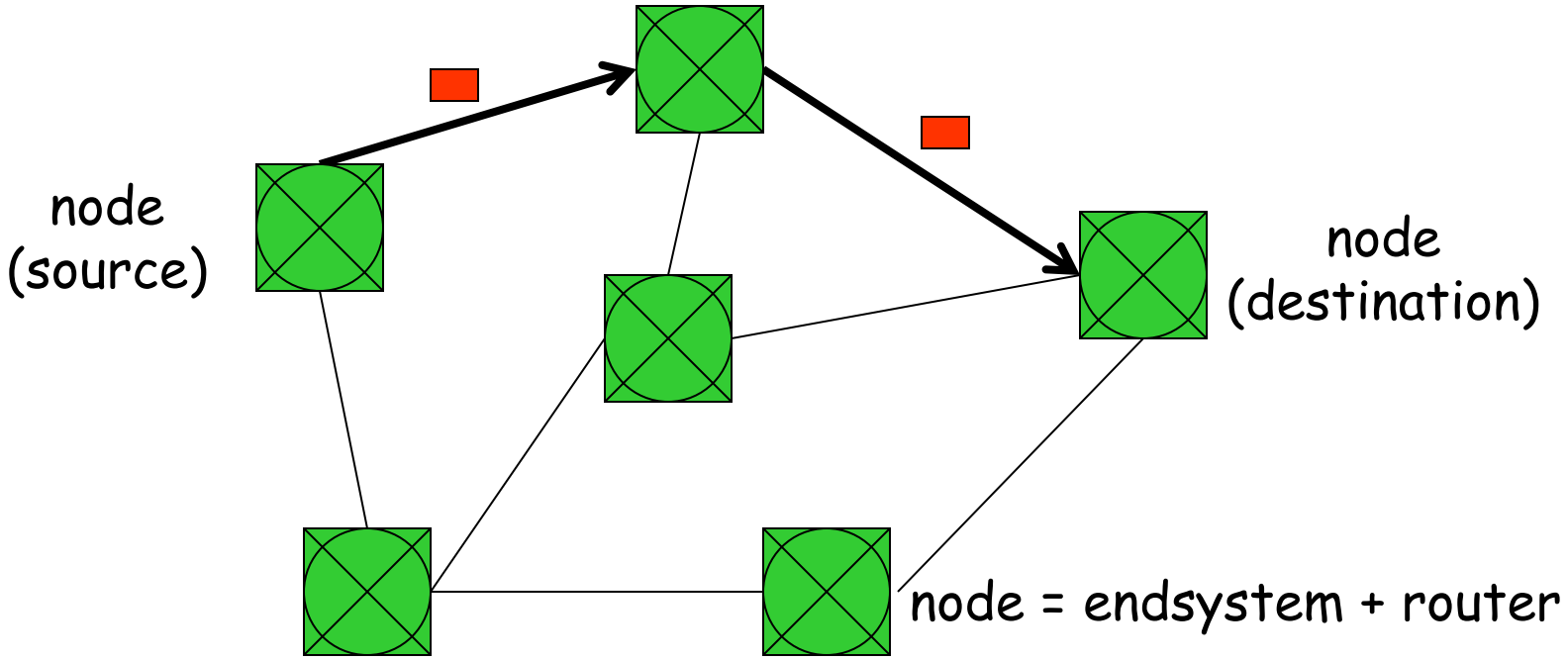
- "Cello" Mobility
- True Mobility

Woody Allen, "Take the Money and Run," 1969

Classes of Mobile Networks

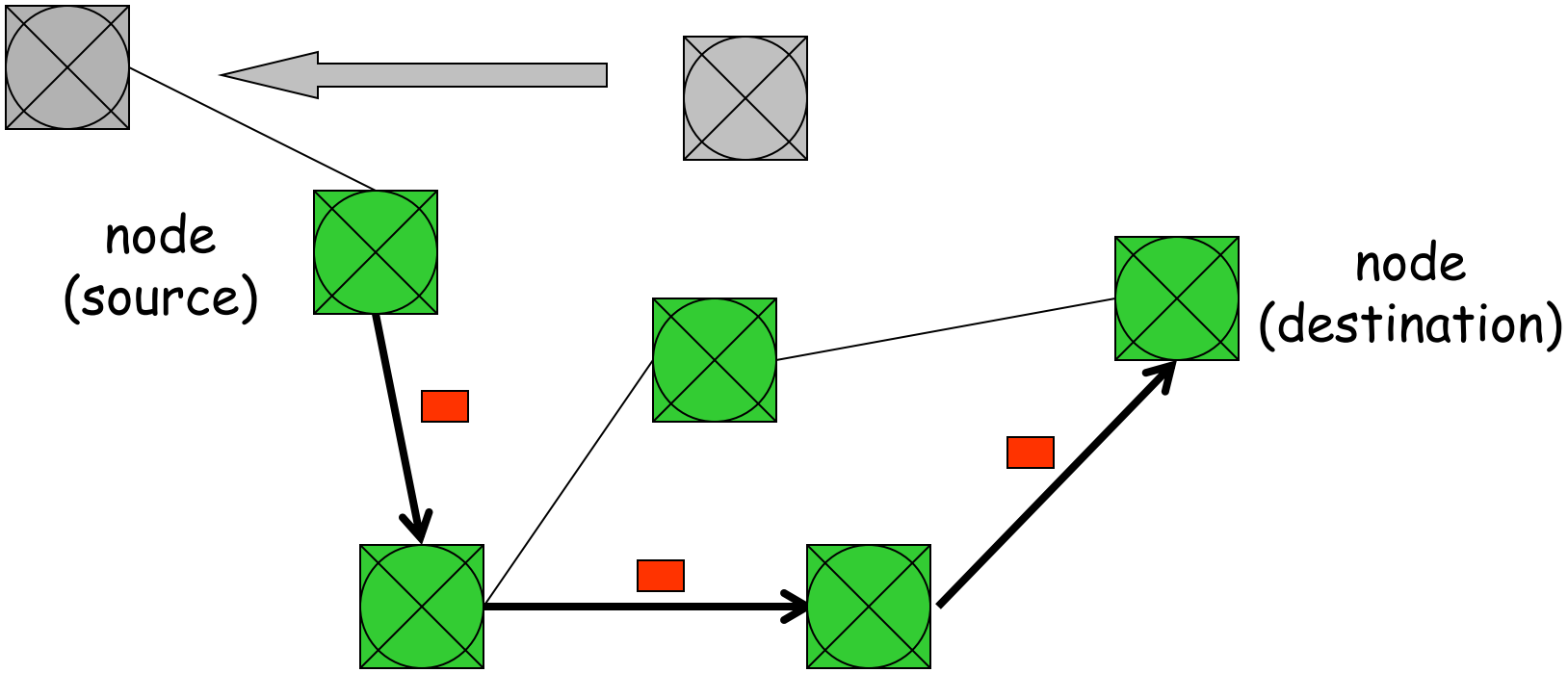
- MANETs -- Implicit Cello Mobility
- Intermittently-Connected Networks
- Sparse Networks

"Traditional" Mobile Ad-hoc Wireless Networks (MANET)



- no separation between endsystems and routers
- nodes responsible for finding stable path

"Traditional" Mobile Ad-hoc Wireless Networks (MANET)



- nodes may move
- routing layer responsible for reconstructing (repairing) stable paths when movement occurs

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
  - Mobility is an ERROR condition!!!

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*

Also Known As

- Delay-Tolerant Networks
- Disruption-Tolerant Networks
- Opportunistic Networks
- …

Mobility-Assisted Data Delivery: A New Communication Paradigm

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

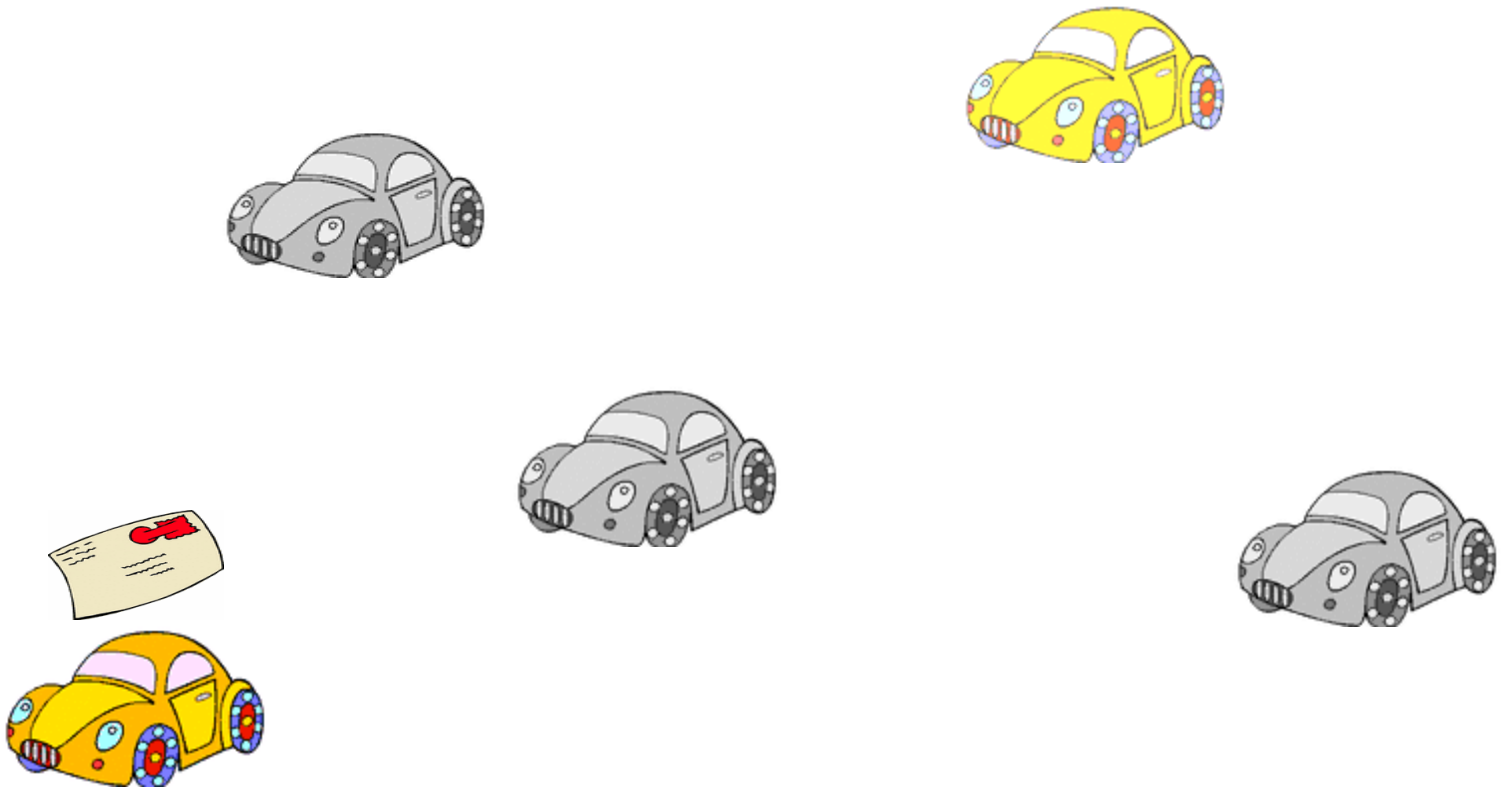
Store

Carry for a while

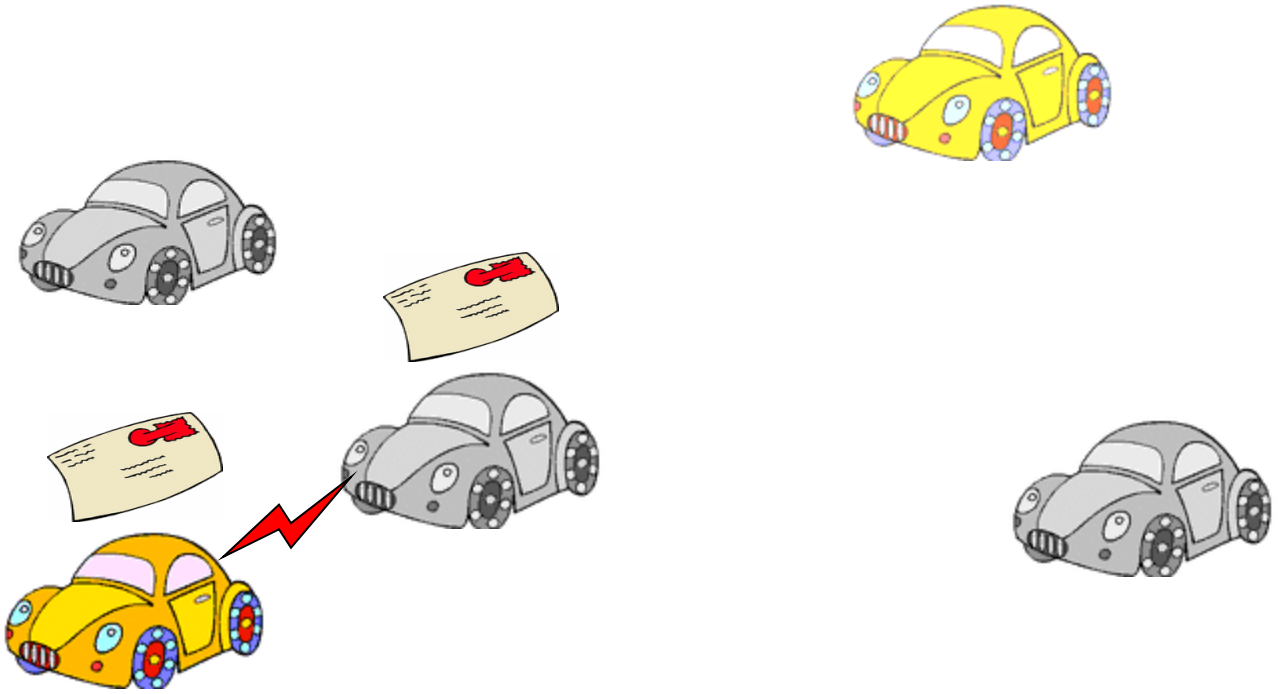
forward

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

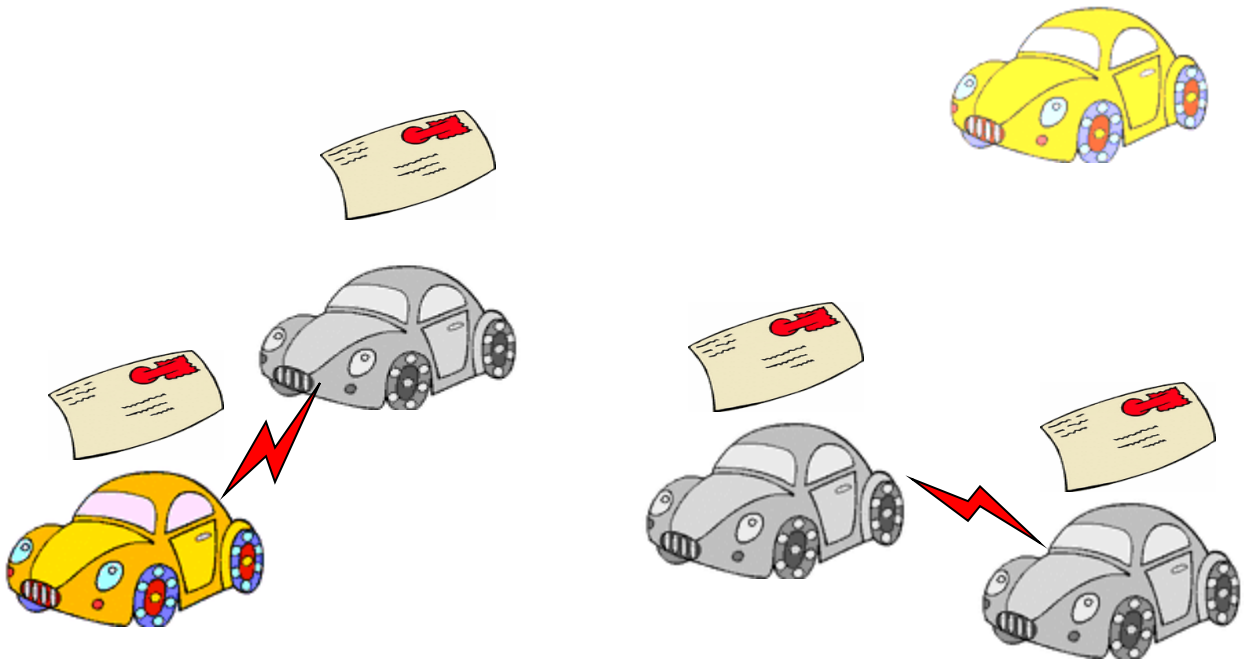
Epidemic Routing



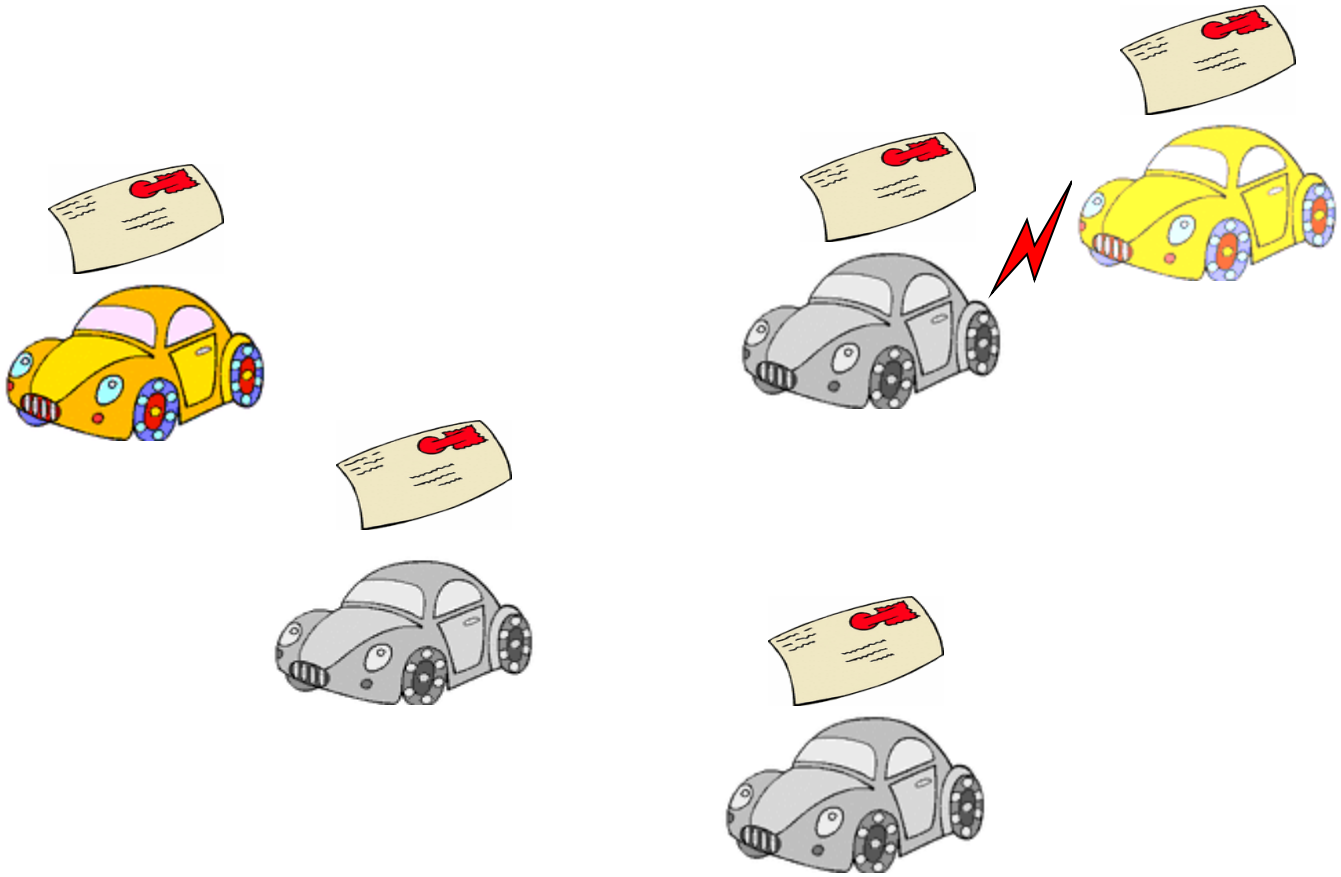
Epidemic Routing



Epidemic Routing



Epidemic Routing



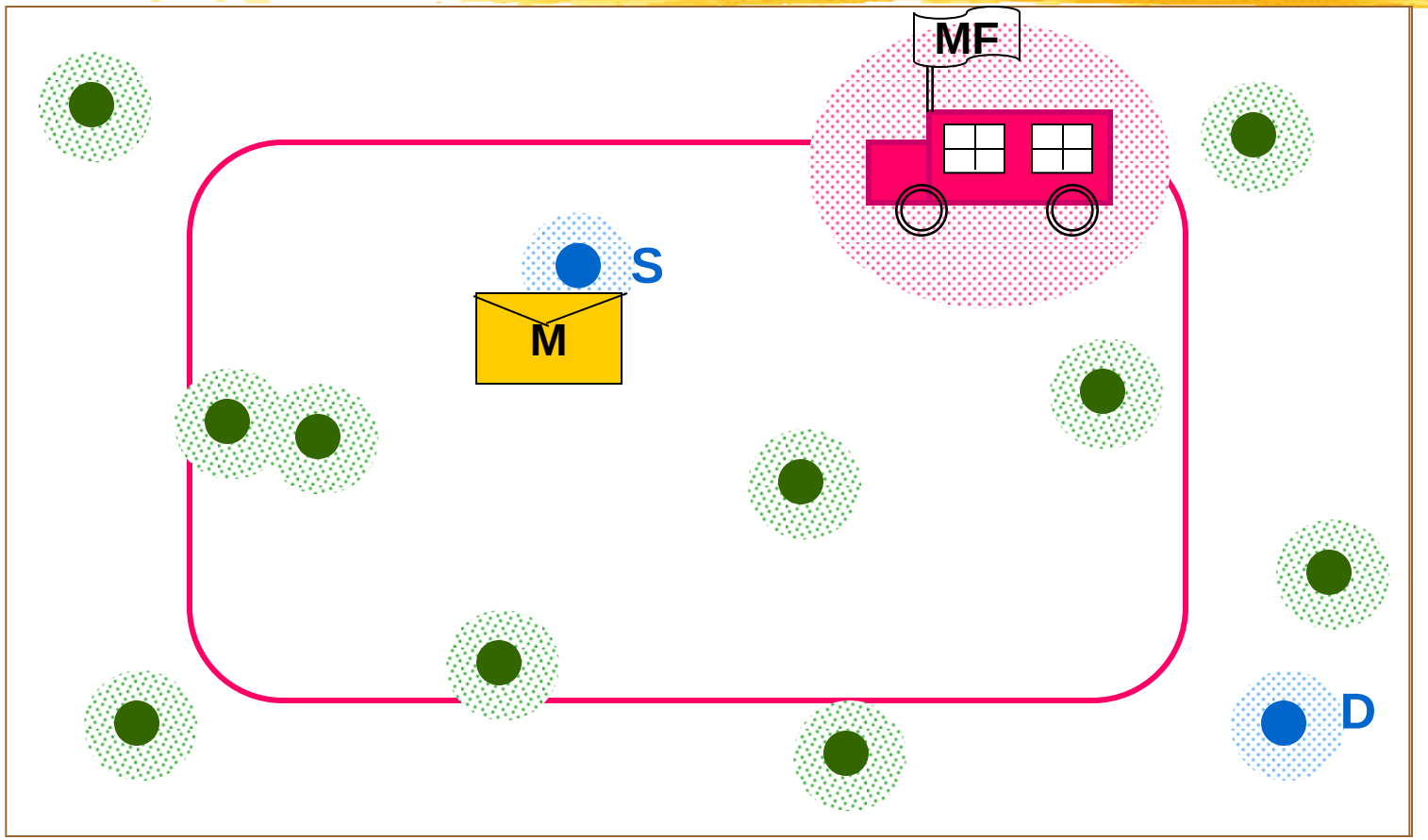
Other "Original" Systems

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

Sparse Networks

- Nodes Mobile or Stationary
- Disconnected because
  - Short radio range
  - Too few
  - Not enough mobility

Message Ferrying
(Zhao and Ammar)



Outline

- Three classes of mobile networks
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  - Does a mobile network have a backbone?
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  - Can mobile networks compute?

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?

The WAM Continuum Framework

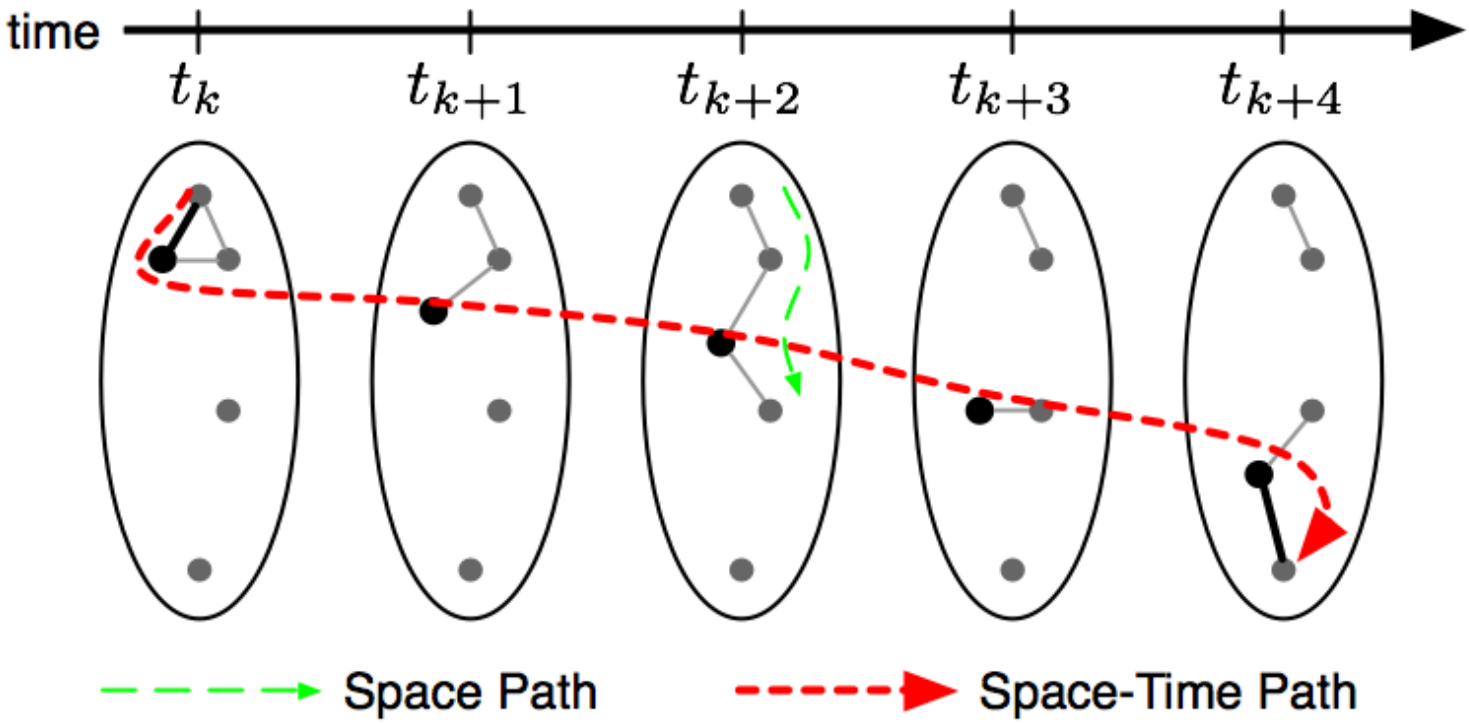
- Formalize relationships among networks
- Understand hybrid networks or ones that change over time
- Basis for operation adaptation
- Network classification informs performance

Chen, Borrel, Ammar, and Zegura,"A Framework for Characterizing the Wireless and mobile Network Continuum," SIGCOMM CCR, January 2011.

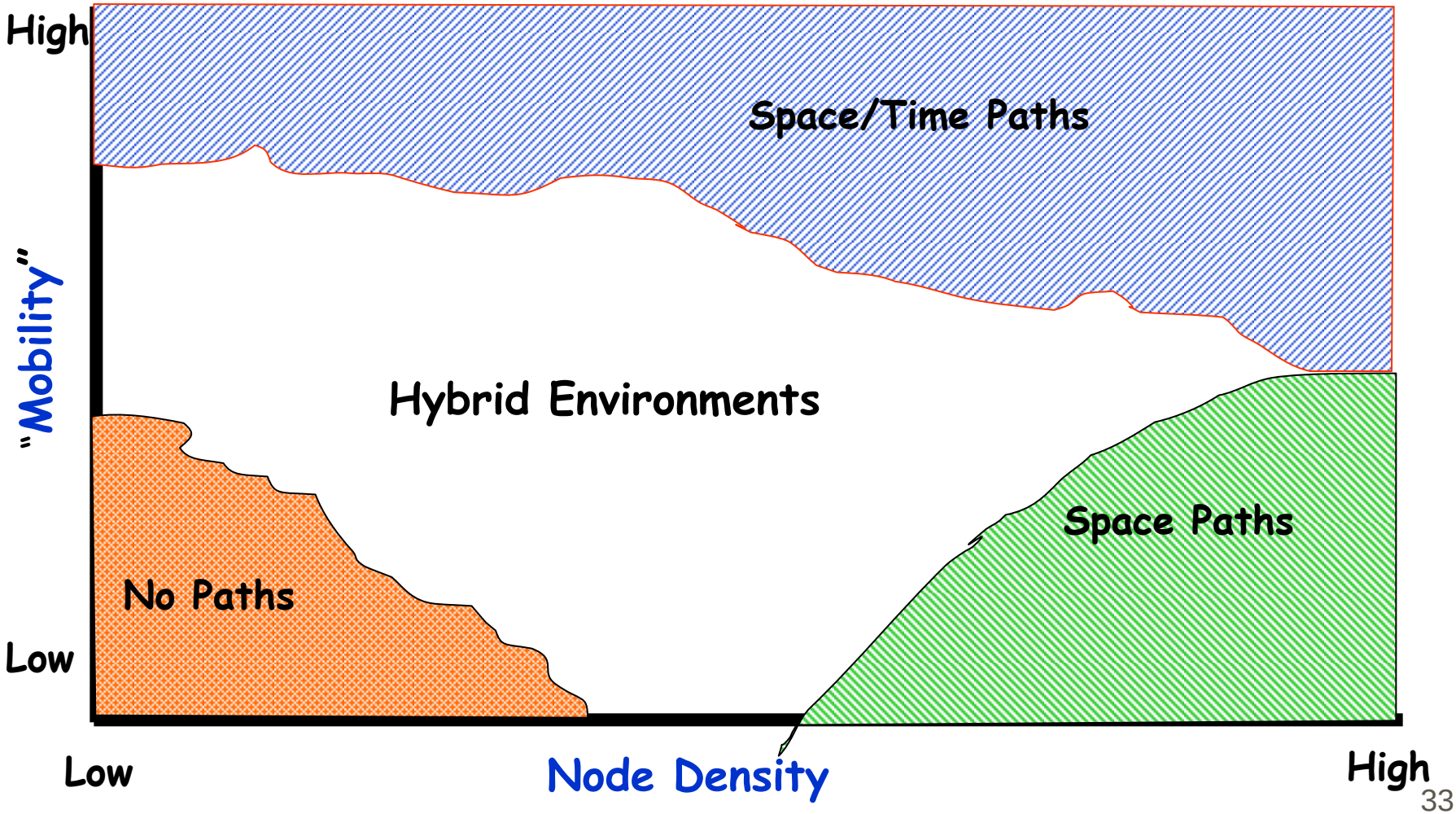
Some Terminology

- 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

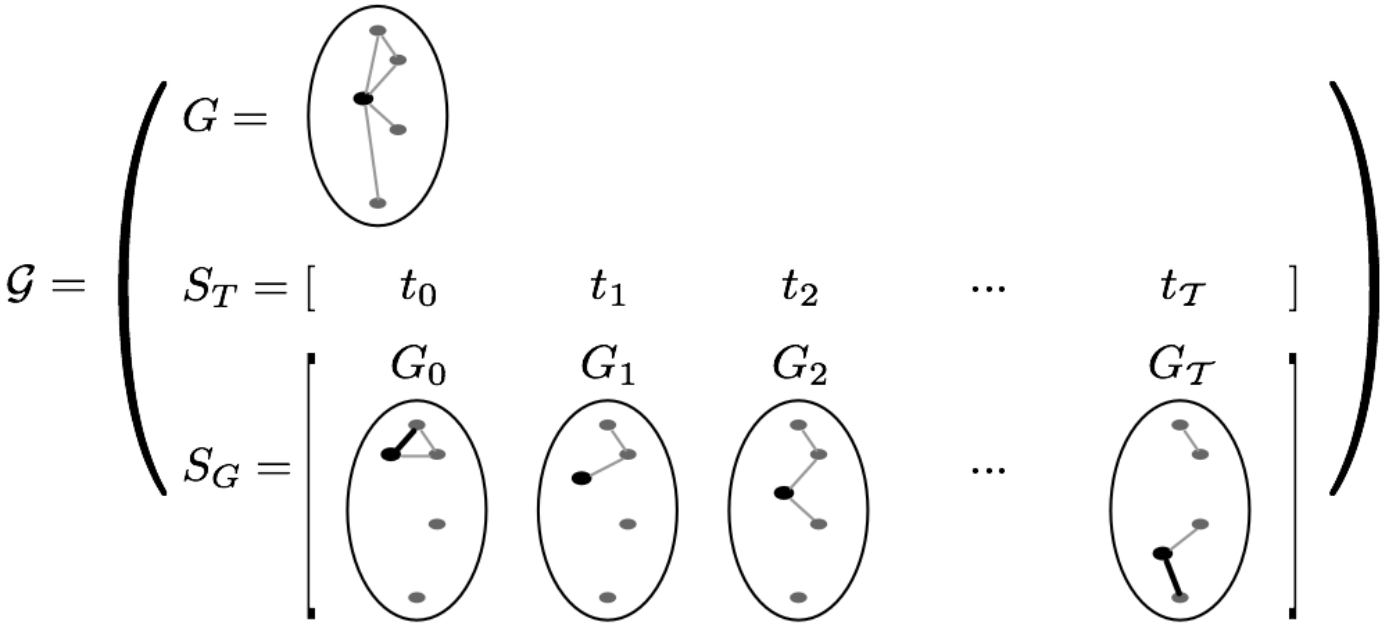


Evolving Graph (EG)*

*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
- Journey = Space-Time Path:

WAMs as Evolving Graphs

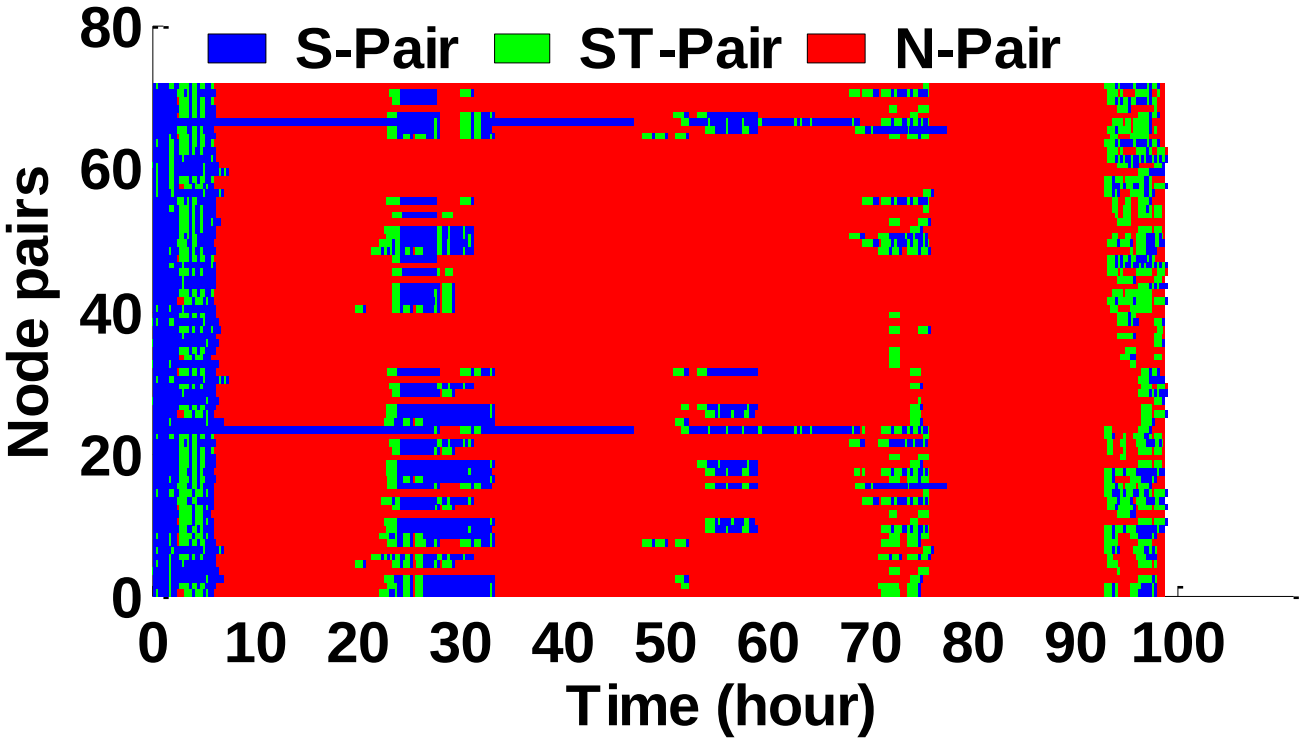


Our Classification – Node Pairs

- S-Pair: A space path exists between nodes
- S/T-Pair: A journey (space/time path) exists
- N-Pair: No Path Exists

Classifying Networks From Network Traces

Epoch by Epoch Classification



9 nodes trace from Haggle Project: γ = 1 hour, δ = 5 seconds

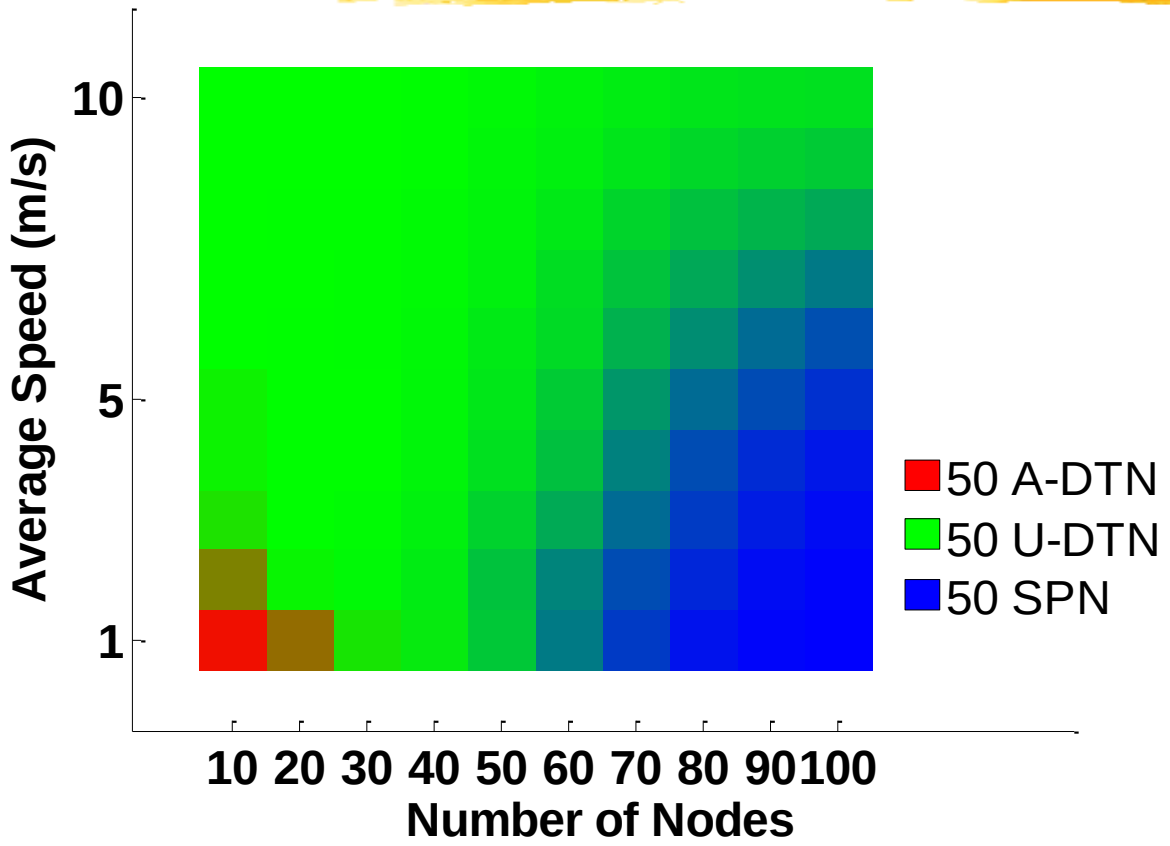
Whole Network Classification

- SPN: Space Path Network
  - Specified percentage of S-Pairs
- UDTN: Unassissted DTN
  - Specified percentage of ST-Pairs
- ADTN: Assistance Needed DTN
  - Specified percentage of N-Pairs

Whole Network Classification in terms of node pair classification

- 100-SPN in an epoch
  - 100% of node pairs are classified as S-Pair in that epoch
- 100-UDTN in an epoch
  - 100% node pairs are classified as S-Pair or ST-Pair in that epoch and this epoch is not classified as x-SPN
- 100-ADTN
  - This epoch is classified as neither 100-SPN nor 100-UDTN

Joint Effect of Node Density and Speed

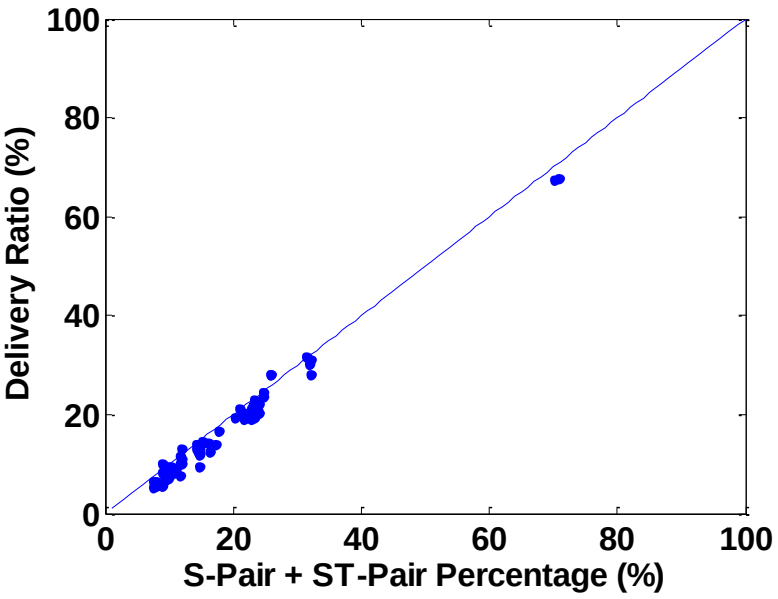


Random Way Point mobility model
x = 100, γ = 600 seconds, δ = 5 seconds

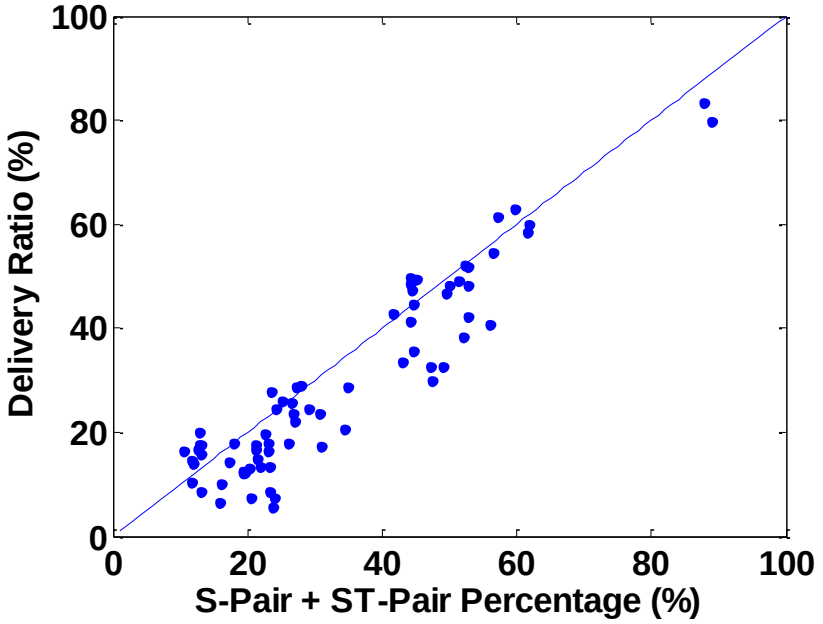
Applications

- First-order Performance Prediction
  - Faster than simulation of analysis
- Network Design
- Adaptive Network Operation
  - Requires distributed classification scheme (see Antonellis et al.)
- Other dimensions – e.g., Energy

Correlation between Classification and Simulation Results



Short Journeys



Long Journeys

9 nodes trace from Haggle Project

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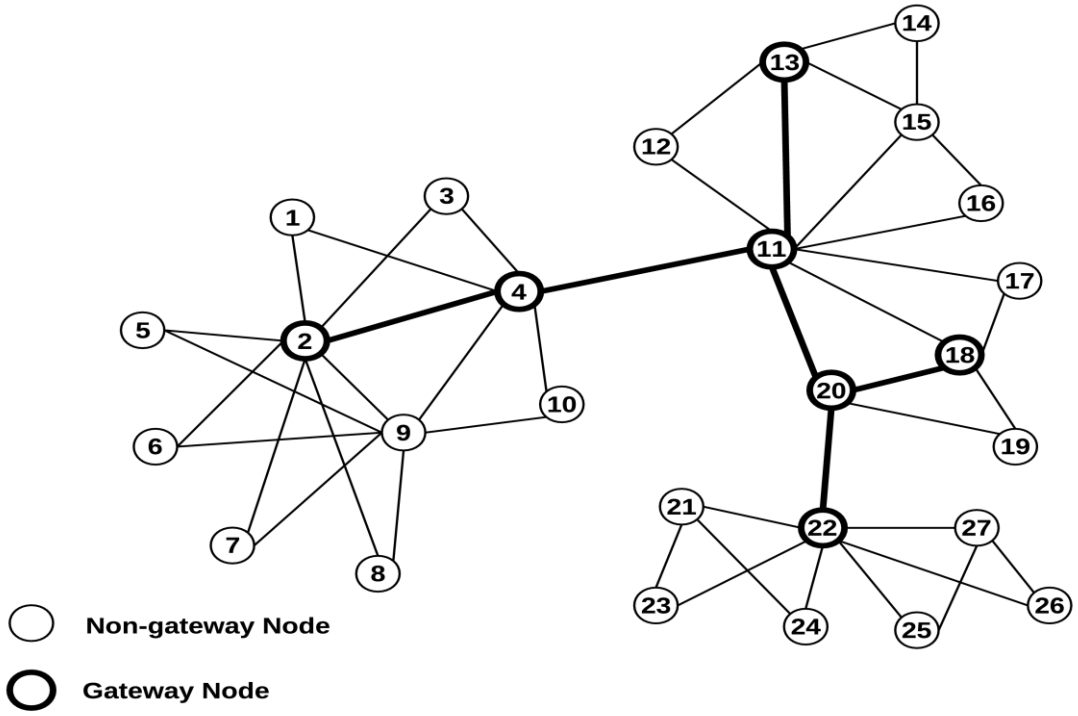
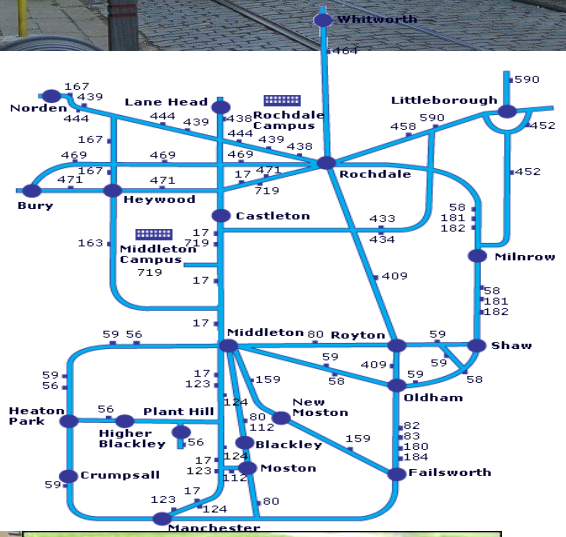
Connected Dominating Sets (CDS)



CDS can be used as a routing backbone in MANETs

Intrinsic Message Ferrying Capability

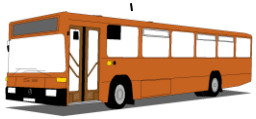


Multiple Message Ferries

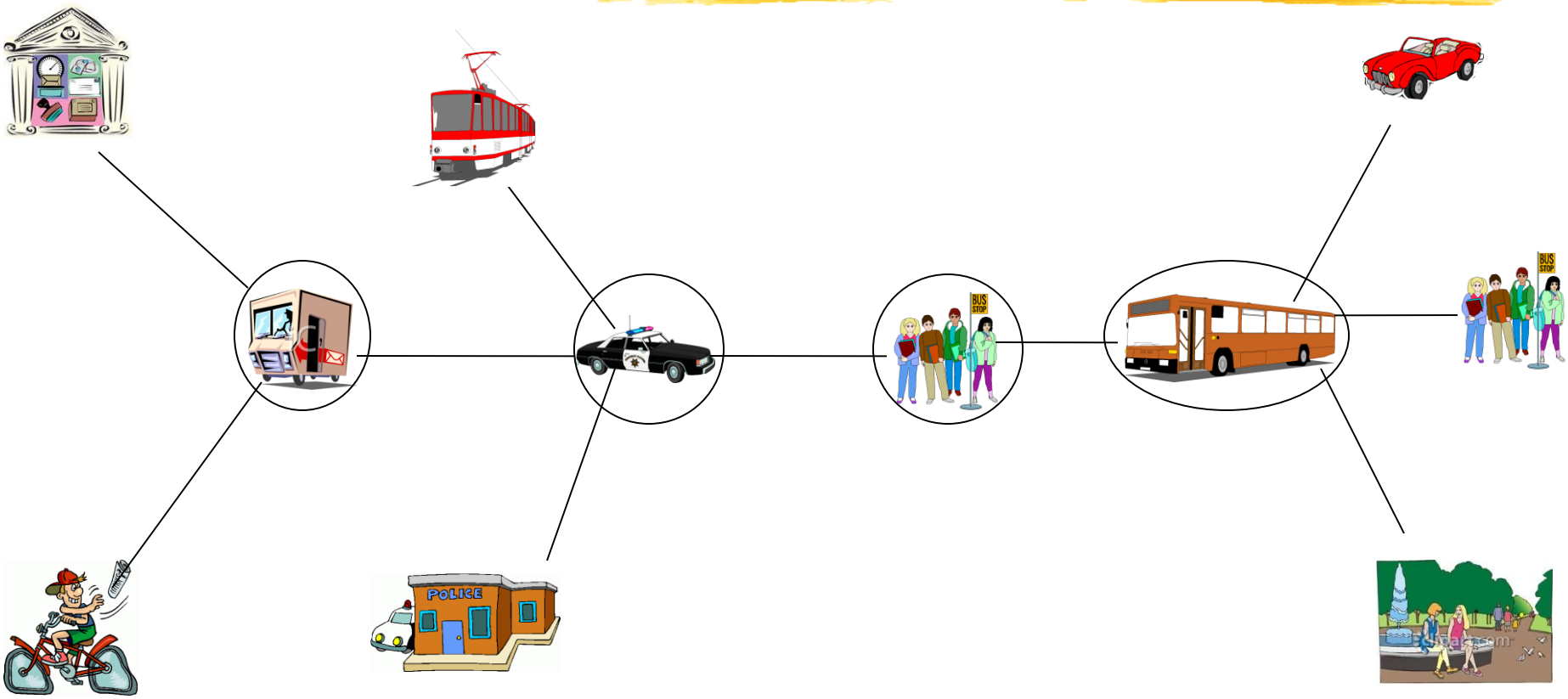









Message Ferry "Backbone"

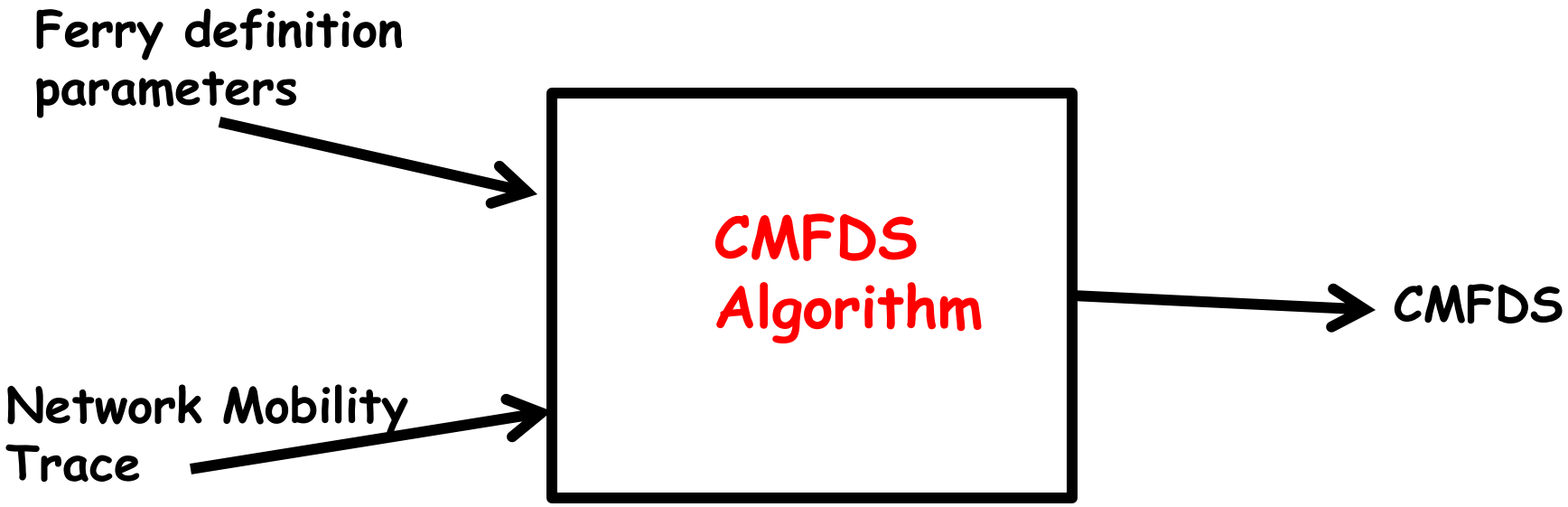


Looks like a "connected dominating set"

Finding a CMFDS in an Intermittently Connected Network

- CMFDS= Connected Message Ferry Dominating Set
- Two Challenges:
  - Definition
  - Algorithm for finding a CMFDS
- CMFDS problem is a generalization of CDS problem

Finding a CMFDS



Polat, Sachdeva, Ammar, Zegura,"Message Ferries as Generalized Dominating Sets In Intermittently-Connected Networks," Pervasive and Mobile Computing, April 2011

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Mobility Measurement

- GPS/Location Traces

```
node 1, t=1: x=10,y=20
node 1, t=2: x=12,y=19
...
```

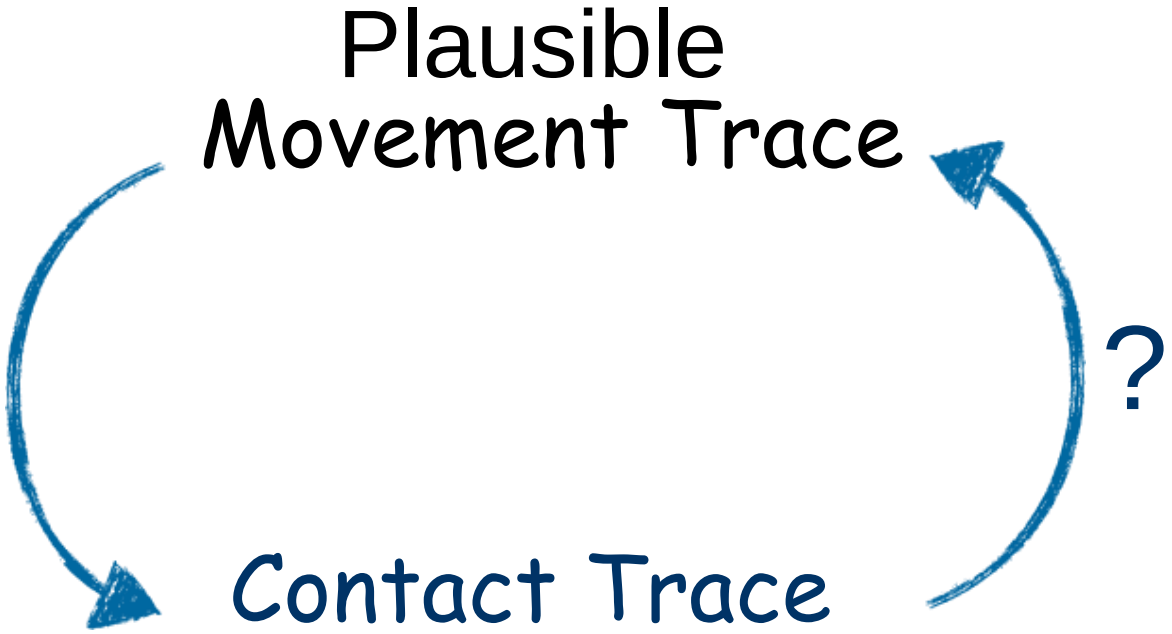
- But: precision issues, indoors, datasets are sparse
- Contact/Proximity Traces

```
t=1, node 1 and node 2: UP
t=1, node 2 and node 4: DOWN
...
```

Mobility Traces are Better

- Visualization: what does the movement look like?
- Better simulations (good interference models)
- Modify existing contact traces
  - Add a node
  - Change radio range
  - etc.

What if?

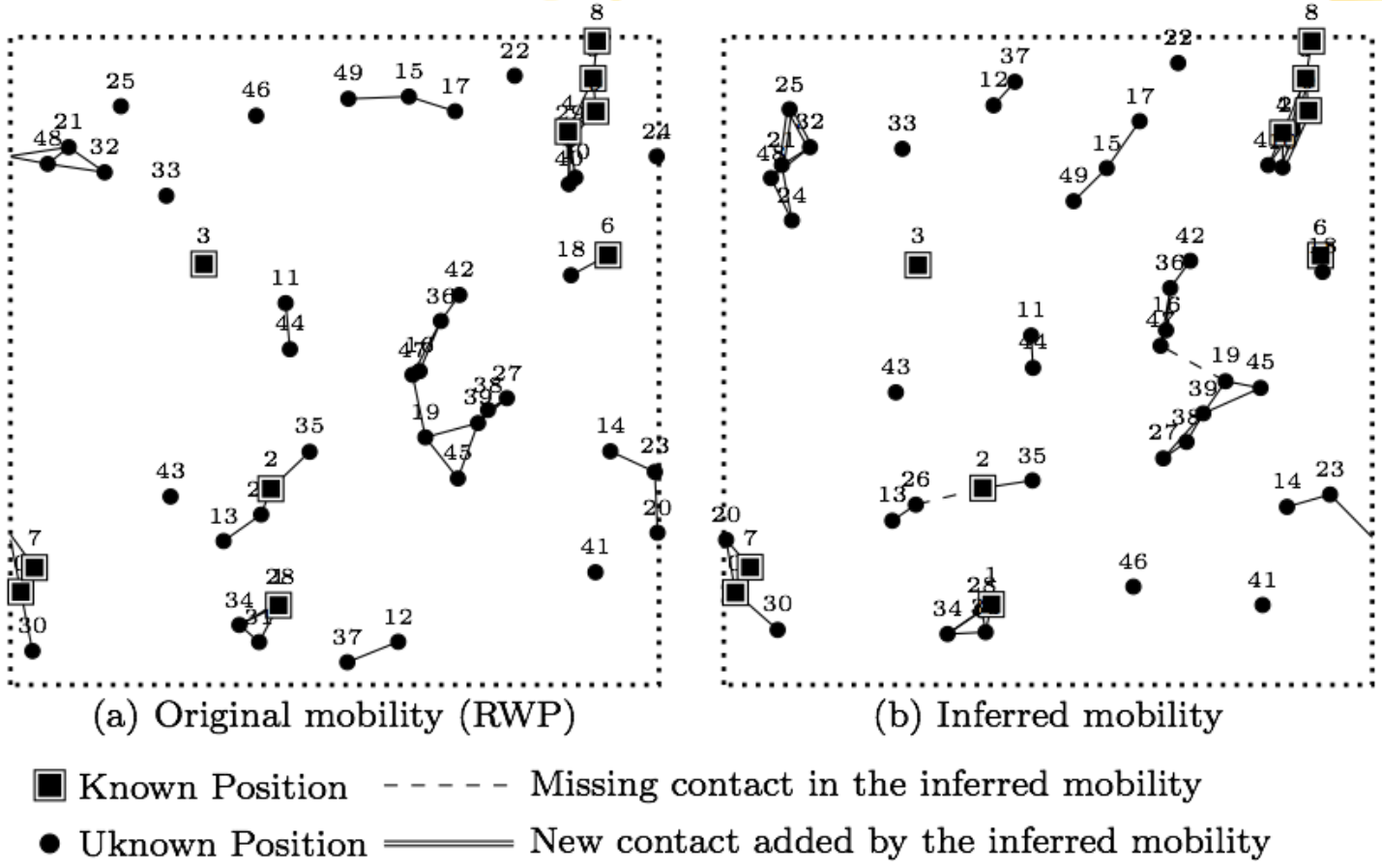


Whitbeck, Dias de Amorim, Conan, Ammar, Zegura, “From Encounters to Plausible Mobility,” J on Pervasive and Mobile Computing, April 2011.

Very Difficult

- We have
  - all contact trace
  - Some speed constraints
  - Minimal localization of some nodes possible
- Can write multivariate, non-linear constraints – not solvable
- Heuristic by dynamic graph force-based layout algorithms.

Results



Videos: http://www-npa.lip6.fr/~whitbeck/plausible.html

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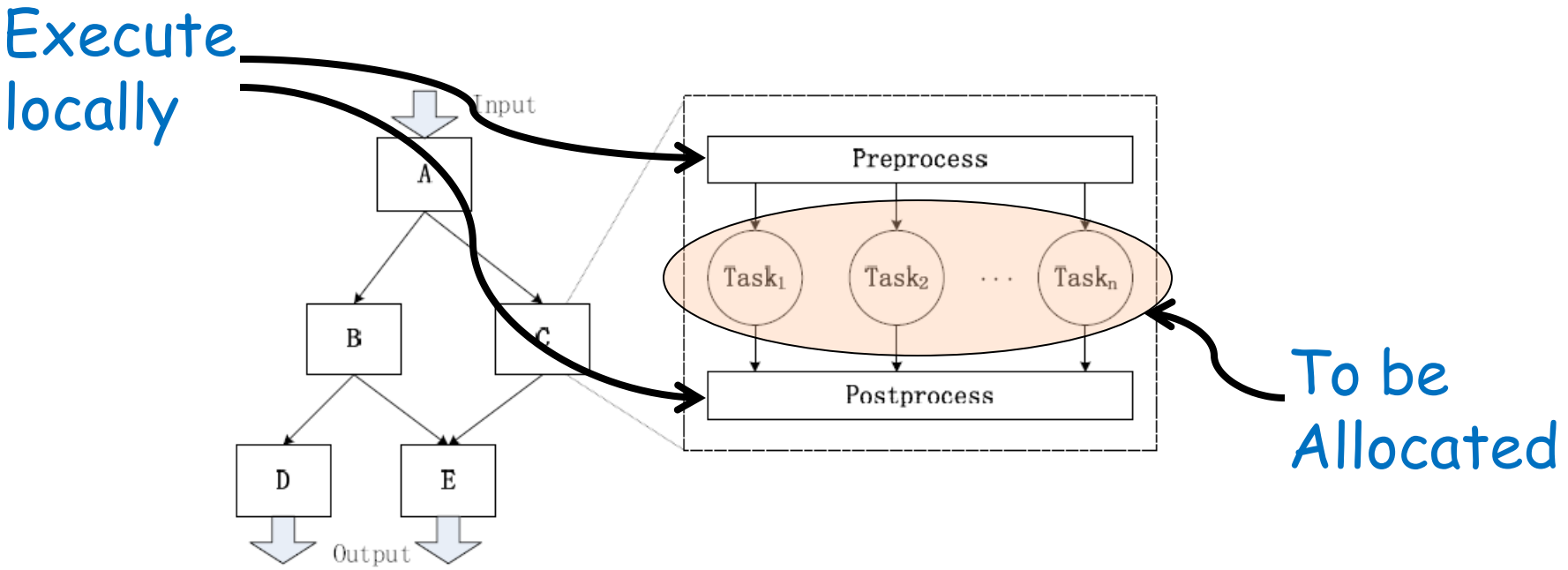
The "Crazy" Idea

- Use the idle processing power in portable mobile devices as a distributed computation resource.
- LOTS OF PROBLEMS TO SOLVE
  - Applications
  - Incentives
  - Power Management
  - …

Why Distributed Computing in Mobile Networks

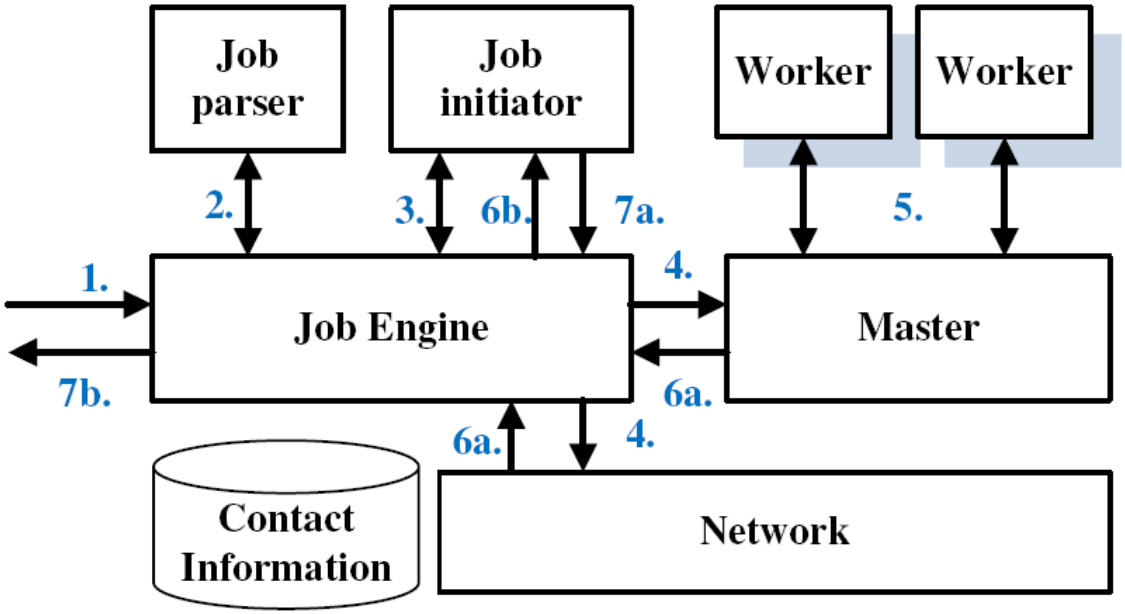
- Speedup compute-intensive applications
  - Instead of going to a central Cloud
- Challenges:
  - It is difficult to map computation onto nodes with an assurance that the code and data can be delivered and the results received timely.
  - The network is likely to be a bottleneck.
  - Coordination and Control are difficult.

A Job Model



A job is a DAG of PNP-blocks

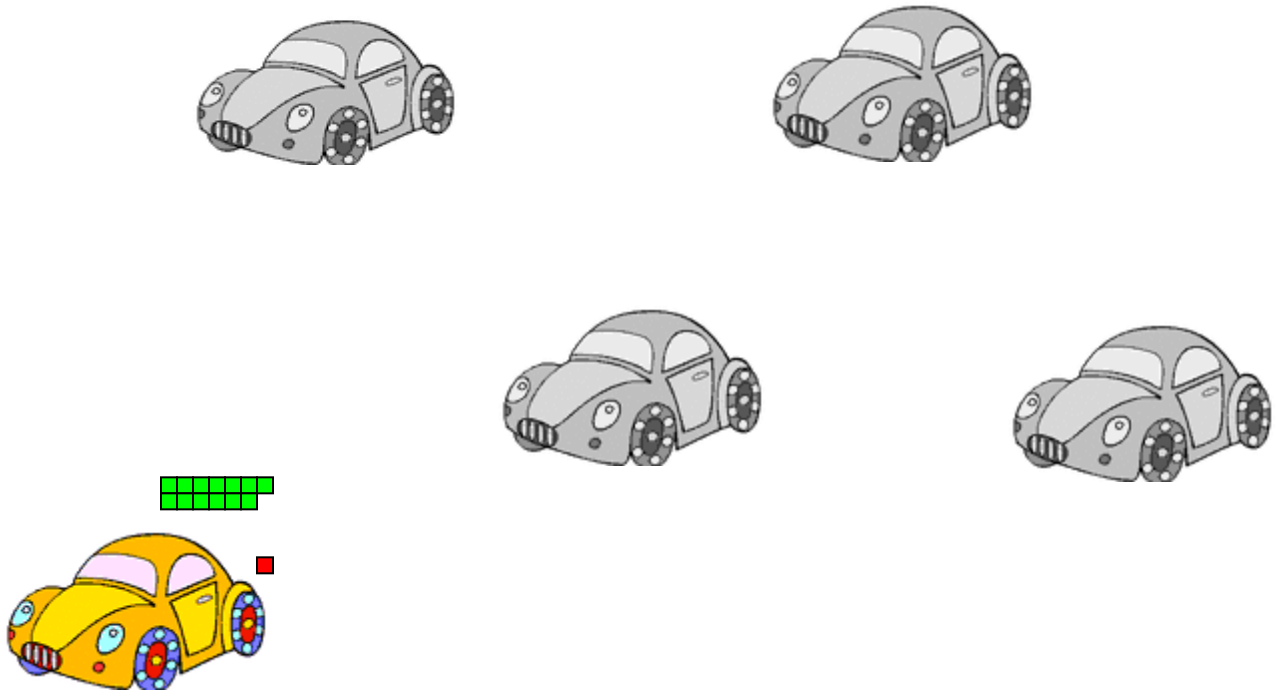
Serendipity Architecture



- 1. A user submit a job.
- 2. Job parser processes the job script.
- 3. Job initiator schedules and monitors the job.
- 4. Job engine allocates the job tasks to local and remote workers.
- 5. Workers execute tasks.
- 6&7. Job initiator collects and returns the results.

Cong, Vasileios, Ammar, Zegura, "Serendipity: A Distributed Computing Platform for Disruption Tolerant Networks," Georgia Tech, Tech Report, January 2011
http://hdl.handle.net/1853/38773

Serendipity in Action



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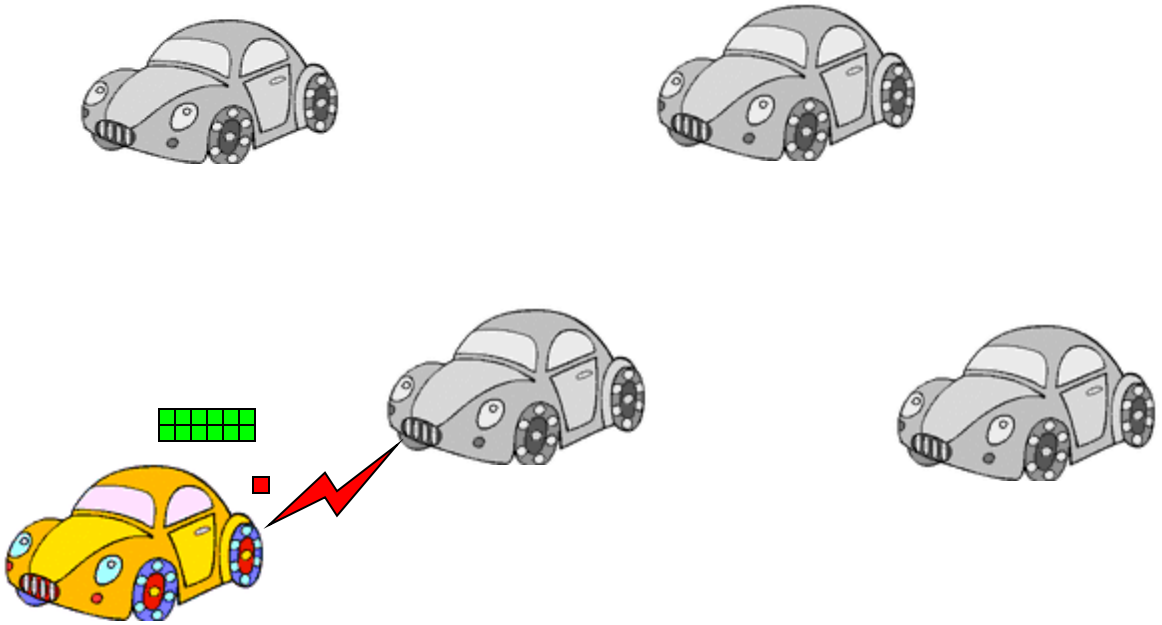

Concluding Remarks

- True WAMs are poorly understood
- They are more general than "Cello" WAMs
- Fundamental Challenges
  - Understanding Properties and Features
  - Measurement and Modeling
  - Novel Applications