Mobile Networking Solutions for First Responders

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Joint work with Dr. Ying Huang, Dr. Wenbo He, Dr. Yan Gao, Dr. Whay Lee

First Responder Mobile Systems (FRS)

Sep. 11'01

Katrina'05

East Amarillo Complex'06

First Responder

EMS

Firefighter

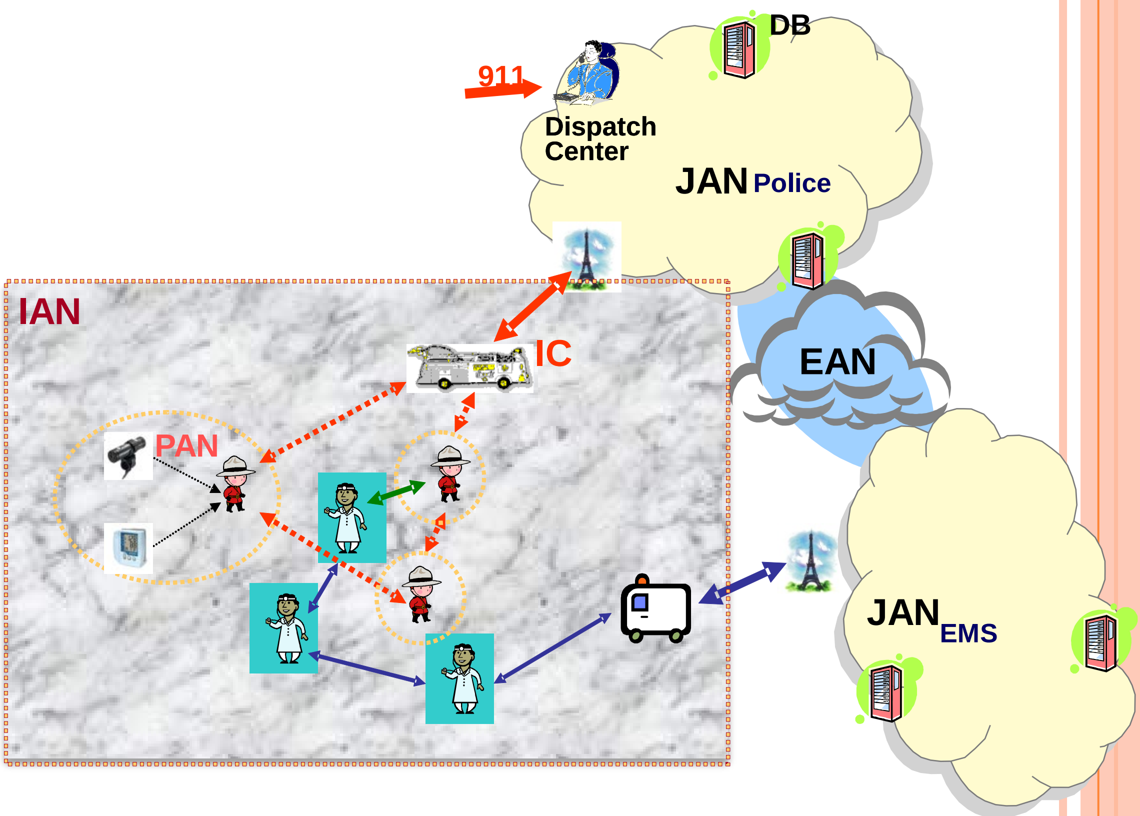
Police

First Responder System – Network Model

- **E**xtended **A**rea **N**etwork
- **J**urisdiction **A**rea **N**etwork

- **I**ncident **A**rea **N**etwork
  - Wireless communication system (MANET)
    - Mobile devices, droppable devices, vehicles
  - Incident command system
    - Command center (CC) at a vehicle

- **P**ersonal **A**rea **N**etwork
  - Sensors, RFID, cameras, microphone, mobile devices
  - Health/equipment monitoring and environmental surveillance



Outline

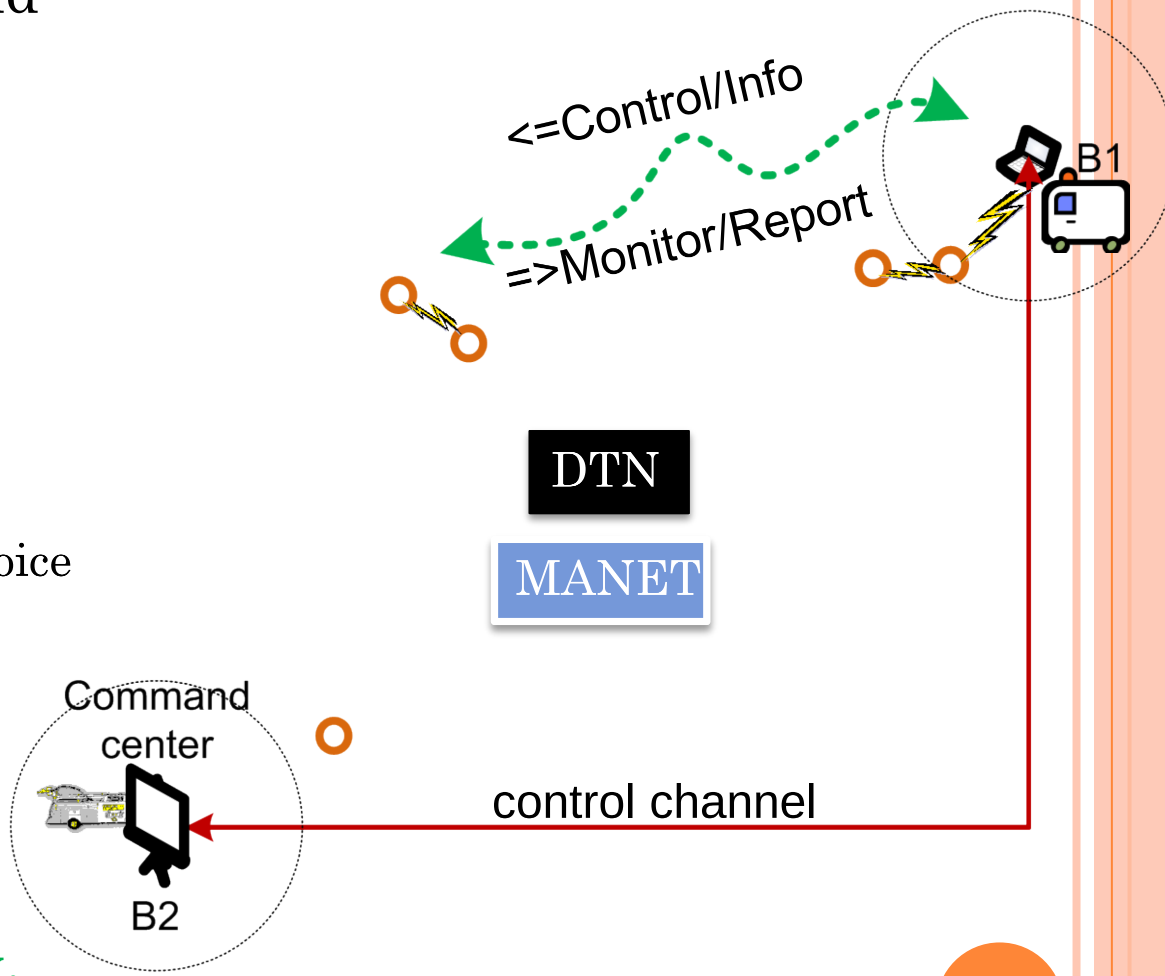
- Relay Placement In Unpredictable Environments
  - Problem Description
    - Polymorphic Networks
    - Optimal Relay Placement
  - Solutions
    - Constrained Relay Placement
    - Unconstrained Relay Placement
  - Evaluation
- Brief Overview of other MONET group projects

PROBLEM: CRITICALITY OF BASE STATION CONNECTIVITY IN FR ENVIRONMENTS

- Goal: Interconnecting Base stations (BS) with Command Center (CC) to improve command coverage
  - Reliable control channel
  - Satellite, cellular, mesh, Internet portal

- Real-time data flow
  - Monitor/Report from FRs
    - Location tracking / health / voice / surveillance
  - Control/Info from CC
    - Resource data, coordination, command

- **We need persistent Base Station (BS) connectivity.**



Dismayed Truth

- D.C. emergency response officers quote:
  - Their radio systems would not operate in the underground tunnels of the Metro system.
- Radio communication often falls out of range
  - Mine, tunnel, caves
  - High-rise buildings
  - Cargo ships (metal)

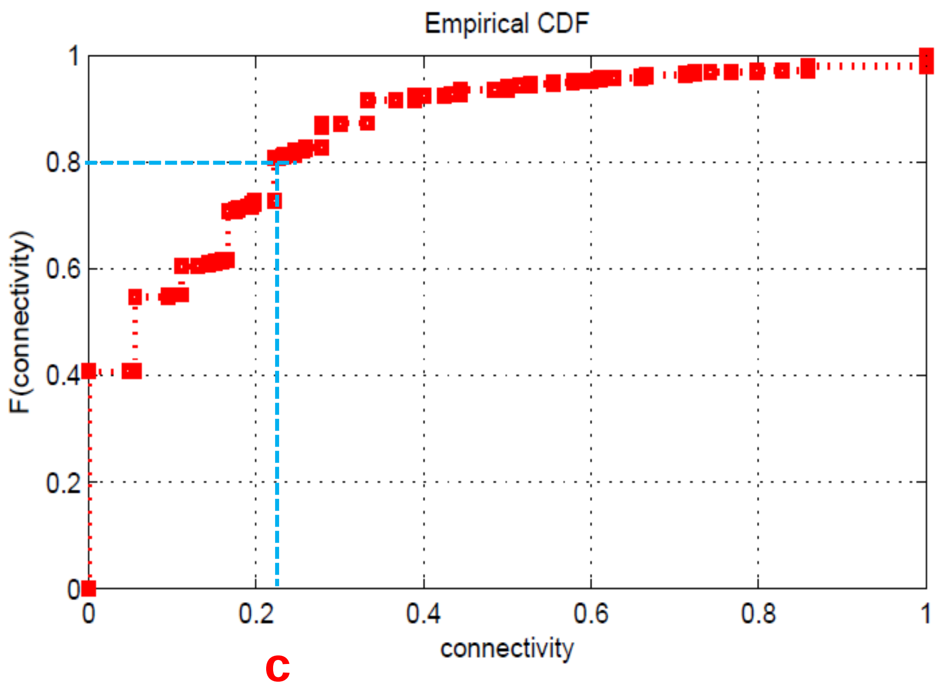
- Signal Degradation
  - Multipath fading
  - Interference
  - Obstacles

Disconnected Wireless Network Numerical Results from Simulation

- Large incident area
- Small # of FRs
- Large-scale fading

- Being mission-oriented, FRs are
  - Separately from others
  - Disconnected from BSes

- BS connectivity metric at a sampled time *t* is the percentage of FRs, who have BS connectivity
- F(*c*) = Fraction of sampled time instances, when BS connectivity metric is lower than *c*



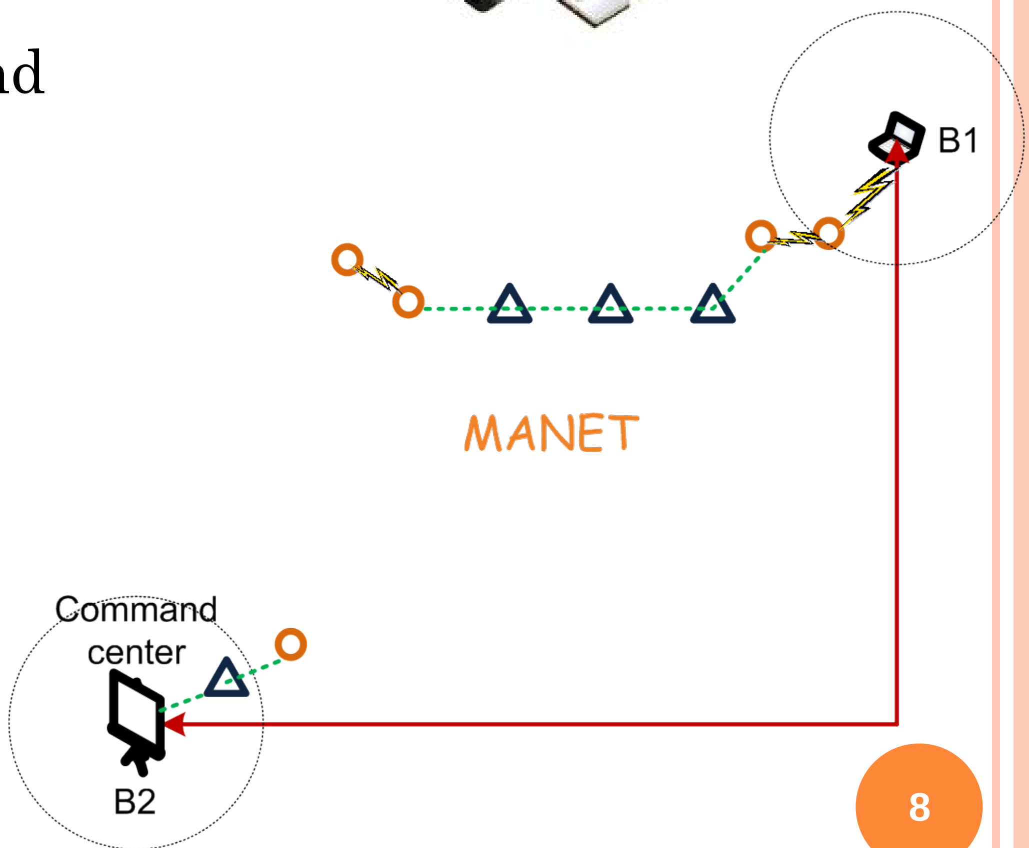
BS Connectivity

For 80% time, less than 22% FRs have connectivity to BSes.

Droppable Relays to Improve Connectivity

- Affordable wireless relays
  - Communication devices, whose exclusive function is to forward packets for terminals, base stations and other relays, whenever needed.
- Static relays
- No need to maintain BS connectivity for isolated relays.

bread crumbs

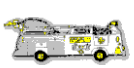
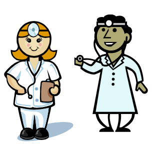


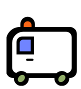
Optimal Relay Placement Scheme

- **Relay placement scheme**
  - Dropped locations for relays → # of relays
- **Optimal relay placement scheme**
  - **Minimum** number of relays

- Relays are resources. We need to concern about
  - **Number:** A finite # in total
  - **Weight**: A FR can only carry a small # of relays

- Optimal placement scheme is case by case
  - BS connectivity for all snapshots of network topologies – **polymorphic networks**



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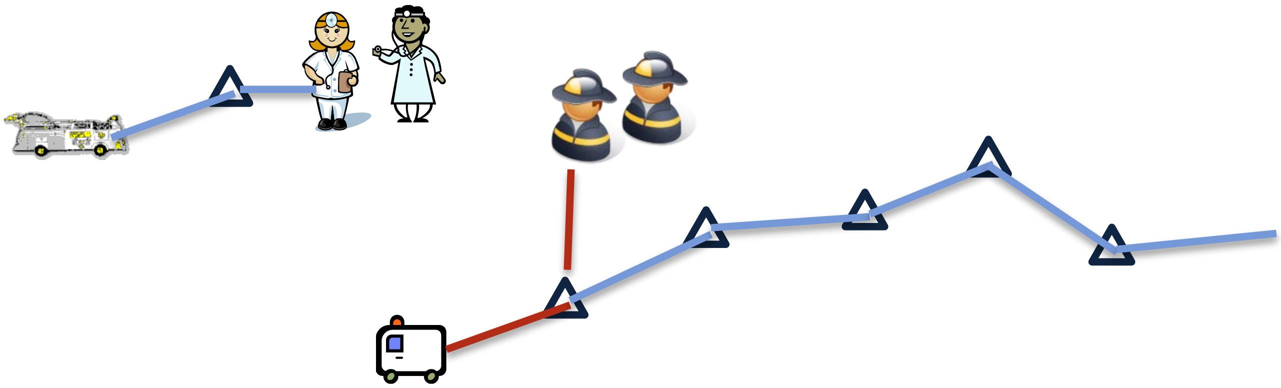
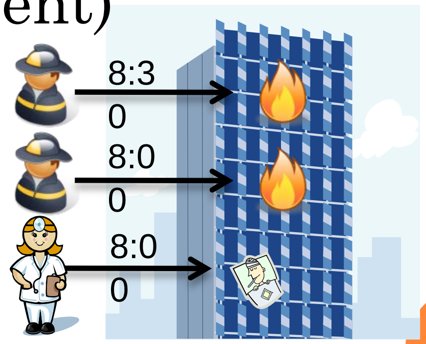


Usage of Topology-aware Relay Placement

- Offline - Analysis
  - Input: Discrete-ized mobility traces
  - Output: Performance reference for online algorithms

- Online - Incident preparation and planning phase
  - Input: Critical topology snapshots to maintain connectivity
    - Major events and dispatch commands
    - FRs' behavior coded by training
  - Output: Relay placement scheme (+ movement)
  - Predictability

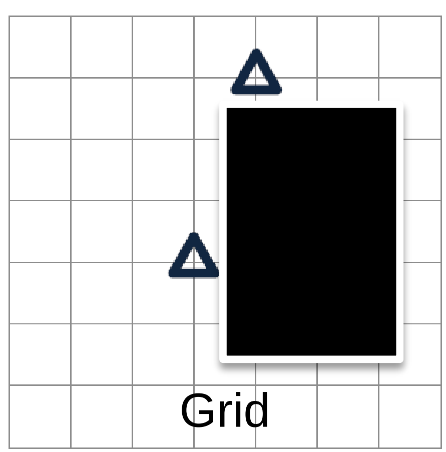
- Assumption: no hostile environment

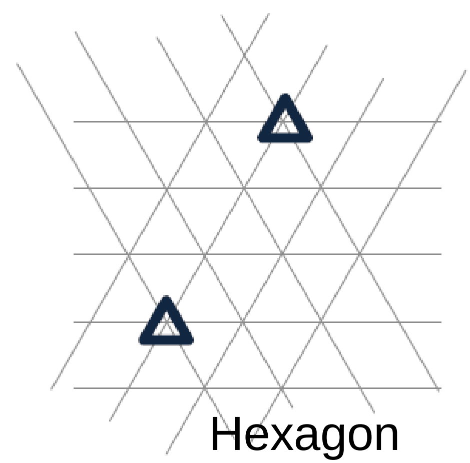


Constrained Relay Placement (CRP)

- Relays are placed at a subset of candidate locations
  - Safe distance between adjacent relays
    - Region-correlated crash/failure (fire, flood)
  - Forbidden areas
    - Impenetrable areas, obstacles
- A deployment scheme: the set of candidate relay places

$\mathcal{RP}$





GRAPH REPRESENTATION FOR CRP

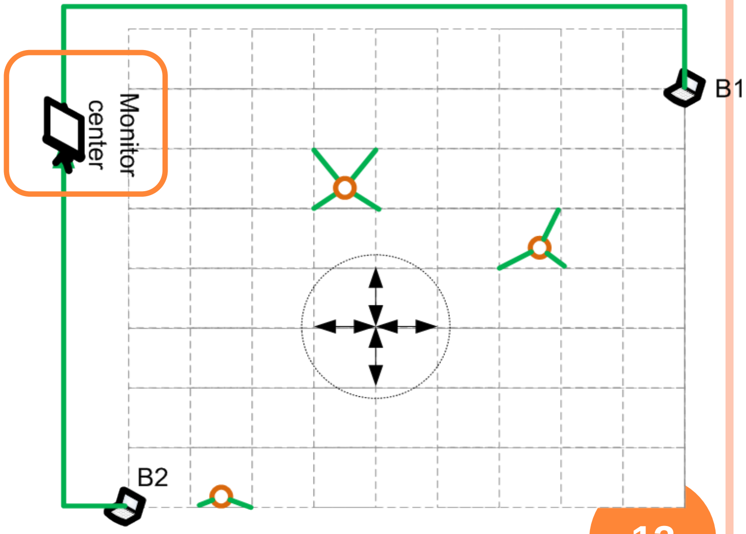
- A graph per topology
  - Vertex set $\mathscr{T}^t \bigcup \mathscr{B} \bigcup \mathscr{RP} \bigcup M$
  - Edge set

$$E^t = \{ab \,||\, ab \,| \le \min((tr(a), tr(b))), \forall a, b \in \mathscr{T}^t \bigcup \mathscr{B} \bigcup \mathscr{RP}\}$$

$$\bigcup \{MB \mid B \in \mathscr{B}\}$$

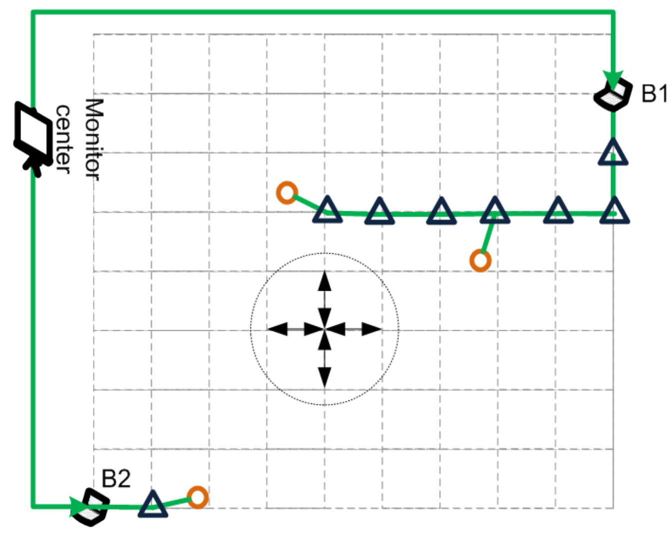
- For a terminal,
  - finding a multi-hop path towards at least one BS
  - finding a multi-hop path towards M.

Equivalent

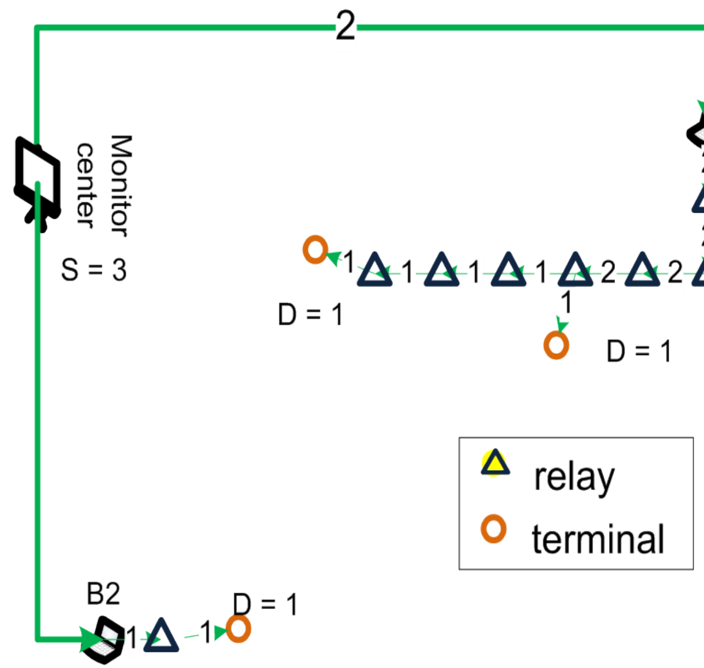


1-BS-CONNECTIVITY

- Node-weighted Steiner tree
  - Unit weight for relays; 0 weight for other nodes
- Commodity flow from MC to terminals
  - 1 unit towards each terminal
  - Place relays at places → commodities can flow via relays

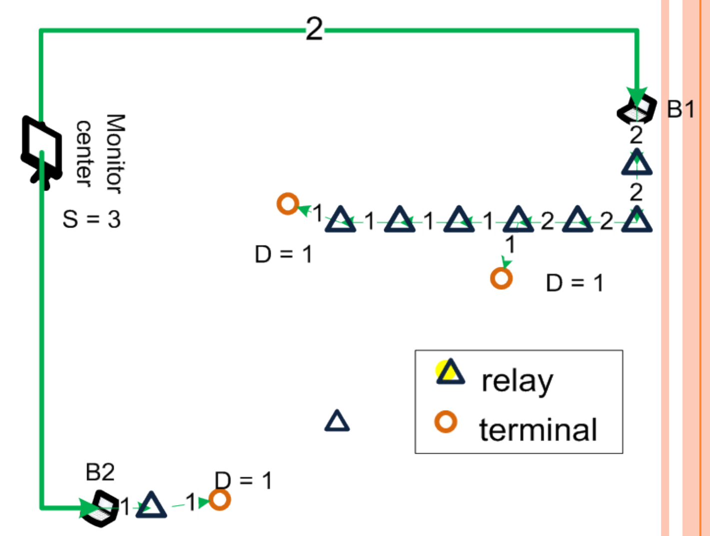


Minimum node-weighted Steiner tree (8)



Optimization Formulation (1)

- **Single topology**



$$\min \sum_{p \in \mathcal{RP}} y_p$$

$$s.t. \quad \sum_{j: ij \in E} x_{ij} - \sum_{j: ji \in E} x_{ji} = \begin{cases} |\mathcal{T}|, & i = M \\ -1, & i \in \mathcal{T} \\ 0, & \text{otherwise} \end{cases}$$

Flow conservation constraint

$$\sum_{j: pj \in E} x_{pj} \le |\mathcal{T}| y_p, \quad \forall p \in \mathcal{RP}$$

Switch constraint

$$y_p \in \{0, 1\}$$

Place relay or not at location p

$$x_{ij} \in [0, |\mathcal{T}|]$$

Flow amount on edge ij

Optimization Formulation (2)

- **Multiple topologies**

$$\min \sum_{p \in \mathscr{RP}} y_p$$

$$s.t. \quad \sum_{j:ij \in E^t} x_{ij}^t - \sum_{j:ji \in E^t} x_{ji}^t = \begin{cases} |\mathscr{T}^t|, & i = M \\ -1, & i \in \mathscr{T}^t \\ 0, & \text{otherwise} \end{cases}$$

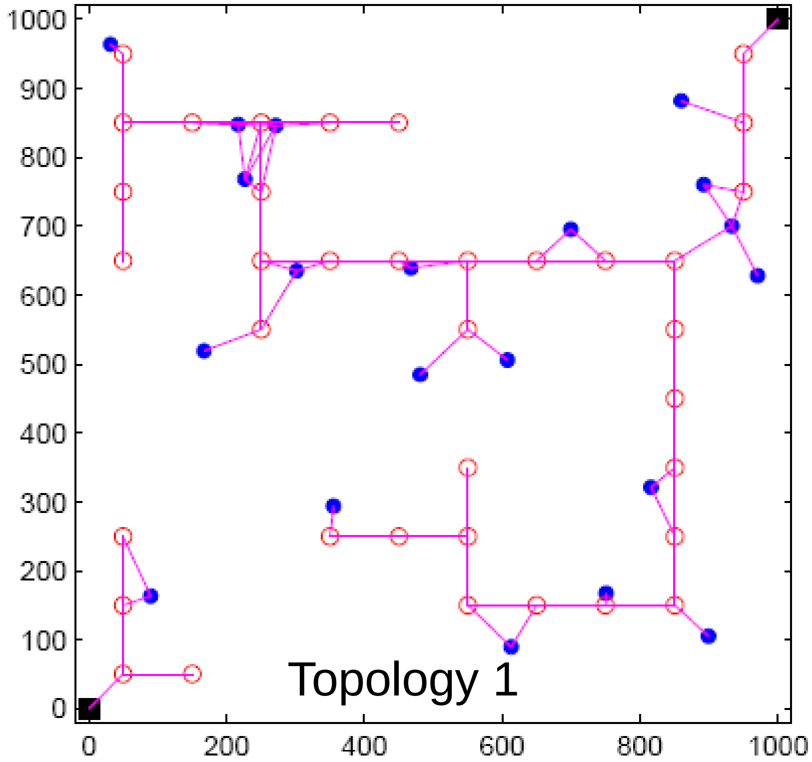
$$\sum_{j:pj \in E^t} x_{pj}^t \le |\mathscr{T}^t| \, y_p, \quad \forall p \in \mathscr{RP}$$

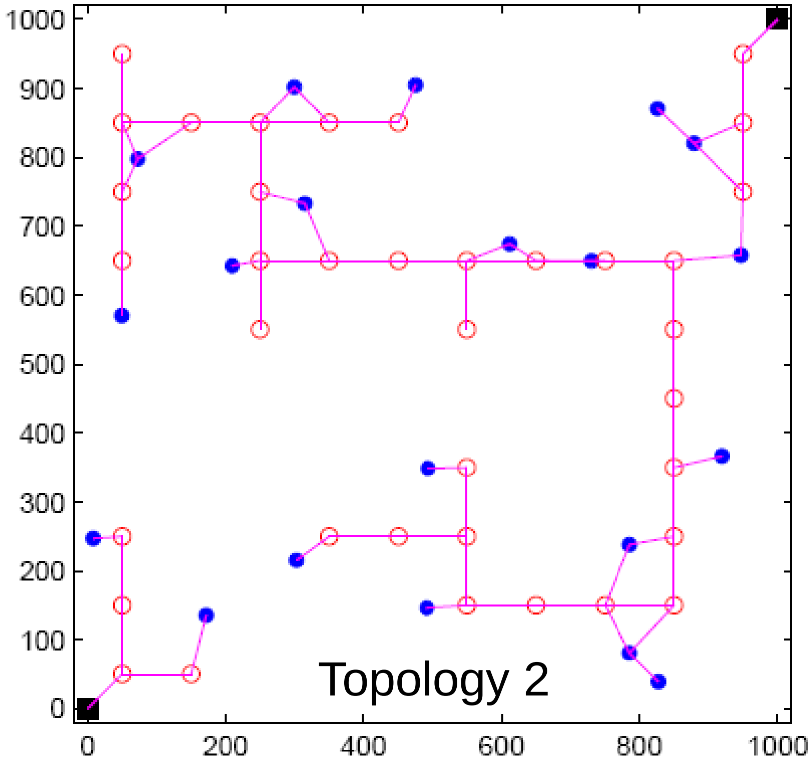
$$y_p \in \{0,1\}$$

$$x_{ij}^t \in [0, |\mathscr{T}^t|]$$

Uneven Load on Base Stations

- Cause congestion around heavily loaded BSes
- Waste connectivity around lightly loaded BSes





Optimization Formulation (3)

$$\min \sum_{p \in \mathcal{RP}} y_p$$

$$s.t. \quad \sum_{j:ij \in E^t} x_{ij}^t - \sum_{j:ji \in E^t} x_{ji}^t = \begin{cases} |\mathcal{T}^t|, & i = M \\ -1, & i \in \mathcal{T}^t \\ 0, & \text{otherwise} \end{cases}$$

$$\sum_{j:pj \in E^t} x_{pj}^t \le |\mathcal{T}^t| \, y_p, \quad \forall p \in \mathcal{RP}$$

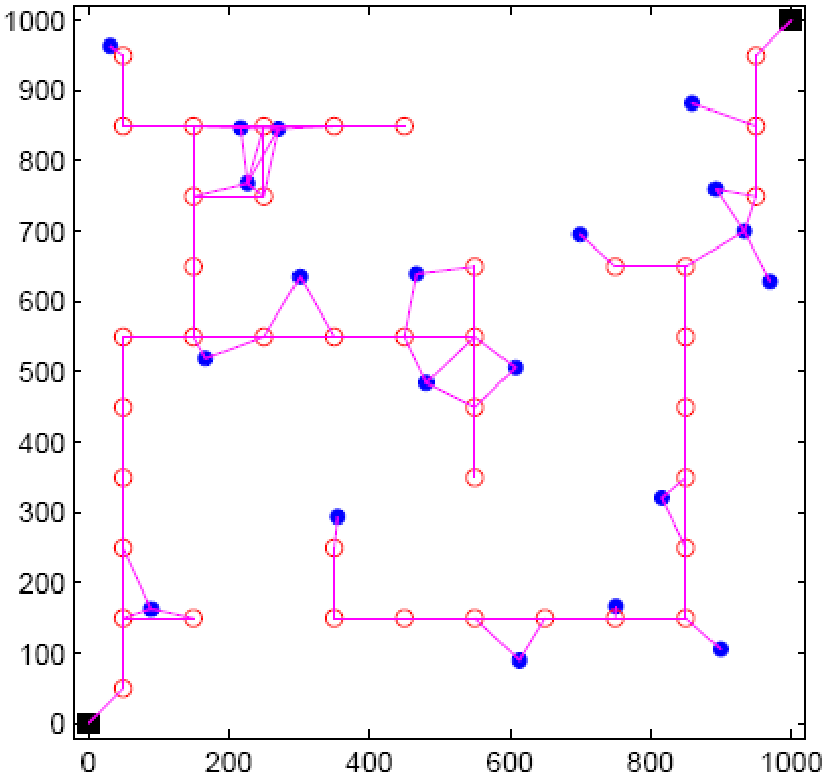
$$\sum_{j:ij \in E^t} x_{ij}^t \le l_i \, |\mathcal{T}^t|, \quad \forall i \in \{\mathcal{T}^t, \mathcal{B}, \mathcal{RP}\}$$

Load balance constraint

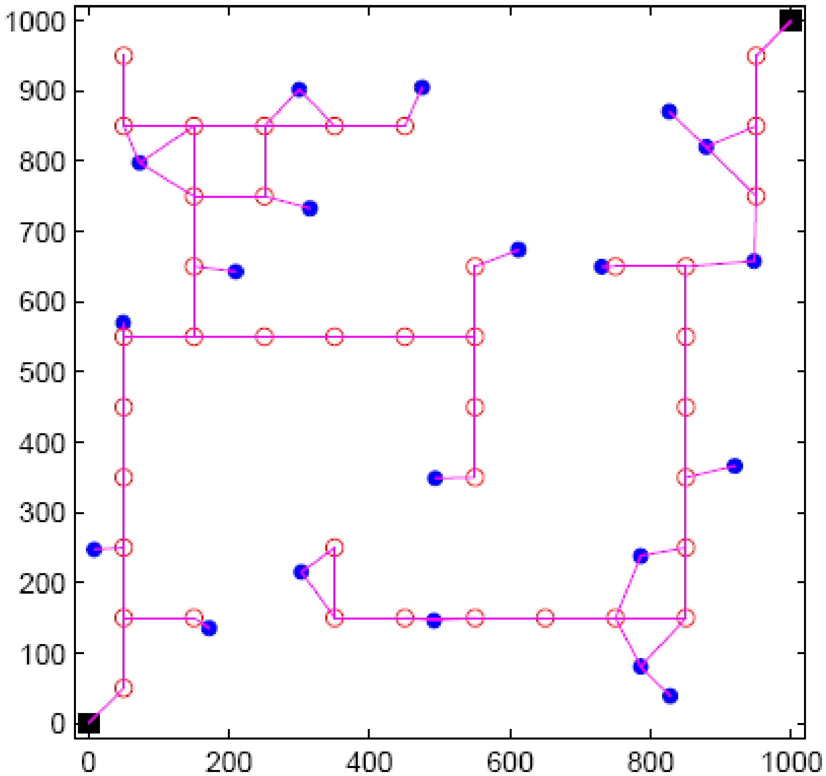
$$y_p \in \{0, 1\}$$

$$x_{ij}^t \in [0, |\mathcal{T}^t|]$$

BALANCED LOAD



Topology 1



Topology 2

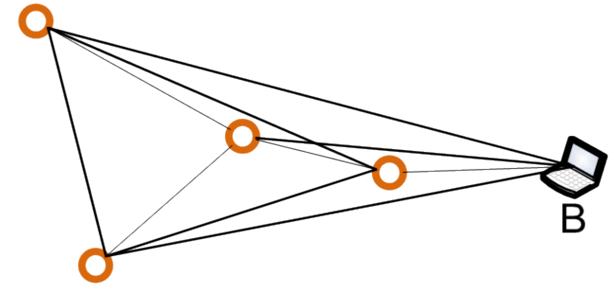
Solving MIP (Mixed Integer Programming) efficiently

- NP-hard
- Integer Programming Algorithm (IPA)
  - Linear relaxation with sequential rounding
  - Prune process

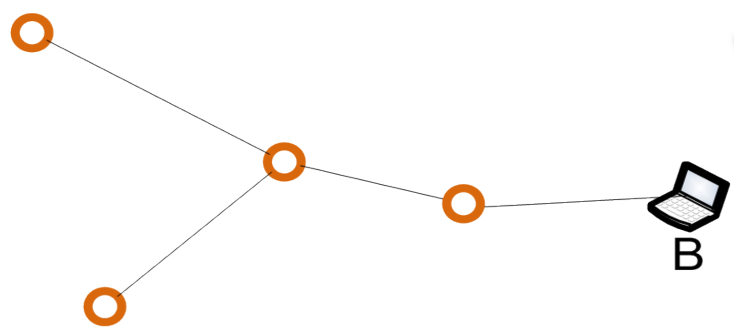
- Advantage of IPA
  - Holistic view across topologies
  - Load balance
  - Environmental factors
    - Obstacles, irregular transmission range, 2D to 3D
  - Flexible cost defined for a candidate relay place
    - Installation cost, reliability

Unconstrained Relay Placement

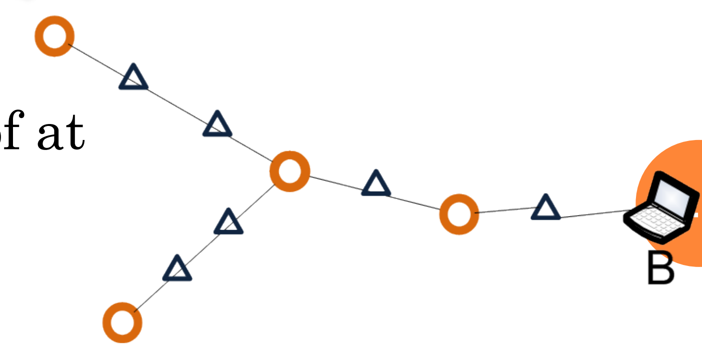
- Relays are placed anywhere in network



- Steinerization approach
  - 1) Minimum spanning tree among terminals and BSes

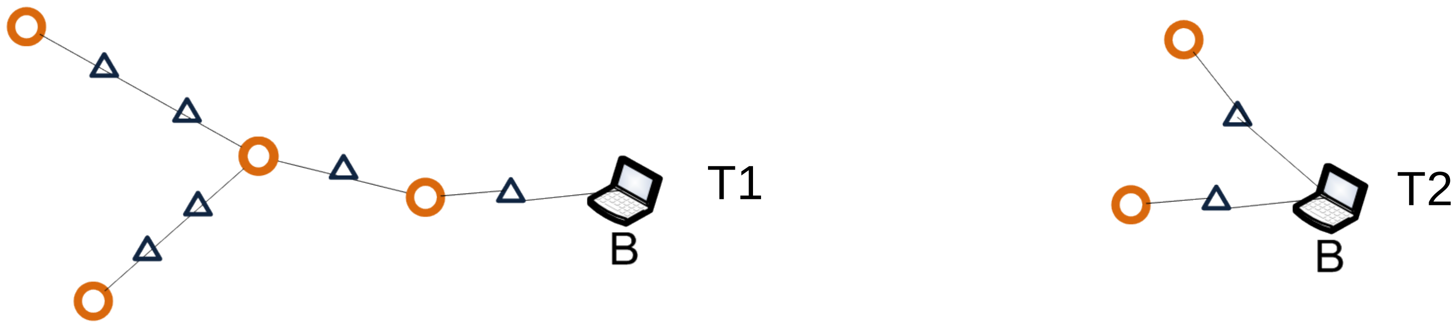


  - 2) Steinerization
    - Break edges into pieces with length of at most transmission range



Stitch-and-Prune algorithm

- Steinerize each topology separately

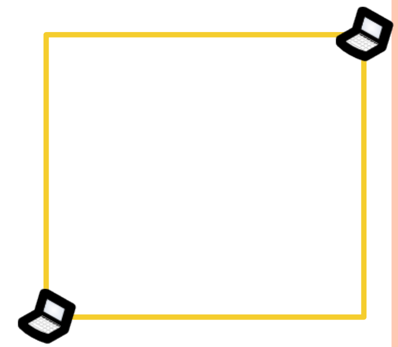


- Combine relays for all topologies

- Prune redundant ones

Performance Evaluation (1)

- Square network area
- 2 BSes
- TxRange = 100m (default)
- Constrained relay placement with regular grid (100m)



- Average over 20 randomly generated scenarios for each configuration

IPA	Integer programming algorithm w.o. load balance
IPA_{LB}	Integer programming algorithm w.t. load balance
SPA	Stitch-and-prune algorithm

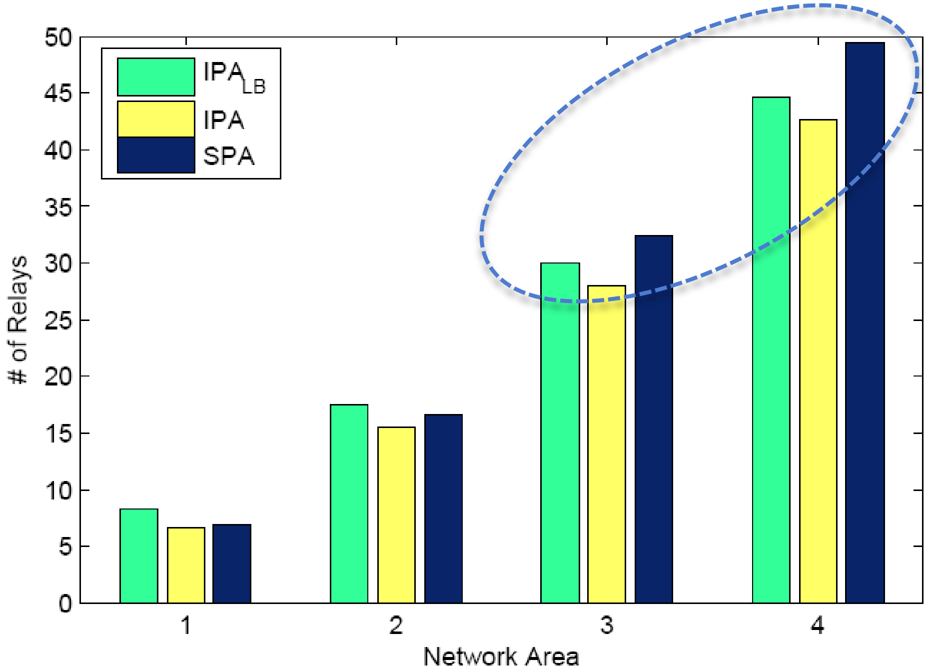
Performance Evaluation (2)

- Number of relays

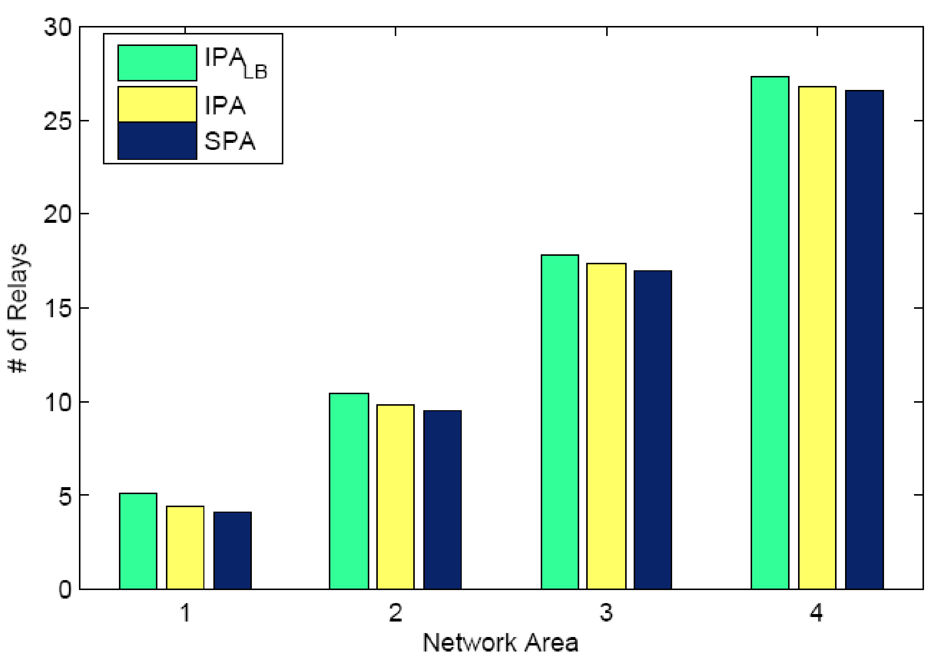
TABLE II
NETWORK CONFIGURATION

Network	Area Size	Number of Terminals Per Topology
1	400*400m	4
2	600m*600m	9
3	800m*800m	16
4	1000m*1000m	25

Same density



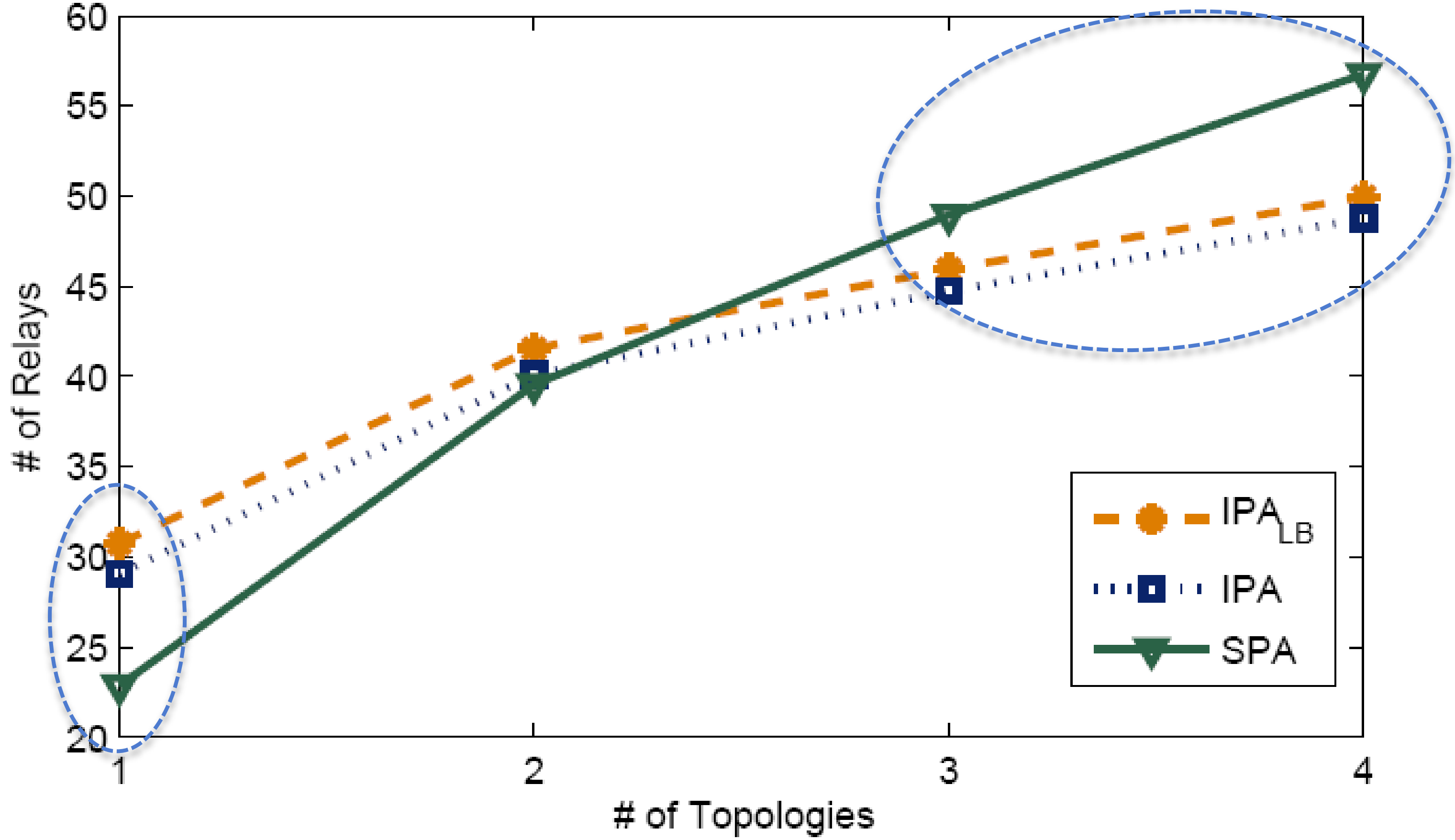
$tr(R) = 100m$



$tr(R) = 200m$

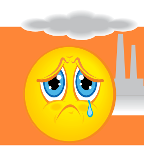
Performance Evaluation (3)

- Gain of global optimization over multiple topologies



Conclusion

- Relay placement for reliable base station communication
  - Constrained relay placement
    - Integer programming formulation based on network flow
  - Unconstrained relay placement
    - Stitch-and-prune algorithm

		
Constrained (IPA)	Model capability	Optimization overhead
Unconstrained (SPA)	Simple algorithm; Run fast	Cannot handle obstacles, load balance, etc. Local optimization; prune by redundancy

References

- W. He, Y. Huang, K. Nahrstedt, W. C. Lee, *"Mobi-Herald: Alert Propagation in Mobile Ad Hoc Networks"*, **ACM Mobicom 2007** (Poster Session), Montreal, Canada, Sept. , 2007
- Y. Huang, W. He, K. Nahrstedt, W. C. Lee, "*Requirements and System Architecture Design Consideration for First Responder Systems*", **IEEE Conference on Technologies for Homeland Security Conference**, Waltham, MA, May 2007
- Y. Huang, W. He, K. Nahrstedt, W. Lee, *"Incident Scene Mobility Analysis"*, **2008 IEEE Int'l Conf. on Technologies for Homeland Security**, Boston, MA, May 2008.
- Y. Huang, W. He, K. Nahrstedt, W. Lee, "*CORPS: Event-Driven Mobility Model for First Responders in Incident Scene"*, **IEEE MILCOM 2008**, San Diego, CA, November 2008
- Y. Huang, Y. Gao, K. Nahrstedt, "*Relay Placement for Reliable Base Station Connectivity in Polymorphous Networks*, **IEEE SECON 2010**
- T. Pongthawornkamol, S. Ahmed, A. Uchiyama, K. Nahrstedt, "*Zero-knowledge Real-time Indoor Tracking via Outdoor Wireless Directional Antennas*", **IEEE Percom'10** , Germany. March 2010
- (all papers are at http://cairo.cs.uiuc.edu/publications)

Outline

- Relay Placement In Unpredictable Environments

- **Brief Overview of other MONET group projects**

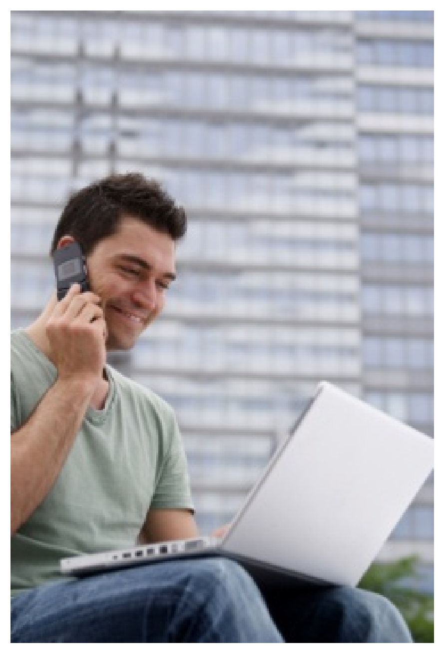
MONET Group Overview

- **Department of Computer Science, University of Illinois at Urbana-Champaign**
  - http://cs.illinois.edu
- **MONET Group Website**
  - http://cairo.cs.uiuc.edu
  - 8 PhDs in Fall 2011
  - 3 Master Students in Fall 2011
- **Active Research Areas**
  - **Mobile Systems**
    - Mobile learning communities
    - First responders system
    - Mobility patterns and data dissemination in P2P mobile systems
  - **3D Tele-immersive Systems**
    - View-casting
    - Monitoring and diagnosis in 3DTI
    - Multi-sender/multi-receiver synchronization
    - H-media – holistic multi-stream resource management for distributed immersive applications
  - **Trustworthy Critical Infrastructures**
    - QoS systems and protocols in SCADA systems
    - Jamming and security in SCADA systems

Mobile Systems - Jyotish

Characterizing and Leveraging Movement of People

Pervasive Mobile Environments and Communities



How do we measure, characterize and leverage people movement

1. Decide on Tracking Methodology
2. Determine Tracking Parameters
3. Collect Tracking Measurements (Mobility Traces)
4. Characterize Mobility Patterns
5. Leverage Mobility for
    1. Mobility Prediction
    2. Content Distribution

1. Decide on Tracking Methodologies

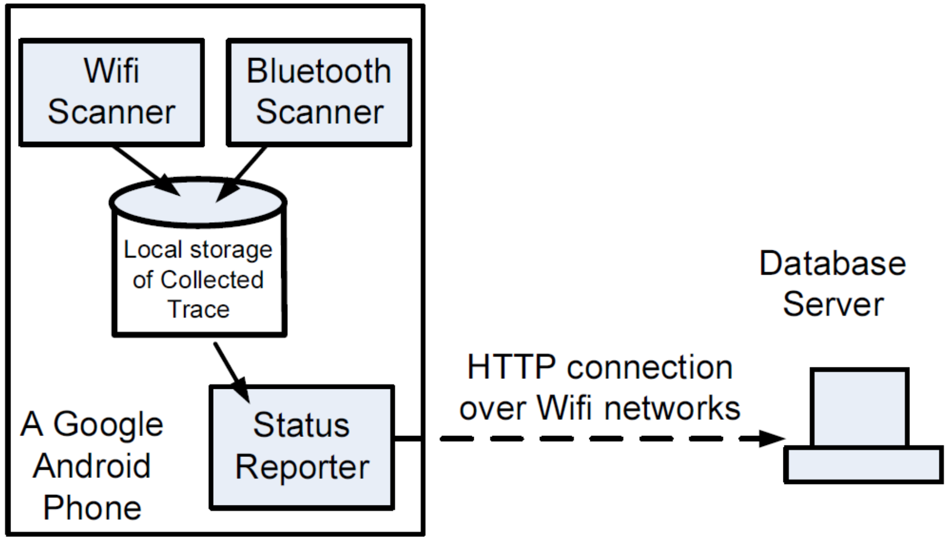
- Surveys/Questionnaires
- Surveillance via Video Cameras
- **New Tracking Methods via mobile devices** such as
  - Cellular Device Monitoring
  - WiFi Device Monitoring
  - Bluetooth Device Monitoring
  - Sound Monitoring

- Combination of Tracking methods

2. Determine Tracking Parameters

- **Contact Parameters**
  - Probability of contact (encounter)
  - Duration of contact
  - Frequency of contact
- **Environment Parameters**
  - Tracking number of days
  - Period of scanning (accuracy of tracked data)
  - Homogeneity of mobility patterns
- **Mobile Device Parameters**
  - Speed of person carrying mobile device
  - Density of mobile devices

3. Collect Trace Example: Tracking via UIM



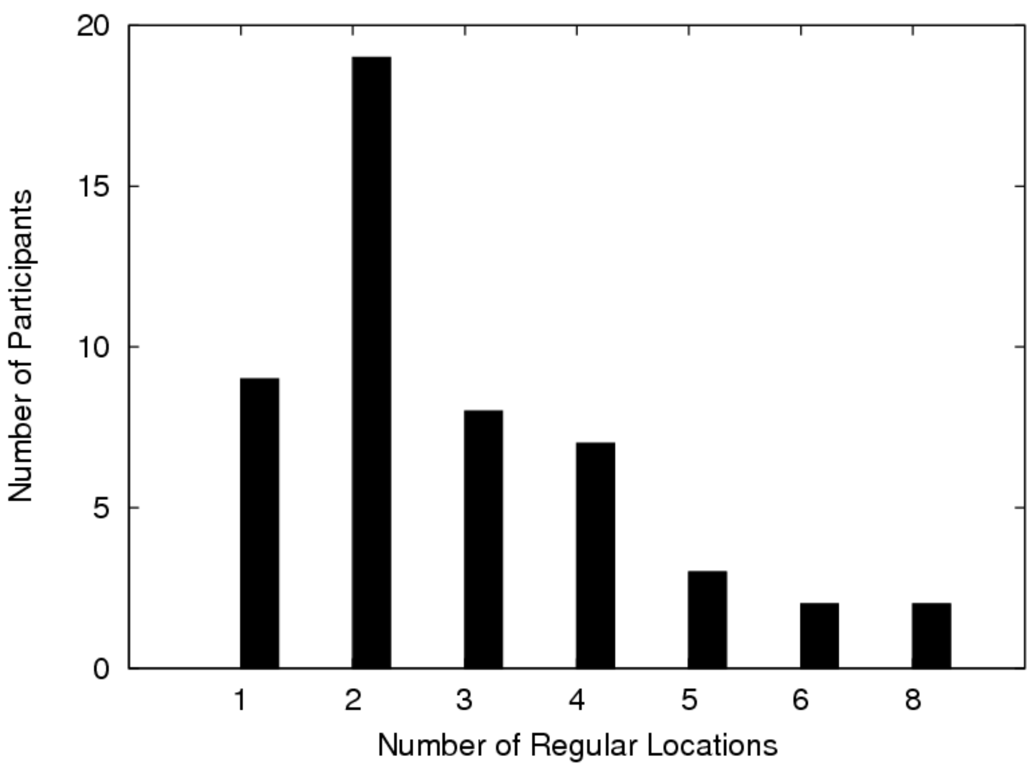
University Campus

UIM – University of Illinois Movement

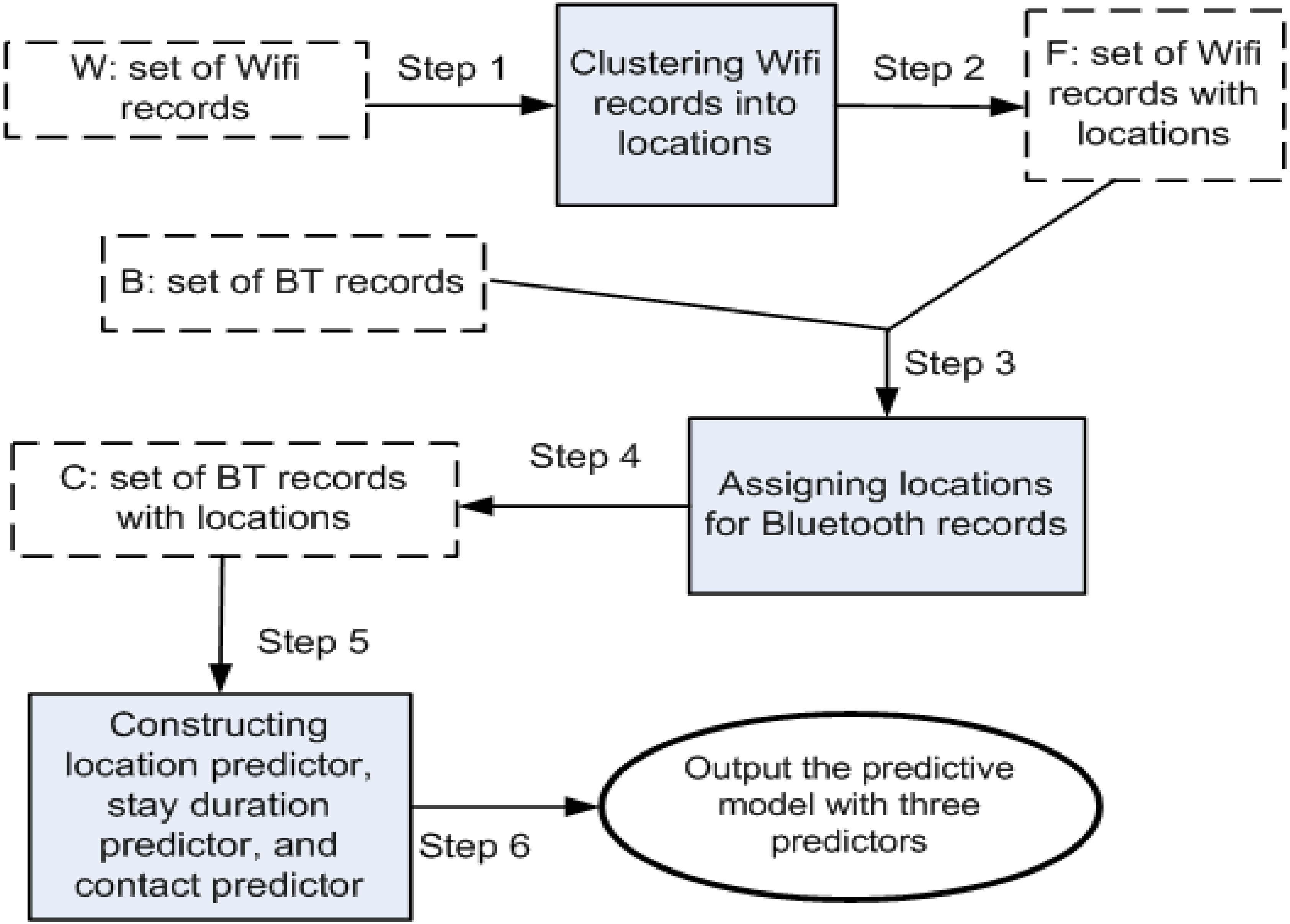
- Collects MAC addresses of Wifi APs and Bluetooth-enabled devices
  - Wifi AP MACs are used to infer location information
  - Bluetooth MACs are used to infer social contact
- Deployed on Android phones carried by professors, staff, and students from March to August 2010
- **UIM trace available online!!!! http://dprg.cs.uiuc.edu/downloads**

4. Characterizing People Movement Found in UIM Trace (1)

- Location is regular if person visits location at the same time slot for at least half number of days
- People visit regular locations (plot is from 50 participants)

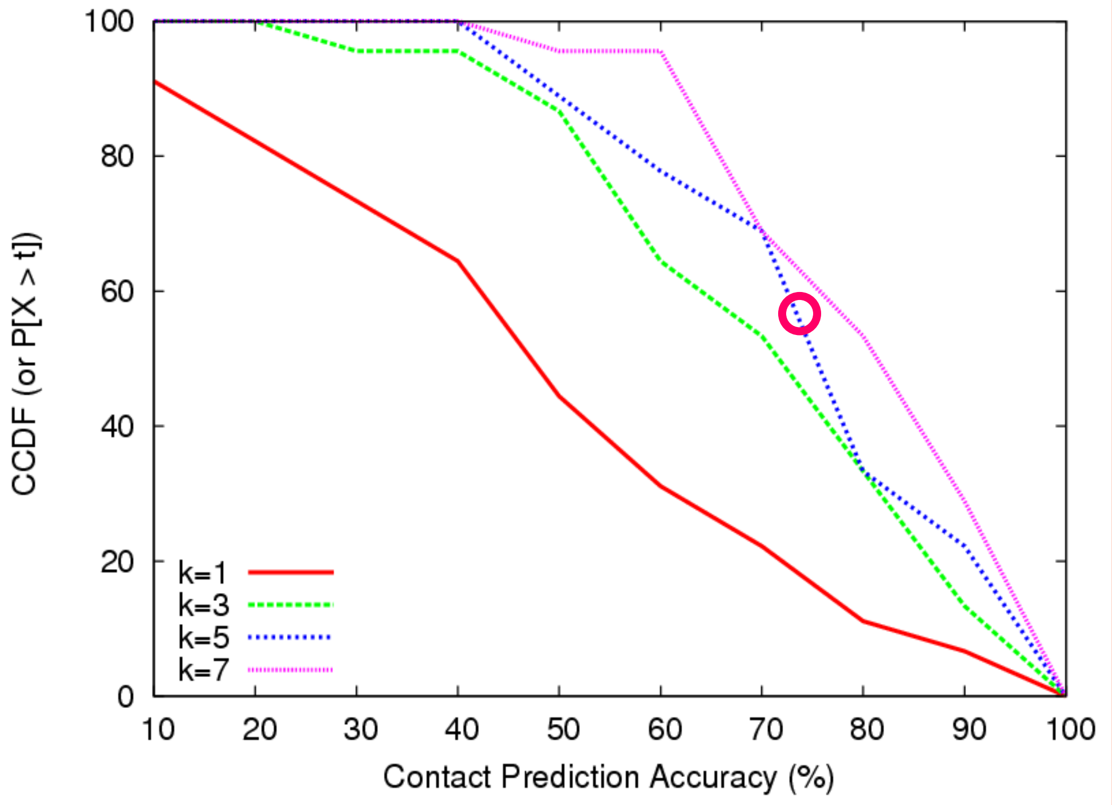


5. Leverage (1): UIM-based Construction Method of Predictive model (Jyotish)



Performance of top-k Contact Predictor

- If at least one contact is predicted correctly, top-k contact predictor is correct

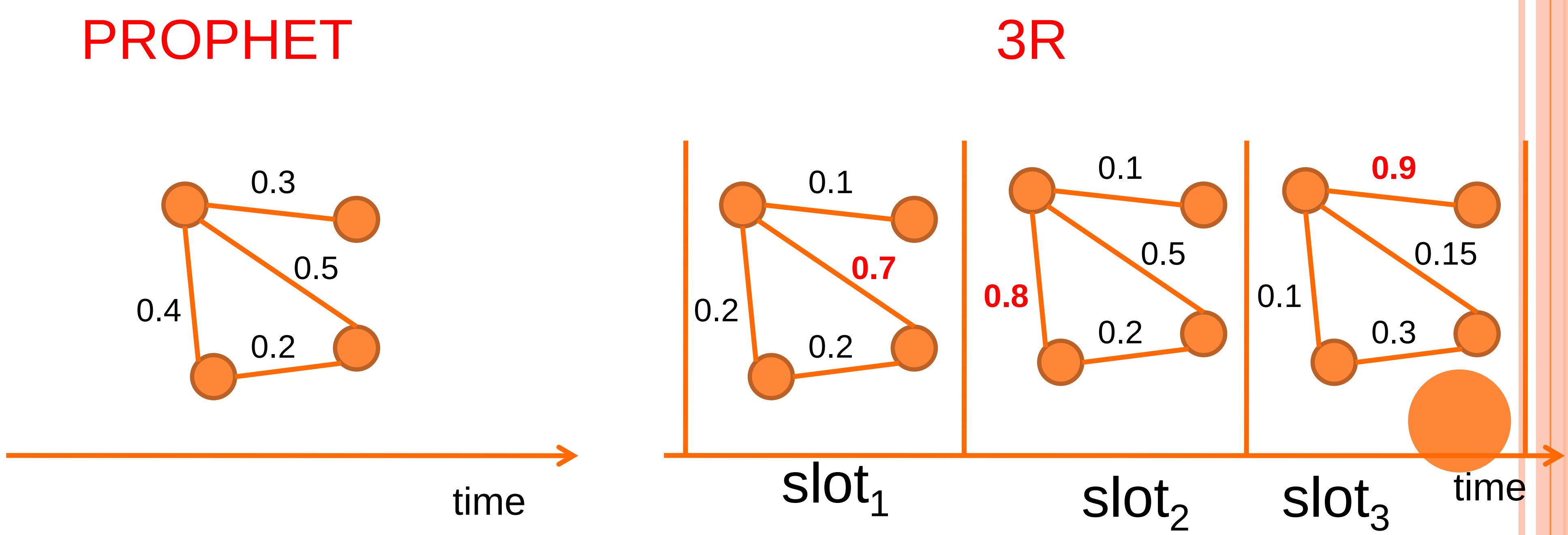


- With k=5, 60% of participants have more than 75% of correct contact predictions

L. Vu, Q. Do, K. Nahrstedt, “Jyotish: A Novel Framework for Constructing Predictive Model of People Movement from Joint Wifi/Bluetooth Trace”**, IEEE Percom 2011 (Mark Weiser Best Paper)**

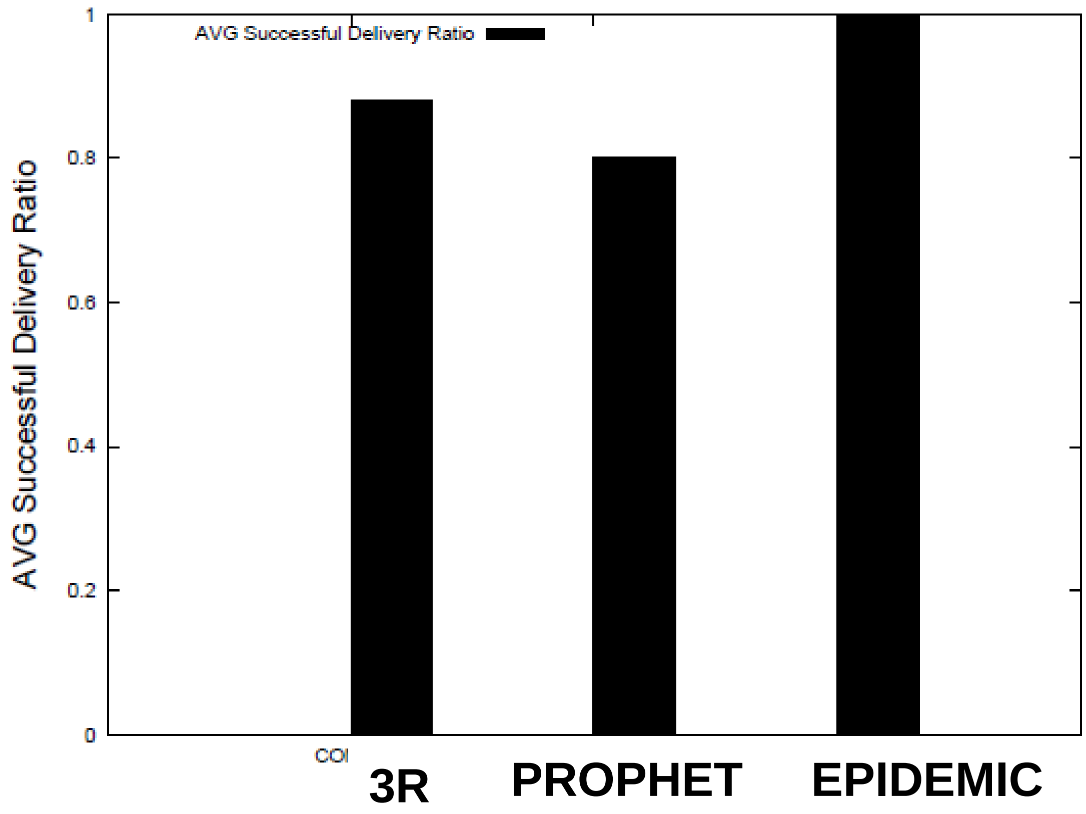
5. Leverage (2): community-based data Routing/Forwarding protocol (COMFA)

- Observation from UIM traces
  - People make regular social contacts in their daily activities and form social communities and share interests such as music or sports
- Approach



3R Results: Delivery Ratio

- Settings
  - 100 senders/receivers via 9 phones carried by MONET research group members from March 01 to March 20, 2010
  - Message delay deadline 12 hours
  - Each node has 20 days of trace



- Epidemic performs best due to its flooding nature
- Epidemic outperforms 3R by 10%
- 3R outperforms Prophet by 9%

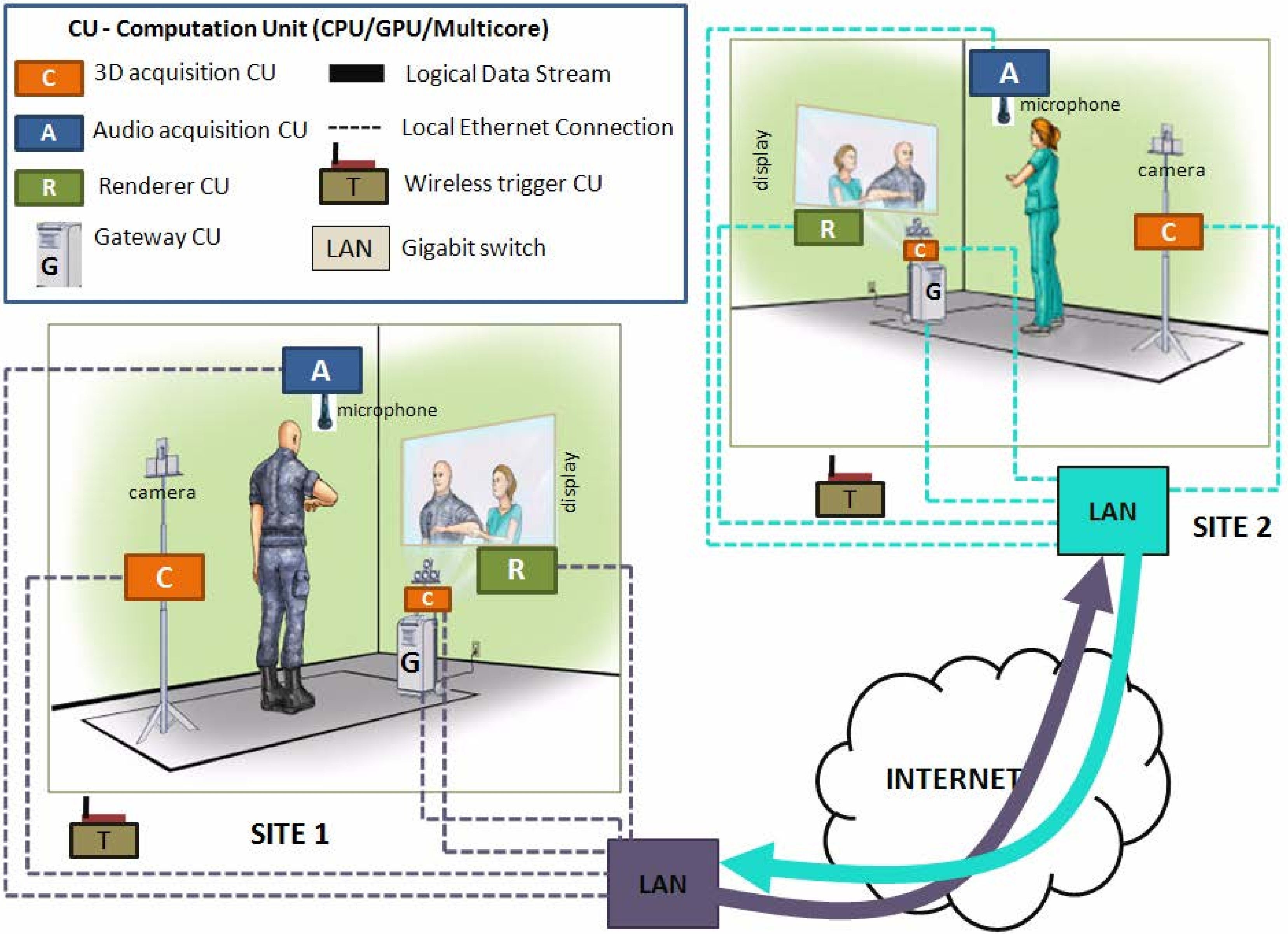
TEEVE – -Environments for Everybody

3D Tele-immersion

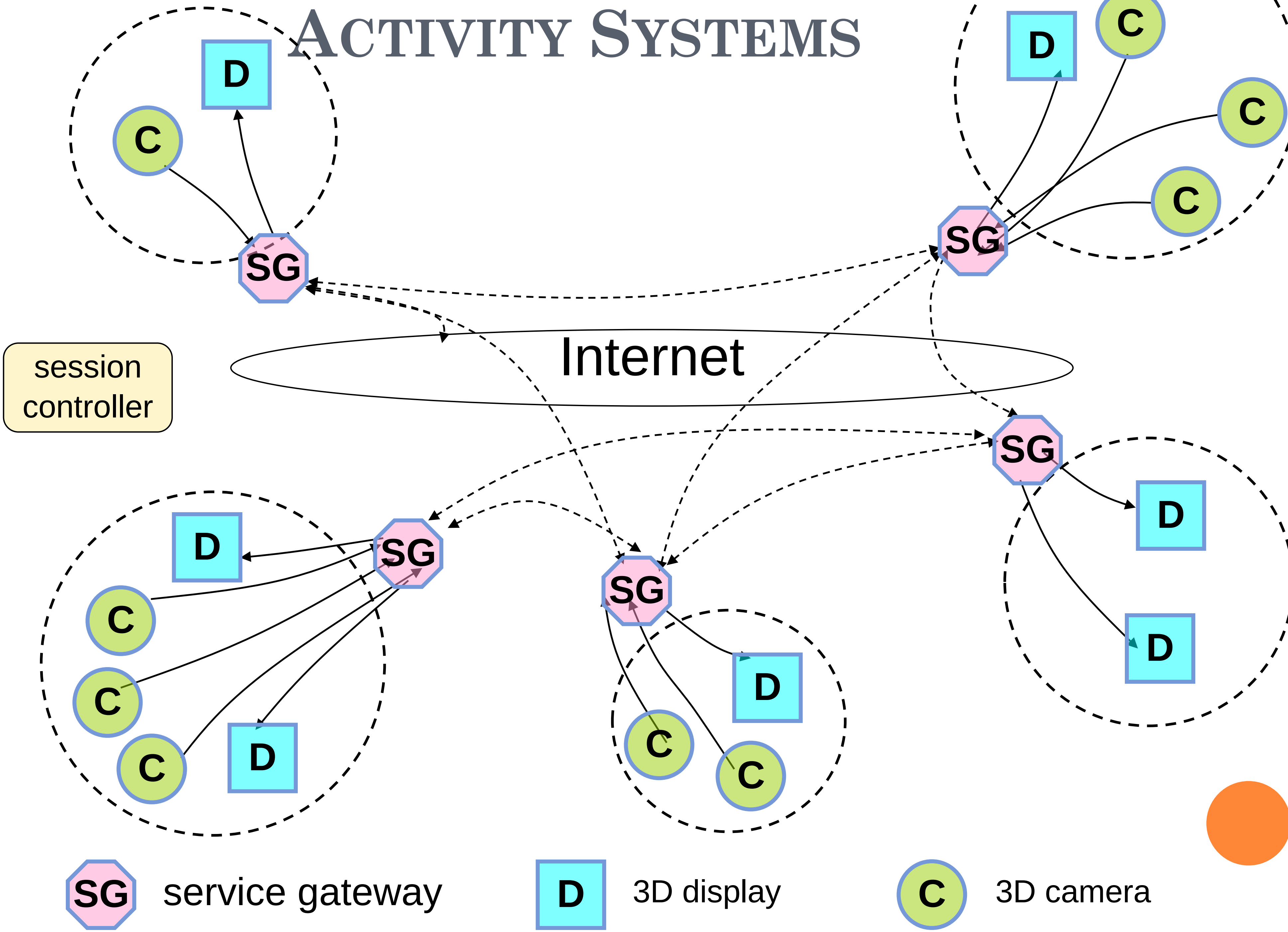
High-Level Vision – Making Distance Irrelevant and Tele-immersion for Everybody (TEEVE)

Photo courtesy of Prof. Ruzena Bajcsy.

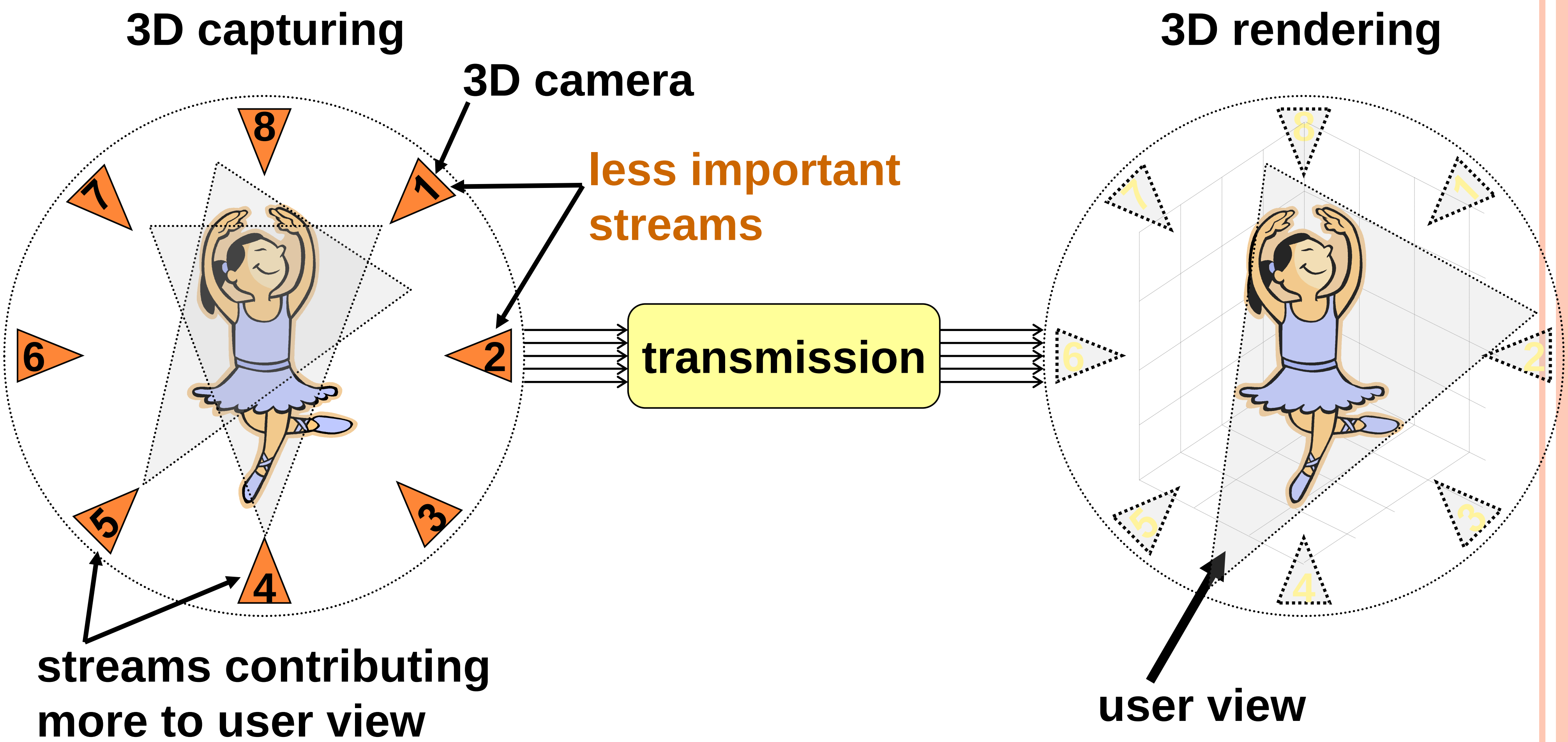
Static Immersive Spaces for Physiotherapy



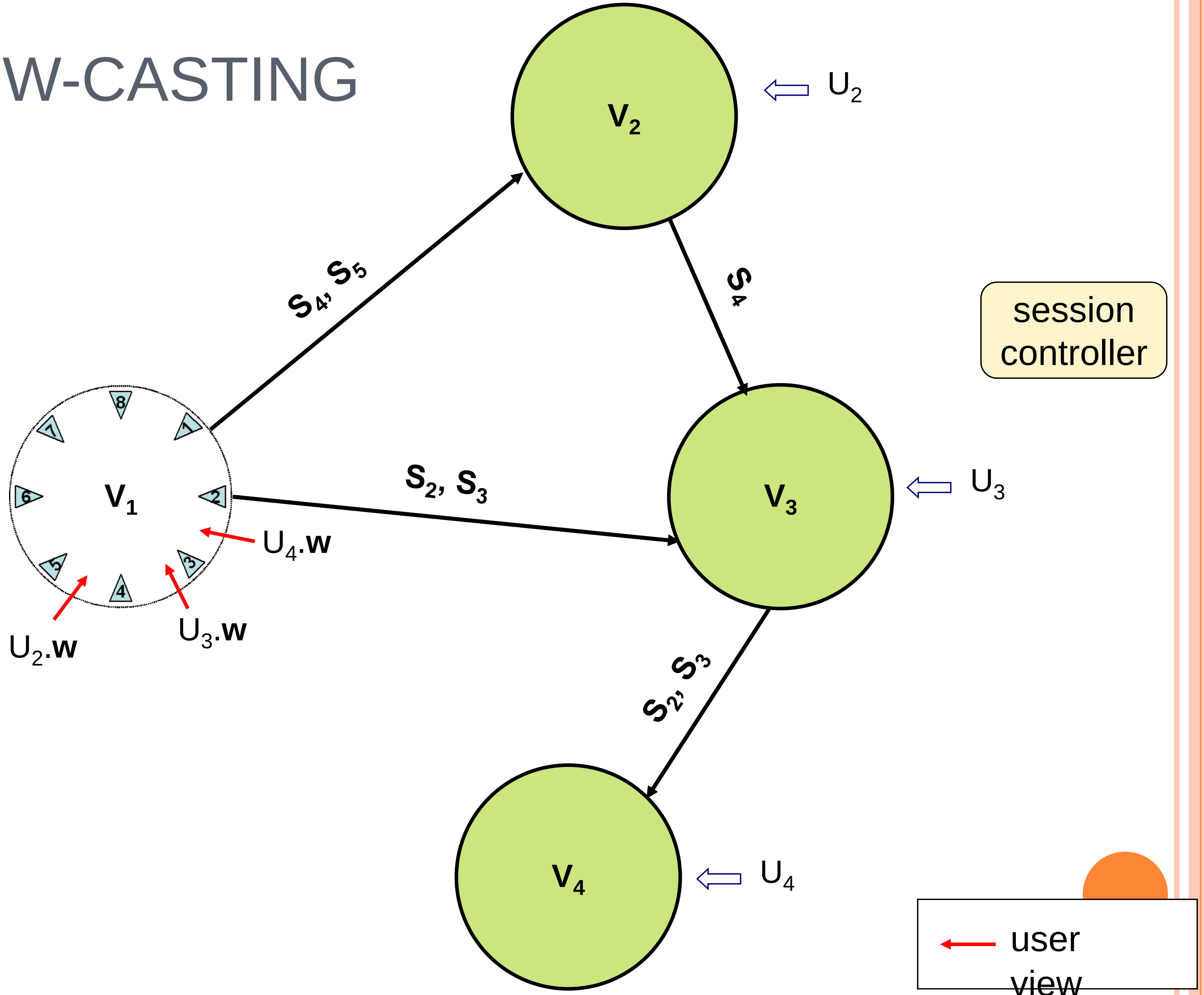
Multi-Party Tele-Immersive Activity Systems



View-aware Stream Differentiation



VIEW-CASTING



Trust in SCADA Systems

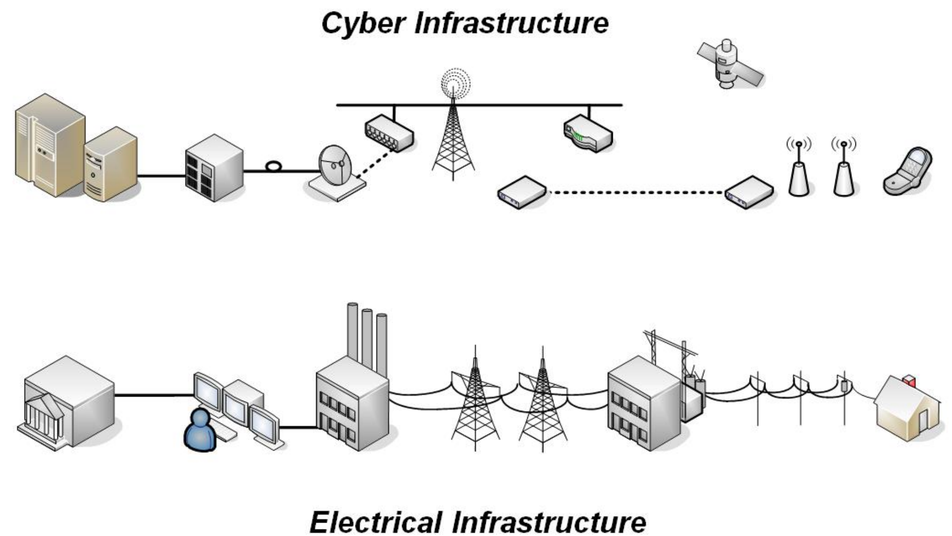
Trustworthy Cyber Infrastructure for Power Grid (TCIPG) Research at University of Illinois, Urbana-Champaign

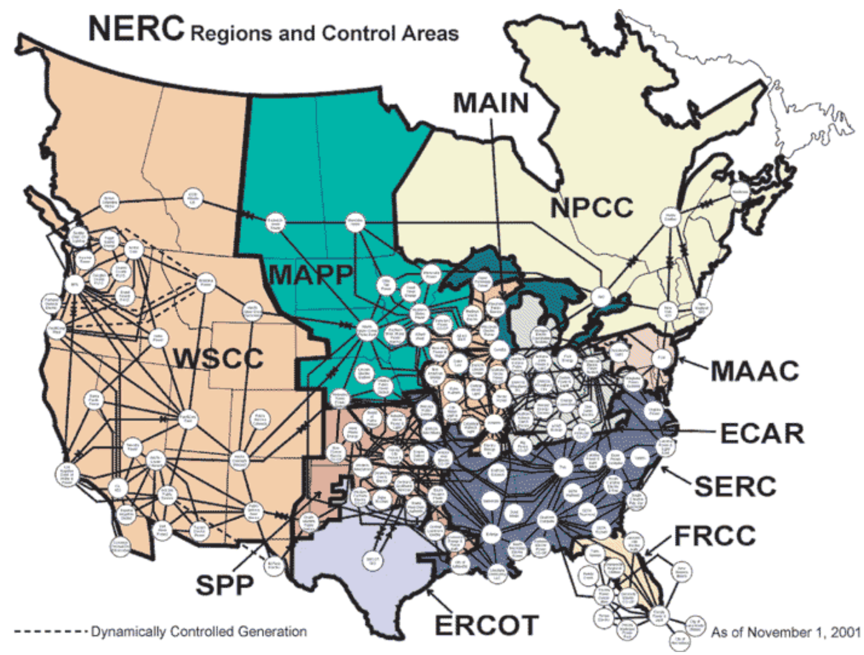
TCIPG Summary

- **TCIPG** – premier center in USA in the area of trust-worthy cyber-infrastructure for power-grid infrastructures
- Trustworthy cyber-infrastructure research for power-grid is now going on
  - Previous **5 years (NSF)** – wealth of knowledge, experiences, scientific results
  - New **5 years** (DOE)
- World-leading experts in **power engineering** are part of TCIPG (Prof. Sauer, Overbye, Gross, Thomas)
- World-leading experts in reliability, security and real-time are part of TCIPG (Prof. Sanders, Gunter, Nicol, Nahrstedt, Campbell, Smith, Hauser, Bakken, Khurana, and other experts)

The Challenge: Providing Trustworthy Smart Grid Operation in Possibly Hostile Environments

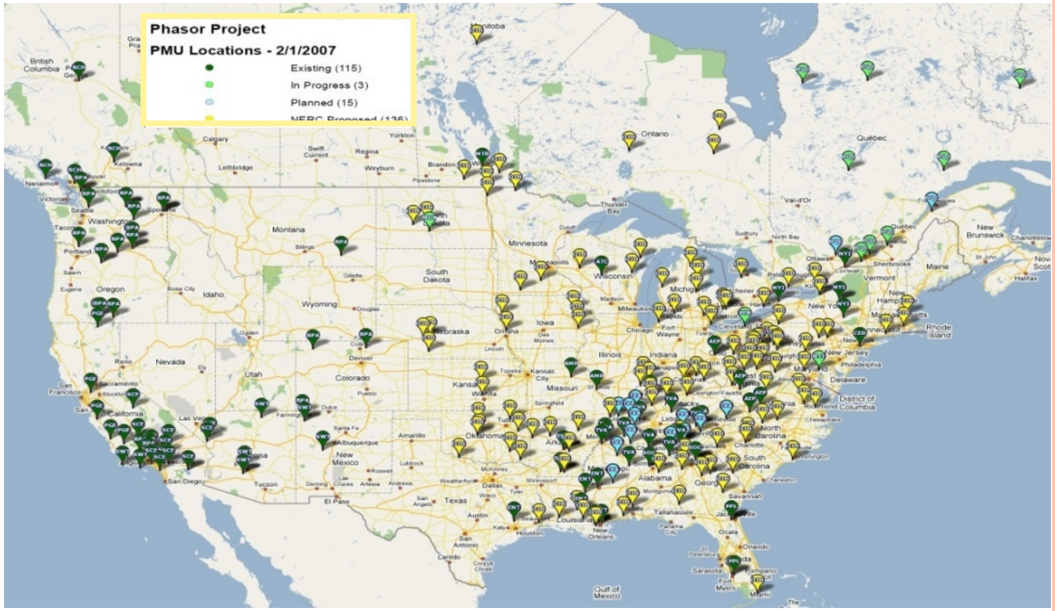
- Trustworthy
  - A system which does what is supposed to do, and nothing else
  - Availability, Security, Safety, …
- Hostile Environment
  - Accidental Failures
  - Design Flaws
  - Malicious Attacks
- Cyber Physical
  - Must make the whole system trustworthy, including both physical & cyber components, and their interaction.

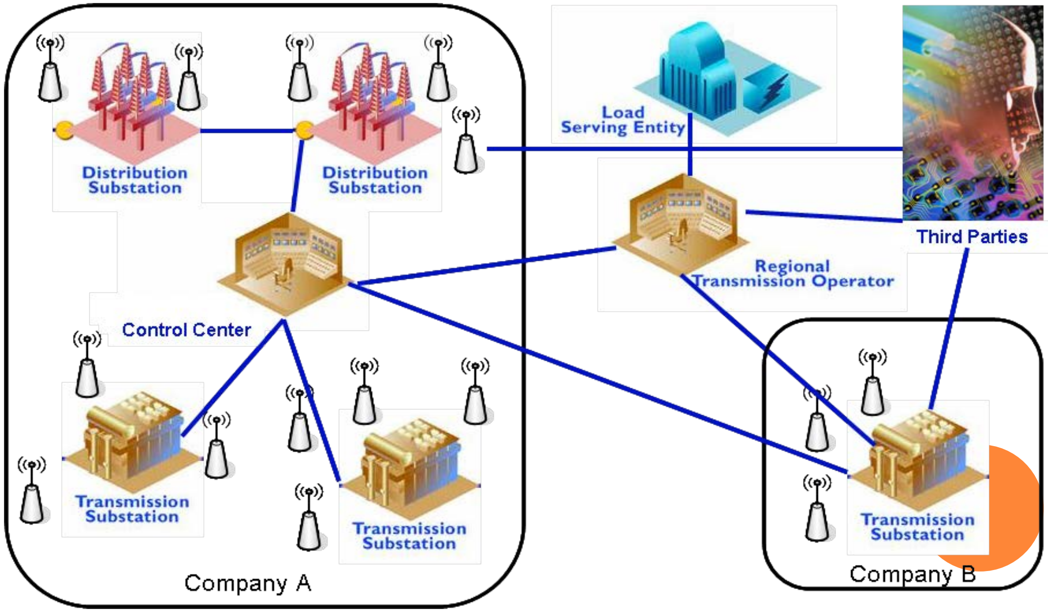




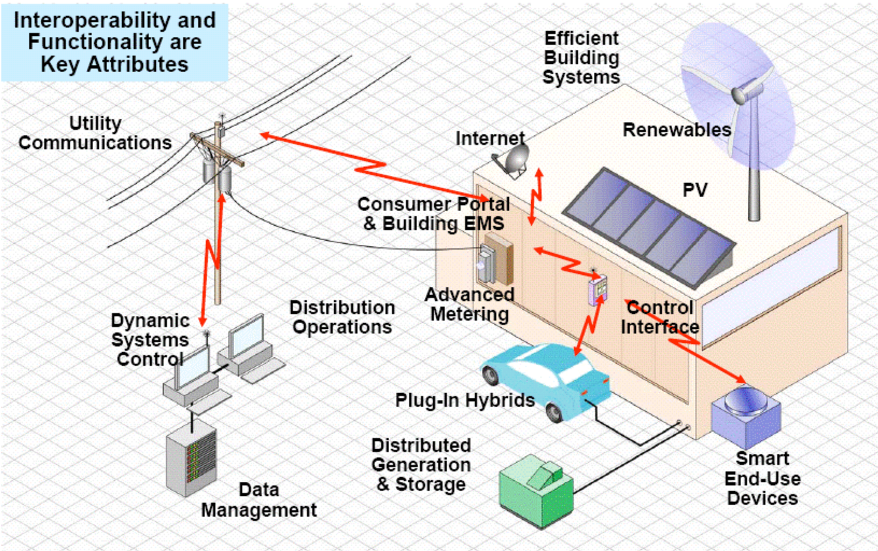
Smart Power Grid of Tomorrow: Transmission Grid with SynchroPhasor Sensors

- NASPI Initiative, funded by DOE and industry, to investigate putting Phasor Measurement Units (PMUs) throughout physical power infrastructure
- Need significant changes in power cyber infrastructure to support PMUs
- “Class A” service requires low latency, data integrity & availability (“no gaps”)





Smart Power Grid of Tomorrow: Control of Electrical Equipment and an Open Grid



Consumer Portal:

- Security issues are huge
  - Privacy, billing integrity, Mischief, vandalism, intrusion, Consumer manipulation of system

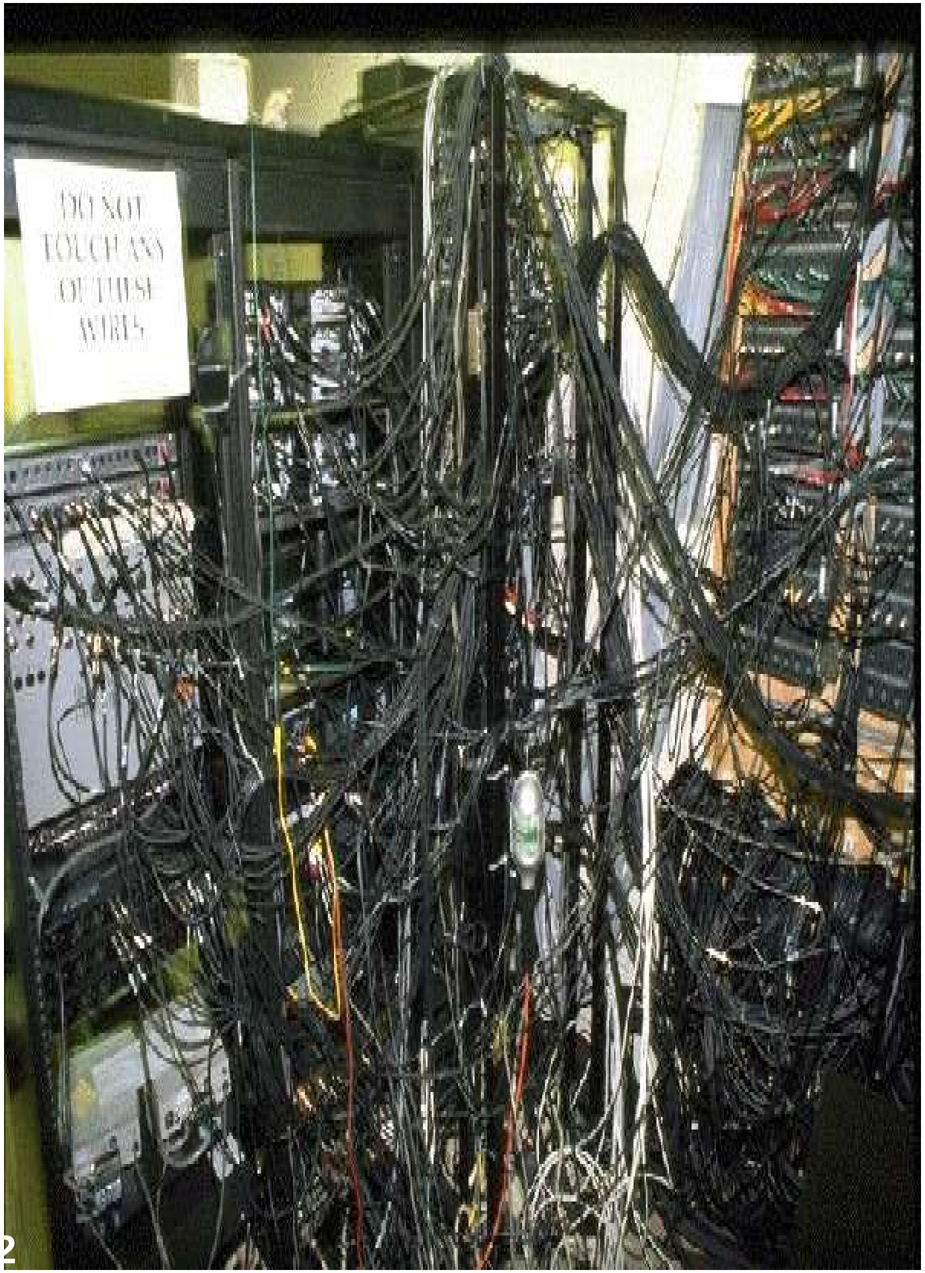
Demand Response:

- Extends the Control Loop
  - Links distribution and transmission
  - Increases real time requirements
  - Provides bigger surface for security violations

Who is responsible for security?

- Consumer? Utility?

(MONET Research) Need for Secure Wireless Networks



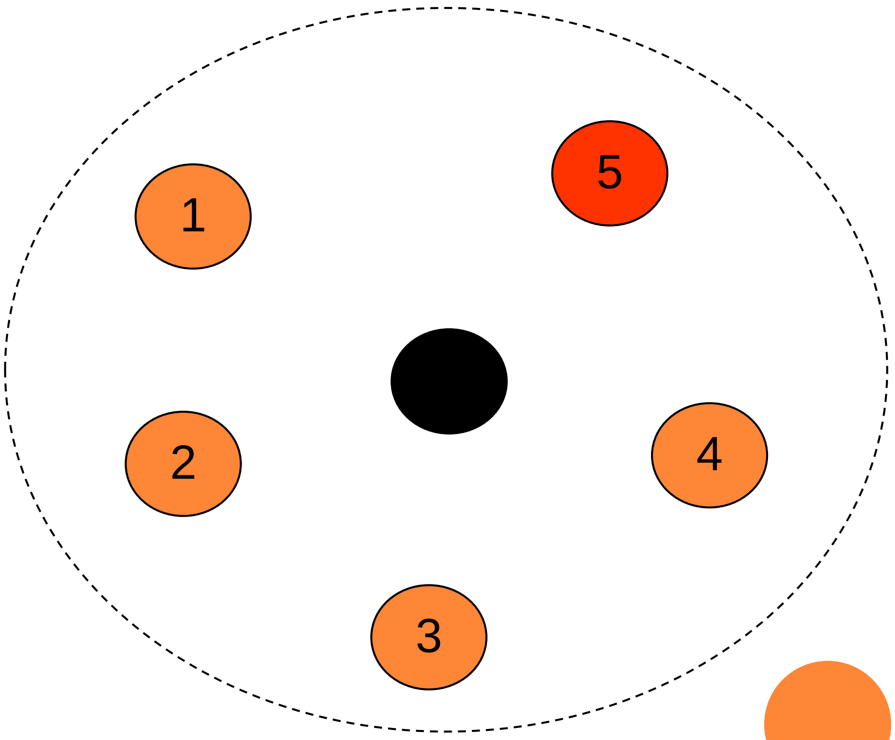
- **No wireless network deployed broadly today in Power Grid (some early adapters – nuclear industry)**
- **EPRI recommendations for usage of wireless technology in substation network architecture (Report, Jan. 2009)**
- **ISA100 standard efforts leveraging other standards, as appropriate, to produce a relevant result in as short a time frame as possible**
  - **ISA99 – Security**
  - **IEEE 1451 – Smart sensor**
  - **FIPS 140-2 – Security**
  - **ISO/OSI 7-layer model for network connectivity**

ALIBI: CONTAINMENT OF JAMMING ATTACKS

- **Goal**
  - Containment of jamming attacks
- **Requirements**
  - Detecting & Identifying one jammer in the single-hop wireless network with time-slotted communication

- **Attack Model**
  - Taking into account one jammer with "inside" knowledge

1. Knows shared hopping pattern
2. Knows any systems' protocol
3. Uses listen-n-jam strategy



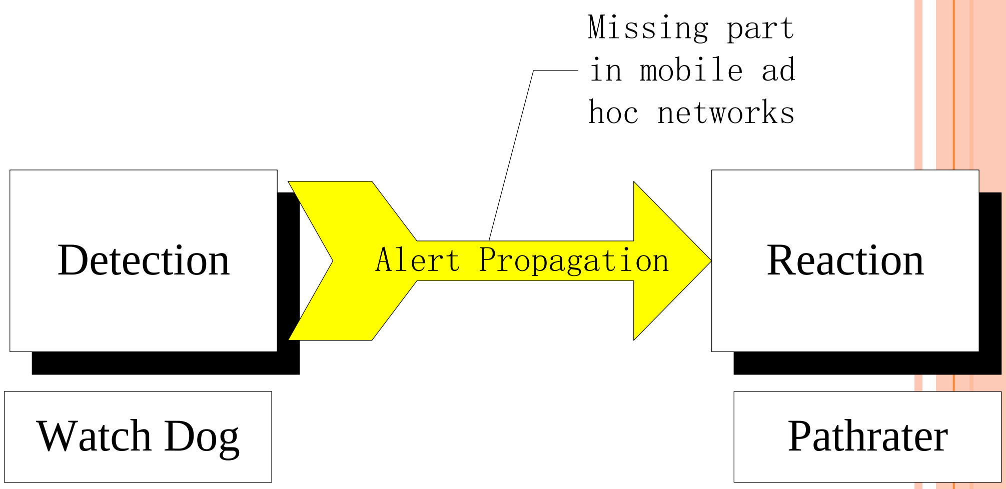
CONCLUSIONS

- FRs move in very challenging unstructured environments
  - FRs with mobile devices represent a challenging mobile ad hoc network that needs to communicate with commanders connected via wireless infrastructure network brought by FRs
- **Challenges:** Deployment of ad hoc and BS communication infrastructure on the incident scene
  - Placement algorithms needed (offline and online)
- **Exciting Projects in MONET group** exploring
  - QoS-issues and security issues in critical infrastructures, mobile infrastructures, and 3D multimedia infrastructures

Acknowledgments

- The work on first responders is funded by Vodafone fellowship, and Motorola Center and Illinois-Boeing Center funding grants.
- The work on Characterizing and Leveraging People Movement is funded by the Illinois-Boeing Center funding grant.
- The work on Tele-immersive Systems is funded by the National Science Foundation (NSF).
- The work on Trustworthy Communication in SCADA networks is funded by the NSF and Department of Energy (DOE).

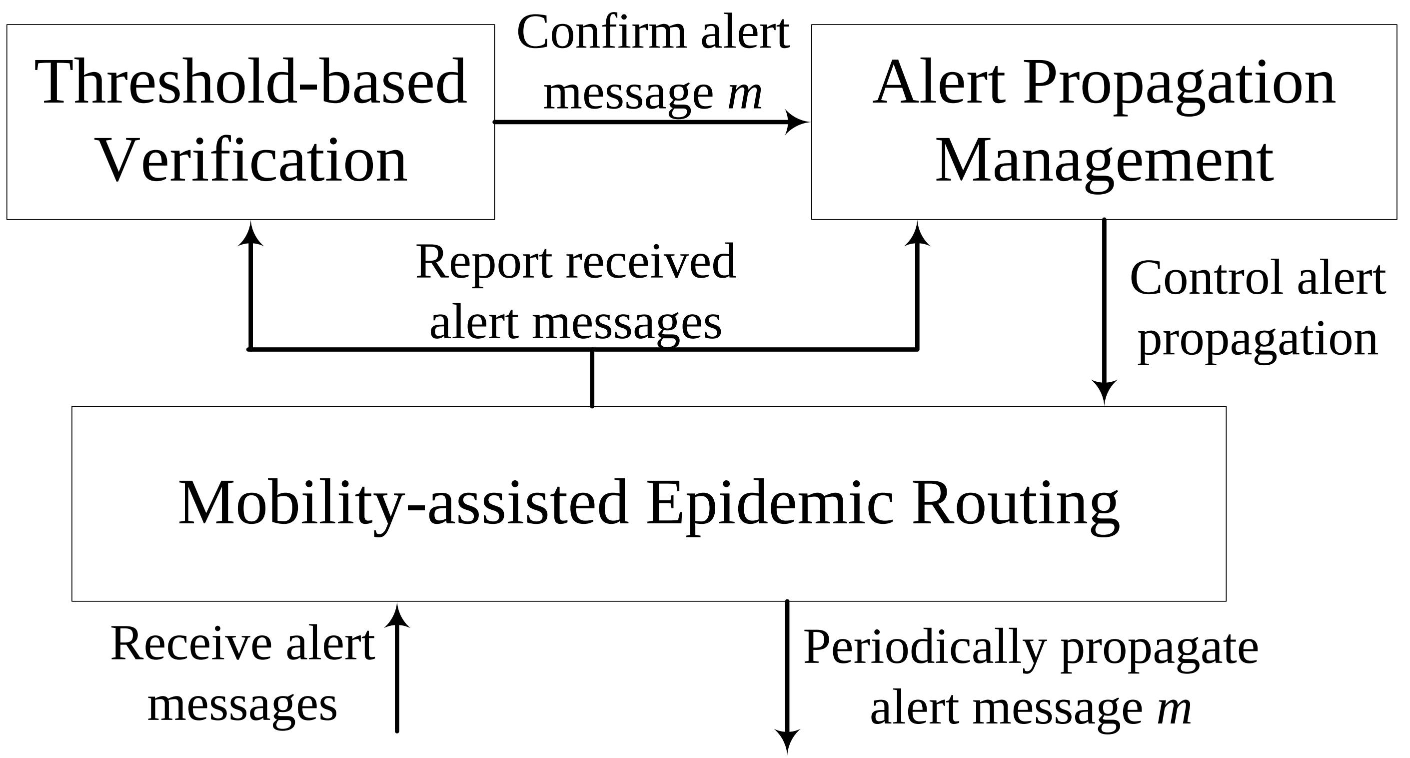
Problem: Efficient Alert Service



- **Efficient Alert Message Distribution**
  - Relatively small communication overhead
  - Capable to handle temporary network partition
  - In spite of mobility, majority of the network can be aware of the alert.
- **Against Collusive Slander Attacks**
  - Slanderers can issue a DoS attack easily by defaming other nodes.

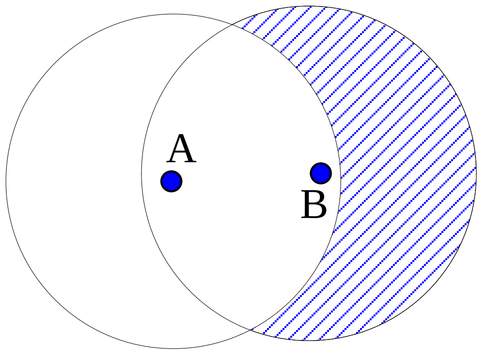
- FR Environment:
  - **Mobile** Ad-hoc Networks
- Problem:
  - How to trigger the defense against malicious attacks in the whole network after malicious behavior is detected locally? → Alert Propagation
- Solution:
  - **Mobility Assisted Alert Propagation**

MOBI-HERALD ARCHITECTURE



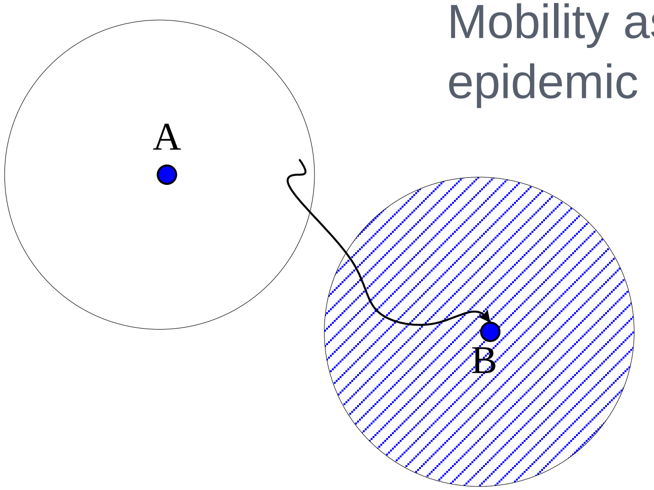
Mobility Assisted Epidemic Routing: Advantages

- Mobility-assisted epidemic routing is able to deliver a message to almost all the nodes even under intermittent network partitions. Flooding protocol cannot deliver message to the whole network if a mobile network is partitioned.
- In mobility-assisted epidemic routing, transmissions can be more efficient.

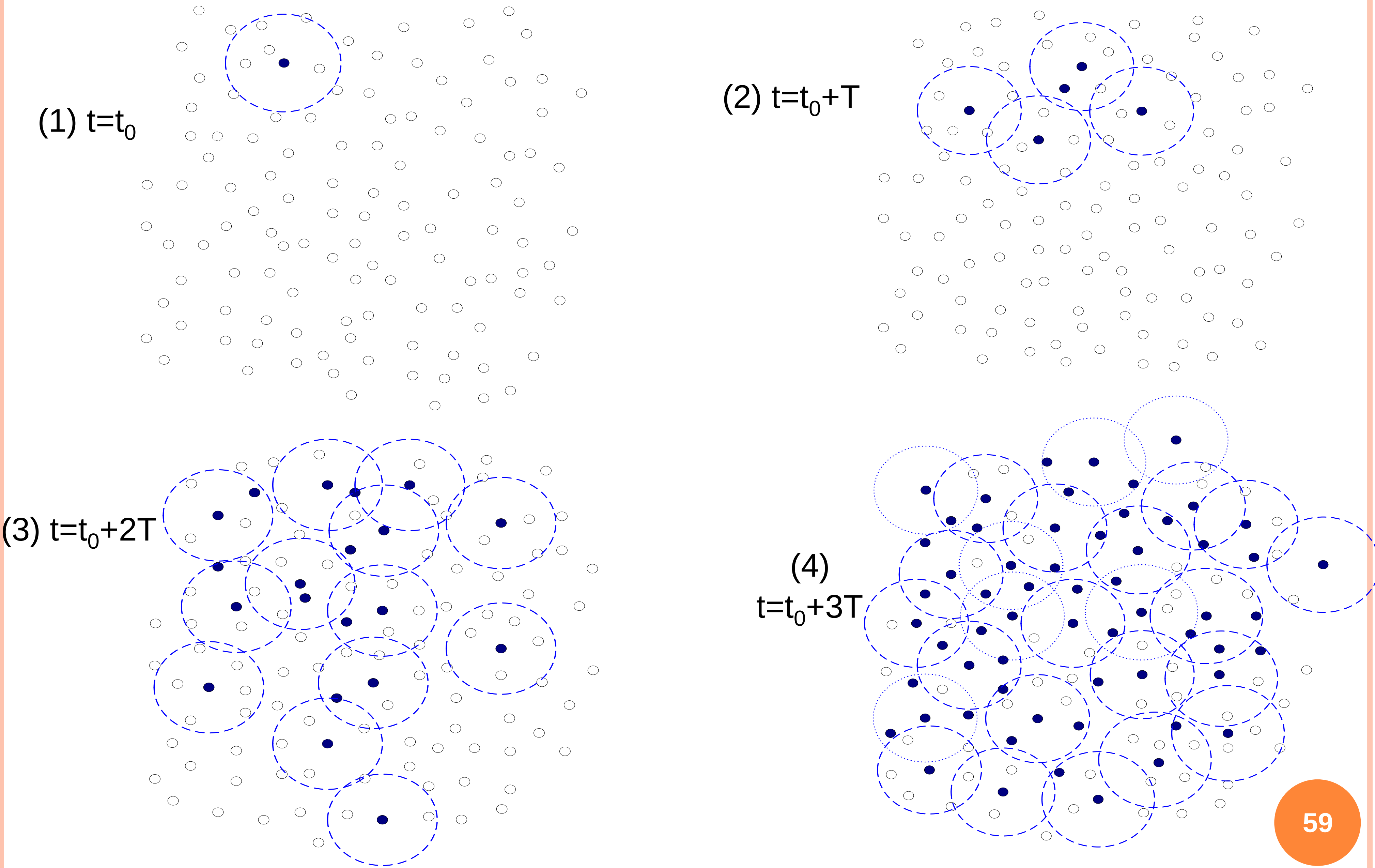


Flooding

Mobility assisted epidemic routing

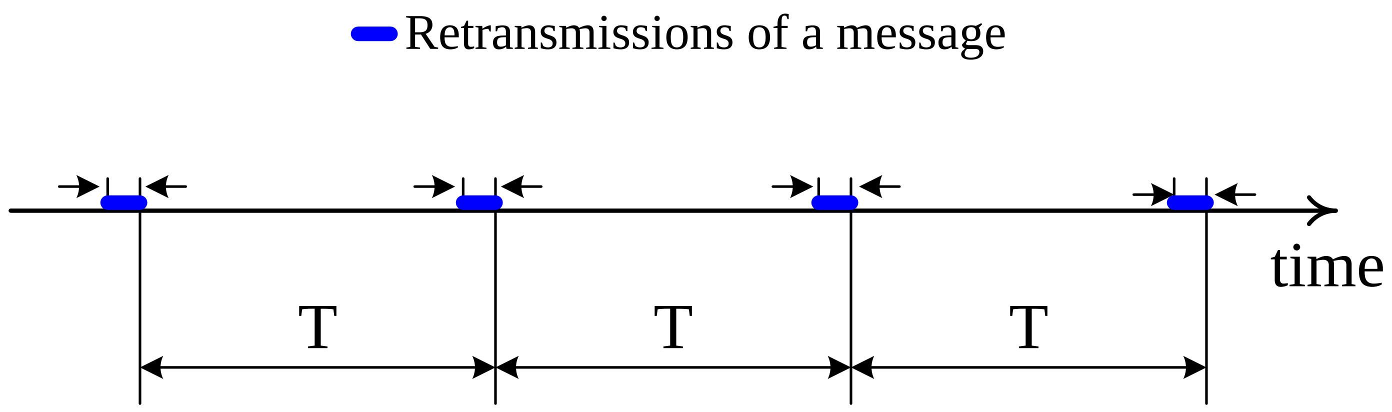


Example



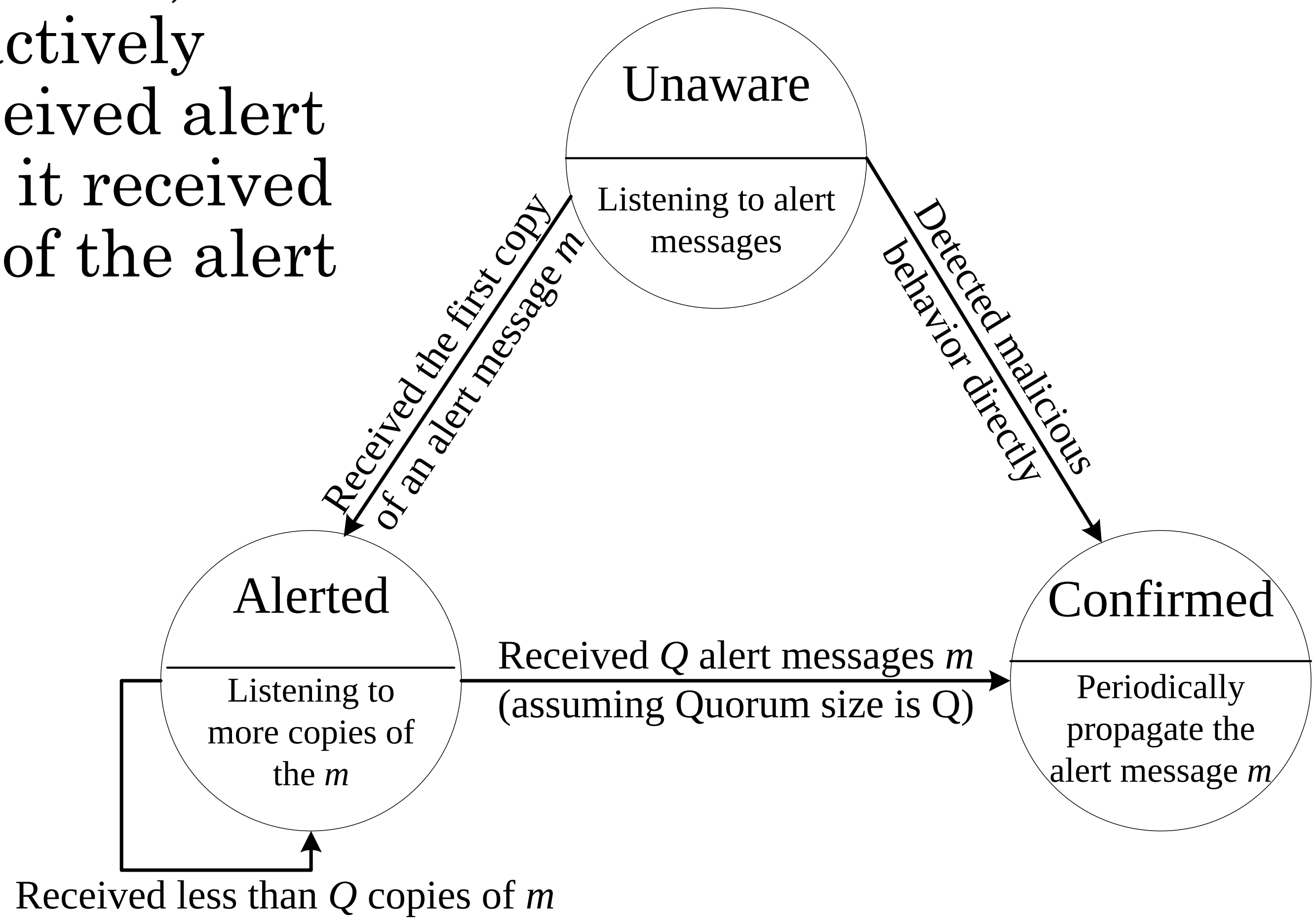
Mobi-Herald Epidemic Routing: Protocol

- A mobile node retransmits a message periodically
- A node suppresses transmission if it hears the transmission in the same period (within Δ time slot).



QUORUM-BASED VERIFICATION

- Assuming *k* is the number of collusive slanders, a node does not actively forward the received alert message before it received Q (Q>k) copies of the alert message.



Alert Propagation Manager

- **Balance reliability and efficiency**

  A parameter "Times-to-send (TTS)" is attached in the message header, which indicates how many times an alert should be retransmitted by a mobile herald.

  Large TTS → large message overhead

  Small TTS → Small coverage of message delivery

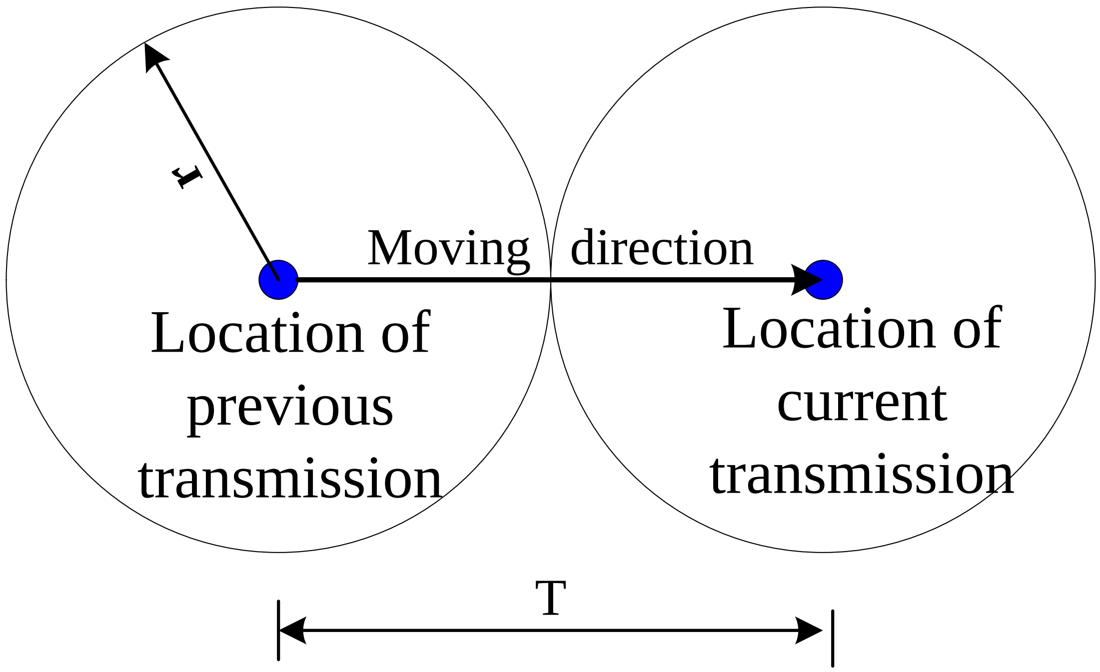
- **Balance end-to-end delay of alert propagation and efficiency**

  Period of alert propagation "T"

  Large T → large end-to-end delay

  Small T → less efficiency of retransmissions

Selection of T



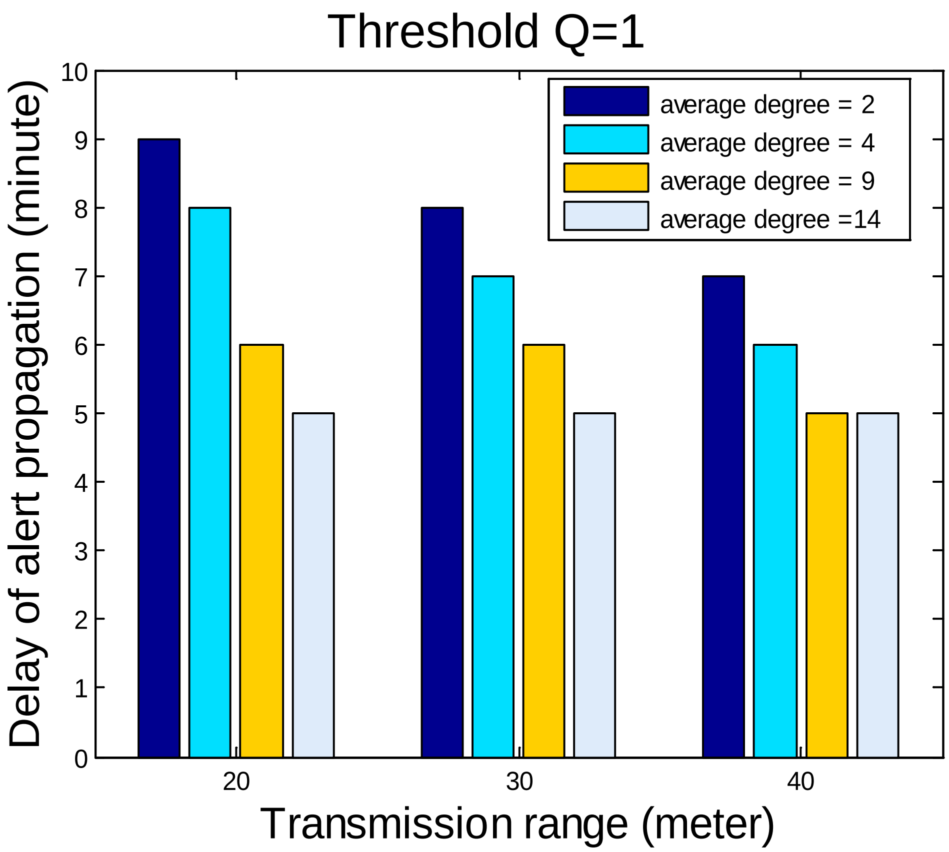
Preferably $$T = \frac{2r}{v_{avg}}$$

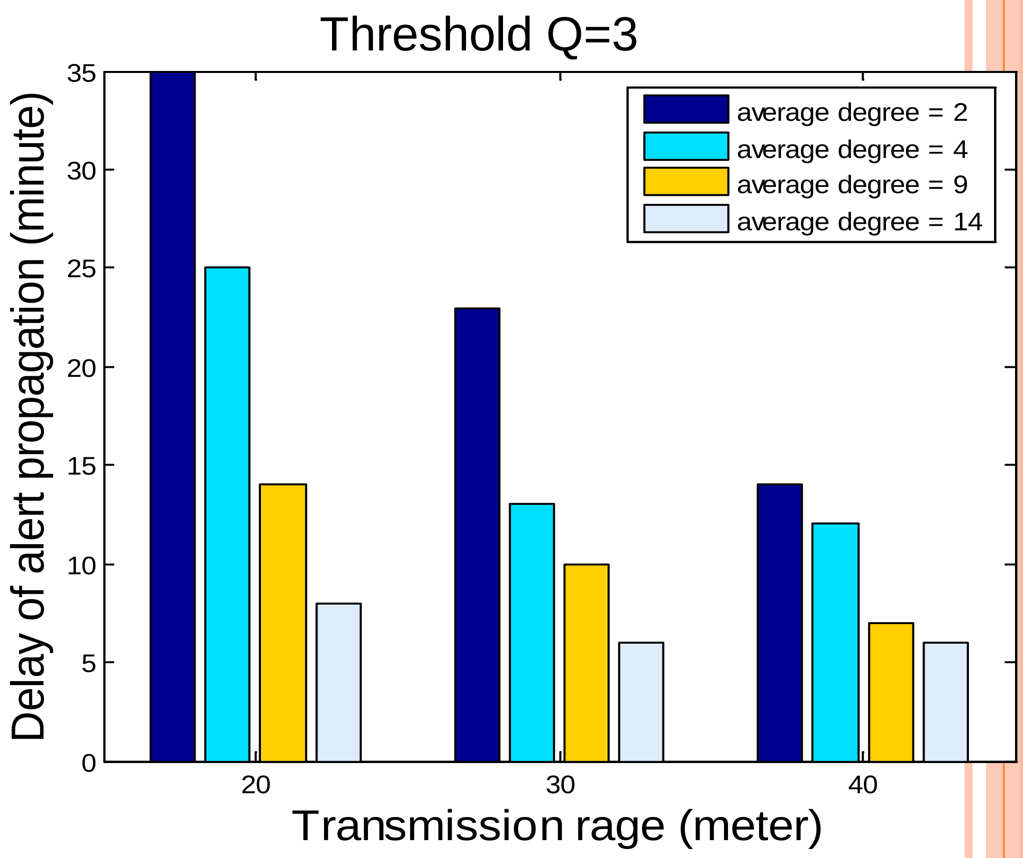
Simulation Results

- We simulate *Mobi-herald* alert propagation protocol under *Random Waypoint* mobility pattern.

- Evaluation Metrics
  - End-to-end alert message delivery delay
  - Coverage of an alert message

End-to-end Alert Message Delivery Delay (Real-time Alert)





Coverage of Message Delivery