CIS 5636 Ad Hoc Networks (Part III)

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Energy Management

- The need of energy management
  - Limited energy reserve
  - Difficulties in replacing the batteries
  - Lack of central coordination
  - Constraints on the battery source
  - Selection of optimal transmission power
- Three techniques
  - Battery management schemes
  - Transmission power management schemes
  - System power management schemes

Battery management

- Device-dependent schemes
  - Modeling and shaping of battery discharge patterns
  - Impact of discharge characteristics on battery capacity
- Data link layer
  - Lazy packet scheduling
    - Minimizing the transmission power
    - Increasing the duration of transmission
  - Battery-aware MAC protocol
- Network layer
  - Battery energy-efficient routing

Power Optimization

- Network Longevity (Wieselthier, Infocom 2002)
  - Time at which first node runs out of energy
  - Time at which first node degrades below an acceptable level
  - Time until the network becomes disconnected
- High throughput volume
  - High total number of bits delivered

Power Optimization

Two related goals (Toh, IEEE Comm. Mag. 2001)

- Saving overall energy consumptions in the networks
- Prolong life span of each individual node

Power Optimization

Source of Power Consumption (Singh et al, MobiCom 1998)

- Communication cost
  - Transmit
  - Receive
  - Standby
- Computation cost

Power-Aware Routing

- Wu et al's Power-aware marking process (Wu et al, ICPP 2001)
  - Use energy level as priority in Rule 1 and Rule 2 of marking process
  - Balance the overall energy consumption and the lifespan of each node

Location-Based Routing

- Let *P(dis)* represent the power consumption of transmitting with distance *dis*
- Stojmenovic et al's greedy method (Stojmenovic et al, IPDPS 2001)
  - Each node knows the location of destination and all its neighbors
  - Source *s* selects a neighbor *n* to reach destination *d* with minimum *P(dis(s,n))+P(dis(n,d))*

Adjustable Transmission Ranges

- Power level of a transmission can be chosen within a given range of values
- Transmission cost: $P(dis) = d^{\partial}$

  where *a=2* or *4.*

Power Optimization

Problem: Each node selects a minimum transmission range subject to a global constraint (i.e. network connectivity)

- Heterogeneous: most problems are NP-complete
- Homogeneous: polynomial solutions exist

Uniform Transmission Range

Problem: Use a minimum uniform transmission range to connect a given set of points

Greedy algorithms

- Binary search
- Kruskal's MST (Ramanathan & Rosales-Hain, ICC 2000)
- Prim's MST (Dai & Wu, Cluster Computing 2005)

Power Optimization

Kruskal’s MST:

- Each node is initialized as a separate connected component
- Edges are sorted and traversed in non-decreasing order
- An edge is added to the MST whenever it connects any two connected components.

Power Optimization

Prim’s algorithm

- The approach starts from an arbitrary root and grow a single tree until it spans all the vertices.
- At each step, an edge of lightest possible weight is added.

Non-uniform transmission range

Wireless multicast advantage (Wieselthier, Infocom 2000):

$$P_{i,(j,k)} = \max\{P_{ik}, P_{ij}\}$$

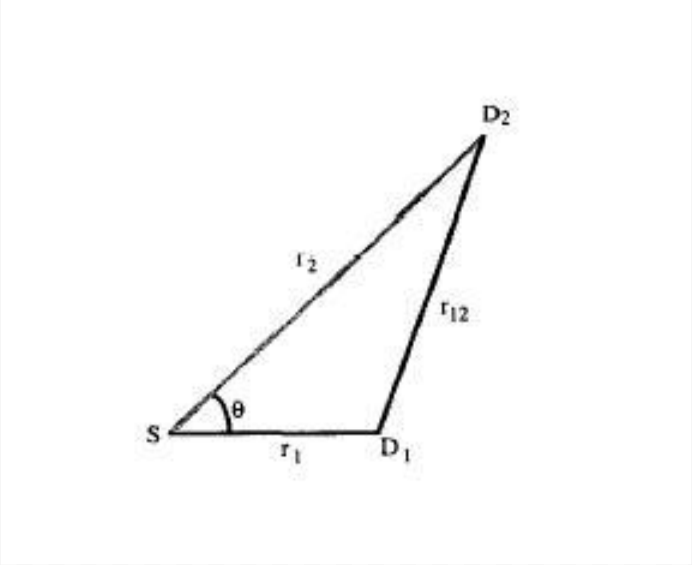
where P_{ij} is power needed between node i and node j

Non-uniform transmission range

- *S* broadcasts to two destinations: *D1* and *D1* (*r1=dis(s, D1),* and *r2=dis(s, D2)).*
  - *Direct*: S broadcasts to both at the same time
  - *Indirect*: S sends the packet to D1 which then relays the packet to D2

Non-uniform transmission range

- Use "direct" if $r_1 > r_2 \cos\theta, where\, \theta$ angle between $\vec{r_1}\ and\ \vec{r_2}$



Non-uniform transmission range

- Broadcast incremental power algorithm (Wieselthier, Infocom 2000)
  - Standard Prim's algorithm
  - Pair *{i, j}* that results in the minimum incremental power for *i* to reach *j* is selected, where *i* is in the tree and *j* is outside the tree.

Non-uniform transmission range

- Other algorithms
  - Broadcast least-unicast-cost algorithm
  - Broadcast link-based MST algorithm
- The sweep: removing unnecessary transmissions

Non-uniform transmission range

- Extensions to directional antennas (Wieselthier, Infocom 2002)
  - Energy consumption:

$$r^{\partial} \frac{\theta}{300}$$

  - Extended power incremental algorithm

Non-uniform transmission range

- Possible extensions
  - Fixed beamwidth
  - Single beam per node
  - Multiple beams per node
  - Limited multiple beams per node
  - Directional receiving antennas

Non-uniform transmission range

- Incorporation of resource limitation
  - Bandwidth limitation
    - Greedy frequency assignment, but cannot ensure coverage (when running out of frequencies)
  - Energy limitation

$$P_{ij}' = P_{ij}\left(\frac{E_i(0)}{E_i(t)}\right)^{\beta}$$

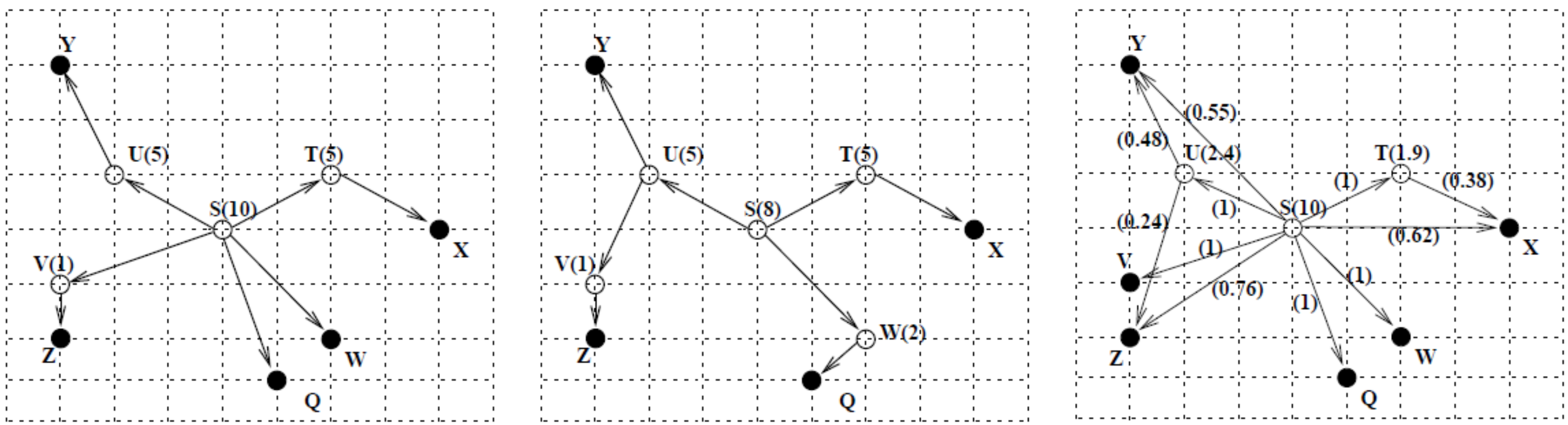
Hitch-hiking (Agrawal, Cho, Gao, Wu, INFOCOM 2004)

- Full and partial coverage (assuming $\gamma_p = 1$)

$$c_{ij} = 1 \text{ for } p_i/d_{ij}^{\alpha} \geq \gamma_p$$

$$c_{ij} = p_i/(d_{ij}^{\alpha} \times \gamma_p) \text{ for } \gamma_{acq} \leq p_i/d_{ij}^{\alpha} < \gamma_p$$

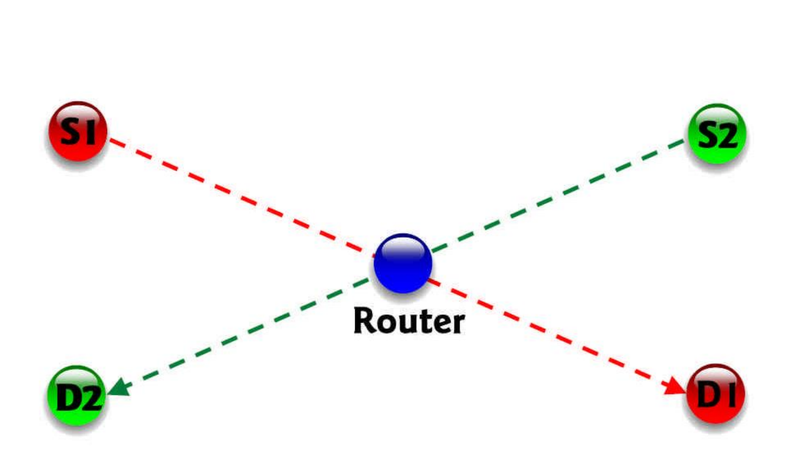
$$c_{ij} = 0 \text{ for } p_i/d_{ij}^{\alpha} < \gamma_{acq}$$



(a) BIP Without Hitch-hiking: cost 21 (b) MST Without Hitch-hiking: cost 21 (c) With Hitch-hiking: cost 14.30

Network Coding

- In early 2000.
- XOR network coding (SIGCOMM 2006)



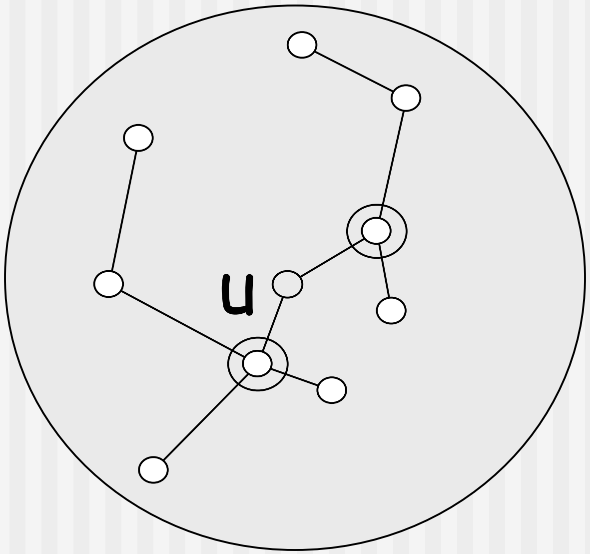
- 3 transmissions instead of 4 using XOR (at router)

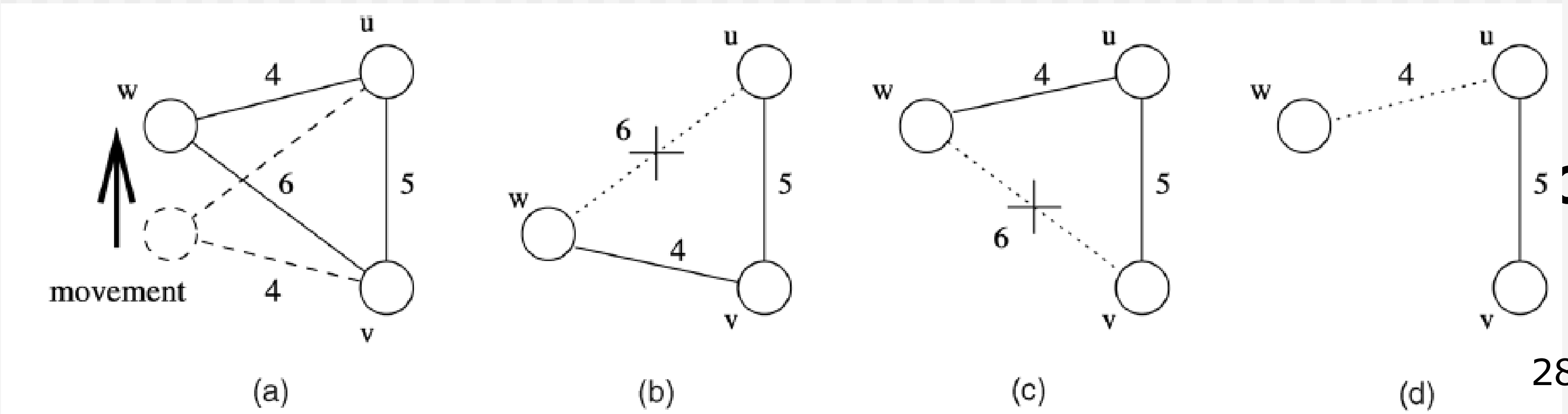
Topology Control (Wu and Dai, TPDS 2006)

- RNG-based protocols
  - An edge (u, v) is removed if there exists a third node w such that d(u,v) > d(u,w) and d(u,v) < d(v,w), where d(…) stands for Euclidean distance.
- Minimum-energy protocols
  - An edge (u,v) can be removed if there exists another node w such that 2-hop path (w, w,v) consumes less energy. It is extensible to k-hop.
- Cone-based protocols (CBTC)
  - If a disk centerd at v is divided into k cones, the angle of the maximal cone is no more than a.
  - When a < 5∏/6, CBTC preserves connectivity, and when a < 2 ∏/3, symmetric subgraph is connected.
- MST-based protocls (next page)

MST-based Topology Control

- 1-hop information (Li, Hou, and Sha, INFOCOM 2003)
  - Network connectivity: if each node connects to its neighbors in the local MST (LMST)





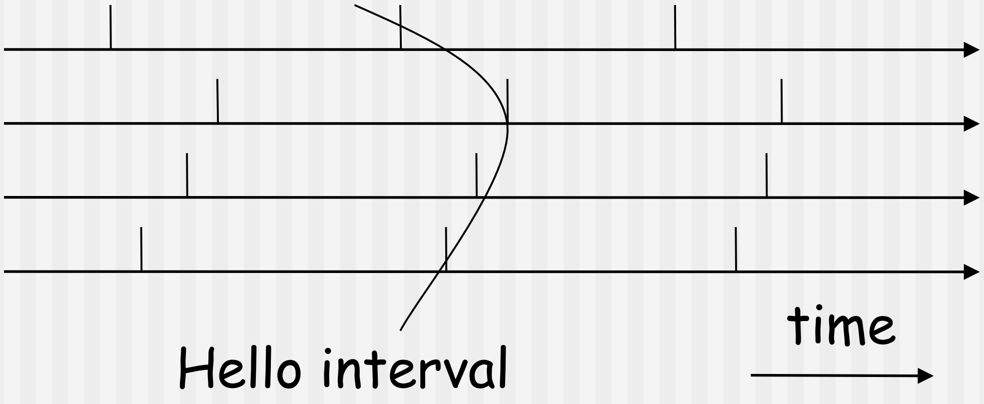
Strong and Weak View Consistency

- Strong Consistency (using timestamp)
  - Requires a certain degree of synchronization
- Weak Consistency (without using timestamp)
  - Max: max cost in a view window: max{1,3,5} = 5, max{2,4,6} = 6
  - Min: min cost in a view window : min{1,3,5} = 1, min={2,4,6}=2
  - MaxMin: Max of “Min” values from all views of a node: 2
  - MinMax: Min of “Max” values from all views of a node: 5
- Local views are weakly consistency if

$$\text{MinMax} \geq \text{MaxMin}$$

Sampling Strategies (handling mobility)

- Two sampling strategies
  - Instantaneous: whenever a new "Hello" is transmitted or received.
  - Periodical: once per "Hello" interval
- Constructing weakly consistent local views
  - Two recent "Hello" messages for the instantaneous model
  - Three recent "Hello" messages for the periodical model



Framework with Consistent View

Link removal conditions: A link (u, v) will be removed from the original topology

1. In an RNG-based protocol, if a path (u, w, v) exists such that $c_{u,v} > \max\{c_{u,w}, c_{w,v}\}$.
2. In an SPT-based protocol, if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v} > c_{u,w_1} + c_{w_1,w_2} + \ldots + c_{w_k,v}$.
3. In an MST-based protocol, if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v} > \max\{c_{u,w_1}, c_{w_1,w_2}, \ldots, c_{w_k,v}\}$.

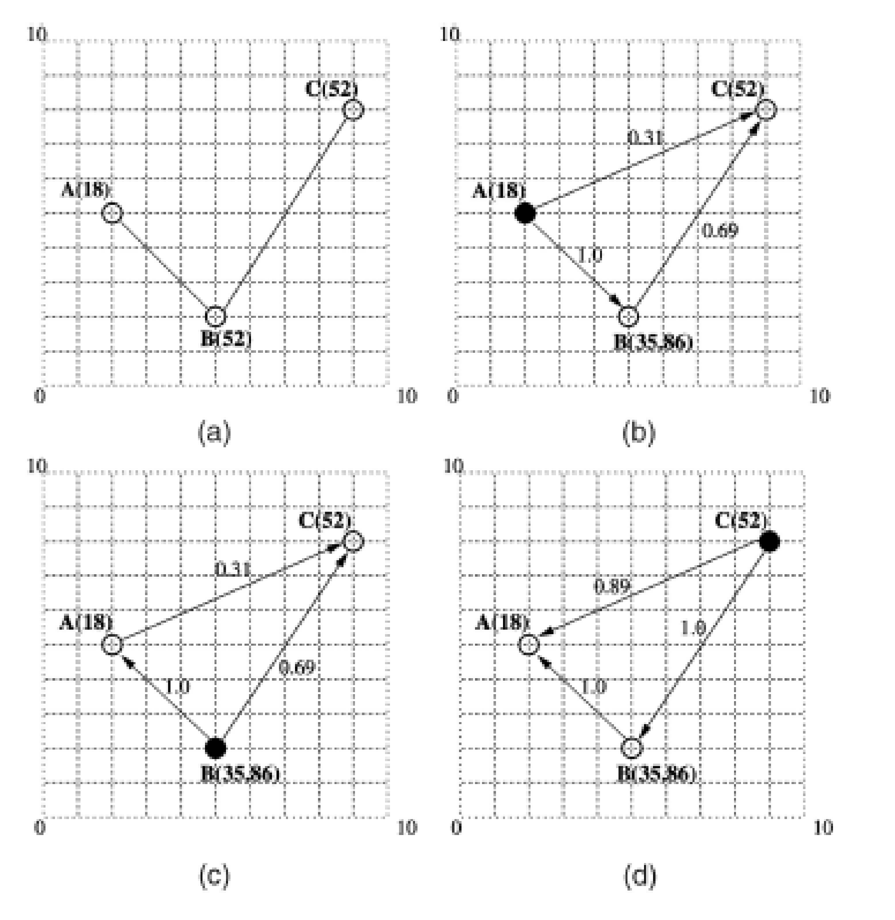
Framework with Weak Consistent View

Enhanced link removal conditions: A link (u, v) will be removed

1. In an RNG-based protocol, if a path (u, w, v) exists such that $c_{u,v}^{Min} > \max\{c_{u,w}^{Max}, c_{w,v}^{Max}\}$.
2. In an SPT-based protocol, if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v}^{Min} > c_{u,w_1}^{Max} + c_{w_1,w_2}^{Max} + \ldots + c_{w_k,v}^{Max}$.
3. In an MST-based protocol, if a path $(u, w_1, w_2, \ldots, w_k, v)$ exists such that $c_{u,v}^{Min} > \max\{c_{u,w_1}^{Max}, c_{w_1,w_2}^{Max}, \ldots, c_{w_k,v}^{Max}\}$.

Topology Control using Hitch-hiking (Cardei, Wu, Yang, TMC 2006)

- *Strong connectivity*: For any node s sending a packet, there should be a "path" to every other node.
- *Forwarding rule.* (a) s has the full packet and (b) only nodes that fully received the packet are able to forward it.



Security

- Availability
  - Survivability of network services despite DoS attacks
- Confidentiality
  - information is never disclosed to unauthorized entities
- Integrity
  - Message being transferred is never corrupted
- Authentication
  - Enables a node to ensure that the identity of the peer node it is communicating with.
- Non-repudiation
  - The origin cannot deny having sent the message

Security Challenges

- The nodes are constantly mobile
- The protocols implemented are co-operative in nature
- There is a lack of a fixed infrastructure to collect audit data
- No clear distinction between normalcy and anomaly in ad hoc networks

Types of Attack

- External attack
  - An attack caused by nodes that do not belong to the network.
- Internal attack
  - An attack from nodes that belong to the network due to them getting compromised or captured.

Sample Security Attacks

- Routing attacks
  - Action of advertising routing updates that does not follow the specifications
  - Examples: add/delete a node in the path, advertise a route with smaller (larger) distance metric (timestamp)
- Packet forwarding attacks
  - Packets are not delivered consistently based on routing states.
  - Examples: drop the packet, inject junk packets

Security Problems in DSR and AODV

- Remote redirection
  - Sequence number (AODV)
  - Hop count (AODV)
  - Source route (DSR)
- Spoofing (impersonation) (AODV and DSR)
- Fabrication
  - Error message (AODV and DSR)
  - Source route (DSR)

Security Solutions

- Routing attacks
  - Traditional cryptography (preventive)
    - message authentication primitives
    - secured ad hoc routing
  - Challenges: cost, key management
- Packet forwarding attacks
  - Watchdog (detective)
  - Challenges: blackmail attacks

Sample Solutions

Property: Techniques

- Timeliness: Timestamp
- Ordering: Sequence Number
- Authenticity: Password, Certificate
- Authorization: Credential
- Integrity: Digest, Digital Signature
- Confidentiality: Encryption
- Non-repudiation: Chaining of digital signatures

Sample: Distance Metric

- Hop count hash chain (Hu et al'03): $h_0, h_1, \ldots h_n$
  - $h_i = H(h_{i-1})$ and H is a known one-way hash function
  - h_n is added to the routing message and the ith node along a path has h_i
  - When a node receives an RREQ or RREP with (*Hop_Count*, h_x), it checks
    - $h_n = H^{n\text{-}Hop\_Count}(h_x)$

  $H^m(.)$ means applying the H function m times

(V) Special Challenges

- Survivability
  - Ad hoc networks should have a distributed architecture with no central entities to achieve high survivability
- Scalability
  - Security mechanisms should be scalable to handle a large network
- Trust
  - Because of frequent changes in topology, trust relationship among nodes in ad hoc networks also changes

Sample Survivability Solution

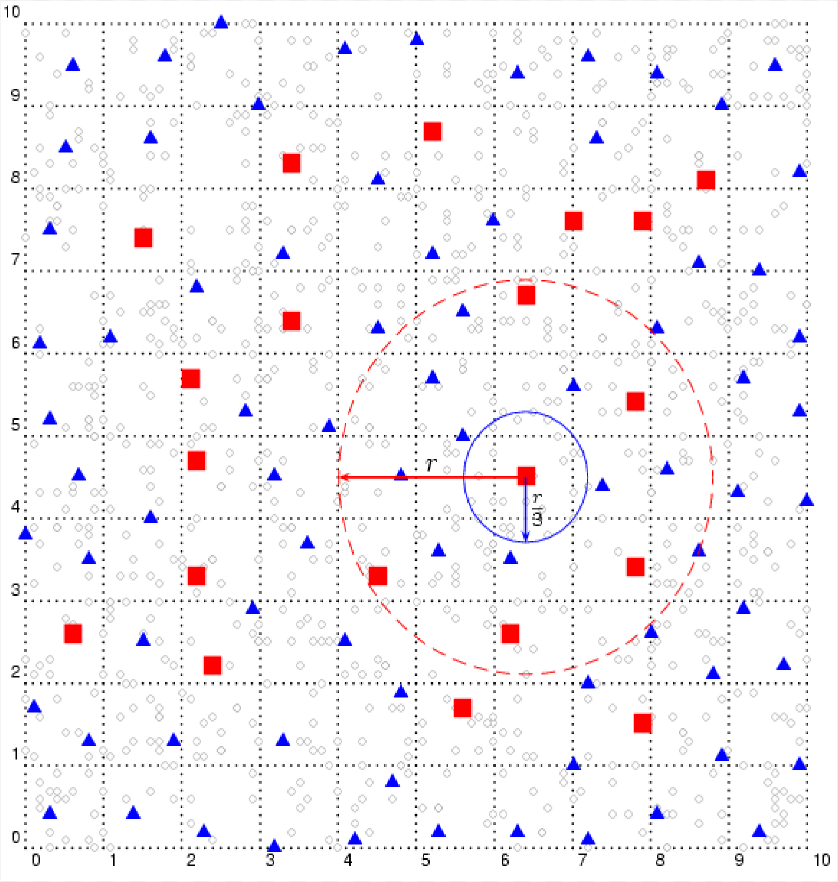
- Threshold cryptography (Zhou and Haas'99)
  - The public key is known to all whereas the private key is divided into n shares
  - Decentralized CA to distribute key pairs
  - The private key can be constructed with any subset of shares of certain sizes
- Proactive security: Share refreshing
  - Servers compute new shares from old ones in collaboration without disclosing the service private key to any server

Scalable Design

Partition the network into groups

- Each group: group head + group members
- Group heads form a dominating set (DS)
  - Also an independent set (IS) to guarantee a constant bound
  - Also connected (CDS) to ensure routing within the heads.

Scalable Design (Con't)



(Wu and Dai'04)

1. Clustering using a short transmission range (r/3)

2. Distributed pruning (delete blue triangles)

3. Transmission using a long transmission range (r)

Scalable Design (Con't)

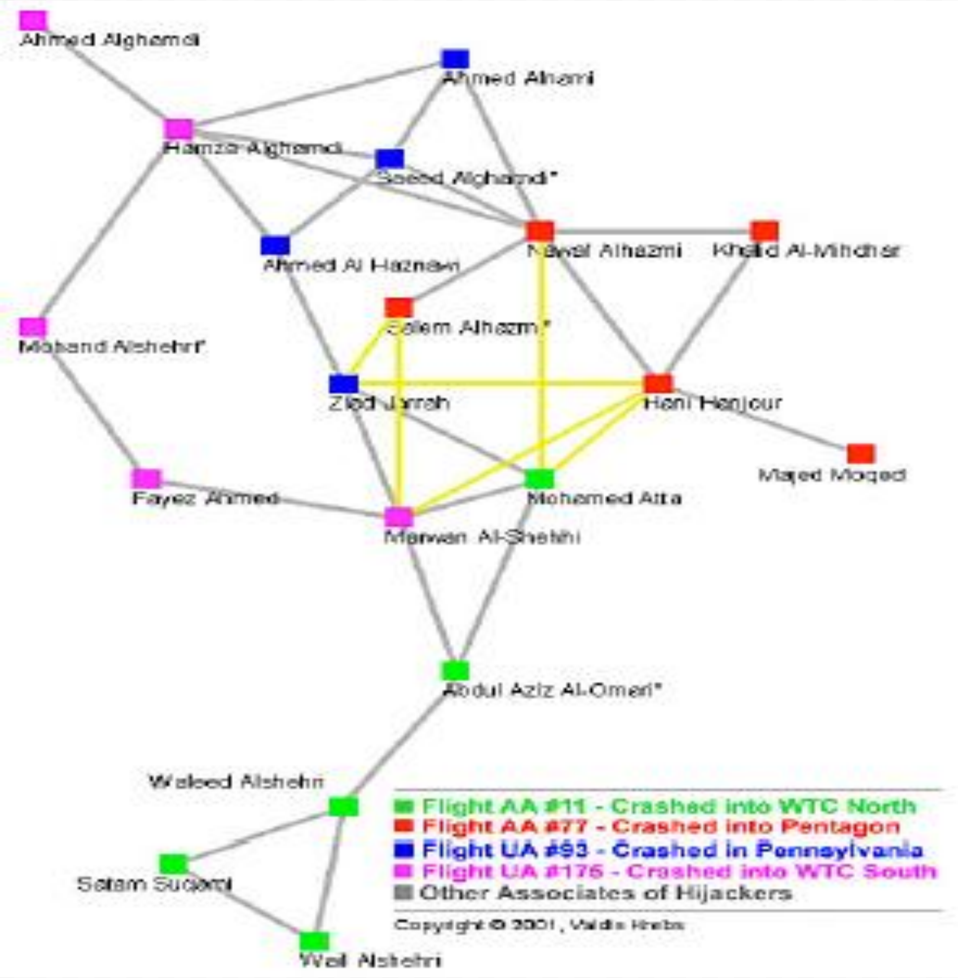
Resurrecting duckling transition association (Stajano and Anderson'99) within a group

- A duckling considers the first moving object it sees as its mother
- Transient master-slave relationship
- When a node is deactivated, it goes back to the pre-birth stage and can be reborn through another imprint (resurrection)

Trust

- A lesson from 9/11
  - Hierarchical trust
  - Funds distribution
  - …
- How to build trust
  - (Zhou & Wu'03)

    Survivable Multi-level
    Ad-Hoc Group Operations



Trust Building (Zhou and Wu'03)

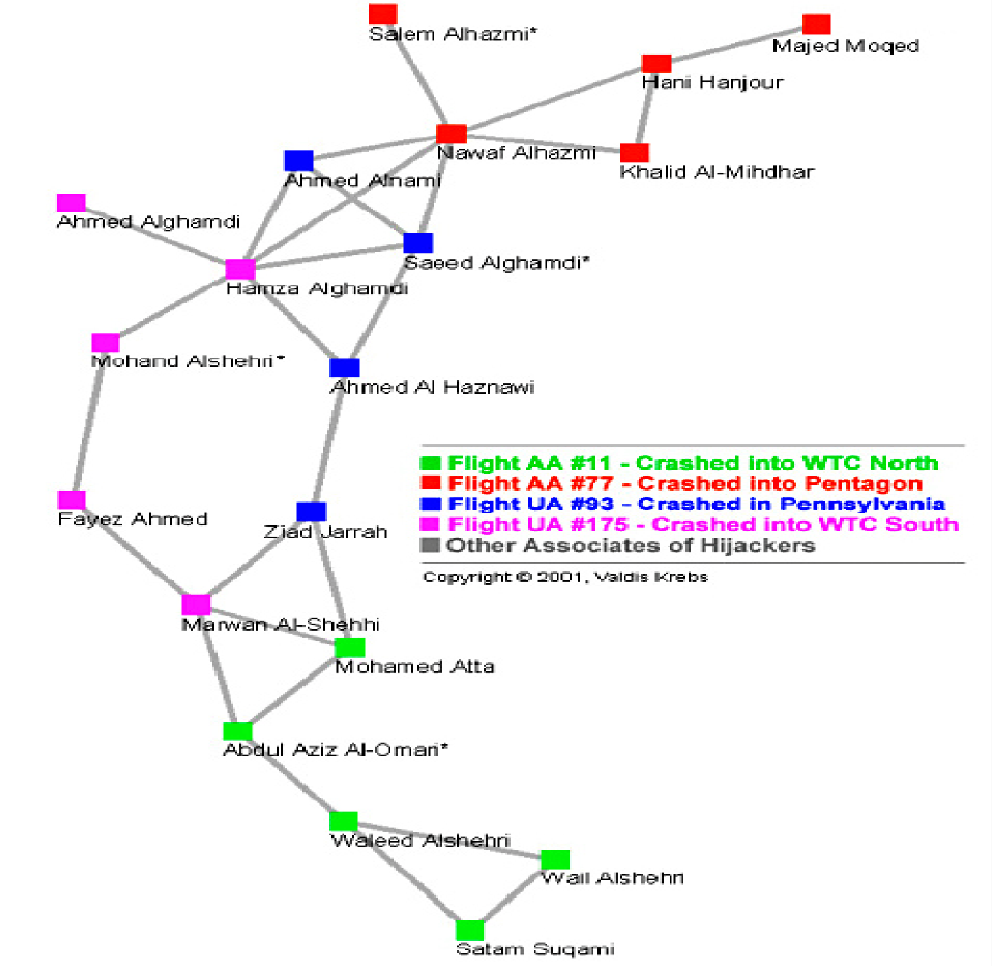
- An ad hoc network cannot succeed without trust within
- Nodes are trustworthy if they have
  - integrity, and
  - proper capability

Operation Policy

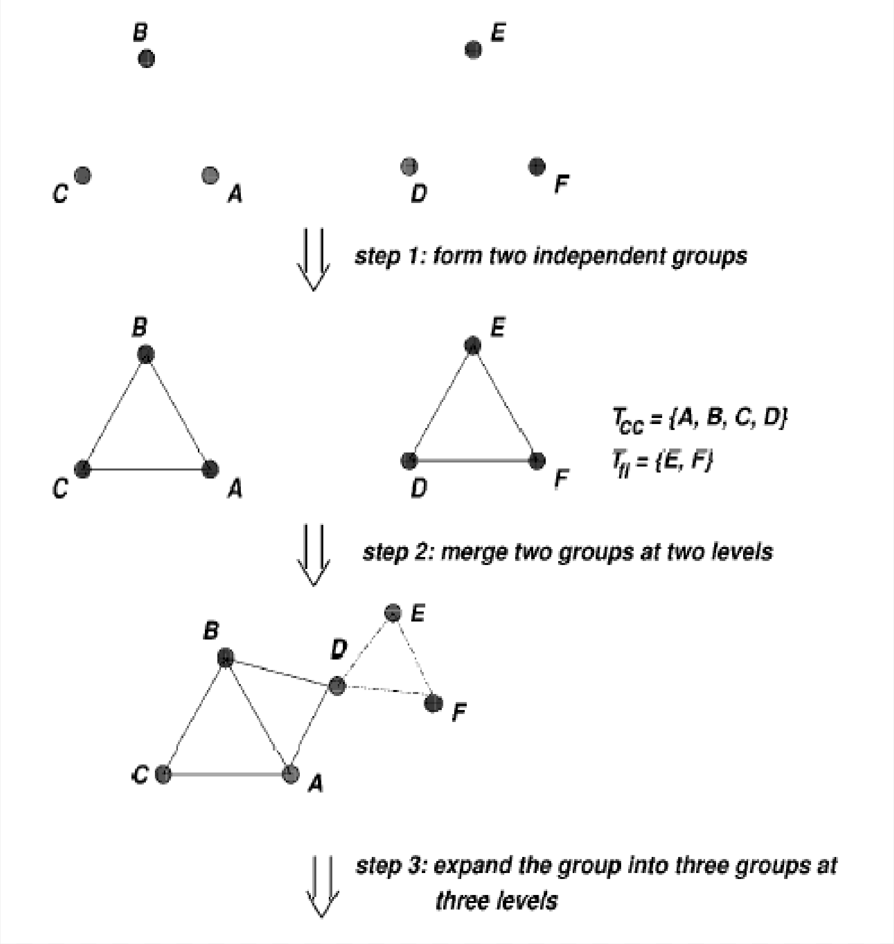
- Information sharing
  - Minimum information was shared to other members whose tasks necessitated their knowledge.
  - Knowledge of a lower-level task group was a subset of that of a higher-level task group.
- Communication
  - Confidential and authentic within the group.
  - Three type of inter-group communications.
- Redundancy

A Terrorist Network

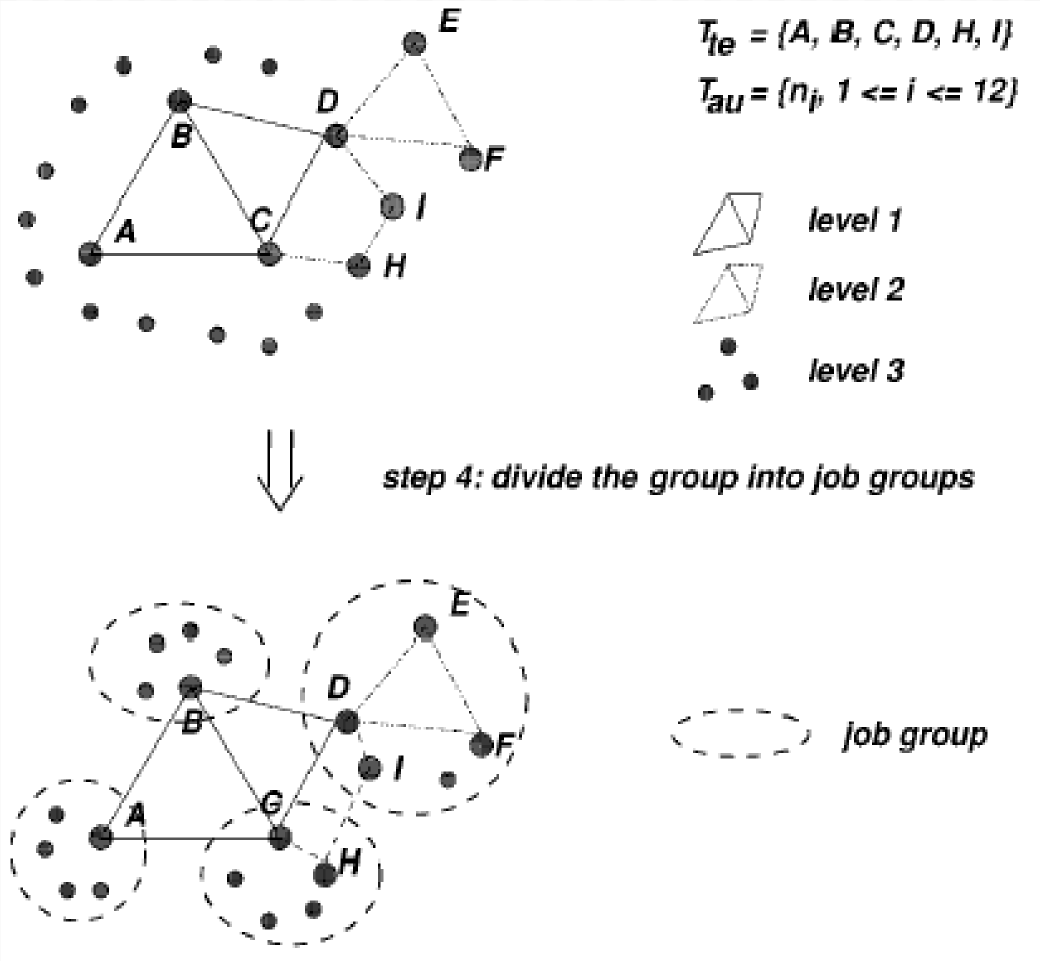
- From Krebs' *Mapping Networks of Terrorist Cells* (Connections, 24(3): 43-52, 2002)



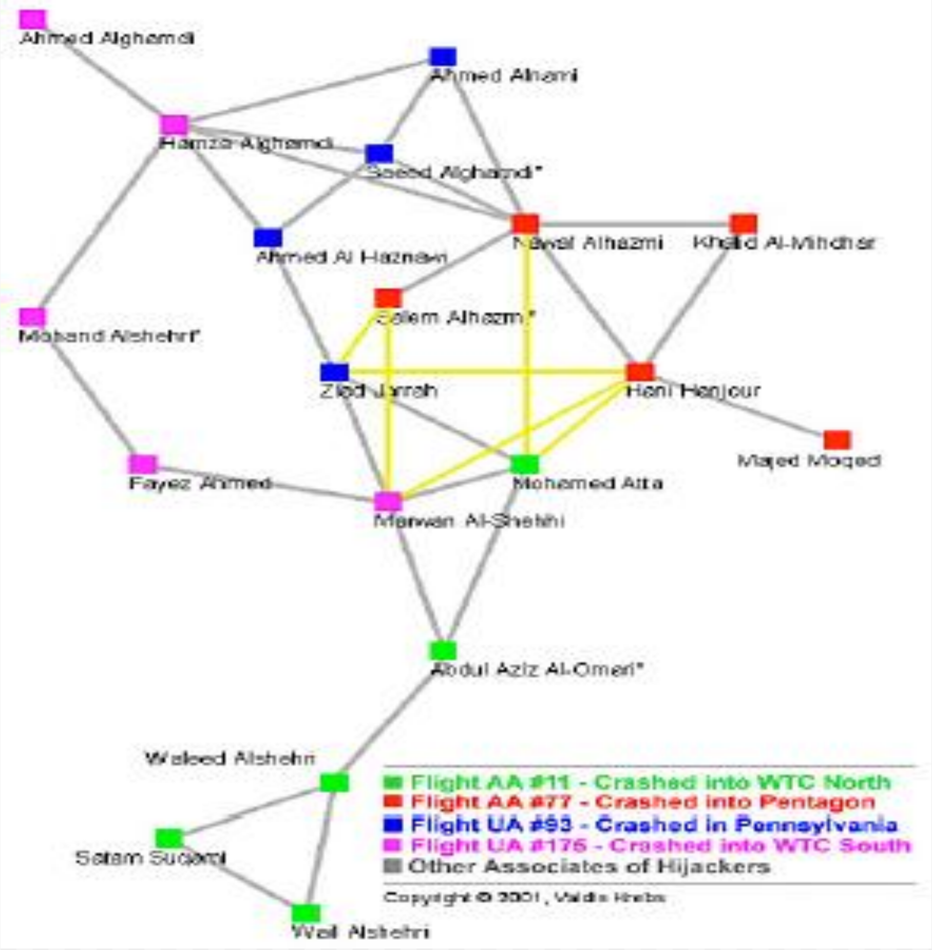
A Terrorist Network (Con't)



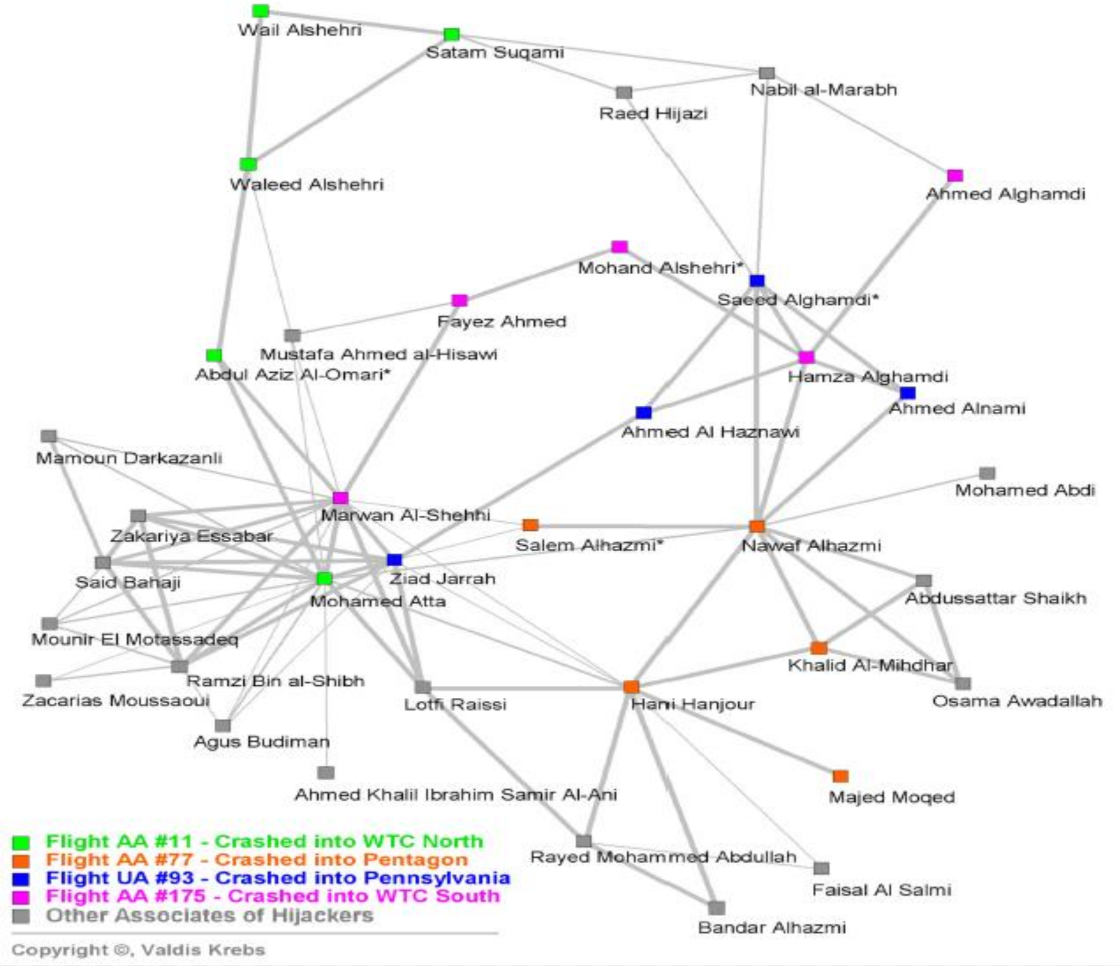
A Terrorist Network (Con’t)



A Terrorist Network (Prior Contacts + Meeting ties [shortcuts])

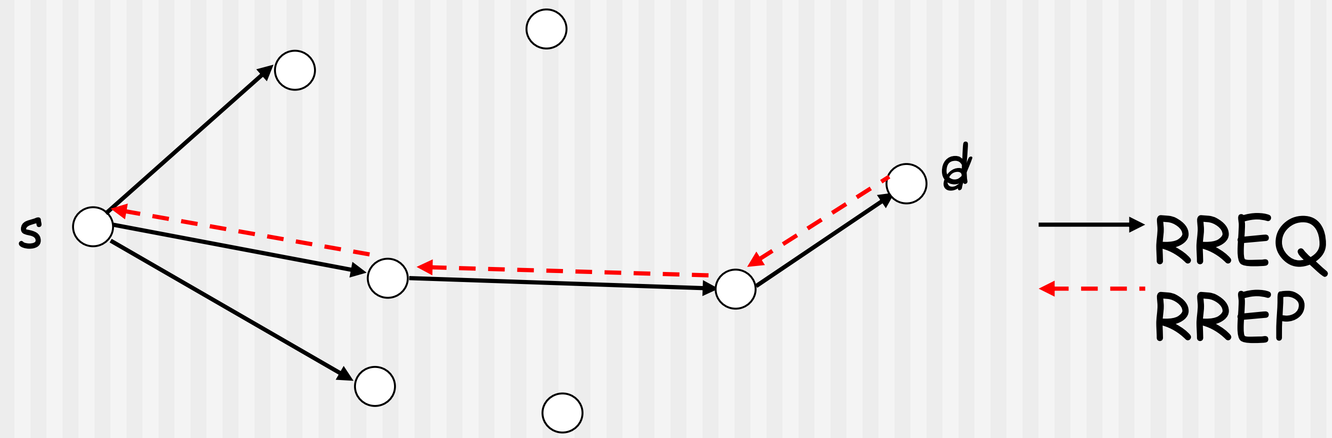


A Terrorist Network (Network Neighborhood)



Node Cooperation in MANETs

- Nodes are formed without any infrastructure
- Nodes cooperate to complete a routing process
  - Route request, route reply, forwarding



Trust vs. Reputation

- Reputation (objective)
  - What is general said or believe about somebody (say B)
- Trust (subjective: judgment + opinion)
  - Trust is the subjective probability by which A expects that another B performs a given action
- Psychological factors
  - Rumor
  - Influence by others' opinions
  - Motives to gain something extra by extending trust
  - …

To be trusting is to be fooled from time to time.

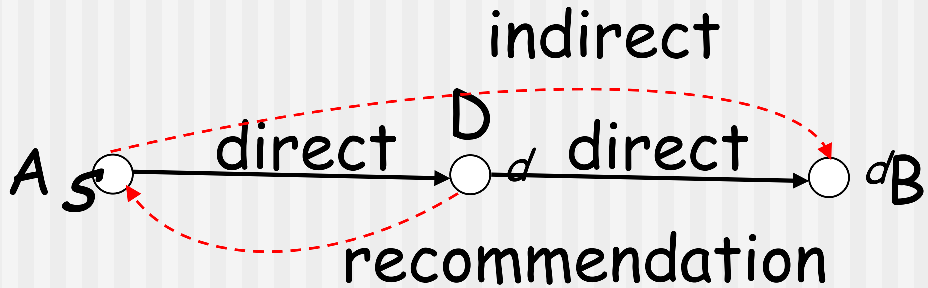
To be suspicious is to live in constant torment.

Trust vs. Reputation (Cont'd)

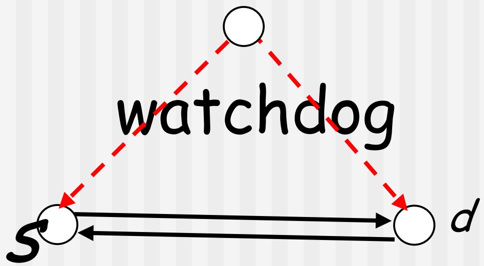
- Reputation system to facilitate trust
  - eBay (business)
  - H-index (academic)
- Trust in multiple disciplines
  - Economics, sociology, psychology, biology, political science, …
  - Computer applications
    - electronics commerce, peer-to-peer networks, and MANETs
  - Computational (e.g. reliability model) vs. non-computational

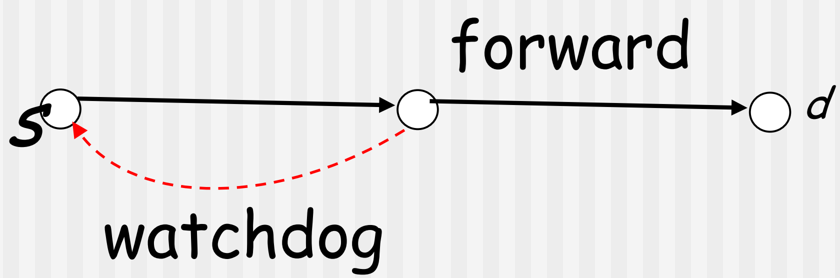
How to Build Trust?

- First-hand (direct) and second-hand (recommendation)



- E.g. watchdog mechanisms in MANETs





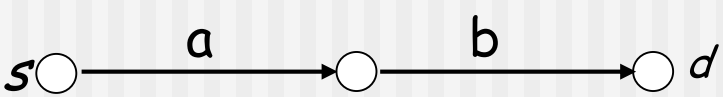
Compound Trust

- First-hand + First-hand/Second-hand

$$D^{new} = D^{current} \pm 1 \qquad D^{new} = w \cdot D^{current} + (1-w) \cdot I$$

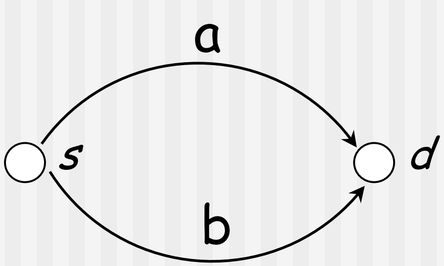
- Compound 1-d: a ◊ b (such as (a, b) and (a : b))

Sequential



$$T_P = a \cdot b$$

Parallel



$$T_W = w \cdot a + (1-w) \cdot b$$

- Commutativity, Monotonicity, and Associativity

Sequential - Generic λ Formula

t-norm (with 1 as identity element)

$$T_\lambda(x,y) = \begin{cases} T_M(x,y) & \text{if } (\lambda = 0) \\ T_P(x,y) & \text{if } (\lambda = 1) \\ T_L(x,y) & \text{if } (\lambda = +\infty) \\ \log_\lambda\left(1 + \dfrac{(\lambda^x - 1)(\lambda^y - 1)}{\lambda - 1}\right) & \text{otherwise} \end{cases}$$

1) Minimum t-norm: $T_M(x,y) = \min(x,y)$

2) Product t-norm: $T_P(x,y) = x \cdot y$

3) Lukasiewicz t-norm: $T_L(x,y) = \max(x + y - 1, 0)$

Parallel - Compound 2-d

(trust (t), confidence (c)): solution 1

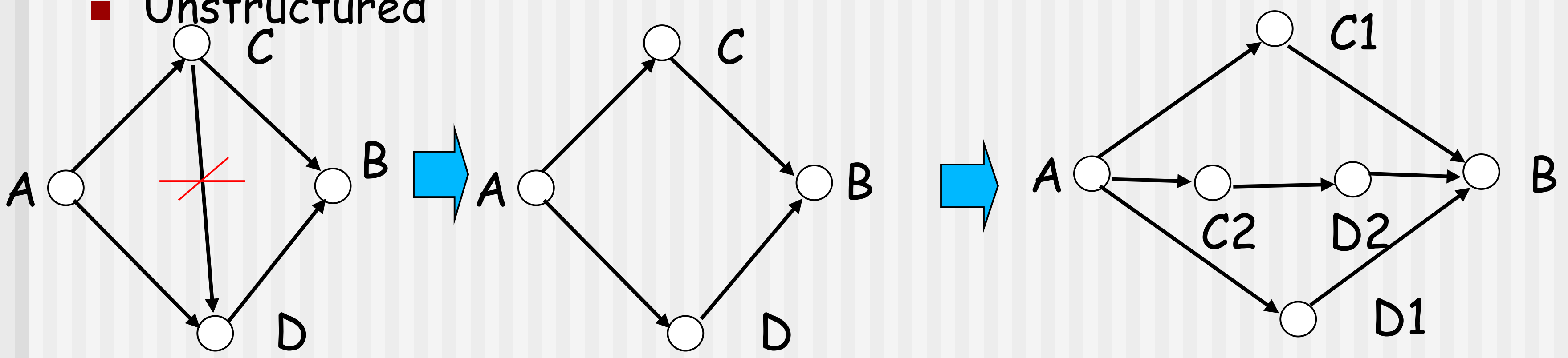
$$(t_i, c_i) \oplus (t_j, c_j) = \begin{cases} (t_i, c_i), \; if \; c_i > c_j \\ (t_j, c_j), \; if \; c_i < c_j \\ (\max(t_i, t_j), c_i), \; if \; c_i = c_j \end{cases}$$

(t, c): solution 2

$$(t_i, c_i) \oplus (t_j, c_j) \rightarrow \left(\frac{c_i + c_j}{\frac{c_i}{t_i} + \frac{c_j}{t_j}}, \; c_i + c_j \right)$$

Compound Trust

- How to compute compound trust (from s to d)?
  - Structured (a well-defined sequential and parallel operations)
  - Unstructured



Removing weakest links

Edge splitting

Trust Equivalence Graphs

- How to compute compound trust based on an arbitrarily complex graph?
- Trust equivalence approach (Wang & Wu'09)

Multi-Dimensional Evidence-based Trust Management with Multi-Trusted Paths

- Use GraphReduce and GraphAdjust algorithms to guarantee that every link will be used exactly once.

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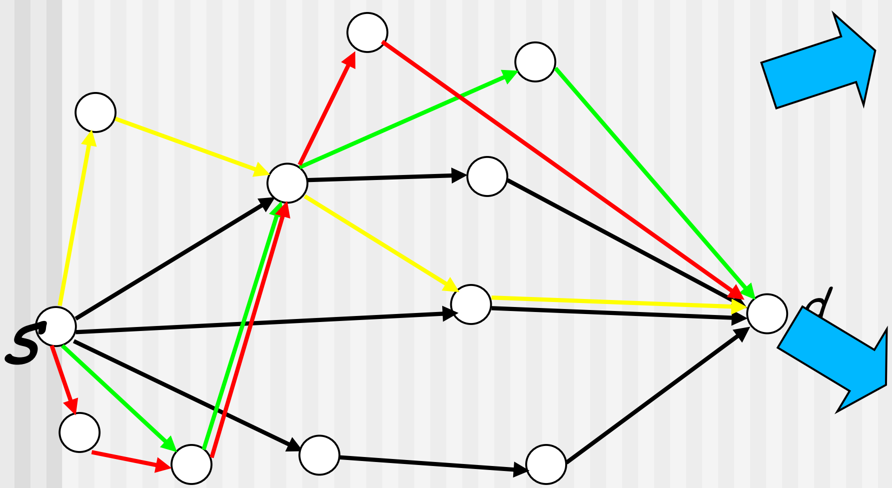
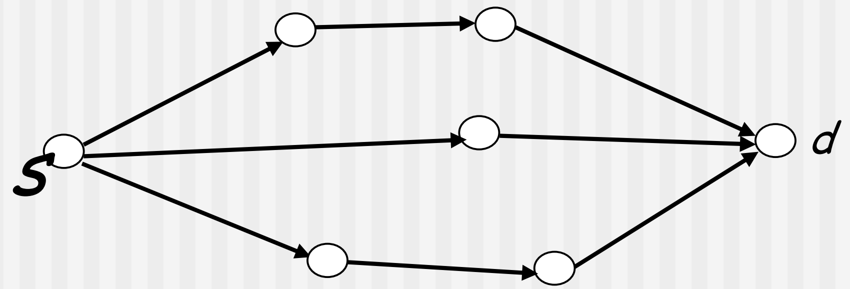
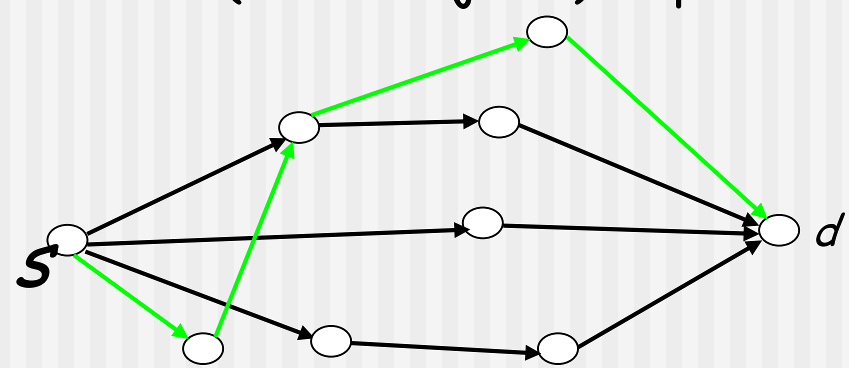
GraphReduce

- To find a maximum number of node- or link-disjoint paths





Reduced (node-disjoint): 3 paths



Original: 6 paths

Reduced (link-disjoint): 4 paths

Multi-dimensional Model

- Multi-dimensional model (Zhou & Wu'03)
  - I: Integrity on a subject (direct)
  - C: Capability on a subject (direct)
  - A: Ability to evaluate I or C of other nodes (indirect)
- Granularity
  - group vs. individual

Computation Models

- Aggregation rules
  - Sequential structure: whole is no more than each part
  - Parallel structure: whole is no less than each part
- Models
  - Reliability model (reliability as trust)
  - Resistive model (current as trust)
  - Flow model (max-flow as trust)
  - Other model (?)

Uncertainty

- Uncertainty as part of trust
  - Sampling size and information asymmetry (on-line shopping)
- Direct observation (evidence)
- Reputation (opinion): b, d, u (3-d subjective logic)
  - b + d + u = 1
  - b , d and u designate belief, disbelief, and uncertainty

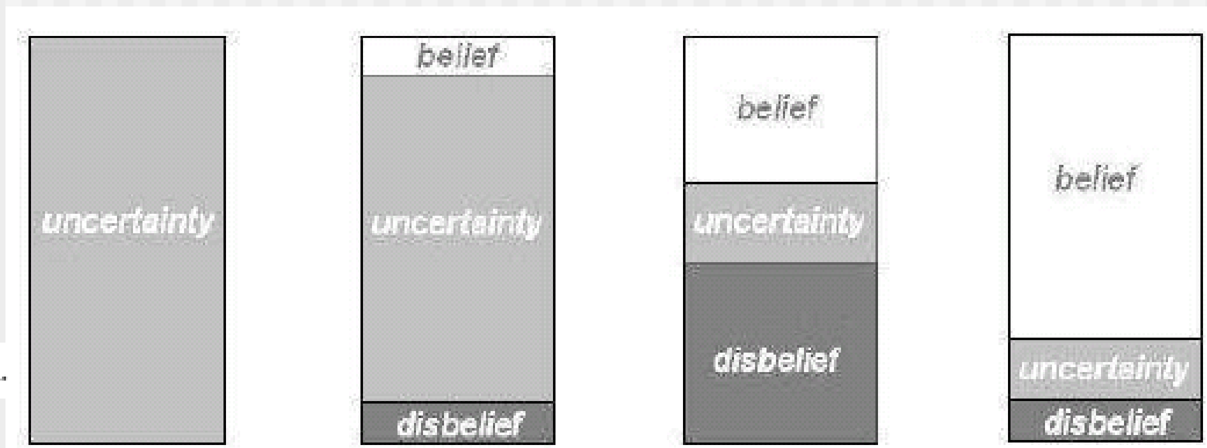


Fig. 1. Reputation representation.

Uncertainty-aware Reputation System (Li &Wu'08)

- Beta distribution Beta(α,β) in the Bayesian inference
  - Statistical inference : observations are used to update or to newly infer the prob. that a hypothesis may be true
- A simple example: Belief = Disbelief = 0.5
  - On the basis of 5 (50) observed successes and 5 (50) failures.
- Attributes
  - Less uncertainty: When the evidence for success /failure dominates
  - Maximum uncertainty: When there is little or no evidence
- Applications: Mobility Reduce Uncertain

Uncertainty Definition

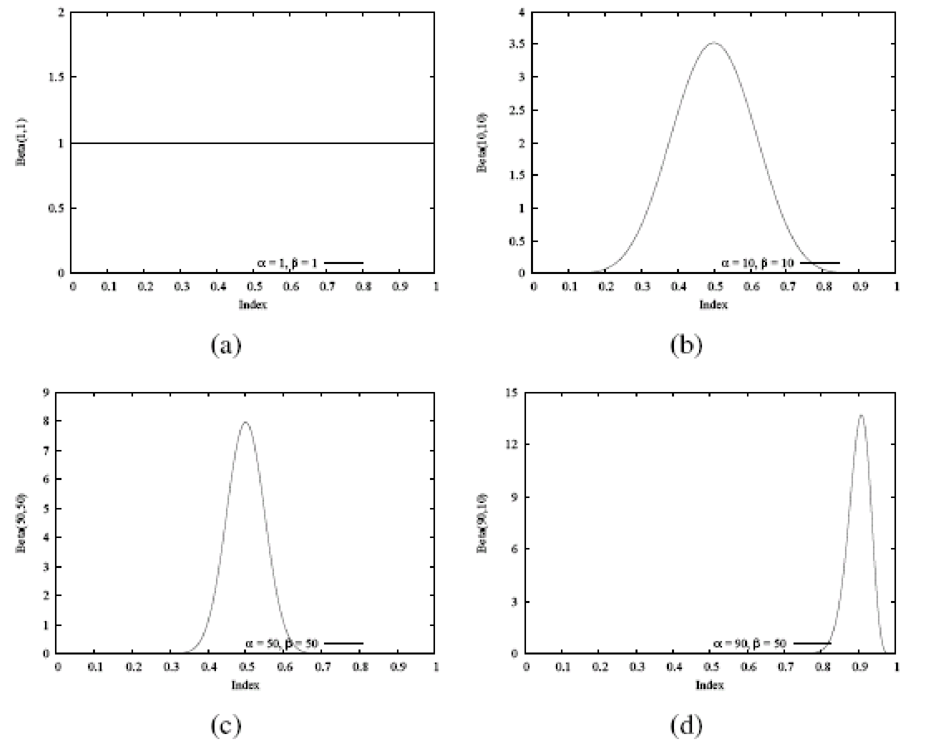


Fig. 2. (a) $Beta(1,1)$, (b) $Beta(10,10)$, (c) $Beta(50,50)$, (d) $Beta(90,10)$. Corresponding b, d, u representation see Fig. 1.

- How to evaluate uncertainty behind α, β : Beta(α, β).

(Uncertainty computation) Let uncertainty be the normalized variance of the Beta function:

$$u = \frac{12 \cdot \alpha \cdot \beta}{(\alpha+\beta)^2 \cdot (\alpha+\beta+1)}$$

$$b = \frac{\alpha}{(\alpha+\beta)} \cdot (1-u)$$

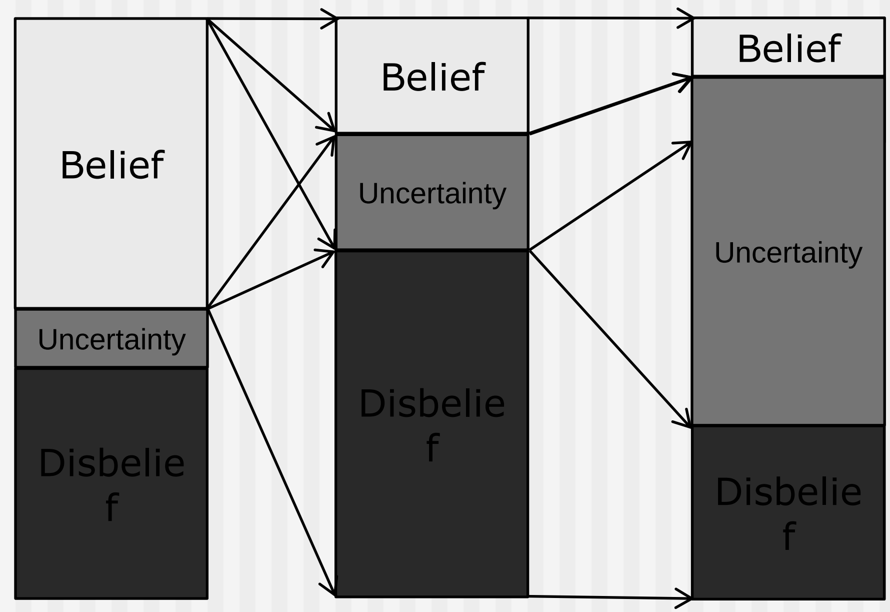
$$d = \frac{\beta}{(\alpha+\beta)} \cdot (1-u)$$

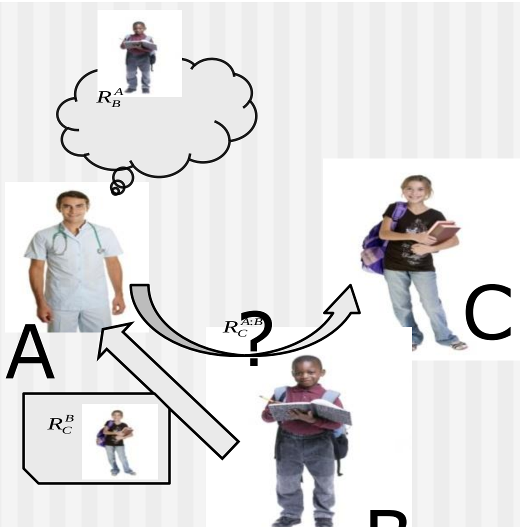
Recommendation Integration

(Recommendation Calculation) Let $R_B^A = \{b_B^A, d_B^A, u_B^A\}$ represent node A's opinion towards B, and $R_C^B = \{b_C^B, d_C^B, u_C^B\}$ represent node B's opinion towards C. A will take B's recommendation towards C as $R_C^{A:B} = \{b_C^{A:B}, d_C^{A:B}, u_C^{A:B}\}$ where:

$$
\begin{aligned}
b_C^{A:B} &= b_B^A \cdot b_C^B \\
d_C^{A:B} &= b_B^A \cdot d_C^B \\
u_C^{A:B} &= b_B^A \cdot u_C^B + d_B^A + u_B^A
\end{aligned}
$$

$R_B^A = \{0.5, 0.4, 0.1\}$ $\quad R_C^B = \{0.2, 0.6, 0.2\}$ $\quad R_C^{A:B} = \{0.1, 0.3.0.6\}$





Opinion Combination

(Recommendation Synthesization) Let $R_C^{A:B_i} = \{b_C^{A:B_i}, d_C^{A:B_i}, u_C^{A:B_i}\}$ represent node *B_i*'s recommendation towards node *C* computed by node *A*, for 1 ≤ *i* ≤ n. Then, node *A* will synthesize these recommendations as:

$$R_C^{A:\{B_1,\ldots,B_n\}} = \{\sum_{i=1}^{n} b_C^{A:B_i} / n, \sum_{i=1}^{n} d_C^{A:B_i} / n, \sum_{i=1}^{n} u_C^{A:B_i} / n\}$$

(Opinion Combination) Let γ be a node's character factor. Each node *A* will combine its first-hand and second-hand opinion towards *B* as

:

$$\begin{aligned} b_B^{A_f} &= \phi \cdot b_B^{A^{1st}} + (1-\phi) \cdot b_B^{A^{2nd}} \\ d_B^{A_f} &= \phi \cdot d_B^{A^{1st}} + (1-\phi) \cdot d_B^{A^{2nd}} \\ u_B^{A_f} &= \phi \cdot u_B^{A^{1st}} + (1-\phi) \cdot u_B^{A^{2nd}} \end{aligned}$$

$$\begin{aligned} \phi &= \frac{\gamma \cdot u_B^{A^{2nd}}}{(1-\gamma) \cdot u_B^{A^{1st}} + \gamma \cdot u_B^{A^{2nd}}} \\ 1-\phi &= \frac{(1-\gamma) \cdot u_B^{A^{1st}}}{(1-\gamma) \cdot u_B^{A^{1st}} + \gamma \cdot u_B^{A^{2nd}}} \end{aligned}$$

Components Design

- Information gathering
  - First-hand vs. second-hand
- Information modeling
  - Single vs. multiple metrics
  - Past vs. recent observations
  - Updating function

Components Design (Cont'd)

- Information sharing
  - First-hand info only (OCEAN and pathrater)
  - First-hand and second-hand info (CORE and CONFIDANT)
  - Second-hand info only (DRBTS)

    (Srinivasan, Teitelbaum & Wu'05) DRBTS: Distributed Reputation-based Beacon Trust System
  - Radical strategy: suicide attacks
- Challenges
  - False praise
  - Bad mouthing

Components Design (Cont'd)

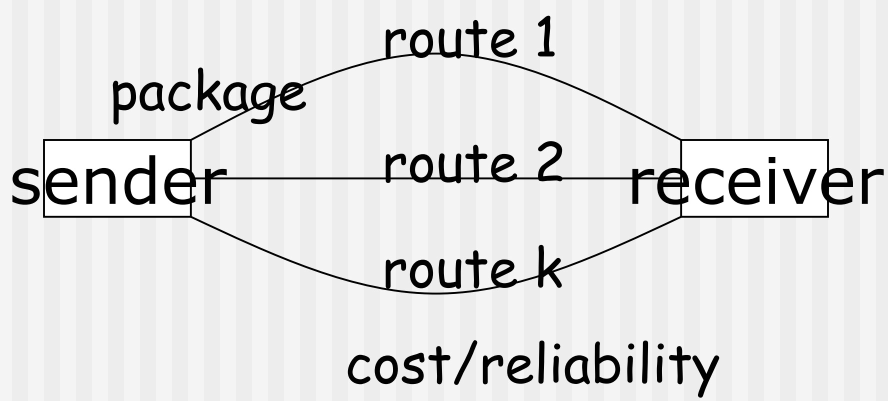
- Information sharing
  - Positive vs. negative information
    - Positive only (CORE)
    - Both positive and negative (with recommender's reputation)
    - Deviation test: A node believes second-hand info only if it does not differ too much from the node's reputation value. (DRBTS)
- Dissemination
  - Proactive vs. reactive
  - Local vs. global (EigenTrust)
  - Content: raw vs. processed

Components Design (Cont'd)

- Decision making
  - Single threshold: cooperative/non-cooperative
  - Multiple thresholds: Anantvalee & Wu'07
    - Selfish node: RF < T(selfish)
    - Suspicious node: T(selfish) ≤ RF < T(cooperative)
    - Cooperative node: T(cooperative) ≤ RF
- Bootstrap
  - Start with a low value and move up
  - Start with a high value and deteriorate over time unless reinforced

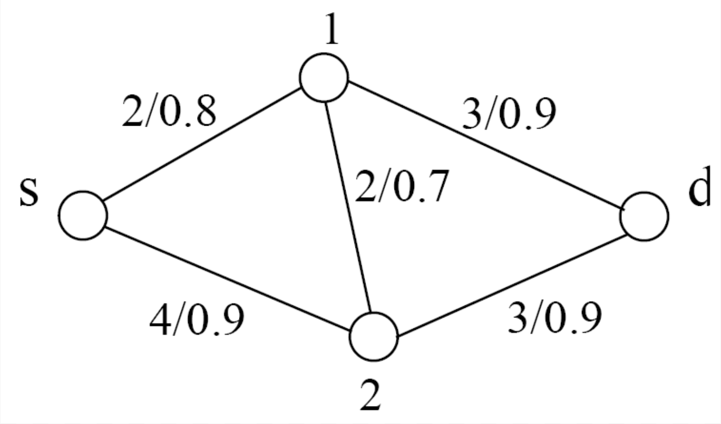
3. Trust Model Revisited

- Risk attitudes in trust: reliability and utility
- Trust: The extend to which one is willing to depend on somebody even though negative consequences are possible
- Best route: importance of the package
  - Valuable package: Fedex (more reliable, costs more)
  - Regular package: Regular mail (less reliable, costs less)



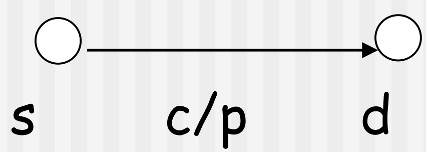
A Sample Network

- Traditional metrics: cost/reliability
  - The minimum cost path: s → 1 → d
    - Cost 2 + 3 = 5
    - Reliability 0.8 × 0.9 = 0.72
  - The most reliable path: s → 2 → d
    - Cost 4 + 3 = 7
    - Reliability 0



Utility-Based Routing (Lu&Wu06)

- Each packet is assigned a benefit value, v
- s transmits a packet with benefit v to d
  - Transmission cost/reliability: c/p
  - Utility: v – c if success, 0 – c otherwise
  - Expected utility: $U = p(v-c) + (1-p)(0-c) = pv - c$
  - The best route maximizes U



A General Expression

- General form of U for path R: s = 1, 2, …, k-1, d = k

$$U_R = \left(\prod_{j=1}^{k-1} p_{j,j+1}\right)v - \sum_{i=1}^{k-1}\left(c_{i,i+1}\prod_{j=1}^{i-1} p_{j,j+1}\right) = P_R v - C_R$$

P_R: route stability and C_R: route cost

Prop. 1: Backward Calculation

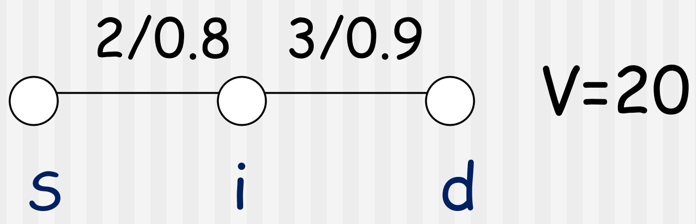
- How to calculate U?

  Direct

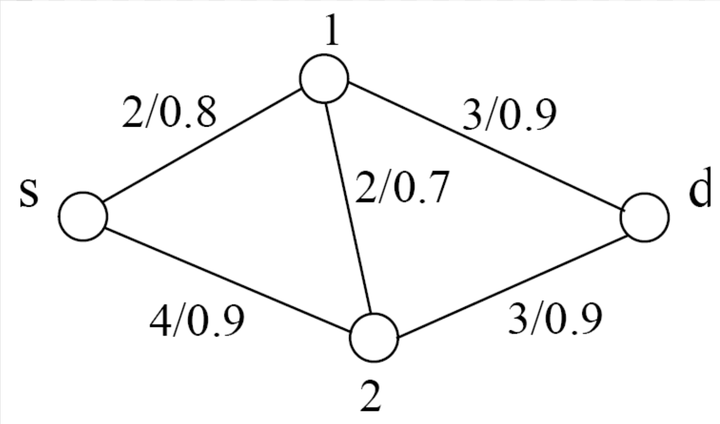
  - (1) 0.8 *0.9*20 – 2 – 3*0.8=10

  Backward calc.: $u_i = p_{i,i+1} u_{i+1} - c_{i,i+1}$ (virtual s/d)

  - (2) 0.9*20 – 3 = 15 (at i)
  - 0.8*15 – 2 = 10 (at s)



Prop. 2: Benefit-dependent Best Path



R_i	P_i	C_i
R_1	0.72	4.4
R_2	0.81	6.7
R_3	0.5	5.3
R_4	0.57	7.7

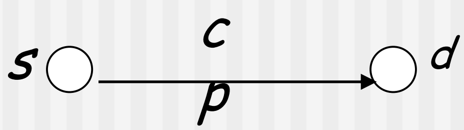
Different benefit values may have different best paths!

For v=20, R1: 10 and R2: 9.5

For v=30, R1: 17.2 and R2: 17.6

Uncertainty Mitigation (Li et al'07)

- Each intermediate node i performs "risk" analysis when selecting a downstream node j
  - i monitors j using (b, d, u) (subjective logic)
  - An uncertainty threshold T is set based on expected utility and cost
  - i selects j if u ≤ T and yields a high utility



Game Theoretical Model

- Game theory
  - Rational economic agents
  - Backward induction to maximize private utilities
  - Node behavior: selfish
  - E.g., VCG mechanism
  - In reality, people are boundedly rational.
- Reciprocity norms (social strategies)
  - Encouraging social cooperation
  - Node behavior: reciprocal altruism
  - Be nice to others who are nice to you
  - E.g., nuglets (virtual currency) and barter exchange

Incentive Compatible Routing

- Nodes are selfish and may give false information
  - Without reimbursement, they will not help relay packets
  - Maximize utility = payment – cost
- Based on VCG payment scheme

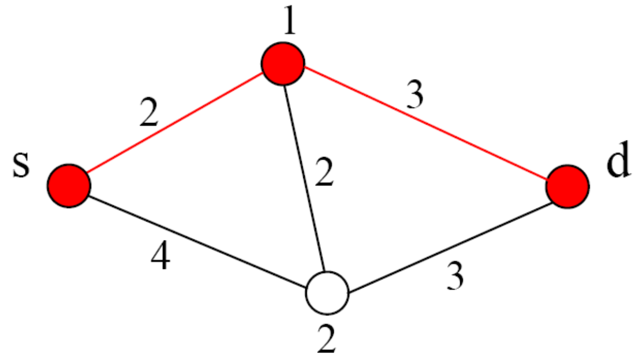
  (enforcing the reporting of correct link costs)
  - Nodes on the optimal path: utility remains the same when lying
  - Nodes not on the optimal path: utility reduces when lying
- Integrative neighbor surveillance mechanism

  (enforcing the reporting of correct link stability)
  - Forwarding status is monitoring by a neighbor (monitor)

Second Price Path Auction

- Why doesn't the first price work?
  - System objective ≠ individual nodes' objectives
- The solution: second price
  - Loser's utility is 0
  - Winner i's payment
    - lowest cost without i - lowest cost + cost of node i

The Sample Network



Case 1: nodes on an optimal path lie

- If (s, 1) is changed to 3
  - S still gets 7 – 6 + 3 = 4 (same as 7 – 5 + 2 = 4)

Case 2: nodes on a non-optimal path lie

- If (2, d) is changed to 1
  - 2 gets 5 – 5 + 1 = 1 < 3 (utility is negative)

Summary of Trust

- Model trust
  - Probability, utility, and game theory
  - One-dimensional vs. multi-dimensional
  - Computational vs. non-computational: reliability, dependability, honesty, truthfulness, security, competence, and timeliness

- Uncertainty integration
  - Dimension reduction or threshold?
  - Right theory: probability, utility, game, rough set, fuzzy logic, entropy, …

Summary of Trust (Cont'd)

- Web of trust
  - Network topology design
  - Finding trusted paths
  - Topology control
- A cross-disciplinary research topic
  - Computer science, economics, psychology, sociology, biology, political sciences
  - NSF NetSE program for network science?

Final Thoughts on Trust

- Robust and Trustworthy Review System
  - Build a good review system that we can trust?

- INFOCOM 2011 (Shanghai)
  - Challenges: bad-mouthing and false-praising
  - Direct and indirect collusion
  - Score a review: (score, confidence)
  - Multi-round decision process
  - Use of trusted reviewers
  - Trust as a finite resource (EigenTrust)?

Open Problems and Opportunities

- Can preventive methods (cryptography) provide a cost-effective solution?
- Hybrid approach: cryptography + trust model.
- Multi-fence security solution: resiliency-oriented design.
- Multi-level approach: application, transport, network, link, and physical

(link layer: jam-resistant communications using spread-spectrum and frequency-hopping)

Open Problems and Opportunities (Con't)

- New approach: incentive-based approaches (to avoid free riders)
  - Credit mechanism (micro payment)
  - Exchange or barter economy (n-way exchange)
  - Game theory (Prisoner's Dilemma game)

Summary of Security

- Research in secured routing in ad hoc networks is still in its early stage.
- Is security in ad hoc networks a problem with no technical solution?

Technical solution:

one that requires a change only in the techniques of the natural sciences, demanding little or nothing in the way of change in human values or ideas of morality.

From Hardin's *The Tragedy of the Commons,* 1968

Sensor Networks

- Sensor networks (Estrin, Mobicom 1999)
  - Information gathering and processing
  - Data centric: data is requested based on certain attributes
  - Application specific
  - Energy constraint
  - Data aggregation (also data fusion)

Sensor Networks

- Military applications:
  - (4C’s) Command, control, communications, computing
  - Intelligence, surveillance, reconnaissance
  - Targeting systems

Sensor Networks

- Health care
  - Monitor patients
  - Assist disabled patients
- Commercial applications
  - Managing inventory
  - Monitoring product quality
  - Monitoring disaster areas

Sensor Networks

Design factors (Akyildiz et al, IEEE Comm. Mag. Aug. 2002)

- Fault Tolerance (sustain functionalities)
- Scalability (hundreds or thousands)
- Production Cost (now $10, near future $1)
- Hardware Constraints
- Network Topology (pre-, post-, and re-deployment)
- Transmission Media (RF (WINS), Infrared (Bluetooth), and Optical (Smart Dust))
- Power Consumption (with < 0.5 Ah, 1.2 V)

Sensor Networks

- Sample problems
  - Coverage and exposure problems
  - Data dissemination and gathering

Coverage and Exposure Problems

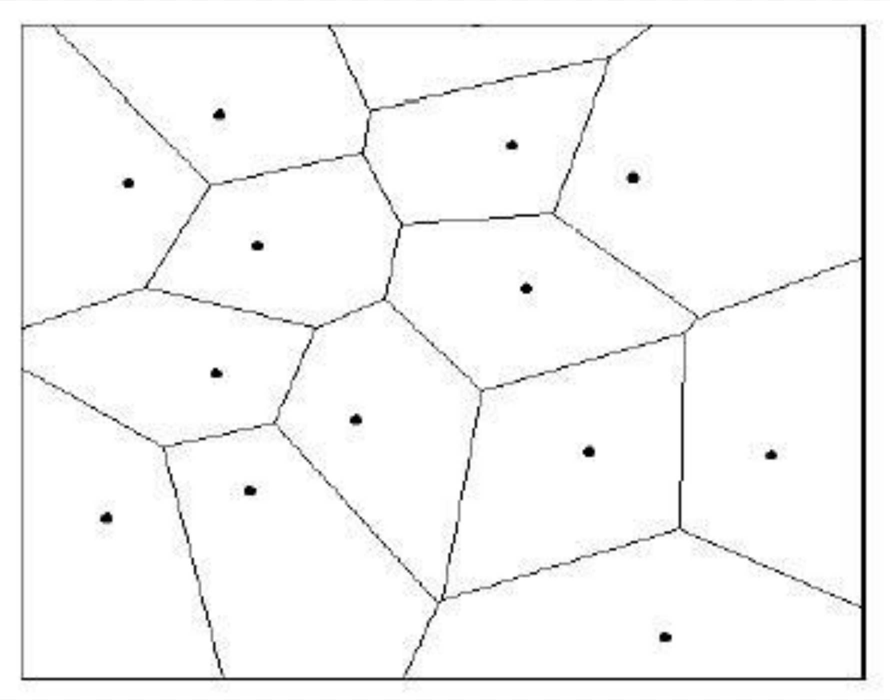
- Coverage problem (Meguerdichian, Infocom 2001)
  - Quality of service (surveillance) that can be provided by a particular sensor network
  - Related to to Art Gallery Problem (solved optimally in 2D, but NP-hard in 3D)
- Exposure problem (Meguerdichian, Mobicom 2001)
  - A measure of how well an object, moving on an arbitrary path, can be observed by the sensor network over a period of time

Coverage and Exposure Problems

- *Voronoi diagram* of a set of points
  - Partitions the plane into a set of convex polygons with such that all points inside a polygon are closest to only one point.

Coverage and Exposure Problems

- A sample Voronoi diagram



Coverage and Exposure Problems

- Delaunay triangulation
  - Obtained by connecting the sites in the Voronoi diagram whose polygons share a common edge.
  - It can be used to find the two closest points by considering the shortest edge in the triangulation.

Coverage and Exposure Problems

- Maximal breach path (worst case coverage)
  - A path p connecting two end points such that the distance from p to the closest sensor is maximized
  - Fact: The maximal breach path must lie on the line segments of the Voronoi diagram.
  - Solution: binary search + breadth-first search

Coverage and Exposure Problems

- Maximal Support Path (Best Case Coverage)
  - A path *p* with the distance from *p* to the closest sensor is minimized
  - The maximal support path must lie on the lines of the Delaunay triangulation

Coverage and Exposure Problems

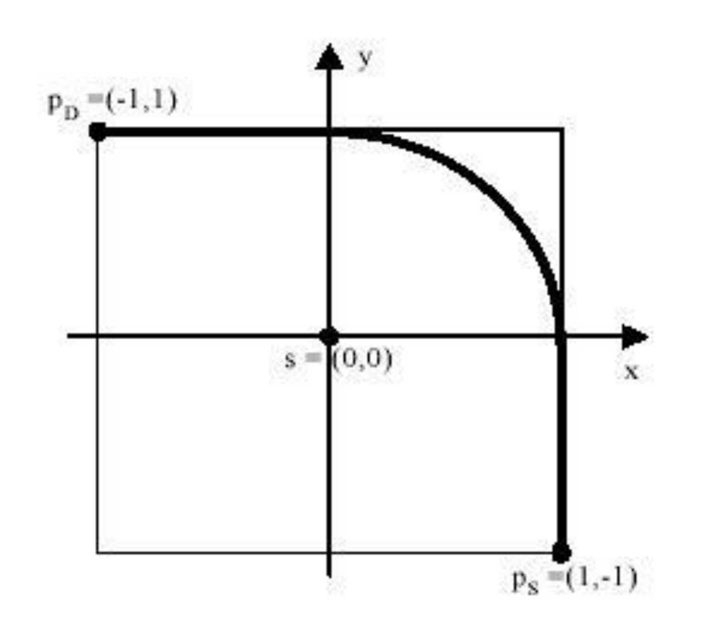
- Exposure problem
  - Expected average ability of serving a target in the sensor field
  - General sensing model:

$$S(s, p) = \frac{\lambda}{dis(s, p)^{\partial}}$$

where s is the sensor and p the point.

Coverage and Exposure Problems

- Exposure problem: integral of the sensing function

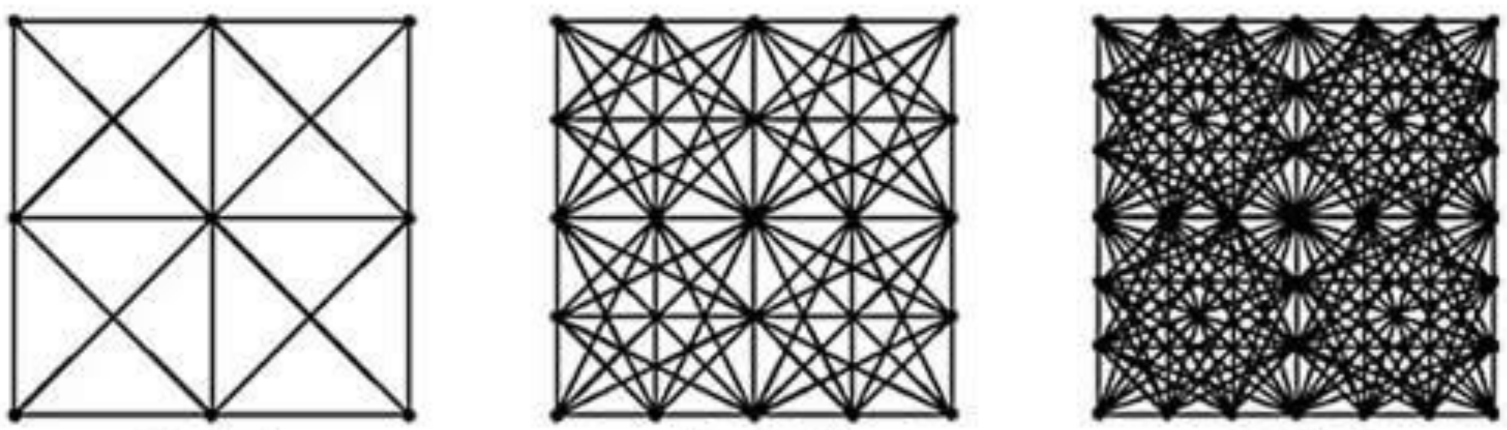


Coverage and Exposure Problems

- Minimal Exposure Path
  - Transform the continuous problem domain to a discrete one.
  - Apply graph-theoretic abstraction.
  - Compute the minimal exposure path using Dijkstra’s algorithm.

Coverage and Exposure Problems

First, second, and third-order generalized 2*2 grid



(a) n=2, m=1 (b) n=2, m=2 (c) n=2, m=3

Data Dissemination and Gathering

- Two different approaches
  - Traditional reverse multicast/broadcast tree with BS as the sink (root).
  - Three-phase protocol: sinks broadcast the interest, and sensor nodes broadcast an advertisement for the available data and wait for a request from the interested nodes.

Data Dissemination and Gathering

- Energy-efficient route (Akyildiz, 2002)
  - Maximum total available energy route
  - Minimum energy consumption route
  - Minimum hop route
  - Maximum minimum available energy node route

Data Dissemination and Gathering

- Sample data aggregation protocols
  - SMECN (Li and Halpern, ICC'01)
  - SPIN* (Heinzelman et al, MobiCom'99)
  - SAR (Sohrabi, IEEE Pers. Comm., Oct. 2000)
  - Directed Diffusion*(Intanagonwiwat et al, MobiCom'00)
  - Linear Chain* (Lidsey and Raghavendra, IEEE TPDS, Sept. 2002)
  - LEACH * (Heinzelman et al, Hawaii Conf. 2000)

Data Dissemination and Gathering

- SMECN
  - Create a subgraph of the sensor network that contains the minimum energy path
- SPIN
  - Sends data to sensor nodes only if they are interested; has three types of messages (ADV, REQ, and DATA)
- SAR
  - Creates multiple trees where the root of each tree is one hop neighbor from the sink; select a tree for data to be routed back to the sink according to the energy resources and additive QoS metric

Data Dissemination and Gathering

- Directed diffusion
  - Sets up gradients for data to flow from source to sink during interest dissemination (initiated from the sink)
- Linear Chain
  - A linear chain with a rotating gathering point.
- LEACH
  - Clusters with clusterheads as gathering points; again clusterheads are rotated to balance energy consumption

Data Dissemination and Gathering

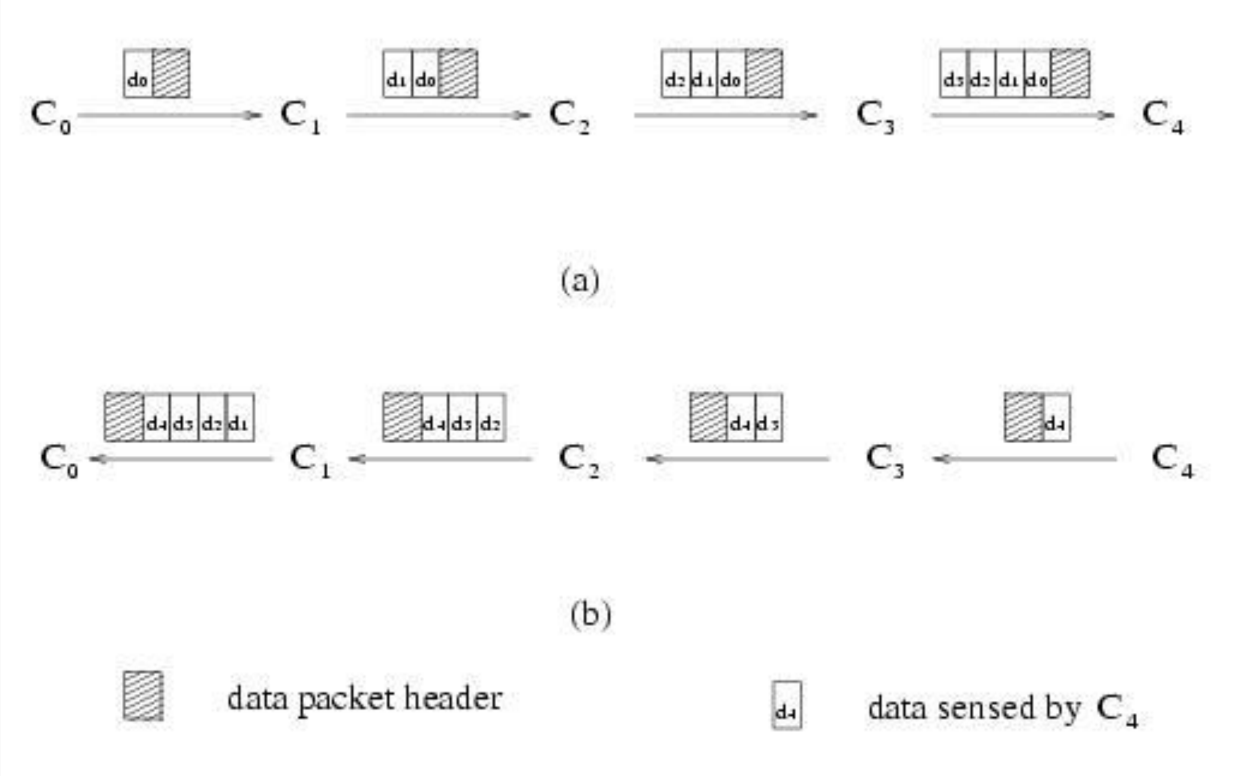
- Directed diffusion with several elements: interests, data messages, gradients, and reinforcements
  - Interests: a query (what a user wants)
  - Gradients: a direction state created in each node that receives an interests
- Events flow towards the originator's of interests along multiple gradient paths
- The sensor network reinforces one, or a small number of these paths.

Data Dissemination and Gathering

- SPIN (Sensor Protocols for Information via Negotiation): efficient dissemination of information among sensors
  - ADV: new data advertisement containing meta-data
  - REQ: request for data when a node wishes to receive some actual data.
  - DATA: actual sensor data with a meta-data header

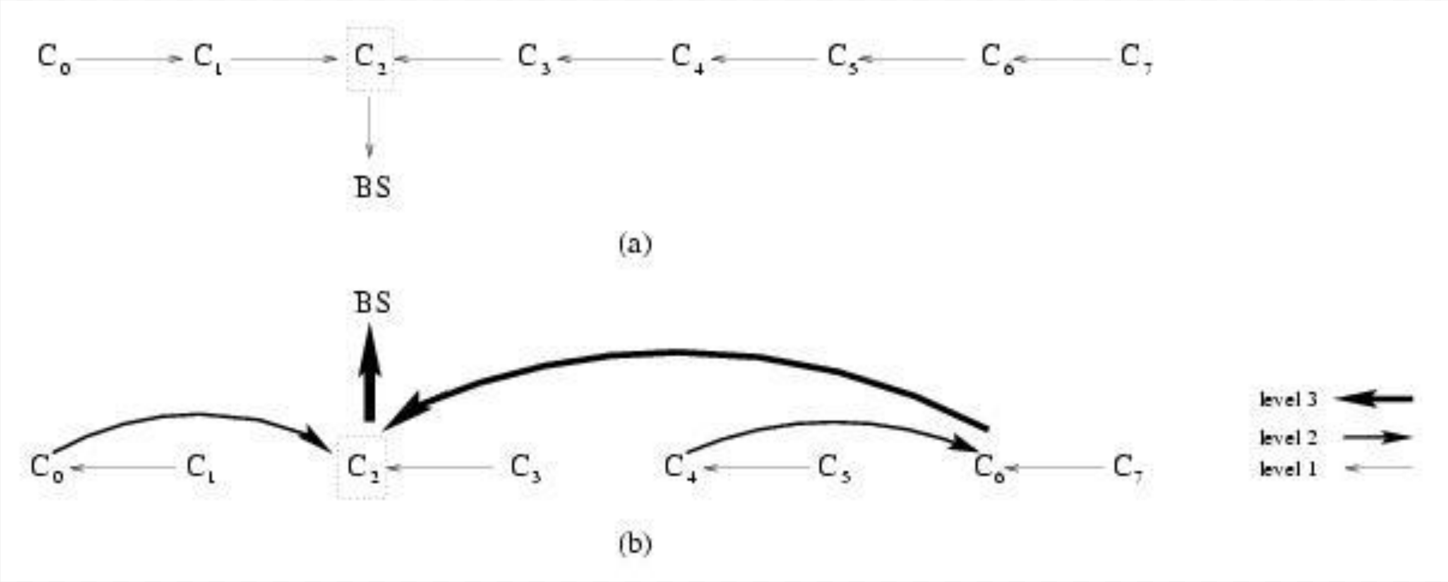
Data Dissemination and Gathering

- Sequential gathering in a linear chain



Data Dissemination and Gathering

- Parallel gathering (recursive double)

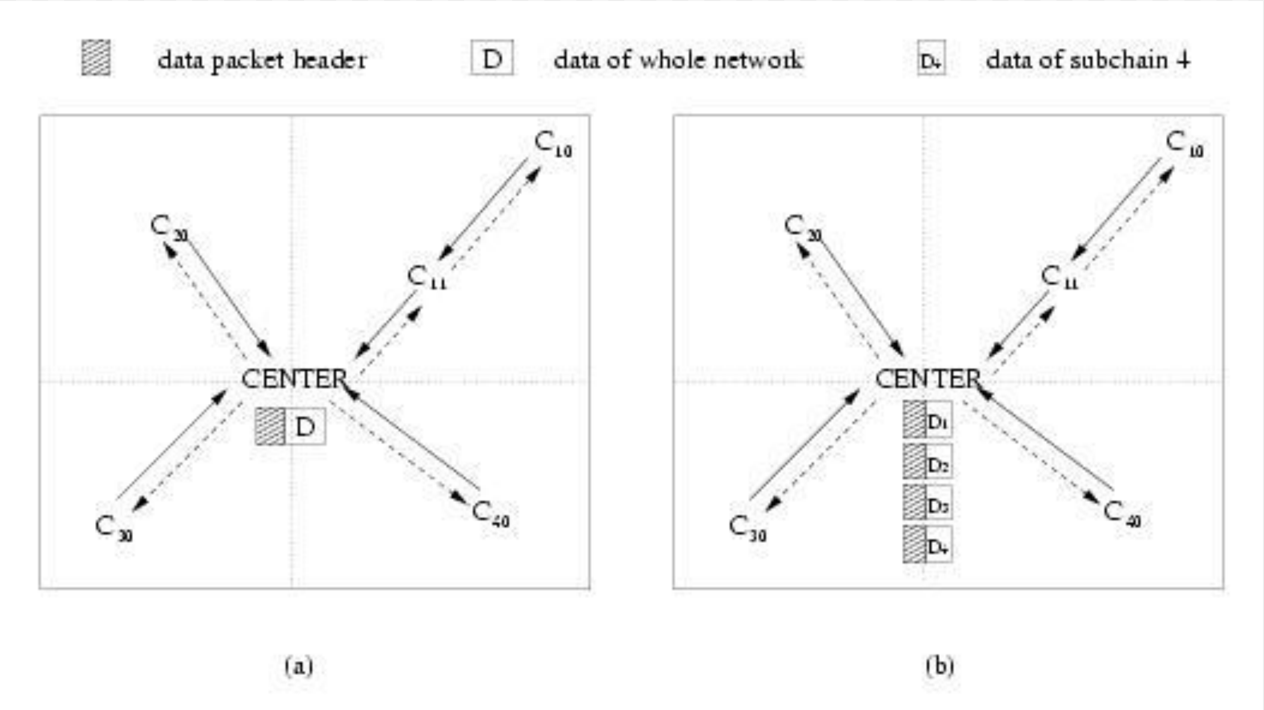


Data Dissemination and Gathering

- Enhancement
  - Multiple chain
  - Better linear chain formation
    - New node always the new head of the linear chain
    - New node can be inserted into the existing chain

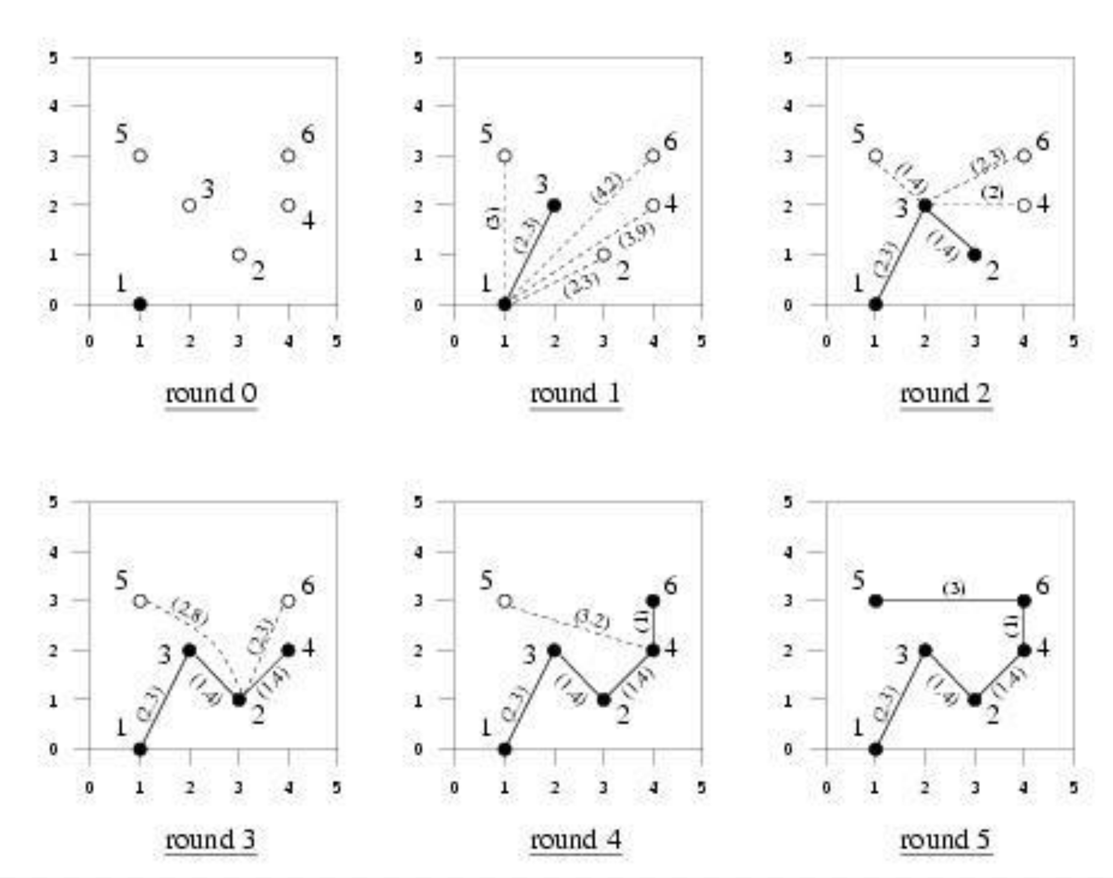
Data Dissemination and Gathering

- Multiple Chains



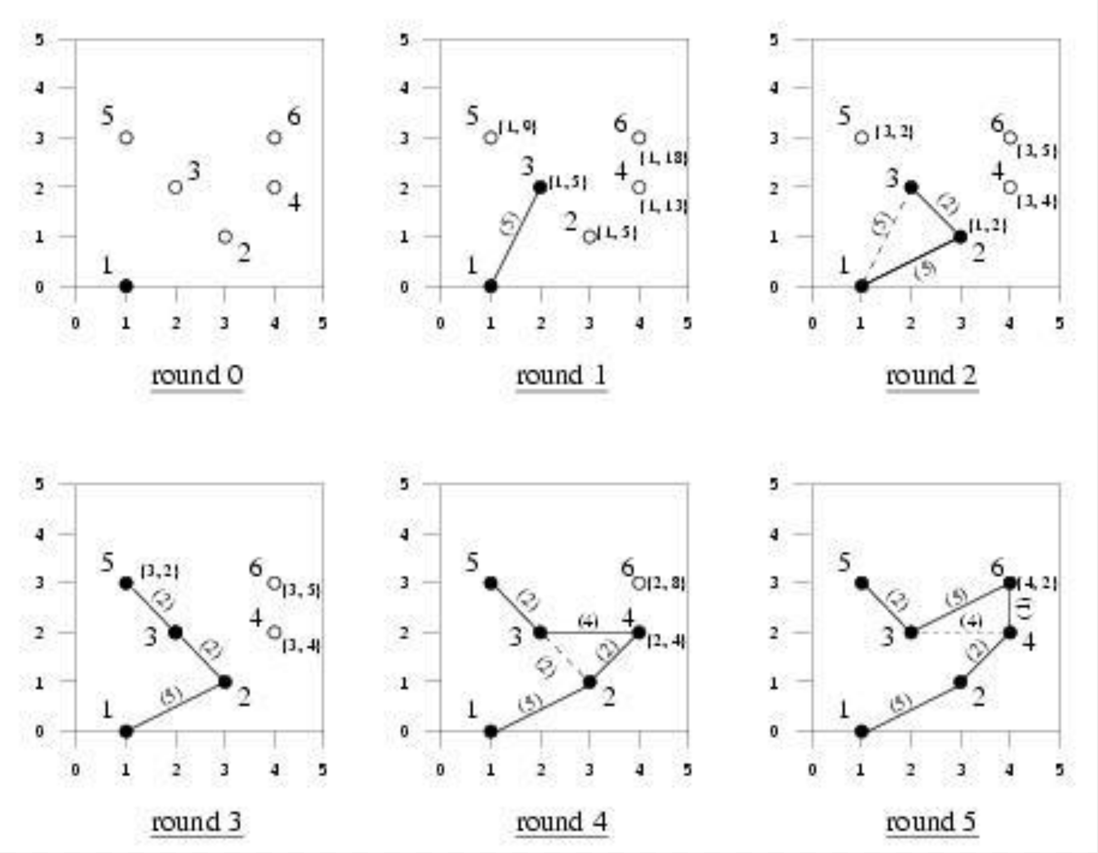
Data Dissemination and Gathering

- Simple chain (new node as head of chain)



Data Dissemination and Gathering

- Simple chain (new node inserted in the chain)



Data Dissemination and Gathering

- LEACH

$$T(i) = \begin{cases} \frac{P}{1-P(r \ mod \frac{1}{P})} & i \in G \\ 0 & otherwise \end{cases}$$

where

- P – the desired percentage of cluster heads (e.g., P=0.05)
- r – the current round
- G – the set of nodes that have not been cluster-heads in the last $\frac{1}{P}$ rounds

Data Dissemination and Gathering

- Extended LEACH (energy-based)

$$T(i) = \begin{cases} K * \frac{P}{1-P(r \bmod \frac{1}{P})} + (1-K) * \frac{E(i)}{E'(i)} * P & i \in G \\ (1-K) * \frac{E(i)}{E'(i)} * P & otherwise \end{cases}$$

where

- P – the desired percentage of cluster heads (e.g., P=0.05)
- r – the current round
- G – the set of nodes that have not been cluster-heads in the last $\frac{1}{P}$ rounds
- $E(i)$ – the current energy of node i
- $E'(i)$ – the current network average energy estimated by node i
- K – the coefficient, k=(0,1)

Sensor Coverage

- How well do the sensors observe the physical space
  - Sensor deployment: random vs. deterministic
  - Sensor coverage: point vs. area
  - Coverage algorithms: centralized, distributed, or localized
  - Sensing & communication range
  - Additional requirements: energy-efficiency and connectivity
  - Objective: maximum network lifetime or minimum number of sensors

Sensor Coverage

- Area (point)-dominating set
  - A small subset of sensor nodes that covers the monitored area (targets)
  - Nodes not belonging to this set do not participate in the monitoring – they sleep
- Localized solutions
  - With and without neighborhood information

Area-dominating set

- With neighborhood info (Tian and Geoganas, 2002)
  - Each node knows all its neighbors' positions.
  - Each node selects a random timeout interval.
  - At timeout, if a node sees that neighbors who have not yet sent any messages together cover its area, it transmits a "withdrawal" and goes to sleep
  - Otherwise, the node remains active but does not transmit any message

Point-dominating set

- With neighborhood info based on Dai and Wu's Rule k (Carle and Simplot-Ryl, 2004)
  - Each node knows either 2- or 3-hop neighborhood topology information
  - A node u is fully covered by a subset S of its neighbors iff three conditions hold
    - The subset S is connected.
    - Any neighbor of u is a neighbor of S.
    - All nodes in S have higher priority than u.

Coverage without neighborhood info

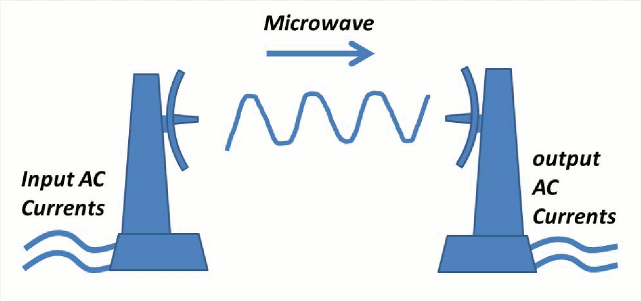
- PEAS: probabilistic approach (F. Ye et al, 2003)
  - A node sleeps for a while (the period is adjustable) and decides to be active iff there are no active nodes closer than r'.
  - When a node is active, it remain active until it fails or runs out of battery.
  - The probability of full coverage is close to 1 if

$$r' \leq (1 + \sqrt{5}\ ) r$$

where r is the sensing (transmission) range

Mobile Charging: State of the Art

- The enabling technology
  - Wireless energy transfer (Kurs '07)
  - Wireless Power Consortium

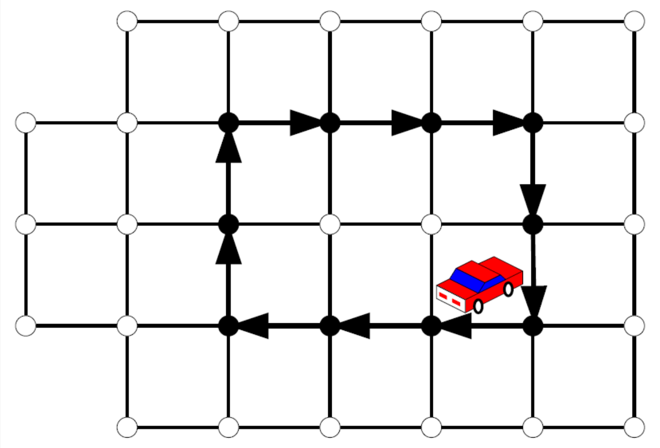


- Mobile chargers (MC)
  - MC moves from one location to another for wireless charging
  - Extended from mobile sink in WSNs and ferry in DTNs
  - Energy consumption
    - The movement of MC
    - The energy charging process

(DTNs: Delay Tolerant Networks)

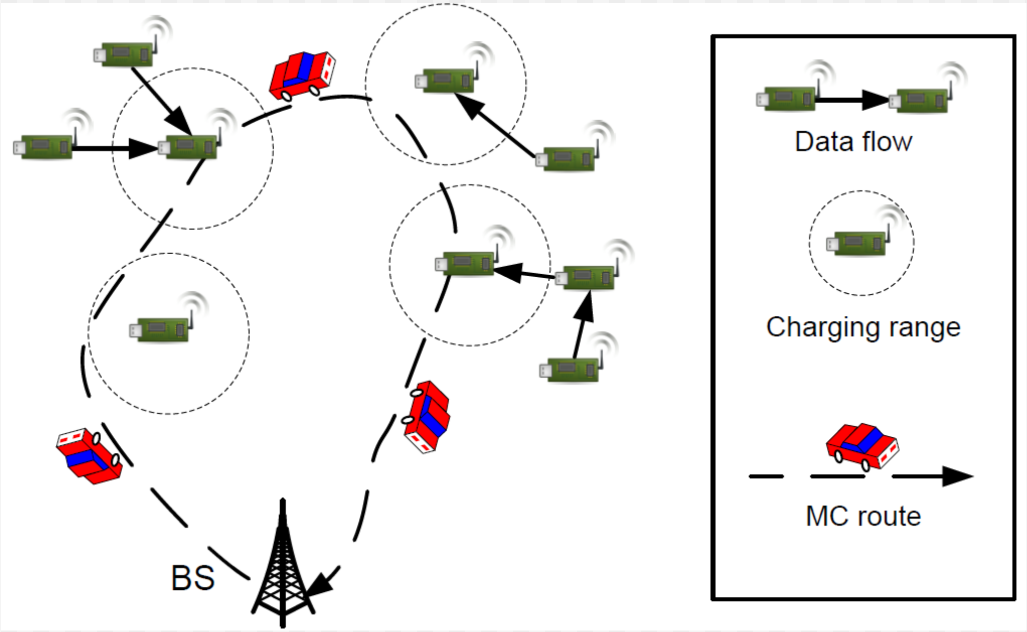
Combinatorics and Graph Models

- Traveling-Salesmen Problem (TSP)
  - A minimum cost tour of n cities: the salesman travels from an origin city, visits each city exactly one time, then returns to the origin
- Covering Salesman Problem (CSP, Ohio State '89)
  - The least cost tour of a subset of cities such that every city not on the tour is within some predetermined covering distance
- Extended CSP
  - Connected dominating set (FAU '99)
  - Qi-ferry (UDelaware '13)



Mobile Sinks and Chargers

- Local trees
  - Data collections at all roots
  - Periodic charging to all sensors
- Base station (BS)
- Objectives
  - Long vocation at BS (VT '11-14)
  - Energy efficiency with deadline (Stony Brook '13)



How to Solve It (Poyla)

- If you can't solve a problem, then there is an easier problem you can solve: find it

- Four principles
  - Understand the problem
  - Devise a plan
  - Carry out the plan
  - Look back

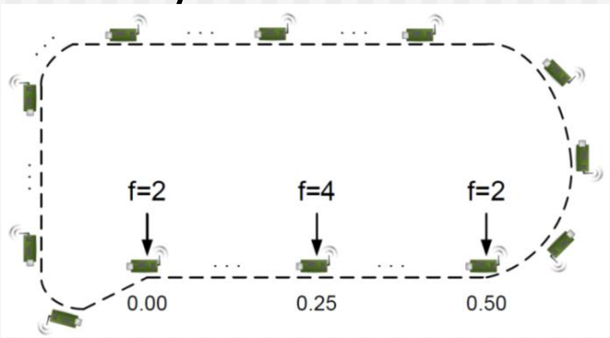
Collaborative Coverage & Charging

- Most existing methods
  - An MC is fast enough to charge all sensors in a cycle
  - An MC has sufficient energy to replenish an entire WSN (and return to BS)
- Collaborative approach using multiple MCs
  - Problem 1: MCs with unrestricted capacity but limitations on speed
  - Problem 2: MCs with limited capacity and speed, and have to return to BS

Problem Description

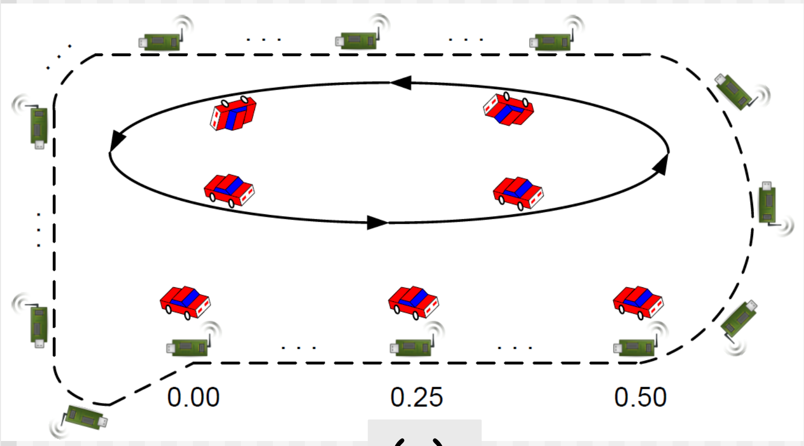
- Problem 1: Determine the minimum number of MCs (unrestricted capacity but limitations on speed) to cover a line/ring of sensors with uniform/non-uniform recharge frequencies

- A toy example
  - A circle track with circumference 3.75 densely covered with sensors with recharge frequency f=1
  - Sensors with f=2 at 0 and 0.5
  - A sensor with f=4 at 0.25
  - What are the minimum number of MCs and the optimal trajectory planning of these MCs? (MC's max speed is 1.)

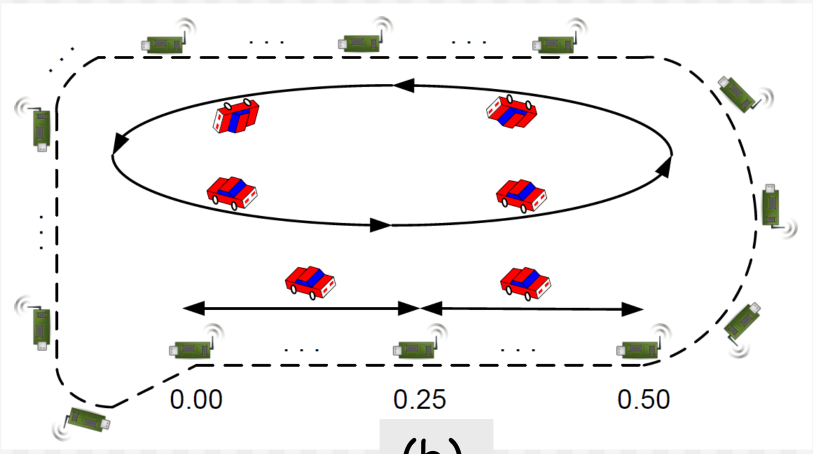


Possible Solutions

- Assigning cars for sensors with f>1 (a) fixed and (b) moving

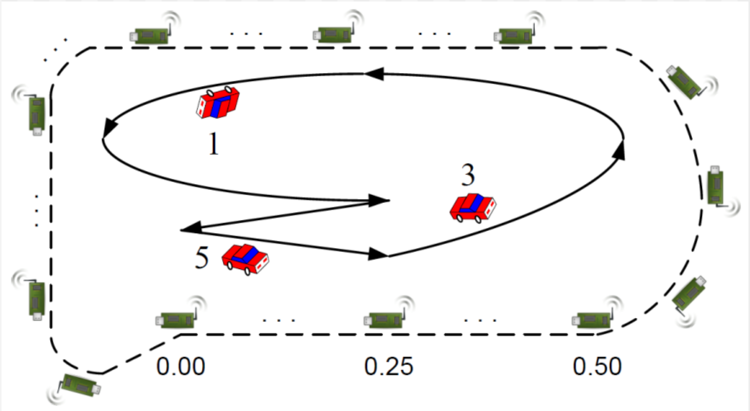


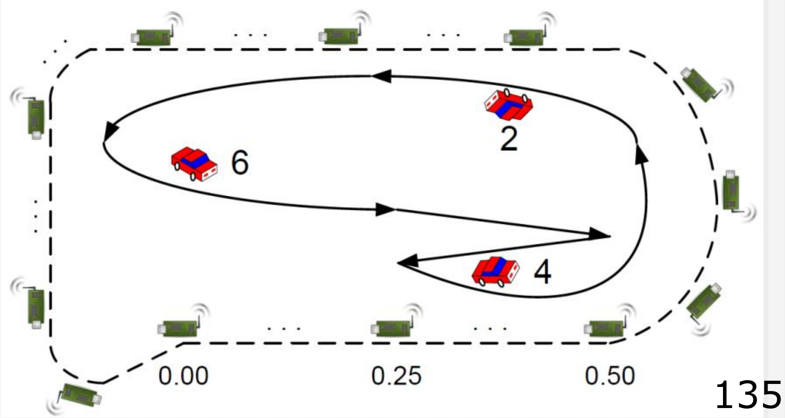
(a)



(b)

- Combining odd and even car circulations (c)

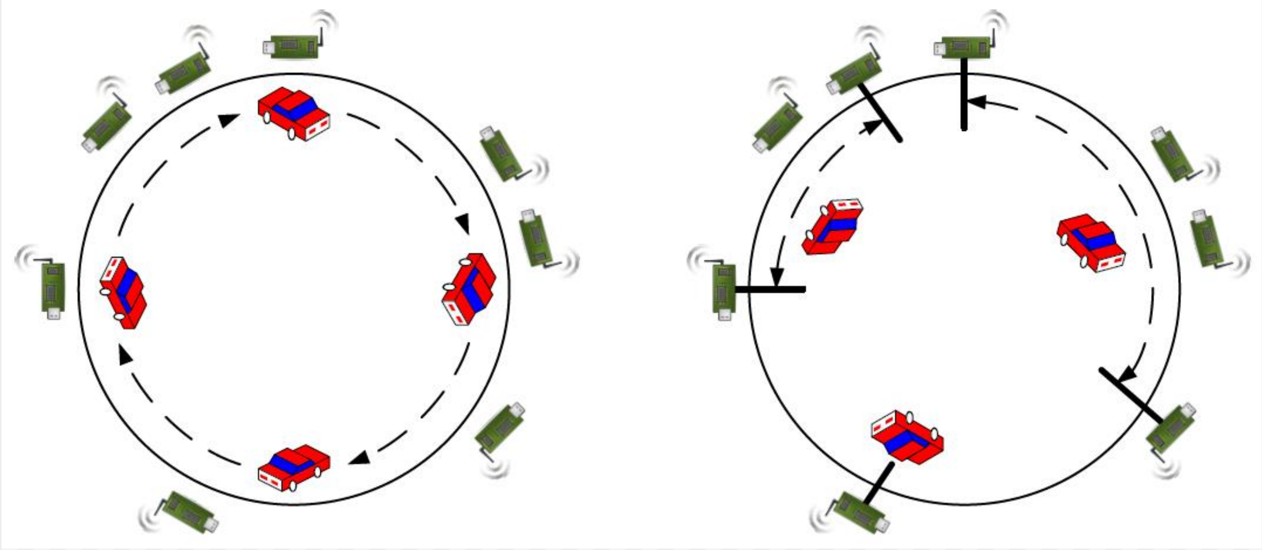




(c)

Optimal Solution (uniform frequency)

- M_1: There are C_1 MCs moving continuously around the circle
- M_2: There are C_2 MCs moving inside the fixed interval of length $\frac{1}{2}$ so that all sensors are covered
- Combined method: It is either M_1 or M_2, so $C = \min\{C_1, C_2\}$

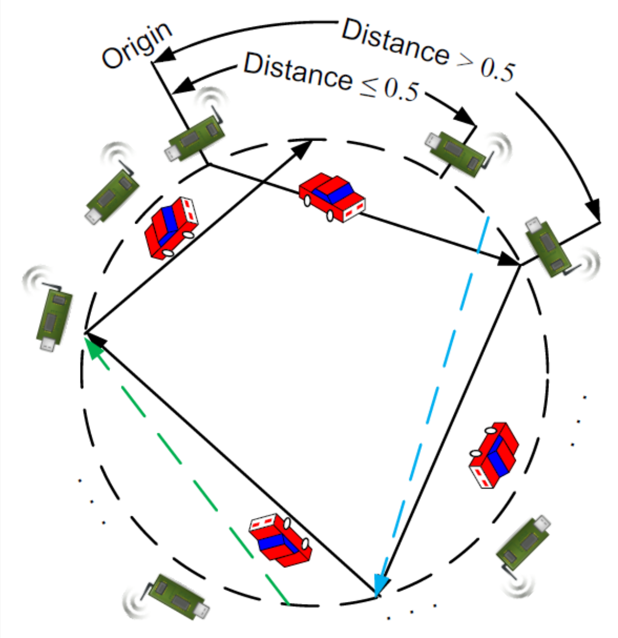


Properties

- Theorem 1 (*ACM MSCC'14*): The combined method is optimal in terms of the minimum number of MCs used
- Scheduling
  - Find an appropriate breakpoint to convert a circle to a line; M_2 in the optimal solution is then followed
  - A linear solution, O(n), is used to determine the breakpoint, assuming n is the number of nodes and the circumference is a known constant

Linear Solution

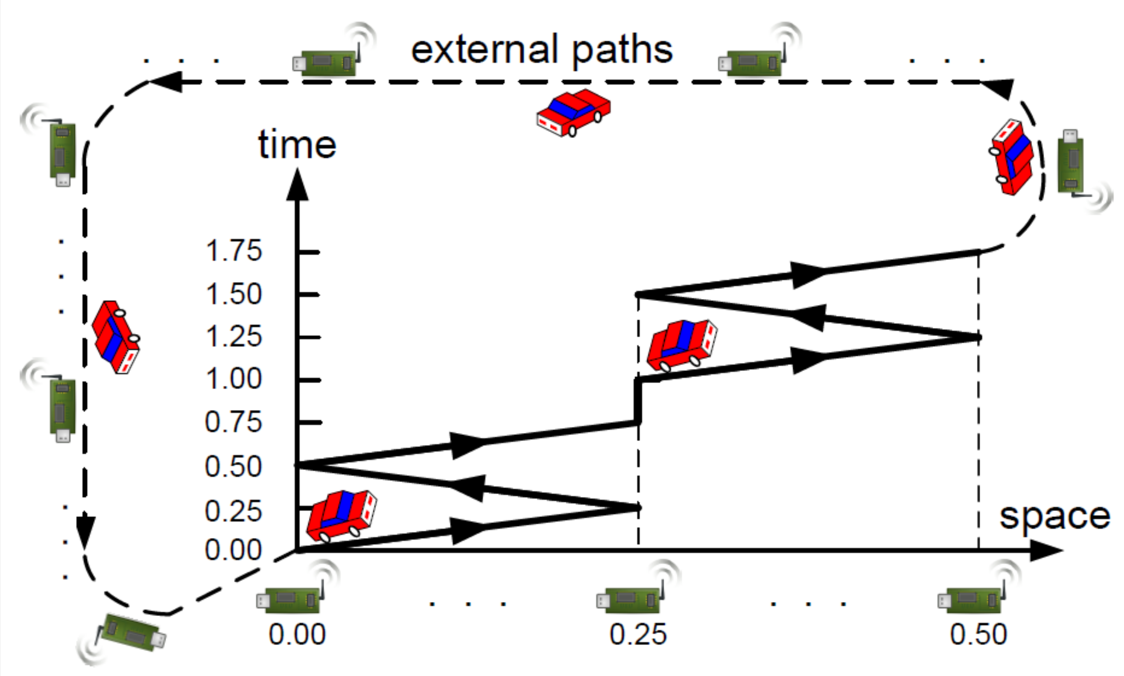
- Directed Interval Graph
  - Each directed link points from the start to the end of an interval (i.e., the first sensor beyond distance 0.5)



- The number of intervals in two solutions differ by one
- Each sensor has one outgoing and multiple incoming links
- The process stops when a path with fewer or more intervals is found or all sensors (with their outgoing links) are examined

Solution to the Toy Example

- 5 cars only, including a stop at 0.25 for ¼ time unit



- Challenges: time-space scheduling, plus speed selection

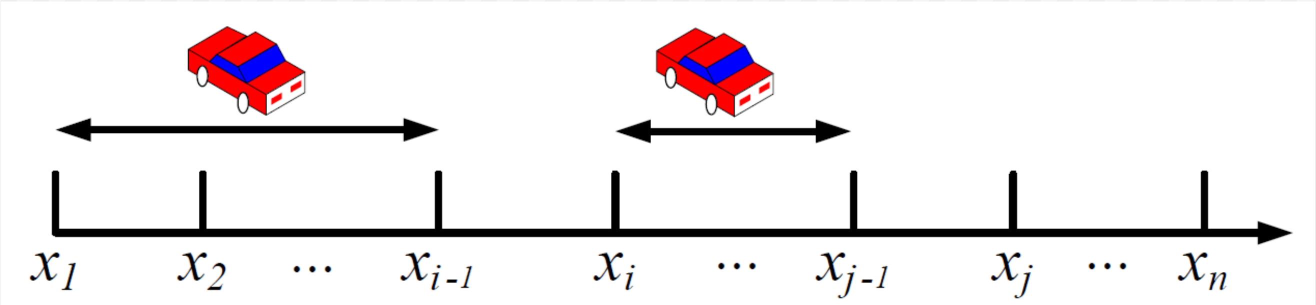
Greedy Solution (non-uniform frequency)

- Coverage of sensors with non-uniform frequencies

serve($x_1,\ldots,x_n$; $f_1,\ldots,f_n$):

When $n \neq 0$, generate an MC that goes back and forth as far as possible at full speed (covering $x_1, \ldots, x_{i-1}$);

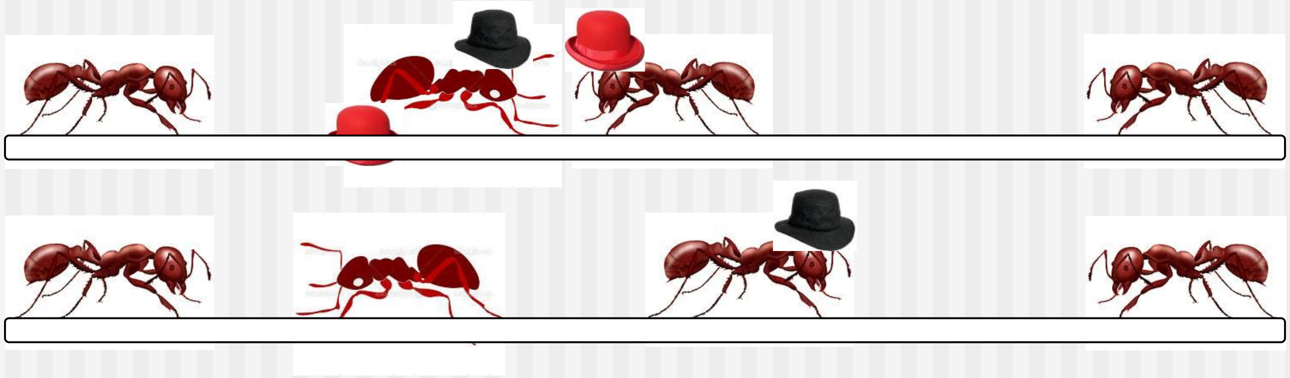
serve($x_i,\ldots,x_n$; $f_i,\ldots,f_n$)



- Theorem 2 (ACM MSCC'14): The greedy solution is within a factor of 2 of the optimal solution

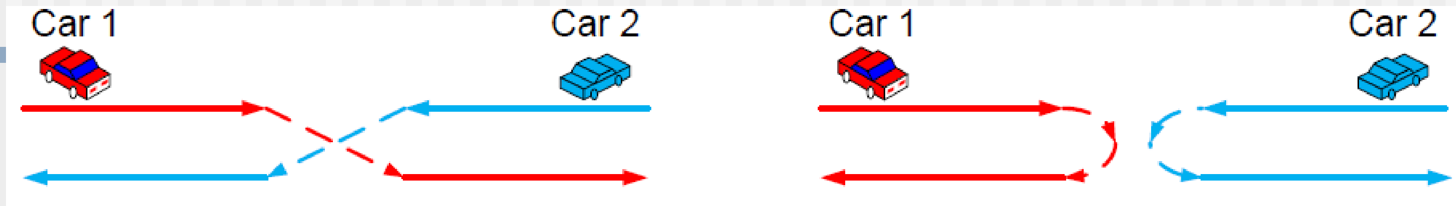
The Ant Problem: An Inspiration

- Ant Problem, Comm. of ACM, March 2013
  - Ant Alice and her friends always march at 1 cm/sec in whichever direction they are facing, and reverse directions when they collide
  - Alice stays in the middle of 25 ants on a 1 meter-long stick
  - How long must we wait before we are sure Alice has fallen off the stick?

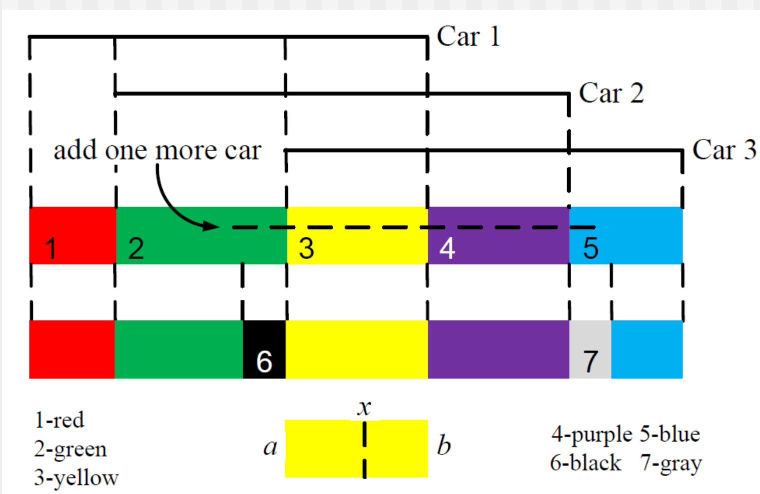


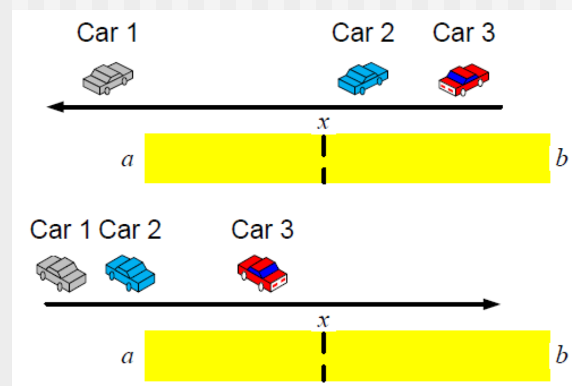
  - Exchange "hats" when two ants collide

Proof of Theorem 2



- Two cars never meet or pass each other
- Partition the line into 2k-1 sub-regions based on different car coverage (k is the optimal number of cars)
- Each sub-region can be served by one car at full speed
- One extra car is used when a circle is broken to a line



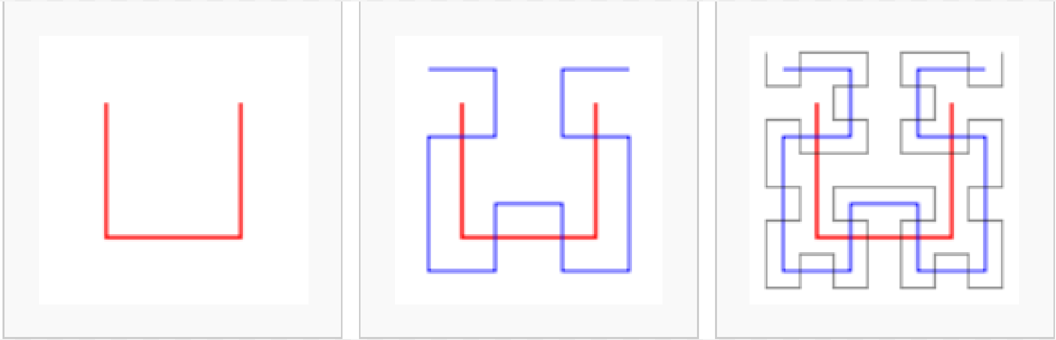


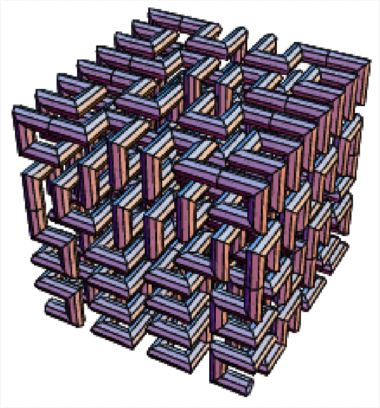
$2(x-a) \le f_x$ and $2(b-x) \le f_x$

$b-a \le f_x$

Imagination

- Hilbert curve for k-D
  - Mapping from 2-D to 1-D for preserving distance locality

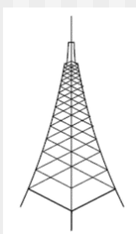


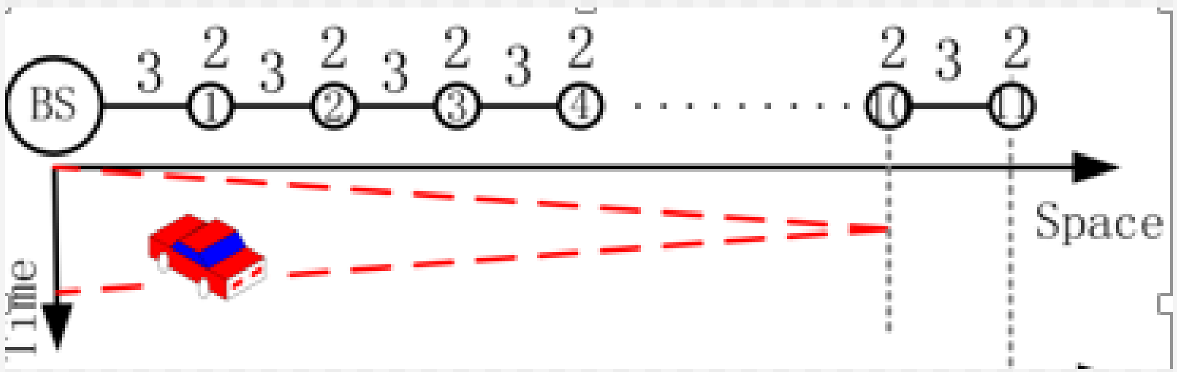


- Charging time: converting to distance
- Limited capacity: using cooperative charging
  - BS to MC
  - MC to MC

Charging a Line (with limited capacity)

- Charge battery capacity: 80J
- Charger cost: 3J per unit traveling distance
- Sensor battery capacity: 2J

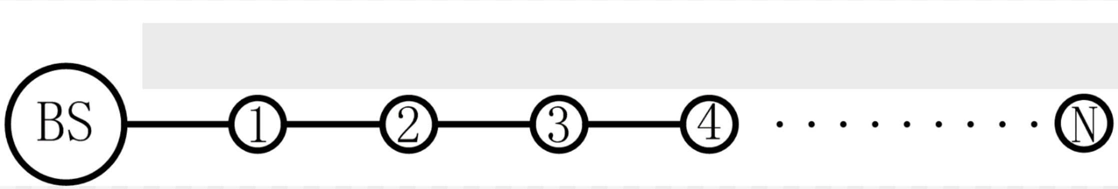




- One MC cannot charge more than 10 consecutive sensors

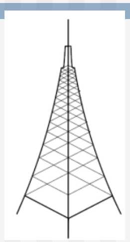
Problem Description

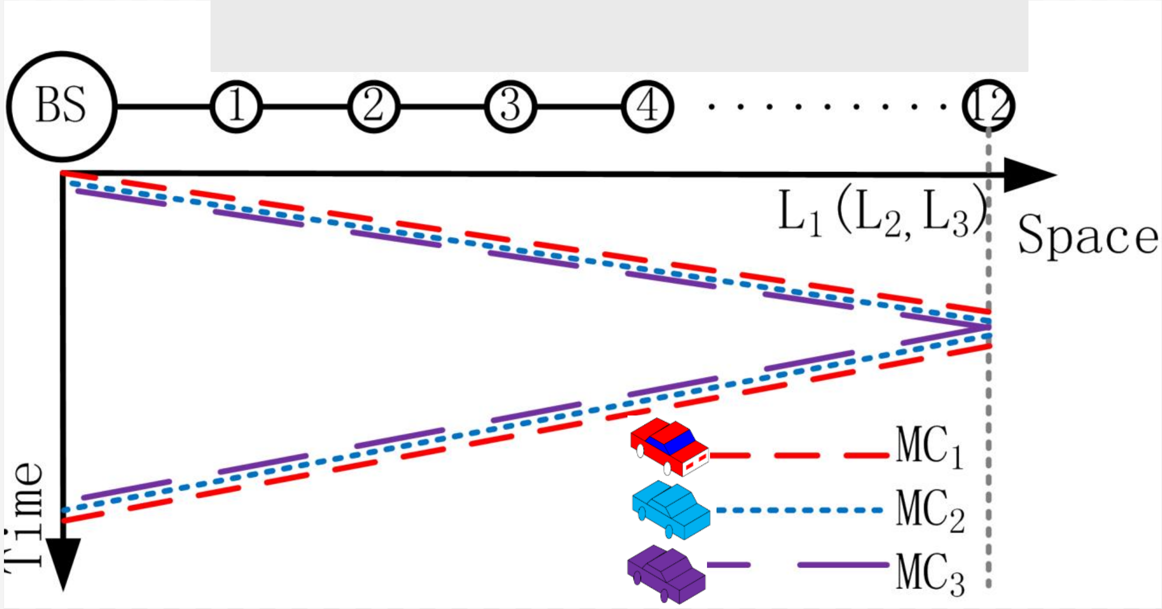
- Problem 2 (IEEE MASS'12): Given k MCs with limited capacity, determine the furthest sensor they can recharge while still being able to go back to the BS
- WSN
  - N sensors, unit distance apart, along a line
  - Battery capacity for each sensor : b
  - Energy consumption rate for each sensor: r
- MC
  - Battery capacity: B
  - Energy consumption rate due to travelling: c



Motivation Example (1)

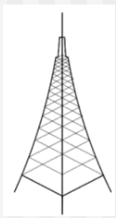
B=80J, b=2J, c=3J/m, K=3 MCs

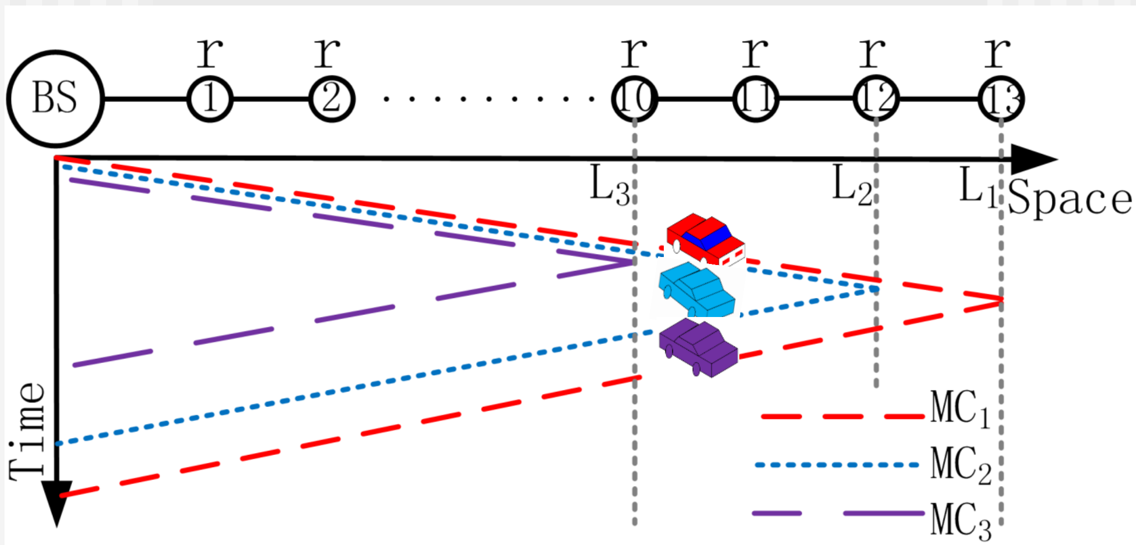




- Scheme I: (equal-charge) each MC charges all sensors b/K J (Joule)
- Conclusion: covers 12 sensors, and max distance is < B/2c (as each MC needs a round-trip traveling cost)

Motivational Example (2)

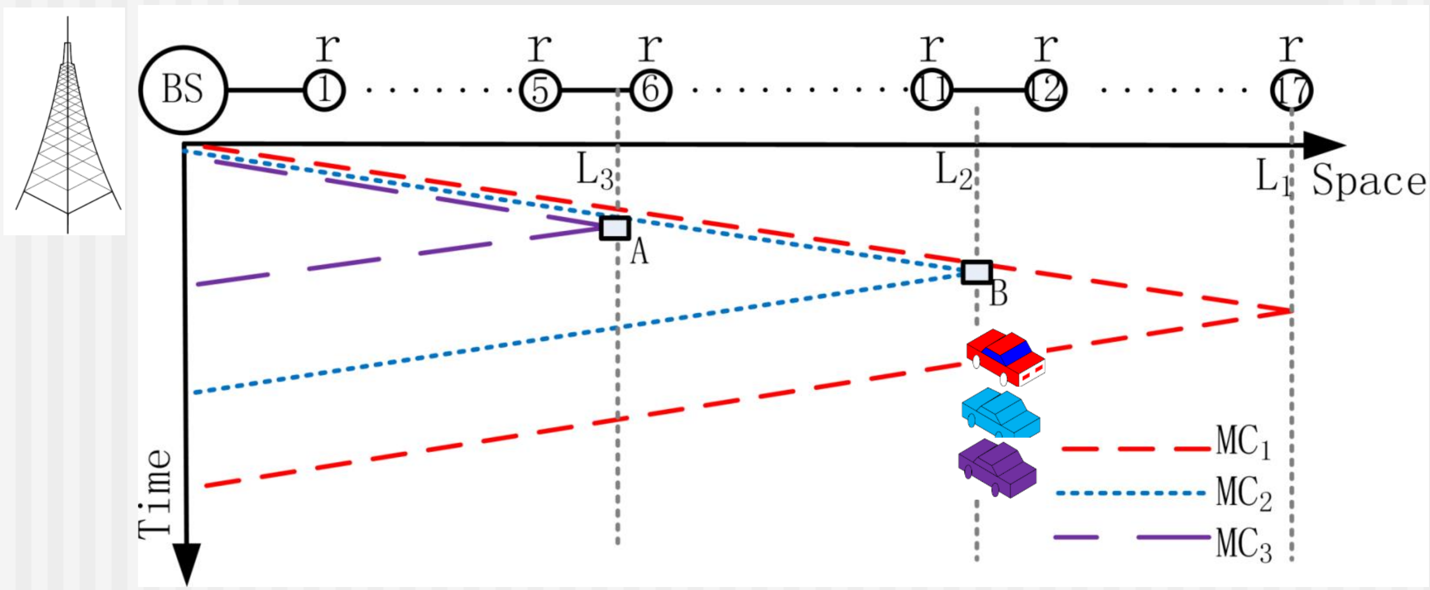




- Scheme II: (one-to-one) each sensor is charged by one MC
- Conclusion: covers 13 sensors, and max distance is still < B/2c

  (as the last MC still needs a round-trip traveling cost)
- Scheme II reaches further than Scheme I

Motivational Example (3)



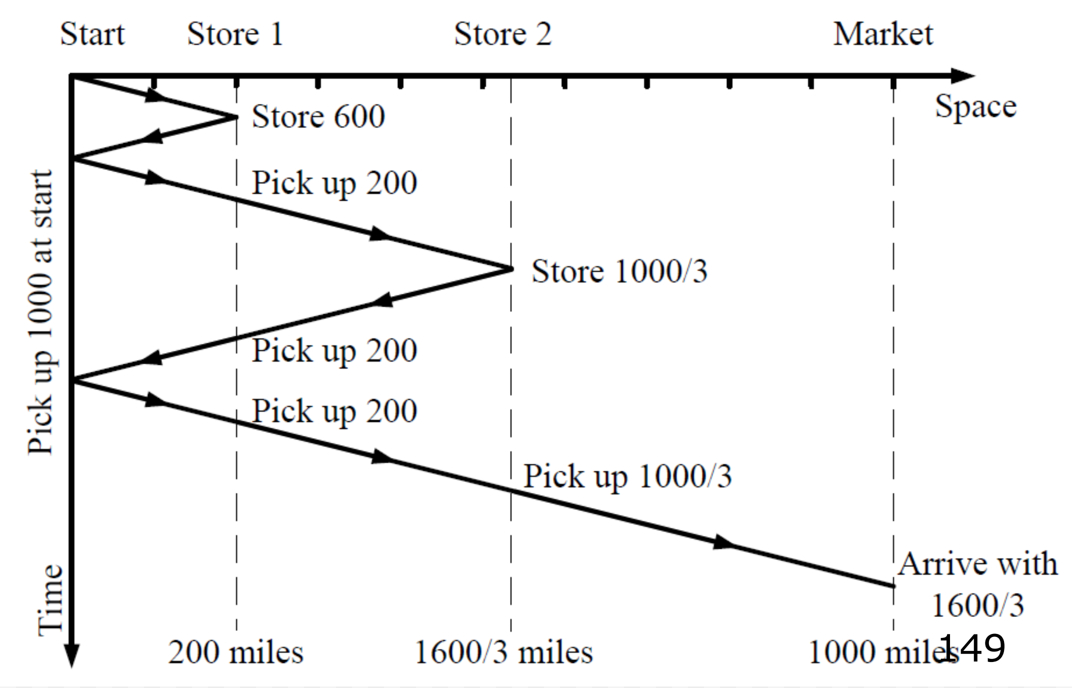
- Scheme III: (collaborative-one-to-one-charge) each MC transfers some energy to other MCs at rendezvous points

- Conclusion: covers 17 sensors, and max distance is < B/c
  (Last MC still needs a return trip without any charge)

Bananas and a Hungry Camel

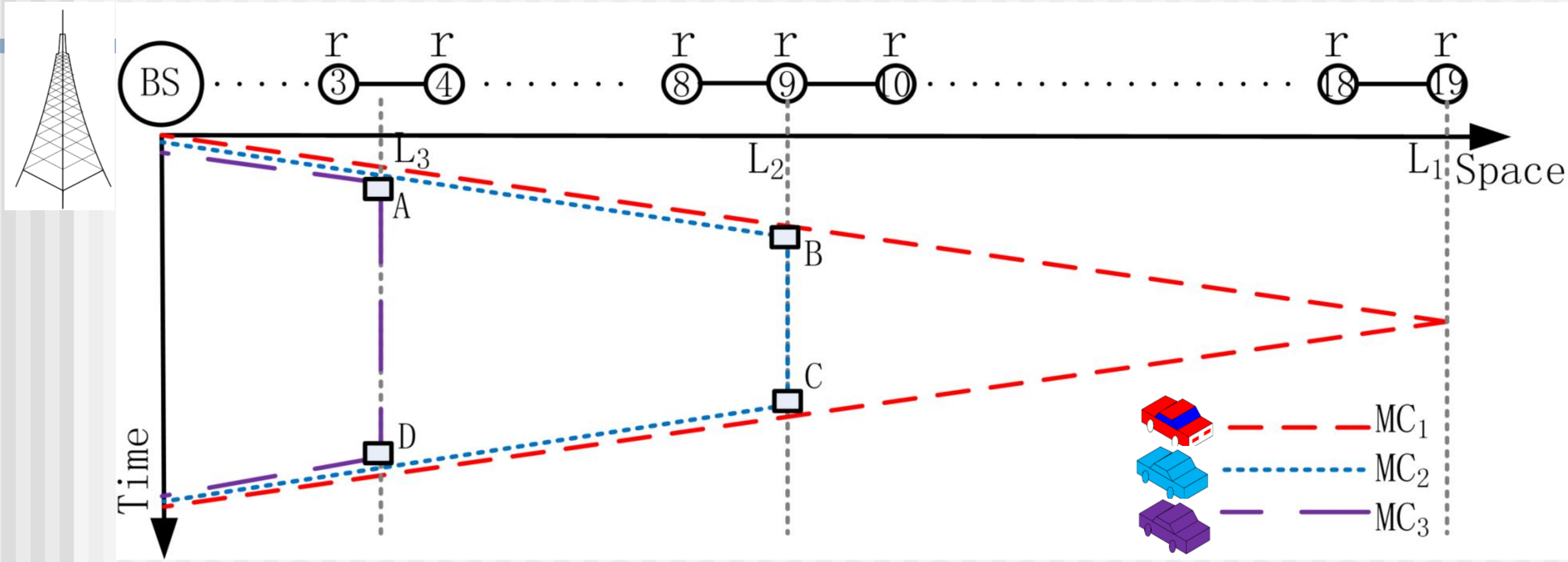
- A farmer grows 3,000 bananas to sell at market 1,000 miles away. He can get there only by means of a camel. This camel can carry a maximum of 1,000 bananas at a time, but needs to eat a banana to refuel for every mile that he walks

What is the maximum number of bananas that the farmer can get to market?

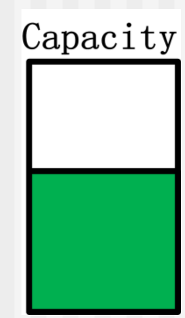


Motivational Example (4): GlobalCoverage

B = 80J, b=2J, c=3J/m, K=3 MCs



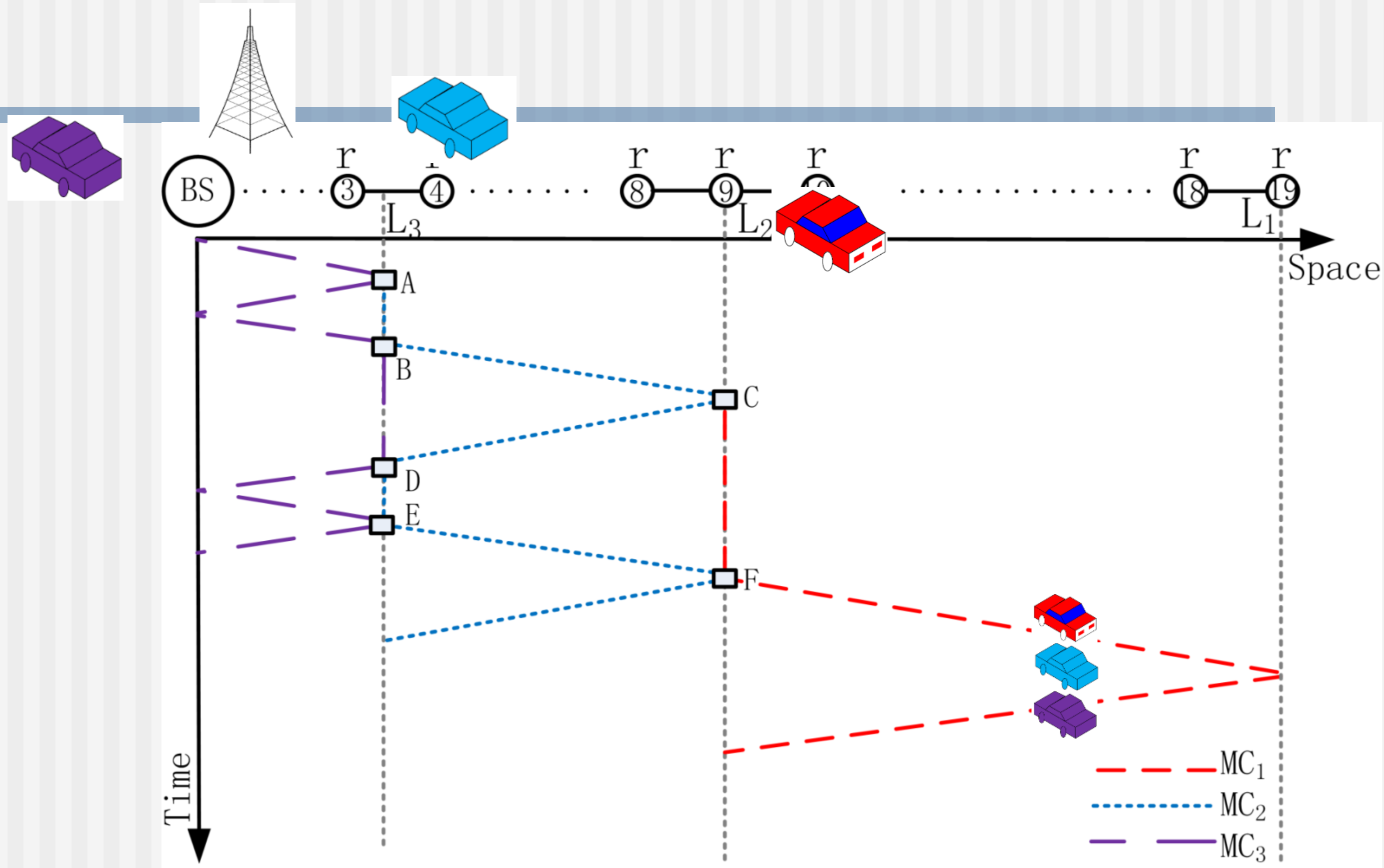
- "Push": limit as few chargers as possible to go forward
- "Wait": efficient use of battery "room" through two charges
- Conclusion: covers 19 sensors, and max distance is ∞ with unlimited number of MCs



Details on Push-and-Wait

- MC_i charges battery to all sensors between L_{i+1} and L_i
- MC_i ($1 \leq i \leq K$) transfers energy to MC_{i-1}, … MC_1 to their full capacity at L_i
- MC_i waits at L_i, while all other MCs keep moving forward
- After MC_i, MC_{i-1}, … MC_1 return to L_i, MC_i evenly balances energy among them (including itself)
- Each Mc_i, MC_{i-1}, … MC_1 has just enough energy to return to L_{i+1}

Another Solution



- Each MC moves and charges (is charged) between two adjacent rendezvous points
- Imagination: MC_i of LocalCoverage "simulates" MC_i, MC_{i-1}, …, MC_1 of GlobalCoverage

Properties

- Theorem 3 (Optimality): GlobalCoverage has the maximum ratio of payload energy to overhead energy
- Theorem 4 (Infinite Coverage): GlobalCoverage can cover an infinite line
  - Summation of segment length ($L_i - L_{i+1}$)

$$\sum_{i=1}^{K} \frac{B}{2 \cdot c \cdot i + b} > \sum_{i=i_0}^{K} \frac{B}{2 \cdot c \cdot i + b} (\text{let } 2 \cdot c \cdot i_0 \geq b)$$

$$> \sum_{i=i_0}^{K} \frac{B}{4 \cdot c \cdot i} = \frac{B}{4 \cdot c} \sum_{i=i_0}^{K} \frac{1}{i} (\text{harmonic series})$$

Imagination: Extensions

- Simple extensions (while keeping optimality)
  - Non-uniform distance between adjacent sensors
    - Same algorithm
  - Smaller recharge cycle (than MC round-trip time)
    - Pipeline extension
- Complex extensions
  - Non-uniform frequency for recharging
  - Two- or higher-dimensional space

Imagination: Applications

- Robotics
  - Flying robots
  - Google WiFi Balloon

- Tesla Moters
  - Tesla Roadster: all-electric
  - Supercharger networks

Conclusions

- Wireless energy transfer
- Collaborative mobile charging & coverage:
  - Unlimited capacity vs. limited capacity (with BS)
  - Charging type: BS-to-MC, MC-to-MC, and MC-to-Sensor
- Other extensions
  - Charging efficiency, MCs as mobile sinks for BS…
- Simplicity + Elegance + Imagination = Beauty

Real Problem I: DC Metro

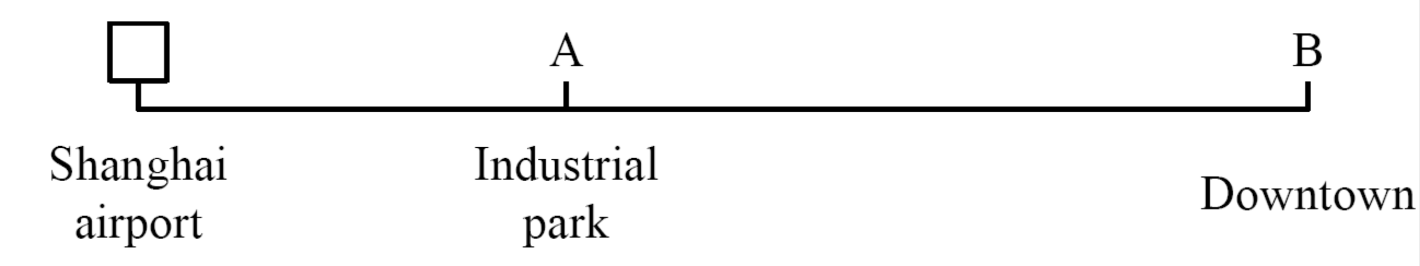
- **Problem:** The Washington, DC subway system charges fees based on travelling distance. For example, a passenger enters station A, stays there for X (say, 10) hours, and exits station B. The charge is proportion to the distance between A and B and is irrelevant to X

- What are potential flaws? Provide possible solutions. What happen if X is limited to 4 hours as in Nanjing, P. R. China?

Real Problem II: Shanghai Taxi

- **Problem:** At the Shanghai international airport, taxi drivers at have to wait for at least 4 hours. It is unfair for a driver if a passenger's destination is the Shanghai industrial park, which is about 20 minutes away, although an overwhelming majority of passengers will go to downtown, which is around 50 minutes

- Find a solution so that interests of both drivers and customers are protected. Find potential flaws with the current solution at the Shanghai international airport.



Localization overview

- Sample Localization Methods
  - Beyond Connectivity (Sensys 09)
  - Push the limit of WiFi (MobiCom 12)
  - I am the antenna (MobiCom 11)

*Some slides are borrowed from authors

GPS is not always good

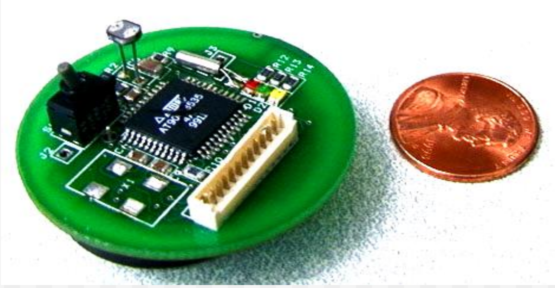
- Requires clear sky, doesn’t work indoor
- Too expensive.

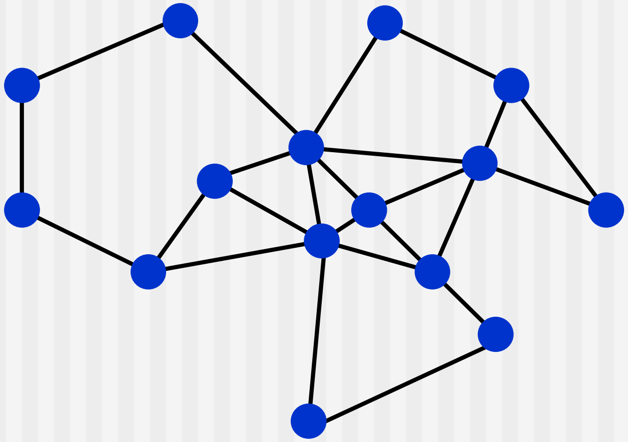
- Localization algorithm:
  - (optional) Some nodes (anchors or beacons) know their locations (e.g., through GPS).
  - Nodes make local measurements;
    - – Distances or angles between two neighbors.
  - • Communicate between each other;
  - • Infer location information from these measurements.

- Find where the sensor is…
- Location information is important.
- Devices need to know where they are.
  - Sensor tasking: turn on the sensor near the window…
- We want to know where the data is about.
  - A sensor reading is too hot – where?
- It helps infrastructure establishment.
  - geographical routing
  - sensor coverage.

Wireless Sensor Networks

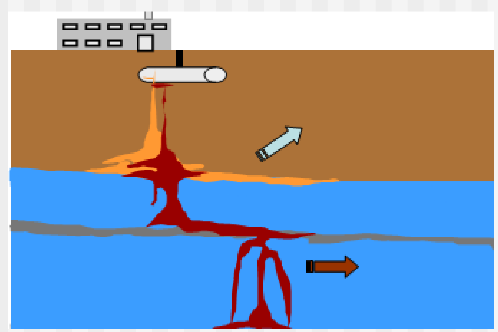
- a large number of self-sufficient nodes
- nodes have sensing capabilities
- can perform simple computations
- can communicate with each other

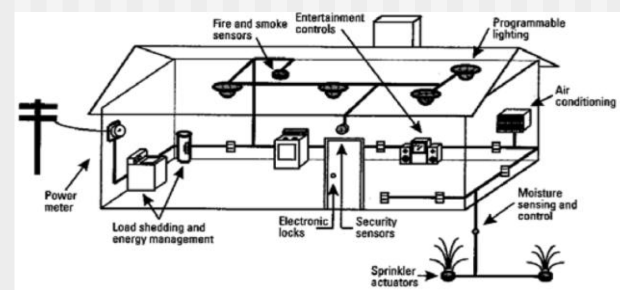




Environments of Deployment

- Indoor vs outdoor
- Stationary vs mobile
- 2D vs 3D





Localization

- What?
  - To determine the physical coordinates of a group of sensor nodes in a wireless sensor network (WSN)
  - Due to application context and massive scale, use of GPS is unrealistic, therefore, sensors need to self-organize a coordinate system

- Why?
  - To report data that is geographically meaningful
  - Services such as routing rely on location information; geographic routing protocols; context-based routing protocols, location-aware services

Problem Formulation

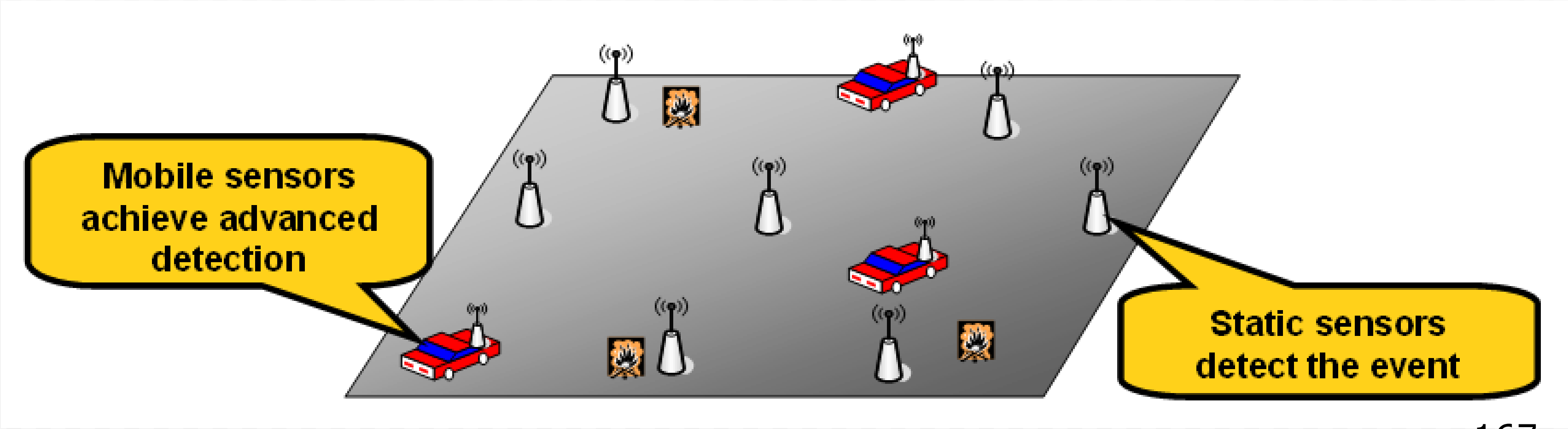
- Defining a coordinate system
- Calculating the distance between sensor nodes

Defining a Coordinate System

- Global
  - Aligned with some externally meaningful system (e.g., GPS)
- Relative
  - An arbitrary rigid transformation (rotation, reflection, translation) away from the global coordinate system

Classifications of Localization Methods

- Centralized vs Distributed
- Anchor-free vs Anchor-based
- Range-free vs Range-based
- Mobile vs Stationary



Centralized vs Distributed

- Centralized
  - All computation is done in a central server
- Distributed
  - Computation is distributed among the nodes

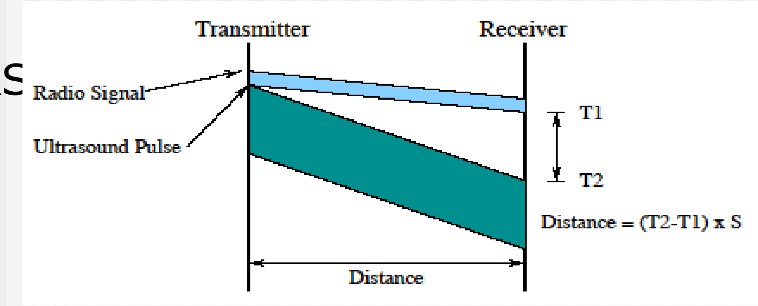
Anchor-Free vs Anchor-Based

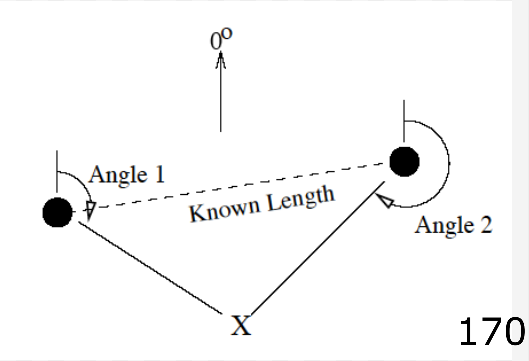
- Anchor Nodes:
  - Nodes that know their coordinates a priori
  - By use of GPS or manual placement
  - For 2D three and 3D four anchor nodes are needed
- Anchor-free
  - Relative coordinates
- Anchor-based
  - Use anchor nodes to calculate global coordinates

Range-Free vs Range-Based

- Range-Free
  - Local Techniques
  - Hop-Counting Techniques

- Range-Based
  - Received Signal Strength Indicator (RS
    - Attenuation
    - RF signal
  - Time of Arrival (ToA)
    - time of flight
  - Time Difference of Arrival (TDoA)
    - requires time synchronization
    - electromagnetic (light, RF, microwave)
    - sound (acoustic, ultrasound)
  - Angle of Arrival (AoA)
    - RF signal





Generic Approach Using Anchor Nodes

1. Determine the distances between regular nodes and anchor nodes. (Communication)

2. Derive the position of each node from its anchor distances. (Computation)

3. Iteratively refine node positions using range information and positions of neighboring nodes. (Communication & Computation)

Using RF for Ranging

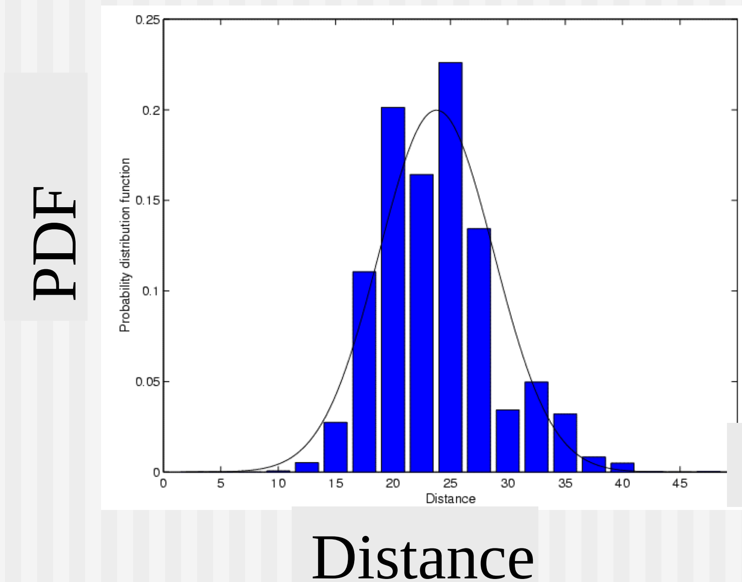
- RF TOF techniques
  - Accurate, deterministic transponders hard to build
    - Temperature-dependence problems in timing of path from receiver to transmitter
    - But, you can use "RBS" techniques… (compare receptions)
  - Measuring TOF requires fast, synchronized clocks to achieve high precision ($c \approx 1$ ft/ns)
    - Fast synchronized clocks generally at odds with low power
    - Trade-off: synchronized infrastructure vs. nodes (e.g. GPS)
- Ultra wide-band ranging for sensor nets?
  - Current research focus in RF community
  - Based on very short wideband pulses, measure RTT to fixed, surveyed base stations
  - FCC licensing?

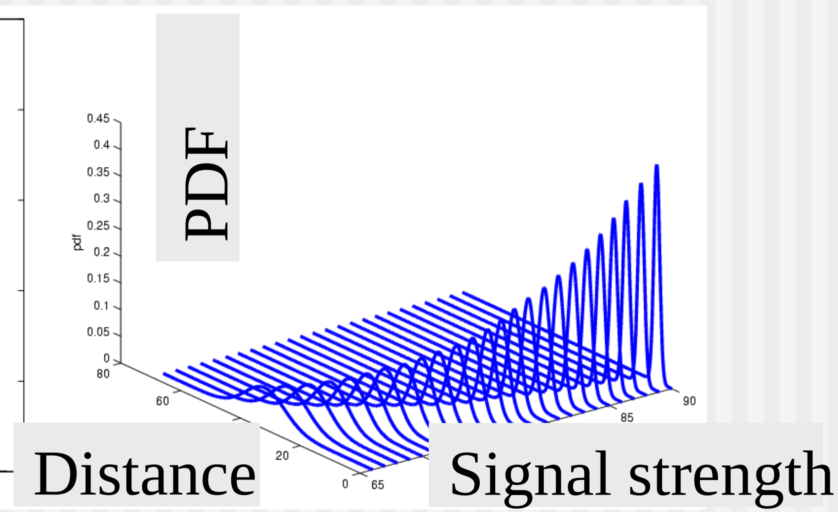
Estimating distances – RSSI

- Received Signal Strength Indicator
  - Send out signal of known strength, use received signal strength and path loss coefficient to estimate distance

$$P_{\text{recv}} = c\frac{P_{\text{tx}}}{d^{\alpha}} \Leftrightarrow d = \sqrt[\alpha]{\frac{cP_{\text{tx}}}{P_{\text{recv}}}}$$

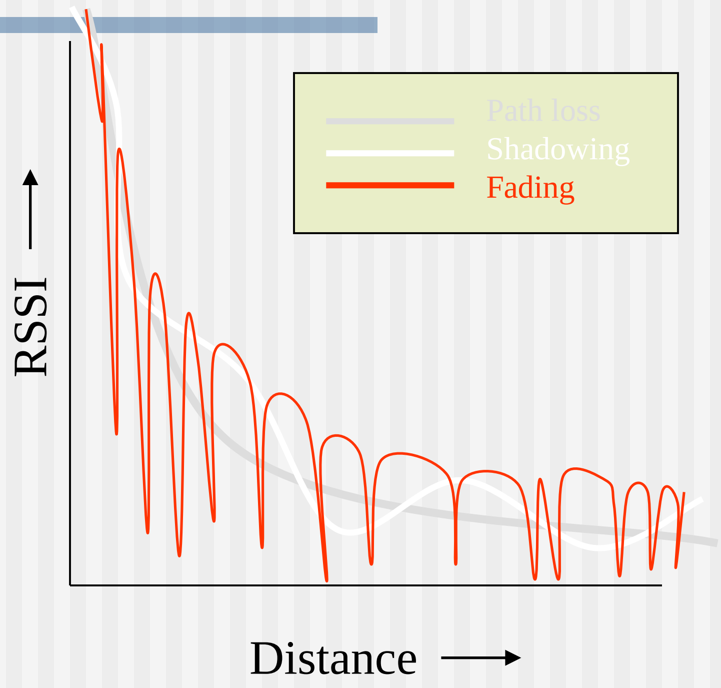
  - Problem: Highly error-prone process – Shown: PDF for a fixed RSSI





Practical Difficulties with RSSI

- RSSI is extremely problematic for fine-grained, ad-hoc applications
  - Path loss characteristics depend on environment ($1/r^n$)
  - Shadowing depends on environment
  - Short-scale fading due to multipath adds random high frequency component with huge amplitude (30-60dB) – very bad indoors
    - Mobile nodes might average out fading.. But static nodes can be stuck in a deep fade forever
  - The relative orientation of antennas among nodes makes difference.
- Potential applications
  - Approximate localization of mobile nodes, proximity determination
  - “Database” techniques (RADAR)



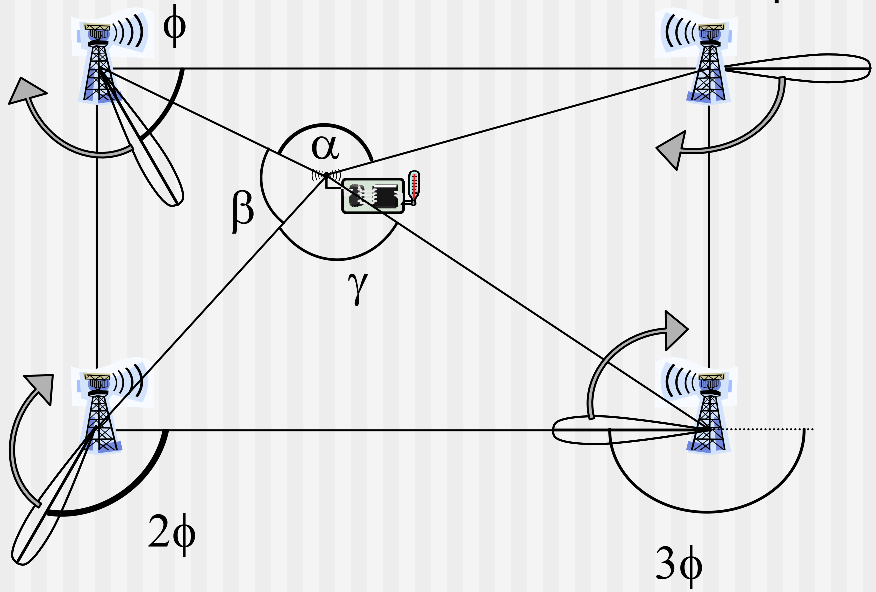
Ref. Rappaport, T, *Wireless Communications Principle and Practice*, Prentice Hall, 1996.

Estimating distances – other means

- Time of arrival (ToA)
  - Use time of transmission, propagation speed, time of arrival to compute distance
  - Problem: Exact time synchronization
- Time Difference of Arrival (TDoA)
  - Use two different signals with different propagation speeds
  - Example: ultrasound and radio signal
    - Propagation time of radio negligible compared to ultrasound
  - Compute difference between arrival times to compute distance
  - Problem: Calibration, expensive/energy-intensive hardware

Determining angles

- Directional antennas
  - On the node
  - Mechanically rotating or electrically “steerable”
  - On several access points
    - Rotating at different offsets
    - Time between beacons allows to compute angles

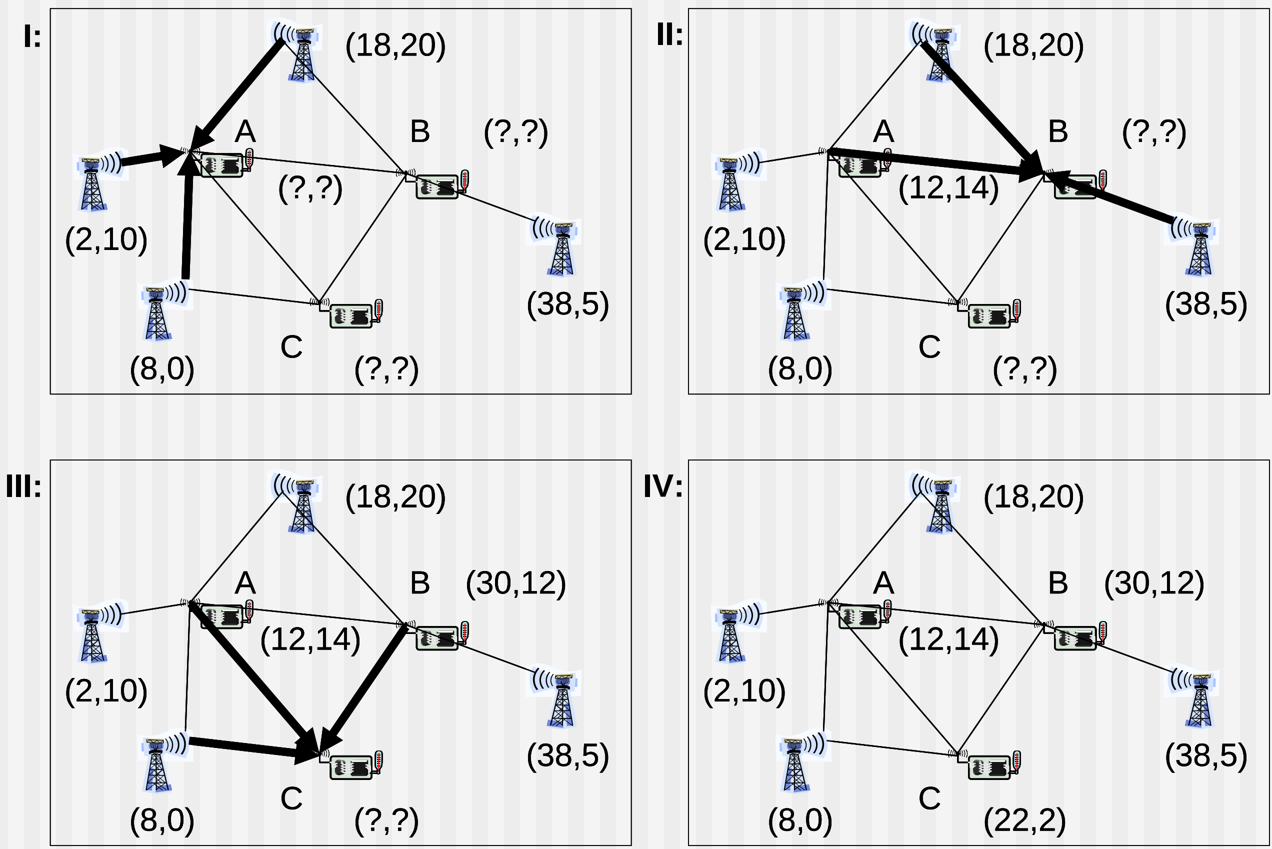


Multihop range estimation

- How to estimate range to a node to which no direct radio communication exists?
  - No RSSI, TDoA, …
  - But: Multihop communication is possible
- Solutions:
  - Idea 1: Count number of hops, assume length of one hop is known (***DV-Hop***)
    - Start by counting hops between anchors, divide known distance
  - Idea 2: If range estimates between neighbors exist, use them to improve total length of route estimation in previous method (***DV-Distance***)
- Then, in presence of range estimates and a sufficient number of neighbors, a node can actually try to compute its true Euclidean distance to a faraway anchor.

Iterative multilateration

- Assume some nodes can hear at least three anchors (to perform triangulation), but not all
- Idea: let more and more nodes compute position estimates, spread position knowledge in the network
  - Problem: Errors accumulate



Using Acoustics for Ranging

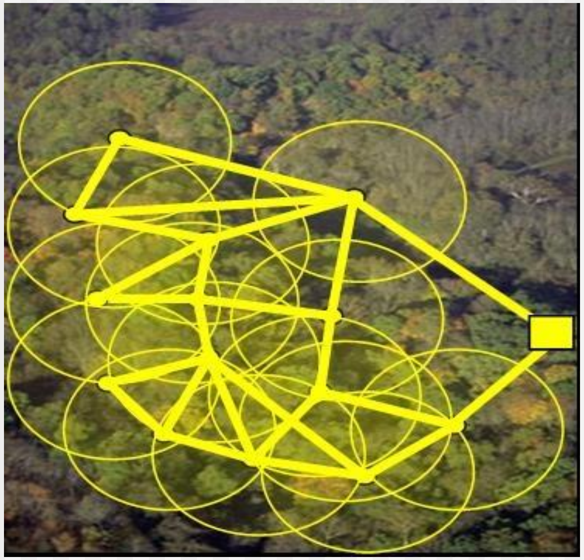
- Key observation: Sound travels slowly!
  - Tight synchronization easily achieved using RF signaling
  - Slow clocks are sufficient (v = 1 ft/ms)
  - With LOS, high accuracy can be achieved cheaply
  - Coherent beamforming can be achieved with low sample rates
- Advantages
  - Acoustics have lower path loss than RF near the ground, because ground reflections in acoustics don't cancel
  - Audible acoustics have very wide range of wavelengths
- Disadvantages
  - Poor penetration $\Rightarrow$ detector picks up reflections in Non-LOS
  - Audible sound: good channel properties, but often inappropriate

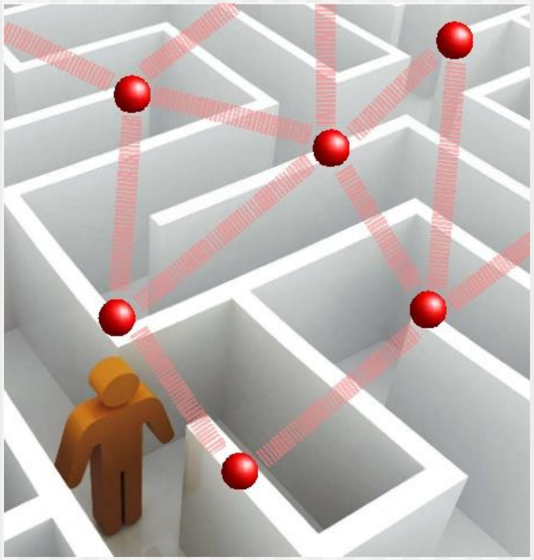
Achieving Range-Free Localization **Beyond Connectivity**

ACM SenSys2009

Spatial Awareness in WSN

- WSN have been proposed for many ***location-dependent*** applications
- ***Spatial awareness*** becomes a challenge under resource constraints
- Mission of this paper: pushing forward sensor node localization in WSN





Images from Internet

History

SenSys 2004	**Counter… Robust …**	***…ilt***
SenSys 2005	**Radio I… Geolocation**	***…ilt***
	…ight	***UVA***
Sen… 200…	**…ust …ing with Binary Proximity**	***UVA UCSB***
SenSys 2007	**RF Doppler Shifts BeepBe… MSP**	***Vanderbilt***
SenSys 2008	**SpinLoc… Radioac… Localization**	

Localization

Range-based Localization

Measure distances or angles among nodes.

Accurate but costly

15 m, 50 m, 20 m

Range-free beyond Connectivity

"Measure" from Sensing

Cheap and more accurate

3, 7, 4

A Metric with Finer Granularity

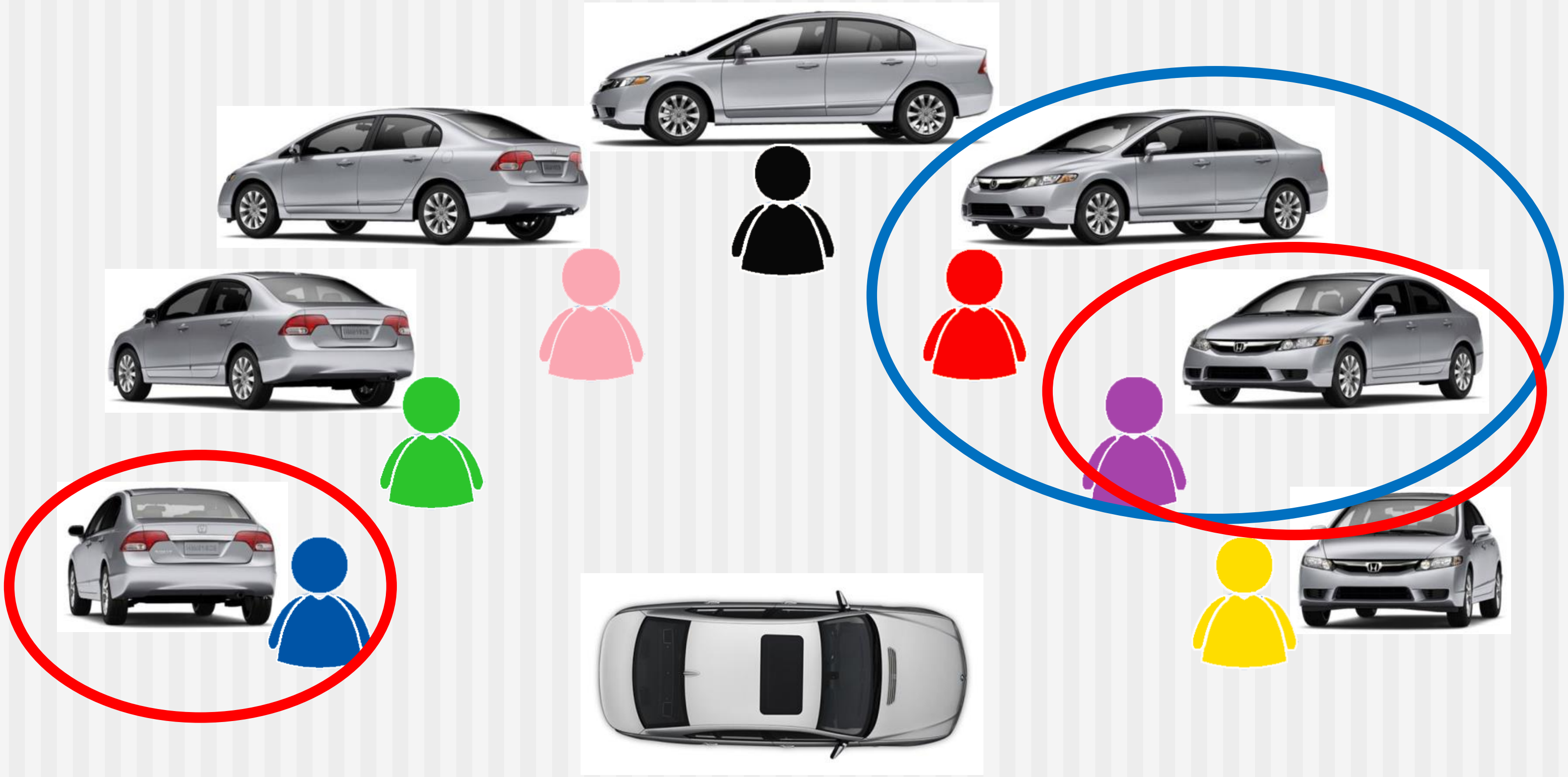
Range-free Localization

Sense proximity, connectivity, events, e…

Cheap but less accurate

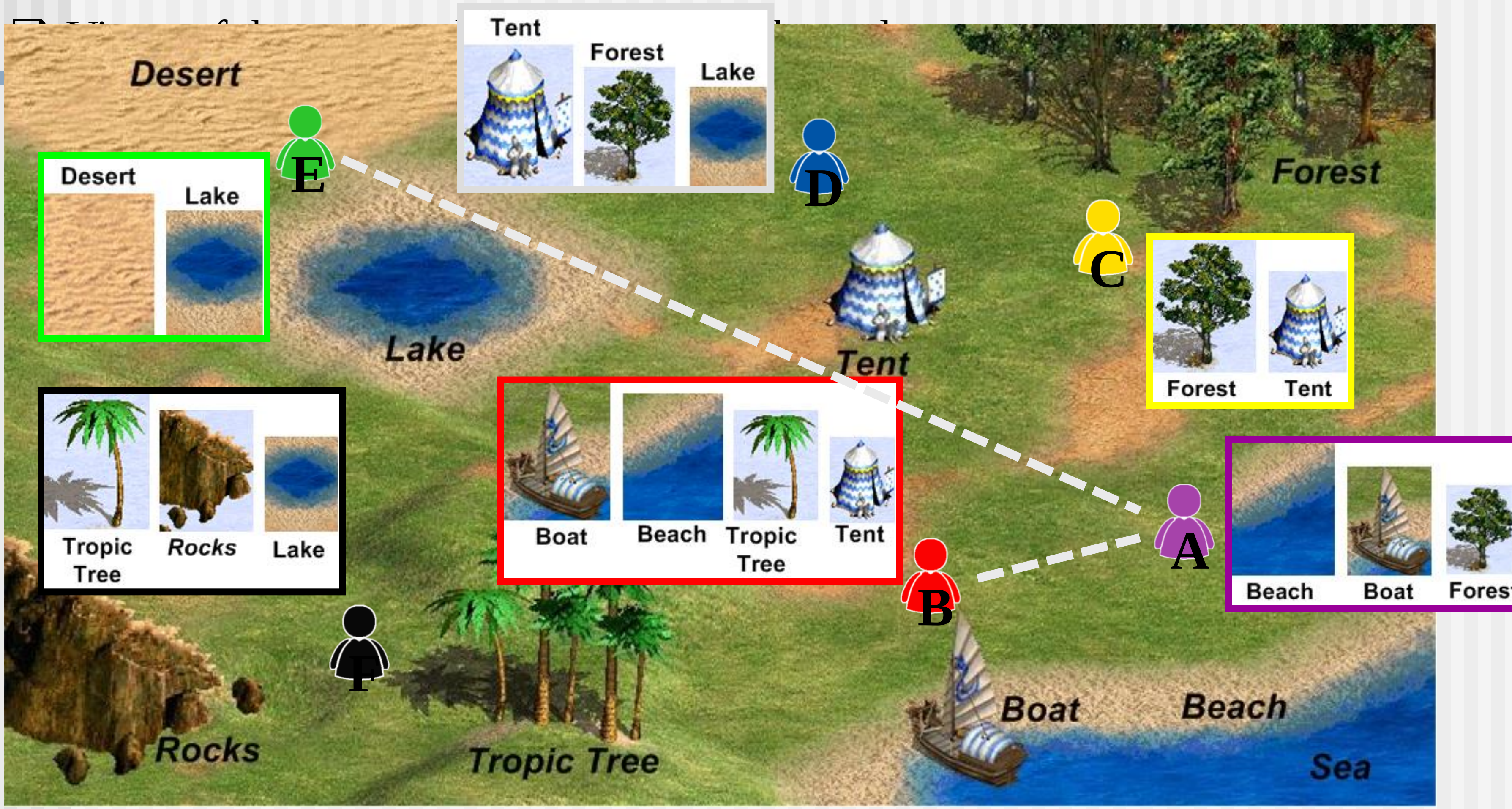
1, 1, 1

Idea: Similar Views Imply Proximity



Similar Views Imply Proximity

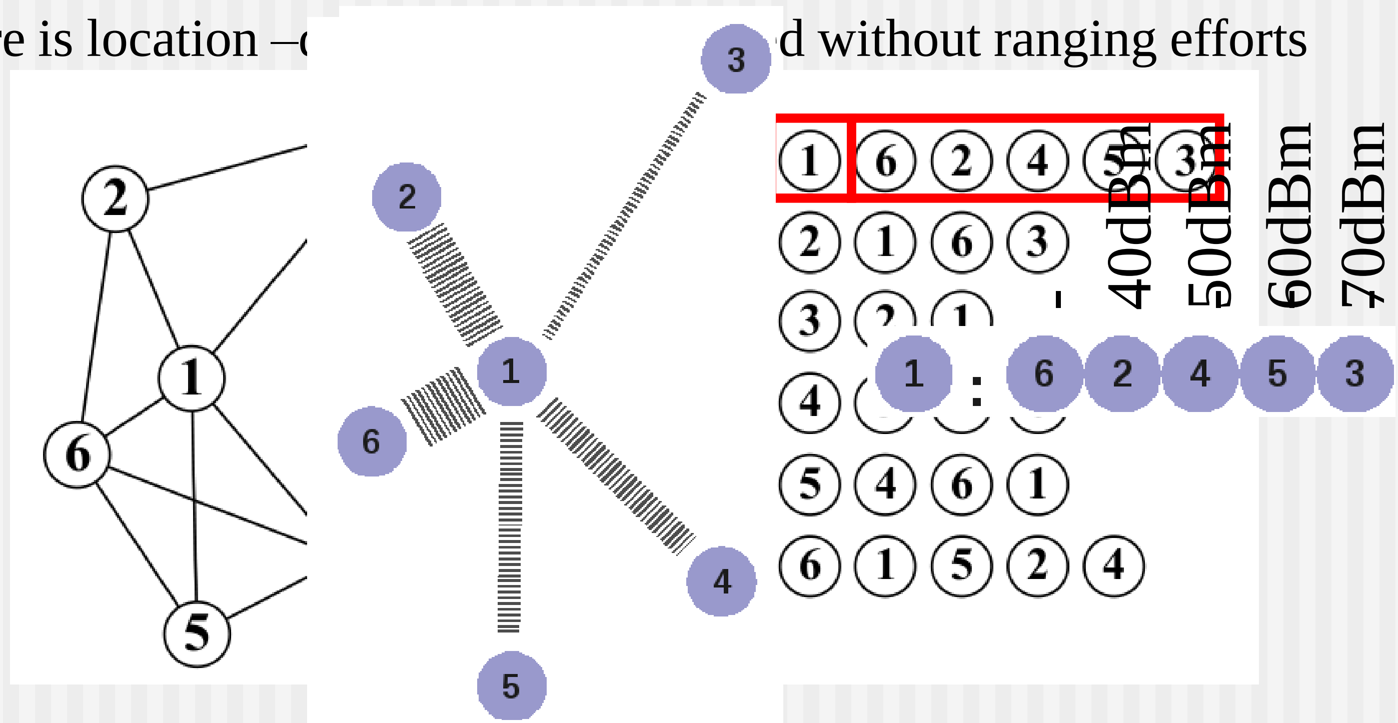
Similar Views Imply Proximity



Map made with Microsoft AoE II

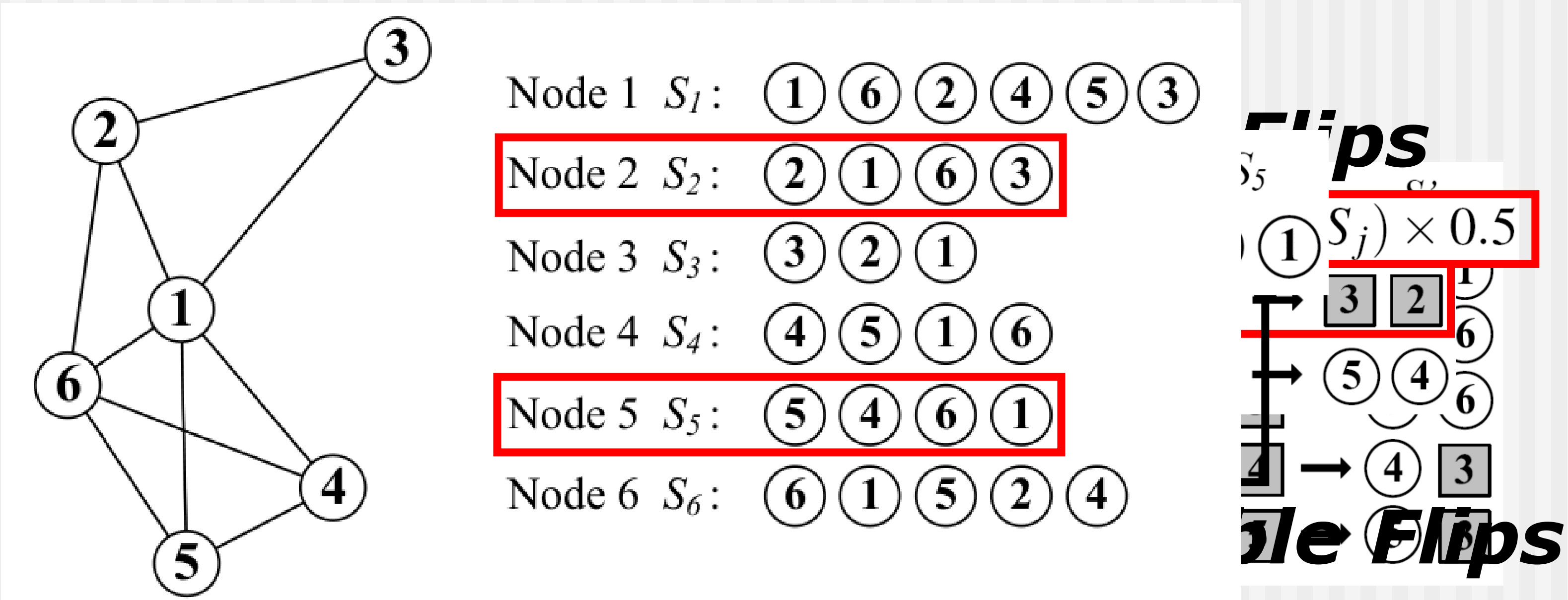
What’s the View of a Node?

- Nodes’ view of the surroundings: radio signal strength (RSS) of neighbors
- Neighboring ordering as a unique signature in the system
- Signature is location –c d without ranging efforts



What’s the Difference between Views?

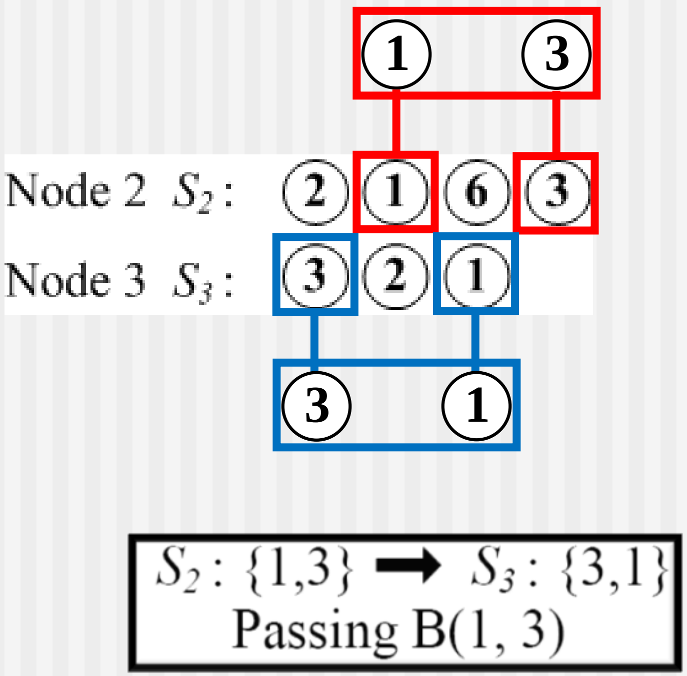
- How to quantify the difference among signatures (views) ?
- SD: Signature Distance
- Count the number of node-pair flips (***explicit***, ***implicit*** and ***possible***)

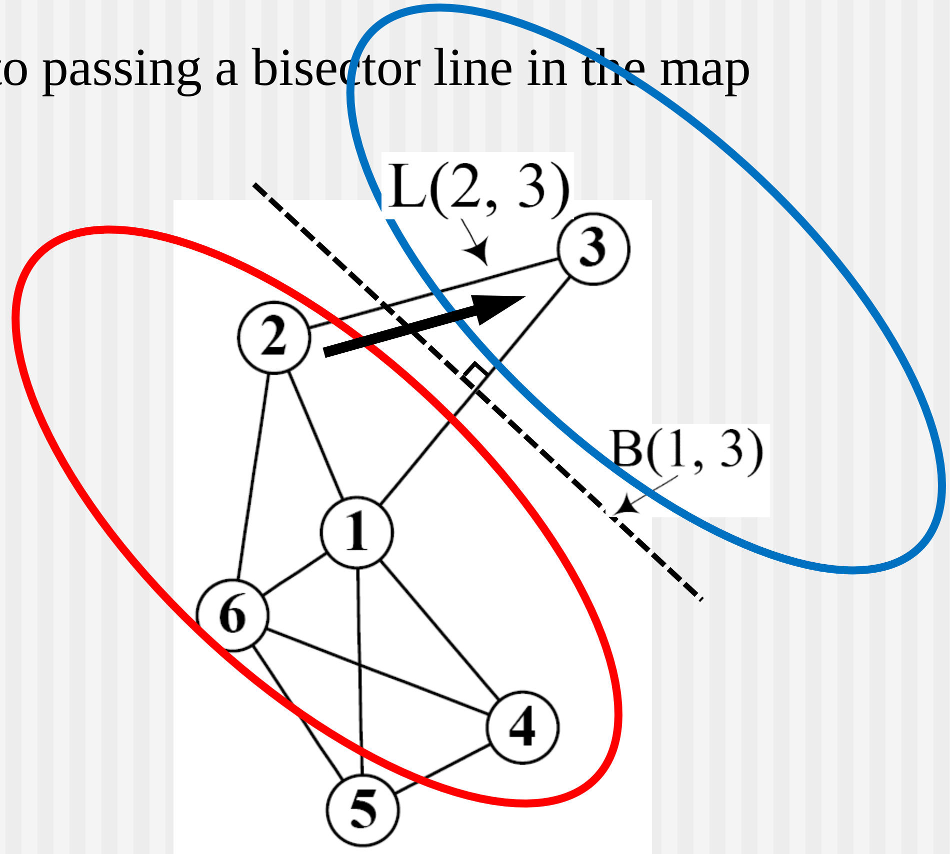


10 Implicit Node-pair
Flips

The Physical Meaning of Node-pair Flip

- The difference among “similar views” is measured with node-pair flips
- Each node-pair flip is equivalent to passing a bisector line in the map





The Physical Meaning of Signature Distance

Signature Distance Counts Node-pair Flips

Node-pair Flip Implies Passing A Bisector

⇩

Signature Distance Counts Passed Bisectors

Longer Distance Passes More Bisectors

⇩

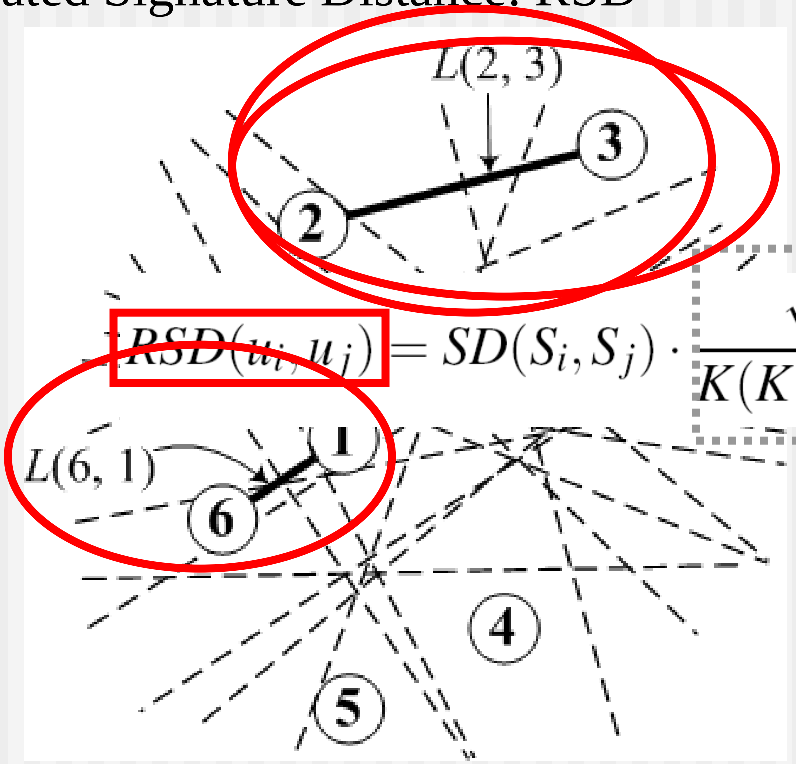
Heuristic Relationship

$$SD(S_i, S_j) \propto PD(u_i, u_j)$$

Signature Distance (SD) is approximately proportional to Physical Distance (PD)

Caveat 1: Consider Bisector Density

- Need to consider local bisector line density in the map
- Regulated Signature Distance: RSD



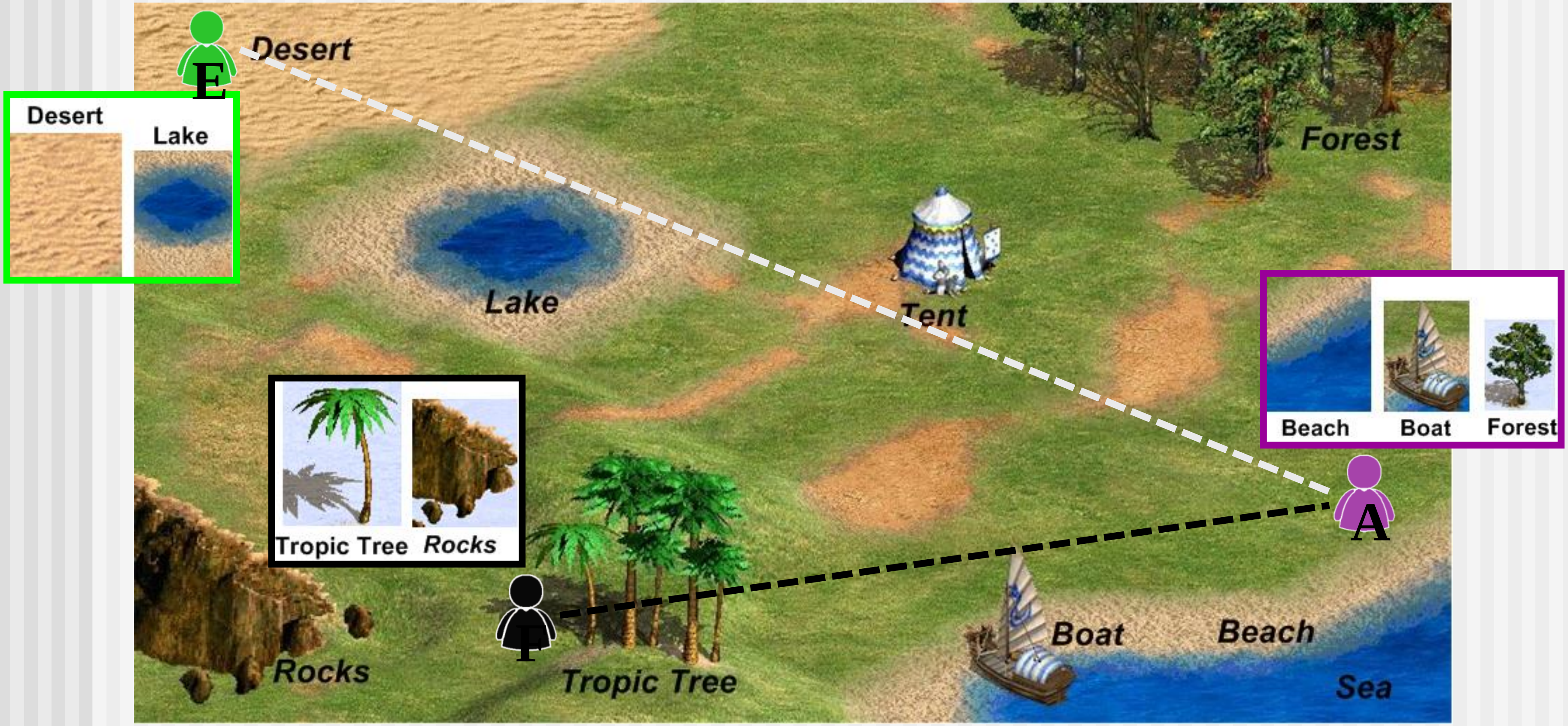
$$RSD(u_i, u_j) = SD(S_i, S_j) \cdot \frac{\sqrt{K}}{K(K-1)/2}$$

Node-pair flip based SD needs to be refined considering the local bisector line density

Scaling factor for bisector line density

Caveat 2: 1-Hop Effective Range

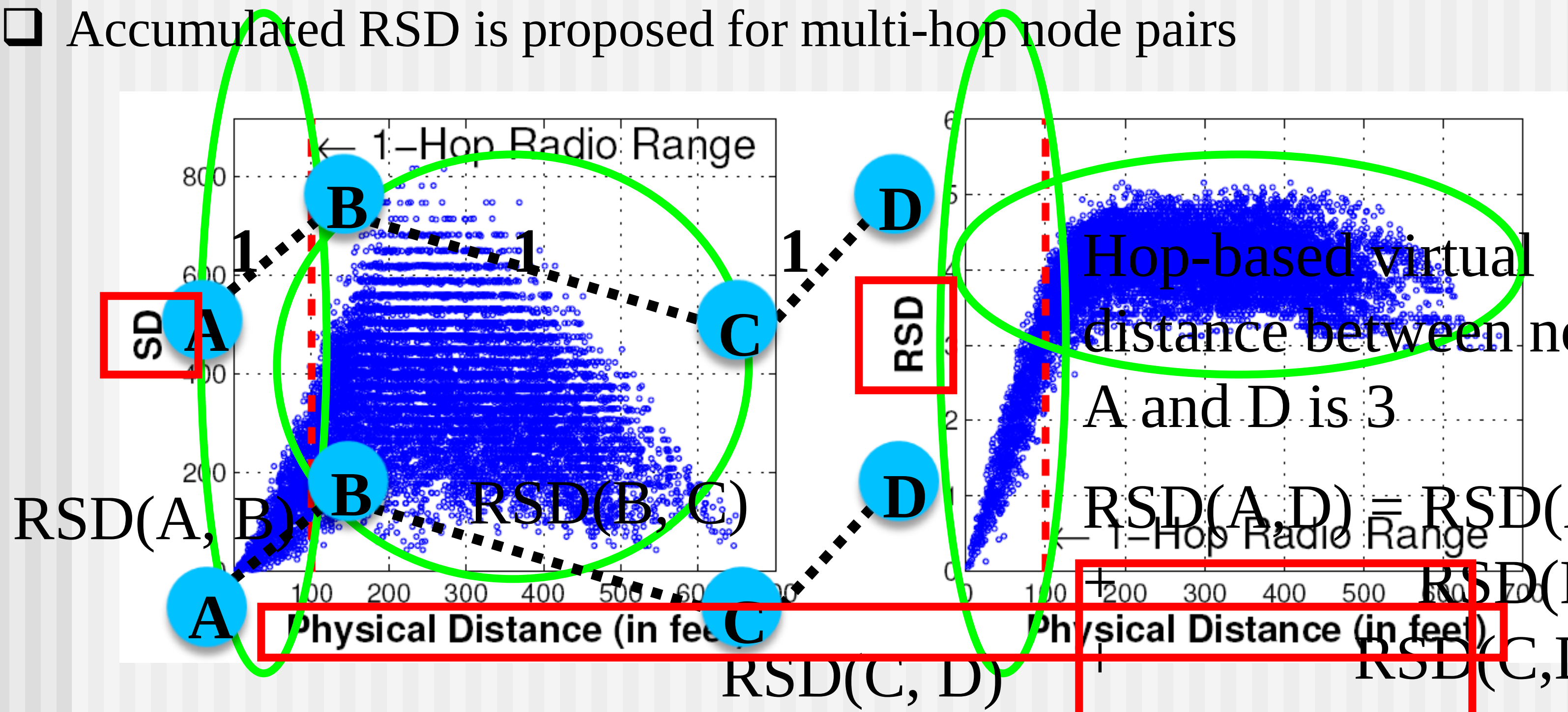
- The heuristic relationship is **NOT** valid for non-neighboring nodes



Map made with Microsoft AoE II

Accumulated RSD for Multi-hop Nodes

- Signature distance (i.e. RSD or SD) are not effective for multi-hop nodes
- RSD has much higher correlation with the physical distance within 1-hop
- Accumulated RSD is proposed for multi-hop node pairs



Hop-based virtual distance between node A and D is 3

RSD(A,D) = RSD(A,B) + RSD(B,C) + RSD(C,D)

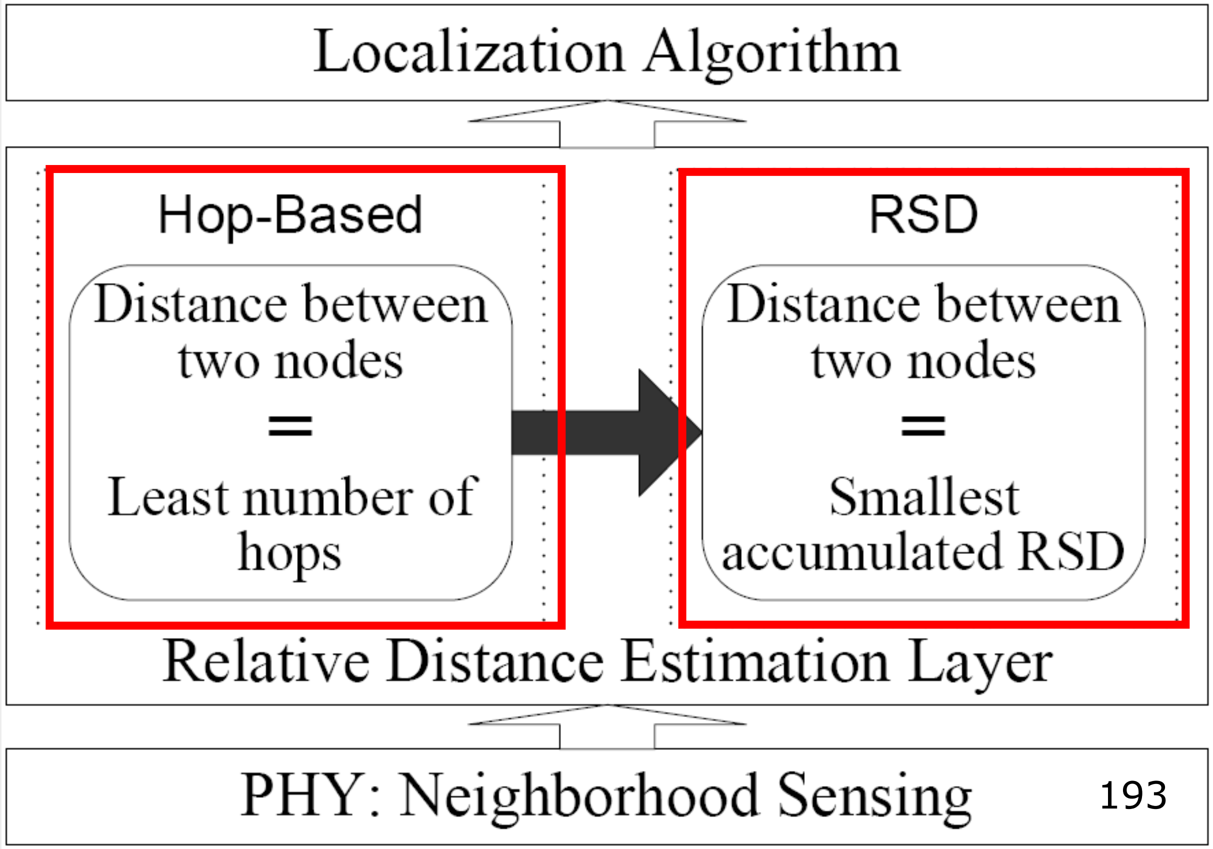
Baseline Localization Algorithms

- Connectivity-based Localization using “0” and “1” for RSS sensing
  - MDS-MAP (hop-based version), by Y. Shang,W. Ruml, et al.
  - DV-Hop, by D. Niculescu and B. Nath.
  - RPA-Hop (hop-based version), by C. Savarese, J. M. Rabaey, et al.
- RSD embedded versions
  - MDS-RSD
  - DV-RSD
  - RPA-RSD

1 → ***RSD***

RSD Embedding for Localization

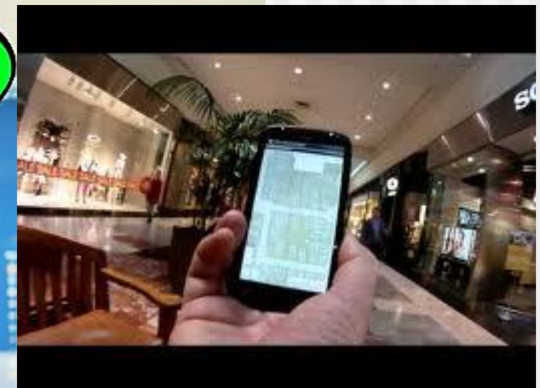
- RSD Embedding
  - MDS-MAP (Isomap)
  - DV-Hop
  - RPA-Hop
  - Amphoroues
  - Complex Shape
  - Holes
  - Convex
  - …



Push the Limit of WiFi based Localization for Smartphones

ACM MobiCom 2012

The Need for High Accuracy Smartphone Localization



- Help users navigation inside large and complex indoor
  ., airport, train station, shopping mall.
  omers visit and stay patterns for business

Train Station

Shopping Mall

Airport

195

Smartphone Indoor Localization
- What has been done?

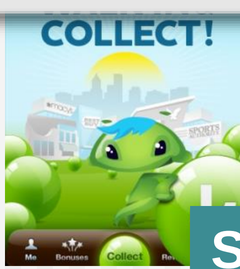
- **Contributions in academic**
  - **WiFi indoor localization** — RADAR [INFOCOM'00], Horus [MobiSys'05], Chen et.al[Percom'08]
  - **High accuracy indoor localization** — Cricket [Mobicom'00], WALRUS [Mobisys'05], DOLPHIN [Ubicomp'04], Gayathri et.al [SECON'09]
  - **WiFi enabled smartphone indoor localization** — SurroundSense [MobiCom'09], Escort [MobiCom'10], WILL[INFOCOM'12], Virtual Compass [Pervasive'10]

- **Com**

P

Is it possible to achieve high accuracy localization using most prevalent WiFi infrastructure?

Google Map

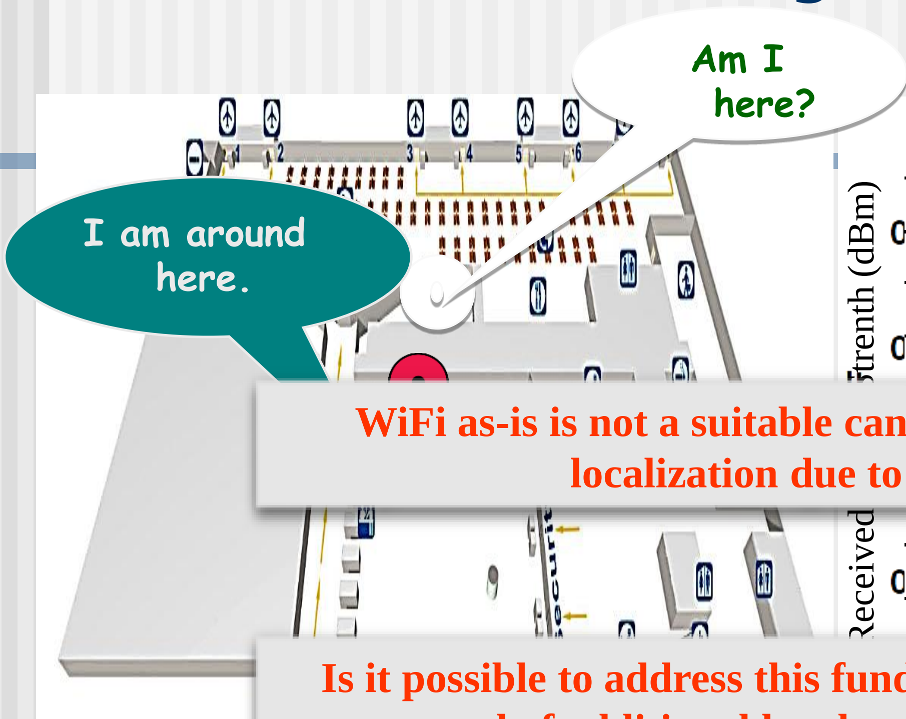


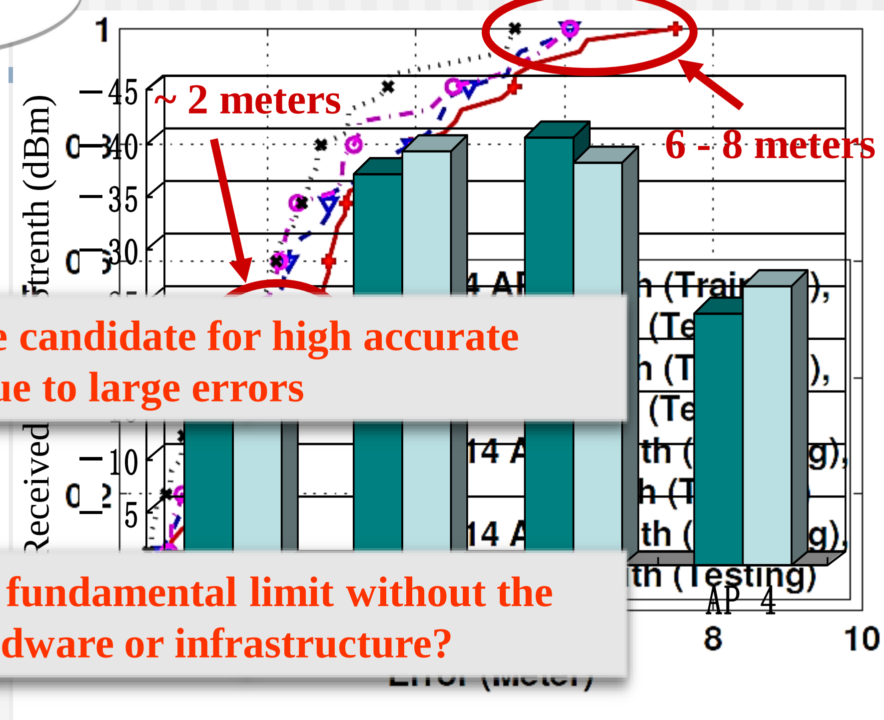
Shopkick

Localization error up to 10 meters

Locate at the granularity of stores

Root Cause of Large Localization Errors





WiFi as-is is not a suitable candidate for high accurate localization due to large errors

Is it possible to address this fundamental limit without the need of additional hardware or infrastructure?

32: [-22dB, -36dB, -29dB, -43dB]

48: [-24dB, -35dB, -27dB, -40dB]

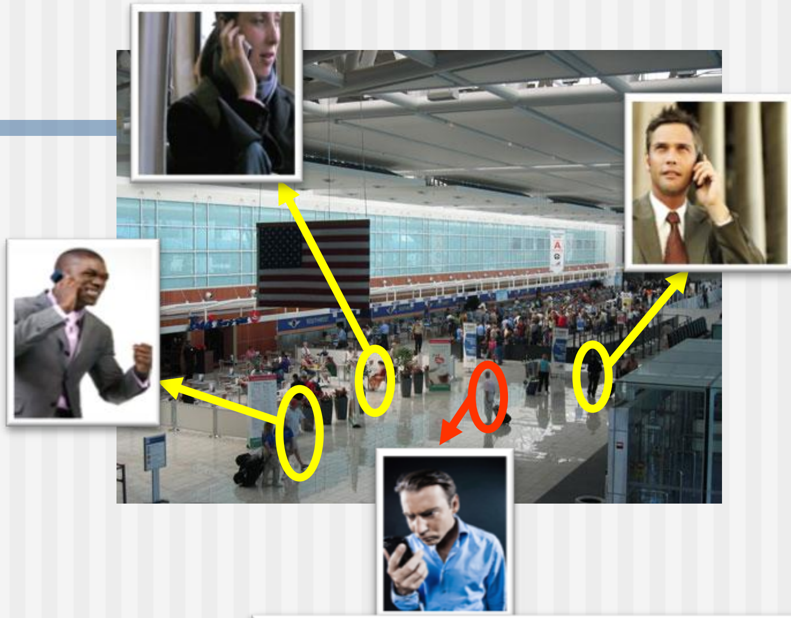
such

obsta

Physically distant locations share similar WiFi Received Signal Strength !

Orientation, holding position, time of day, number of samples

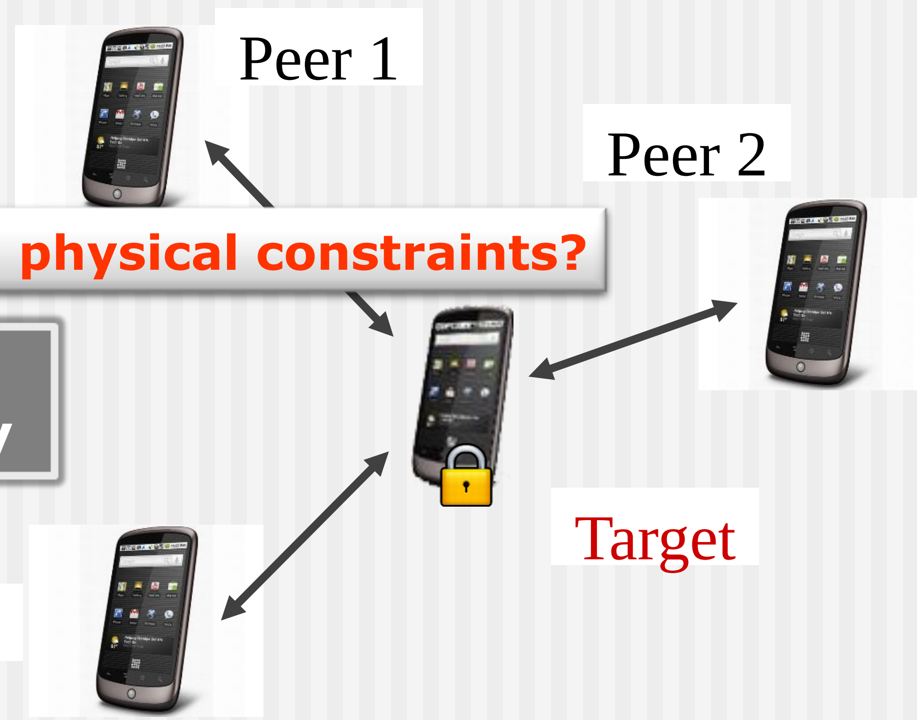
Inspiration from Abundant Peer Phones in Public Place



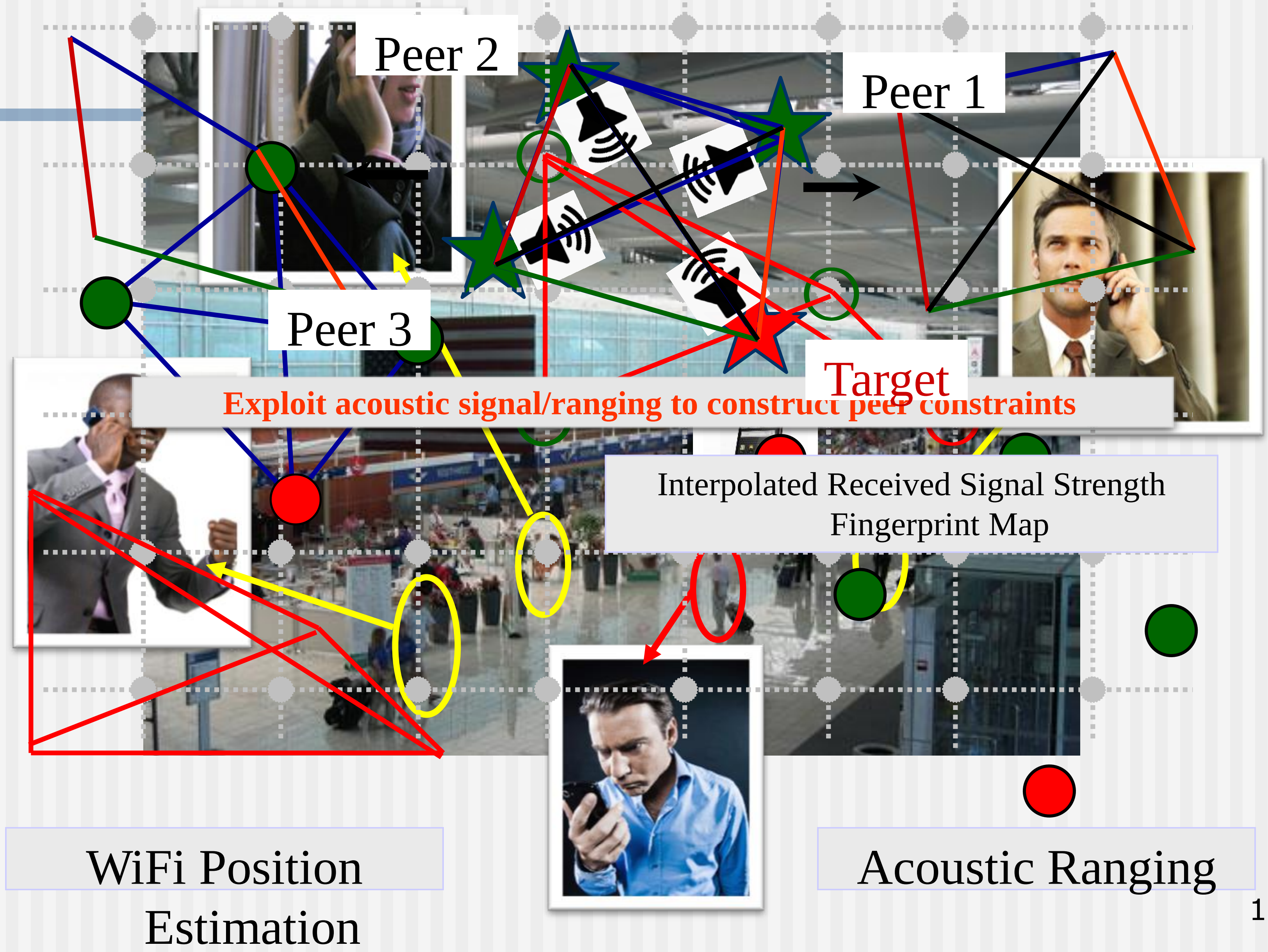
Increasing density of smartphones in public spaces

How to capture the physical constraints?

Provide physical constraints from nearby peer phones



Basic Idea



Peer 2
Peer 1
Peer 3
Target
Exploit acoustic signal/ranging to construct peer constraints
Interpolated Received Signal Strength Fingerprint Map
WiFi Position Estimation
Acoustic Ranging

System Design Goals and Challenges

- Peer assisted localization

> ➢ Exactly what is the algorithm to search for the best fit position and quantify the signal similarity so that to reduce large errors?

- Fast and concurrent acoustic ranging of multiple phones

> ➢ How to design and detect acoustic signals?

- Ease of use

> ➢ Need to complete in short time.
>
> ➢ Not annoy or distract users from their regular activities.

System Work Flow

WiFi position estimation

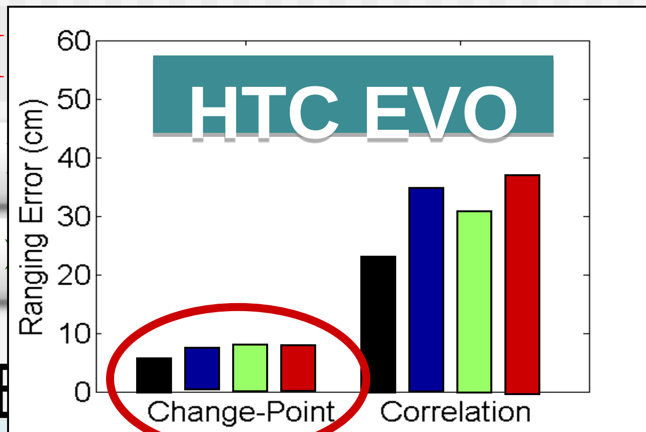
Peer recruiting & ranging

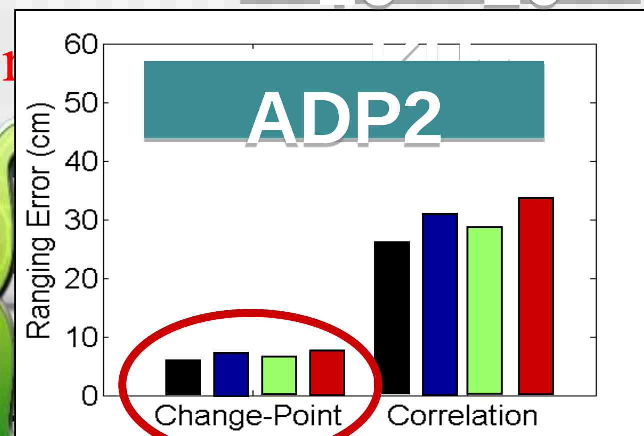
Rigid graph construction

Peer assisted localization

- Peer recruiting & ranging

16 – 20





Employ virt… synchronization sche… based on time multiple…ng

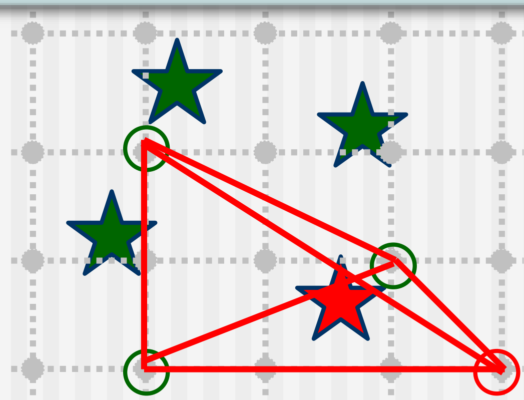
Lab Train Station Shopping Mall Airport

method

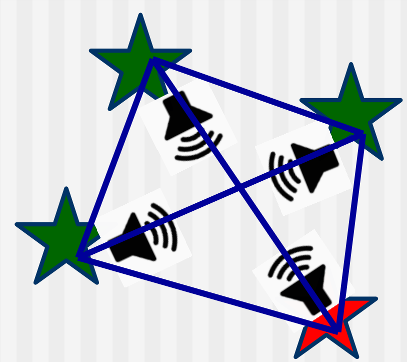
System Work Flow

- Rigid graph construction

  - Construct the graph *G* and *G'* based on initial WiFi position estimation and the acoustic ranging measurements.



Graph *G* based on WiFi position estimation



Rigid Graph *G'* based on acoustic ranging

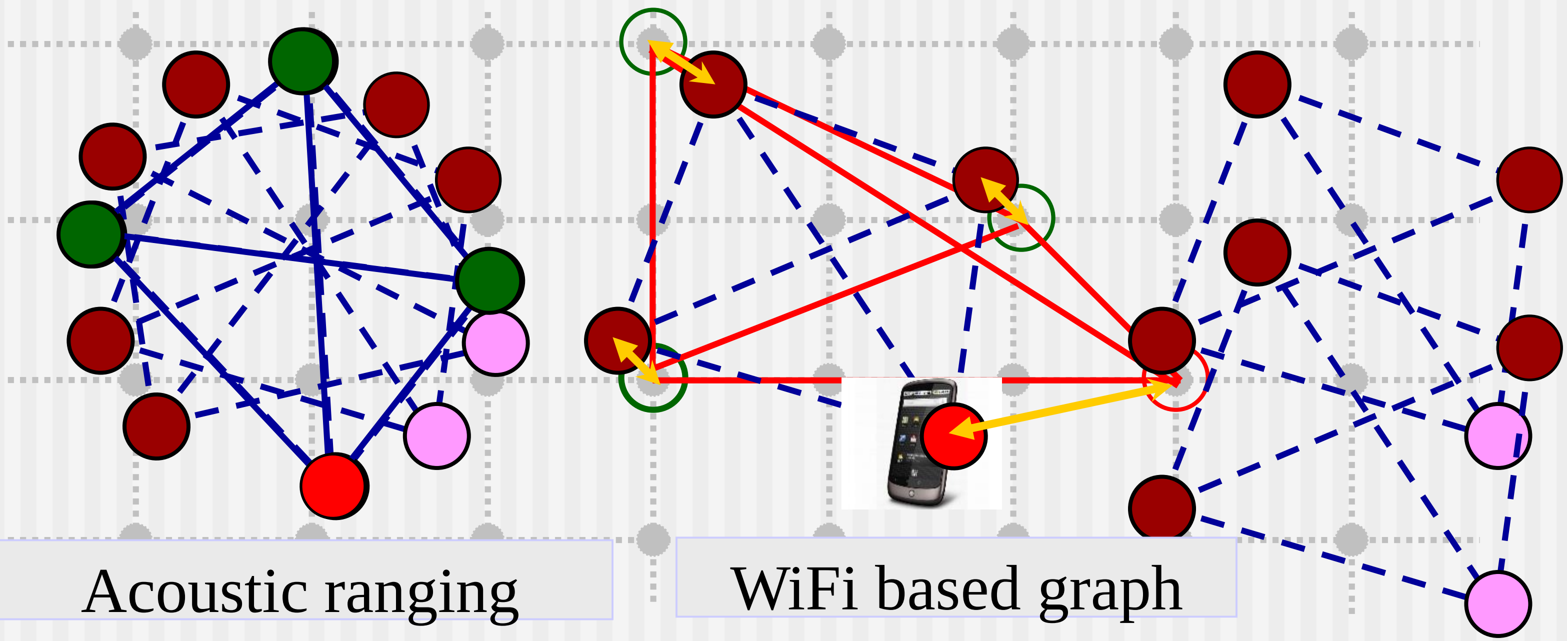
System Work Flow

WiFi position estimation

Peer recruiting & ranging

→ Rigid graph construction → Peer assisted localization

- ❑ Peer assisted localization



Acoustic ranging graph

WiFi based graph

Translational Movement Estimation

Prototype and Experimental Evaluation

- Prototype
  - Devices

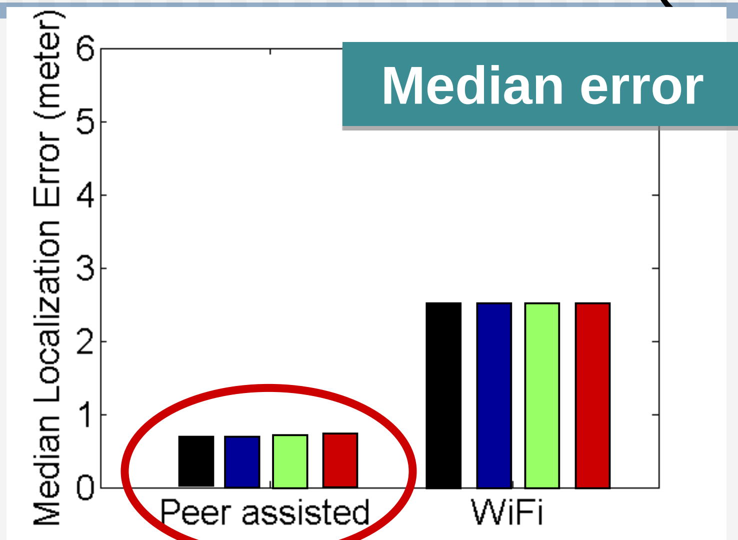
HTC EVO

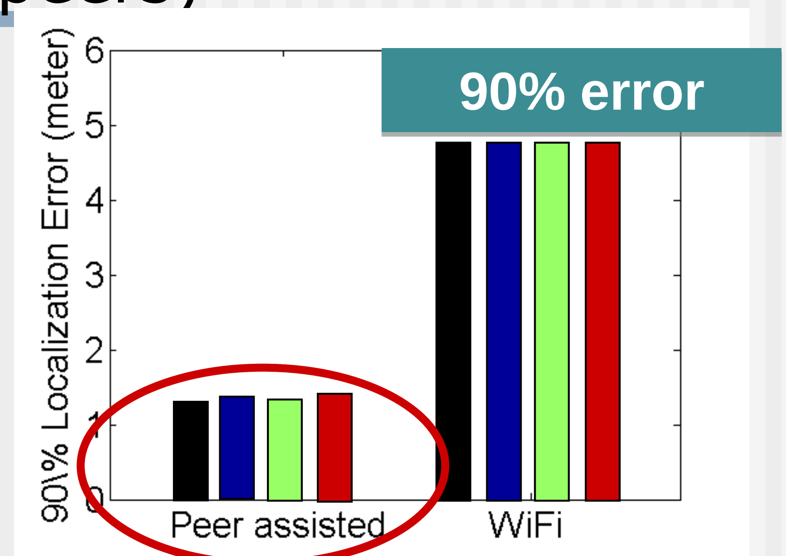
ADP 2

- Trace-driven statistical test
  - Feed the training data as WiFi samples
  - Perturb distances with errors following the same distribution in real environments

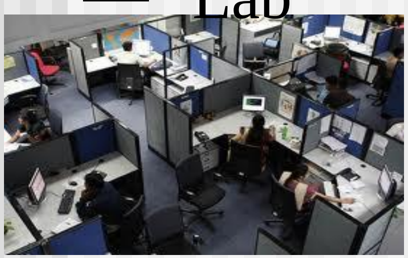
Localization Accuracy

- Localization performance across different real-world environments (5 peers)





Lab | Train Station | Shopping Mall | Airport



Peer assisted method is robust to noises in different environments

Overall Latency and Energy Consumption

- Overall Latency
  - Pose little more latency than required in the original WiFi localization about 1.5 ~ 2 sec

- Energy Consumption
  - Negligible impact on the battery life
    - e.g., with additional power consumption at about 320mW on HTC EVO - lasts 12.7 hours with average power of 450mW

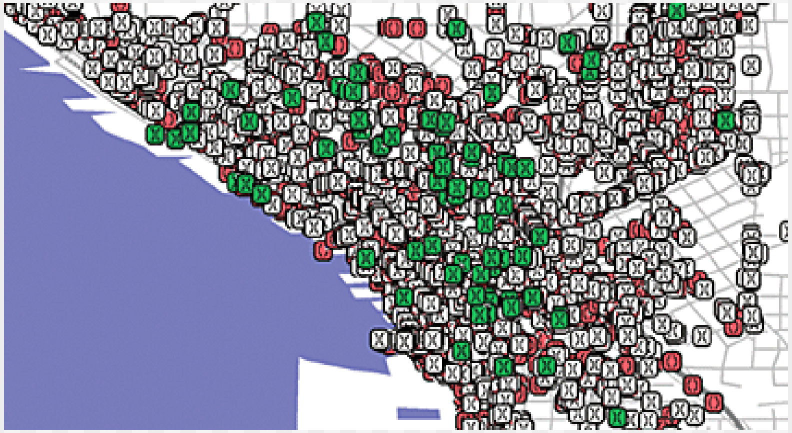
Discussion

- Peer Involvement
  - Use incentive mechanism to encourage and compensate peers that help a target's localization
- Movements of users
  - Do not pose more constraints on movements than existing WiFi methods
  - Affect the accuracy only during sound-emitting period
    - Happens concurrently and shorter than WiFi scanning
- Triggering peer assistance
  - Provides the technology for peer assistance
  - Up to users to decide when they desire such help

I Am the Antenna: Accurate Outdoor AP Location using Smartphones

ACM MobiCom 2011

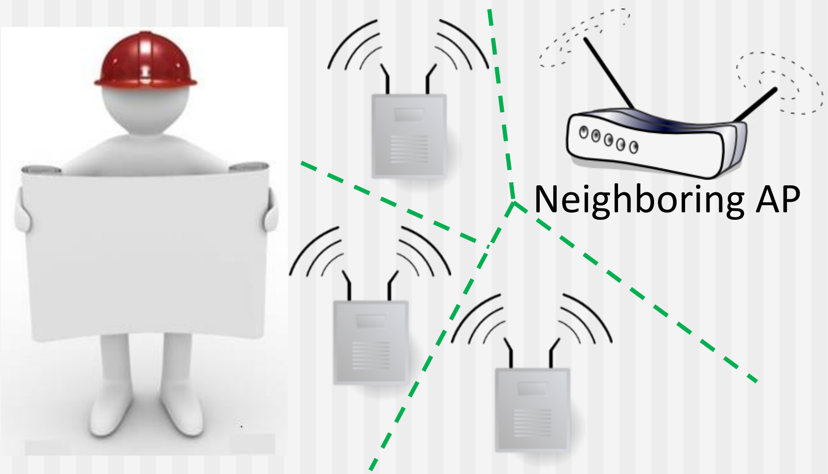
Ubiquitous Broadband Access



- WiFi network is growing rapidly
  - Cisco: WiFi traffic will surpass wired IP traffic in 2015
- High density
  - We need well tuned and managed WiFi networks!

AP Location: A Critical Function

- Better network planning

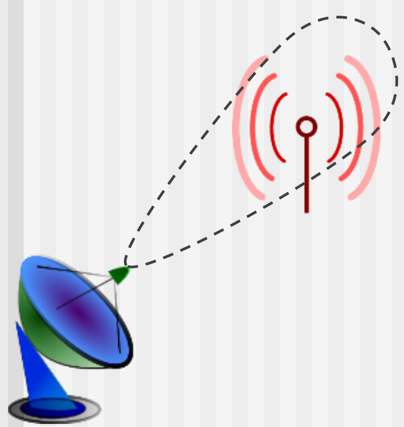


- Finding rogue APs

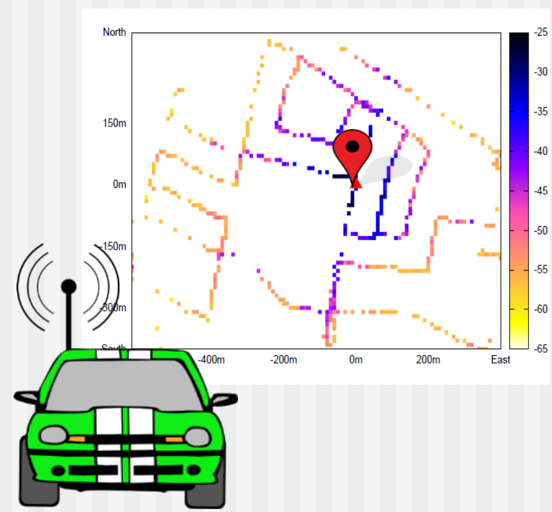
Do we have a better method to quickly and accurately locate the AP?

Conventional AP Location Methods

Directional Antenna

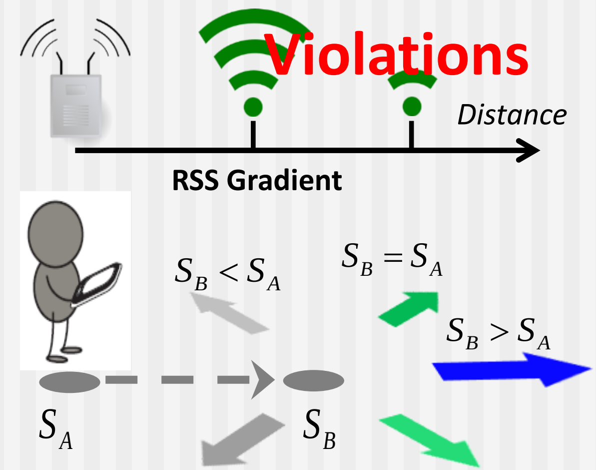


Signal Map



RSS Gradient

20%+ Violations



✓ Fast, very accurate (10°)

X Expensive (hundreds to thousands of dollars)

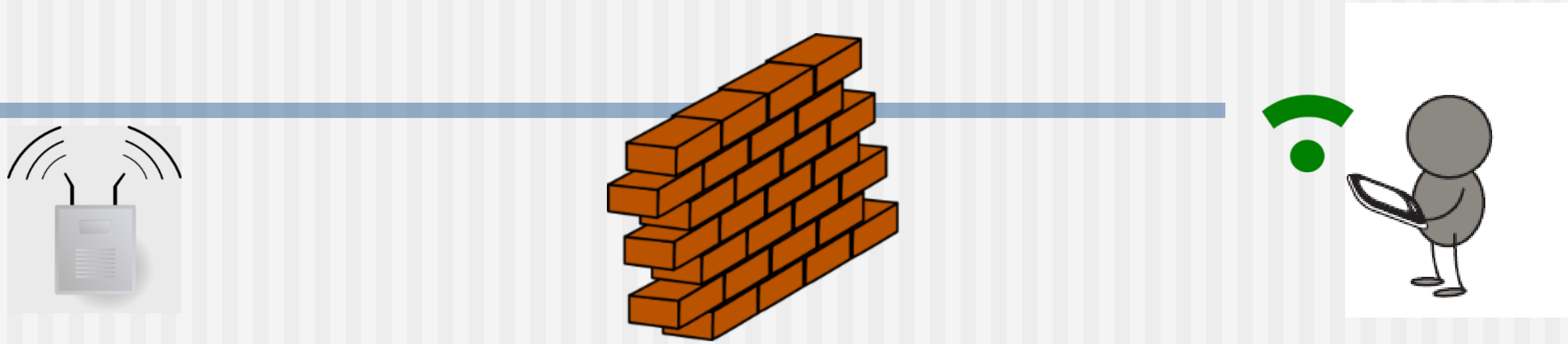
✓ Simple method, easy to perform

X
- Very time consuming

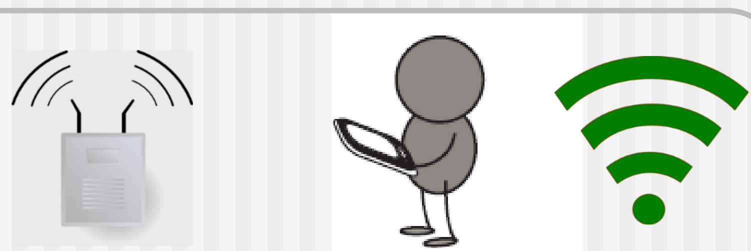
✓ Low measurement overhead

X Low accuracy (often error > 45°)

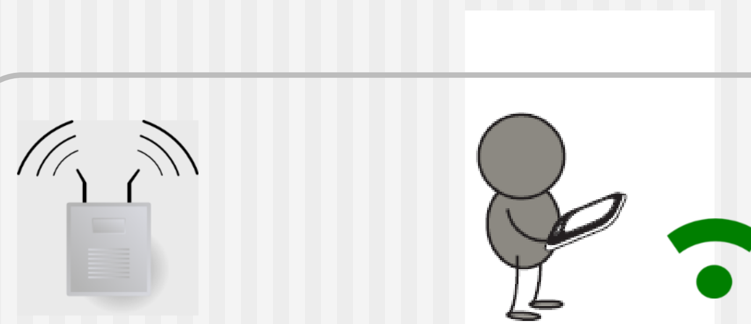
Insight: The Body Blocking Effect



- Can we use this to detect AP location?
  - No…Effect is not clear enough
- Our observation

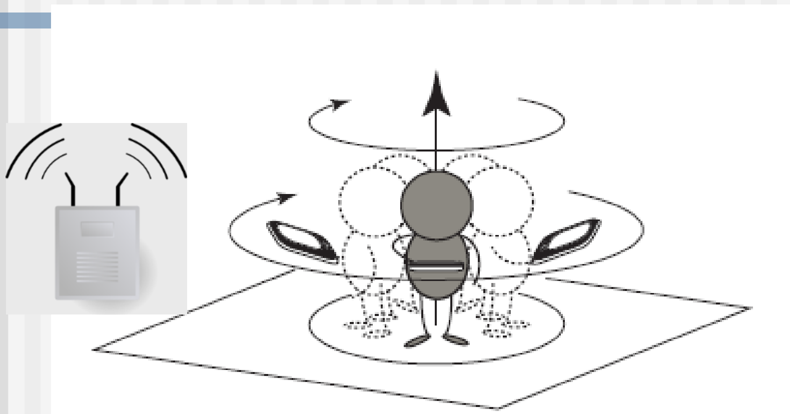


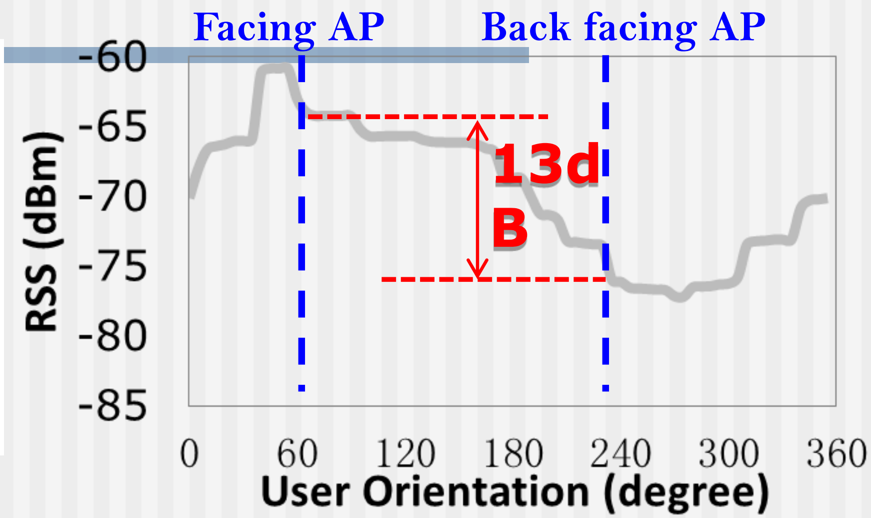
User facing the AP



User's back facing the AP

Rotation based Measurement



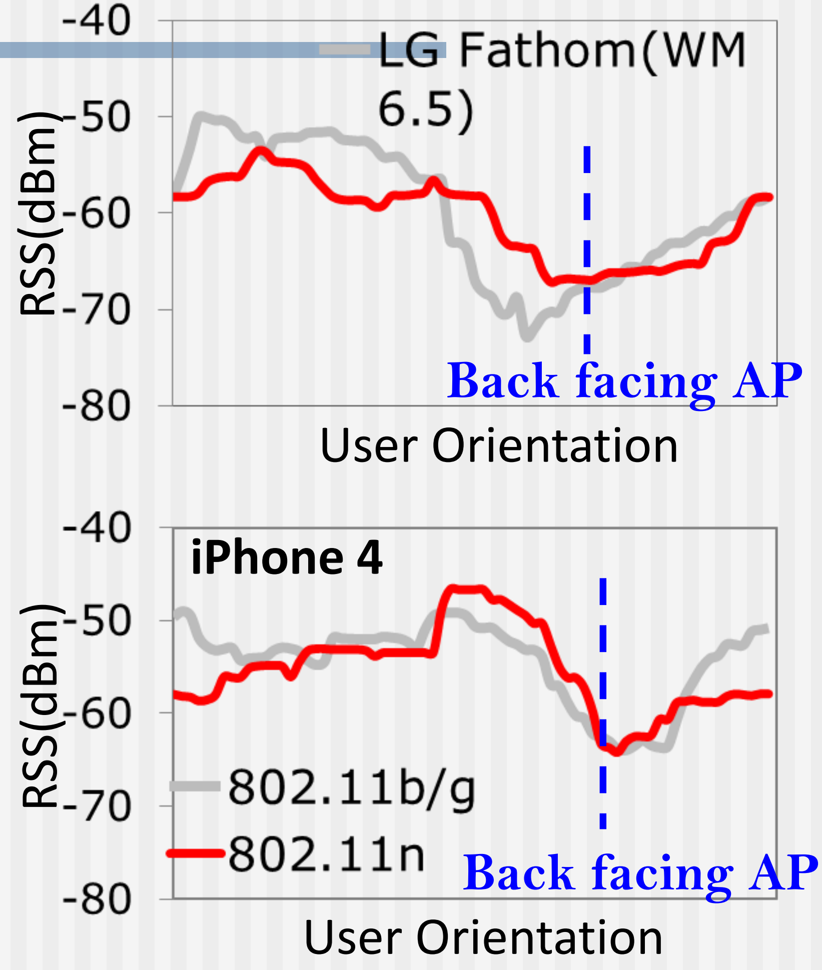


- The difference is significant
  - User's body is much larger than the phone
  - User is close to the phone

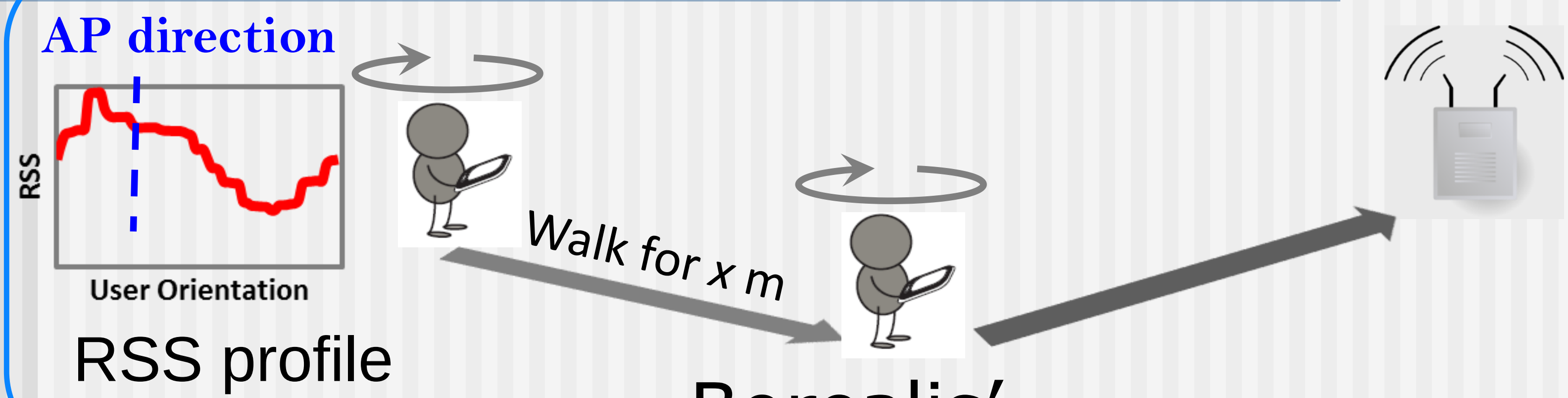
We can emulate a directional antenna just by
Rotating with Smartphones

Generality of the Effect

- Devices
  - Motorola Droid, HTC G1(Android)
  - LG Fathom(WM 6.5)
  - iPhone4 (iOS)
- Protocols
  - 802.11 b/g
  - 802.11n (MIMO)
- Postures and body shapes of the user
  - 7 users in our lab
  - Different phone orientations
- Environments
  - Outdoor LOS/Non-LOS
  - Different distances to AP



User Rotation based AP Location



Borealis' Design

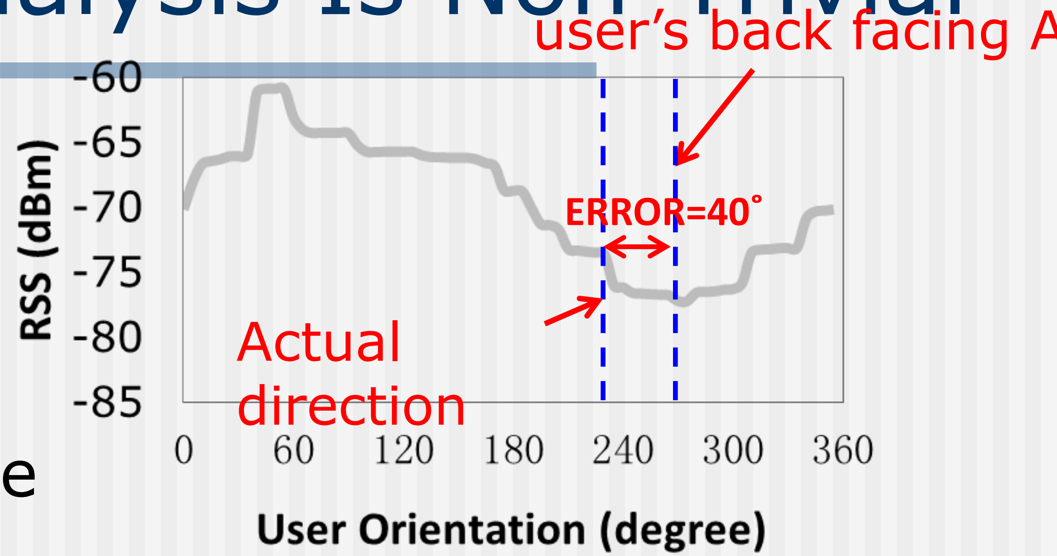
Requirements

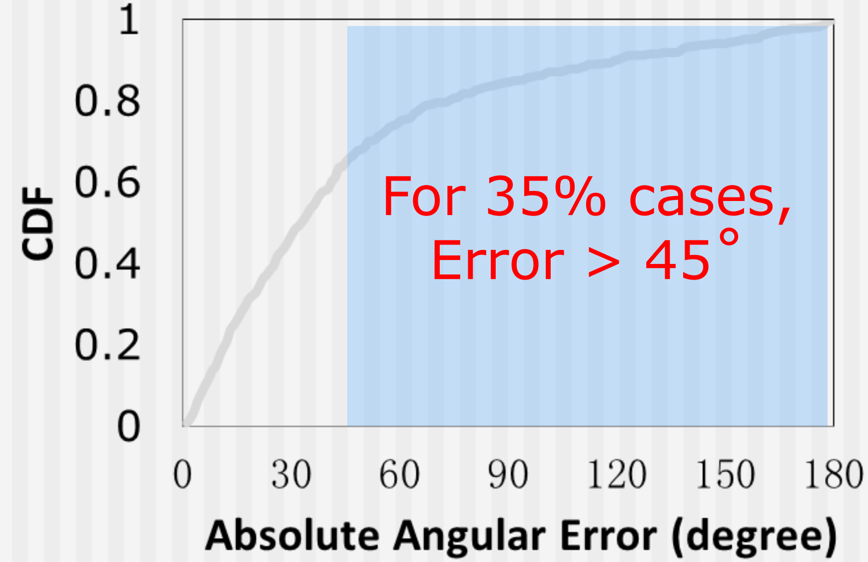
Accurate Directional Analysis

Low Energy Consumption

Directional Analysis Is Non-Trivial

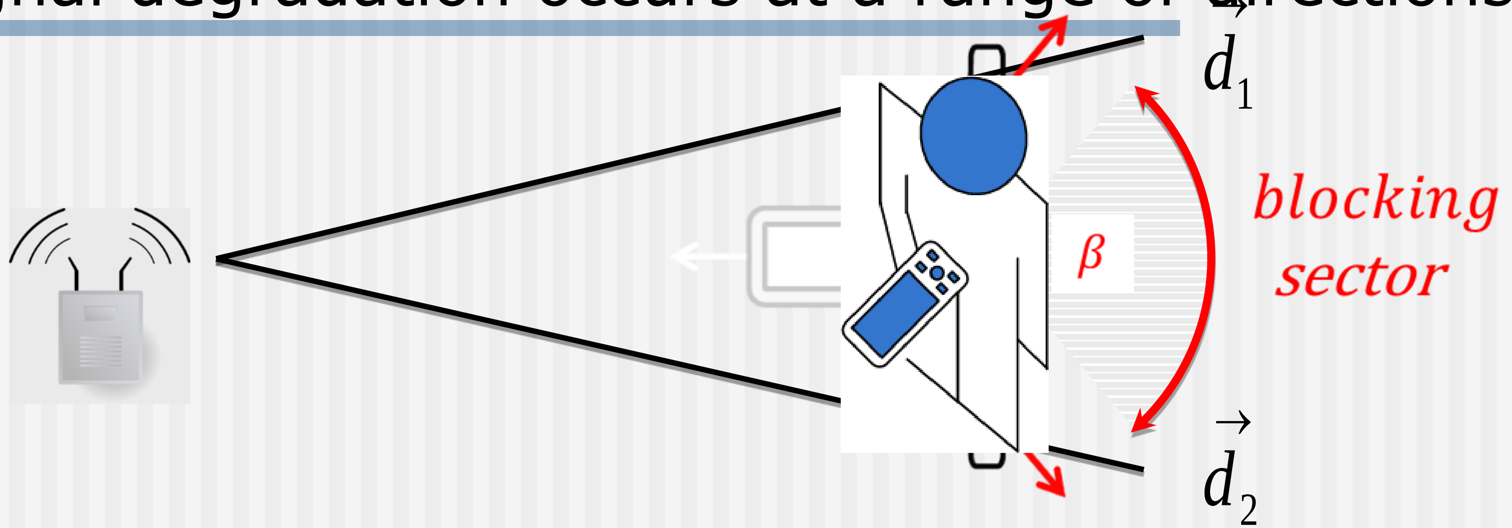
- Min RSS direction?
- Using Min RSS direction would cause large errors

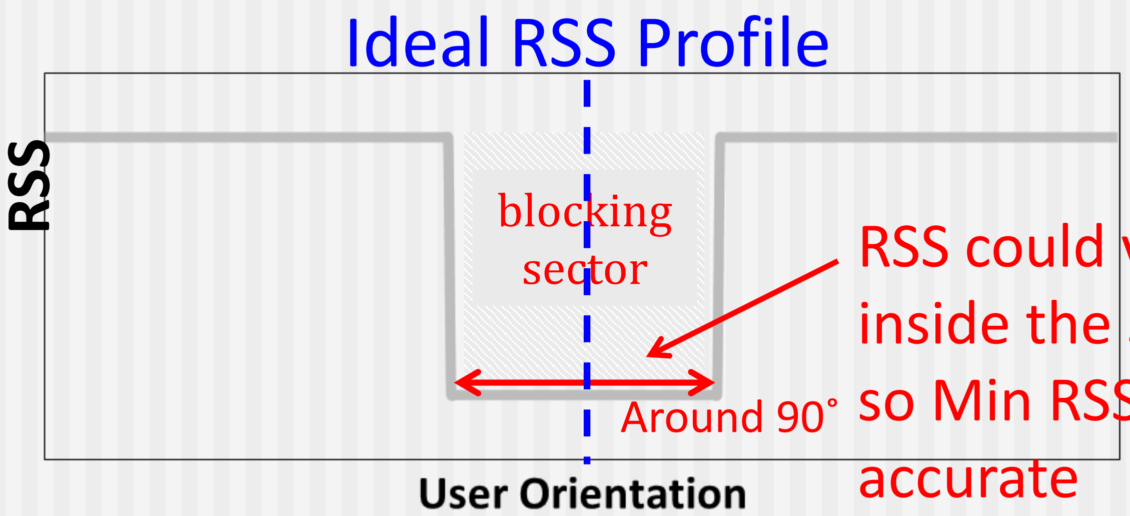




Our Directional Analysis Model

- Signal degradation occurs at a range of directions

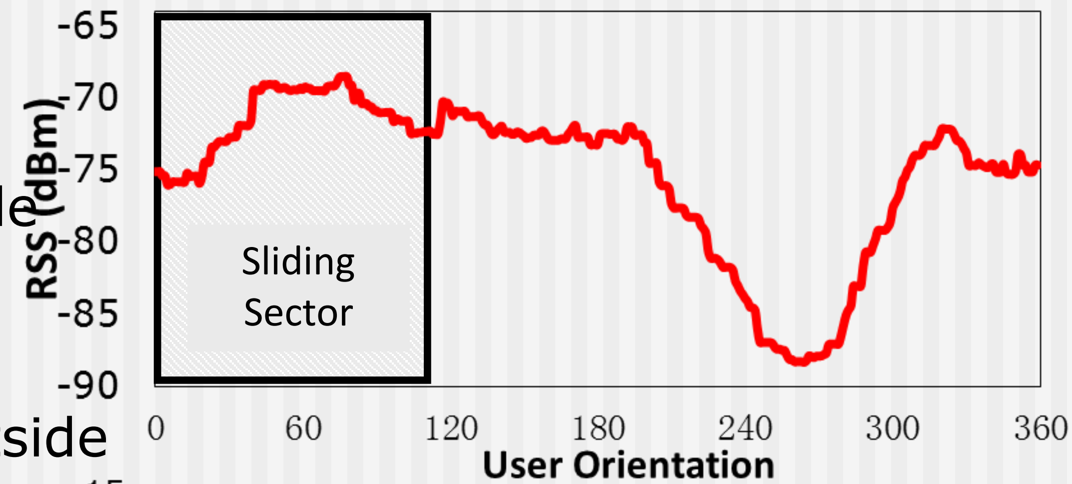


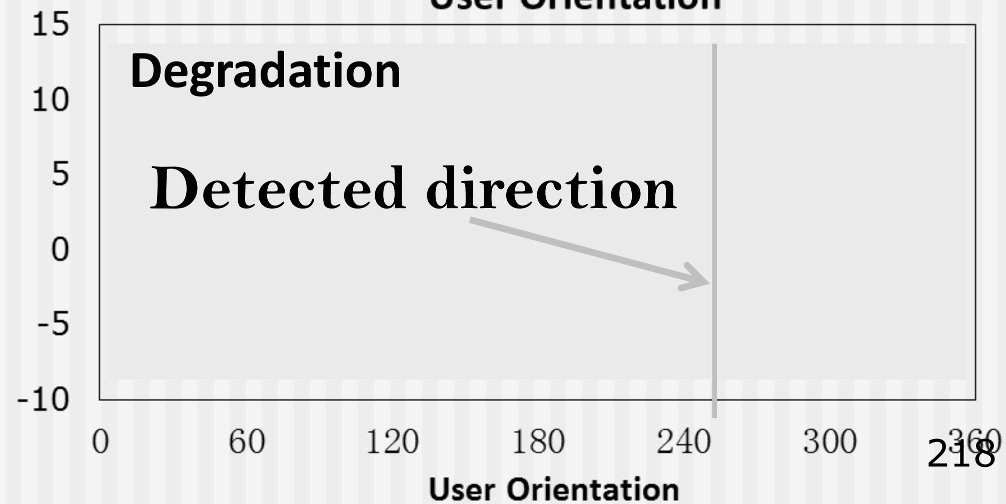


RSS could vary inside the sector, so Min RSS is not accurate

Locating the Blocking Sector

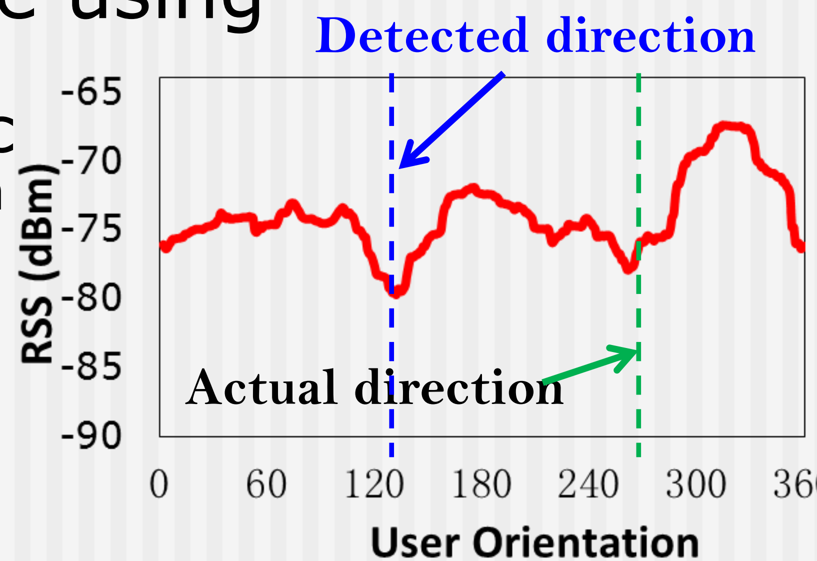
- Find the sector with the largest RSS degradation
  - Sliding window
  - *Sin*: average RSS inside the sliding sector
  - *Sout*: average RSS outside the sliding sector
  - *degradation = Sout - Sin*



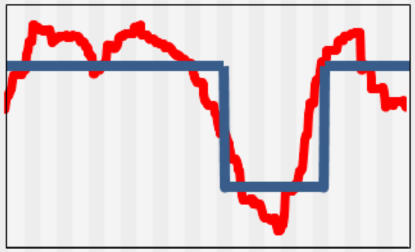


Navigation

- How does a user navigate using directional hints?
  - Strawman design: periodic
    - Refine AP direction every 20m
  - However, nothing is perfect
    - Temporal/spatial variation

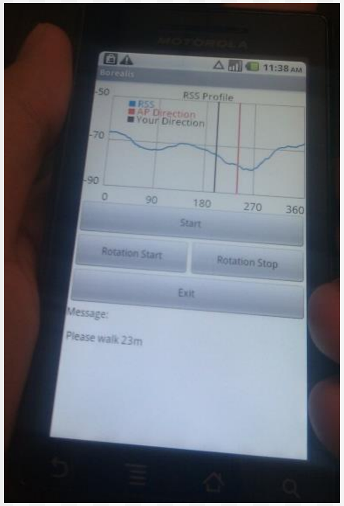


- Our adaptive method
  - Measurement confidence
    - The similarity of measured RSS and ideal RSS profile
  - If confidence is high
    - Walk further between measurements



Implementation

- Application layer
  - Leveraging WiFi scan to read RSS
    - Default scan is very slow
    - Scanning all channels each time



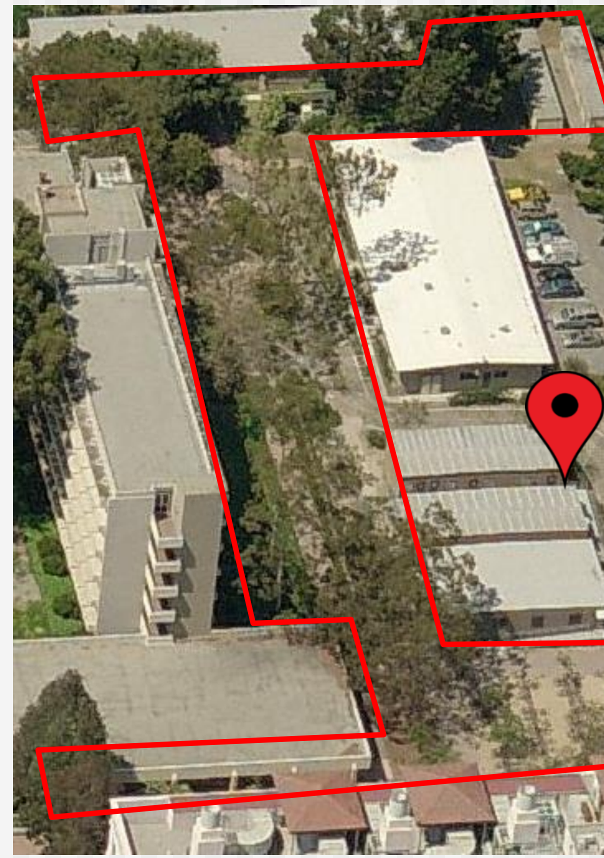
- OS layer
  - Modified WiFi driver
    - Scanning the interested channel only
    - Accelerate the process: 10 seconds per rotation (10 times faster)
    - Save power: WiFi's energy consumption is 14 times less

Testing Scenarios

Simple Line of Sight (Simple LOS)

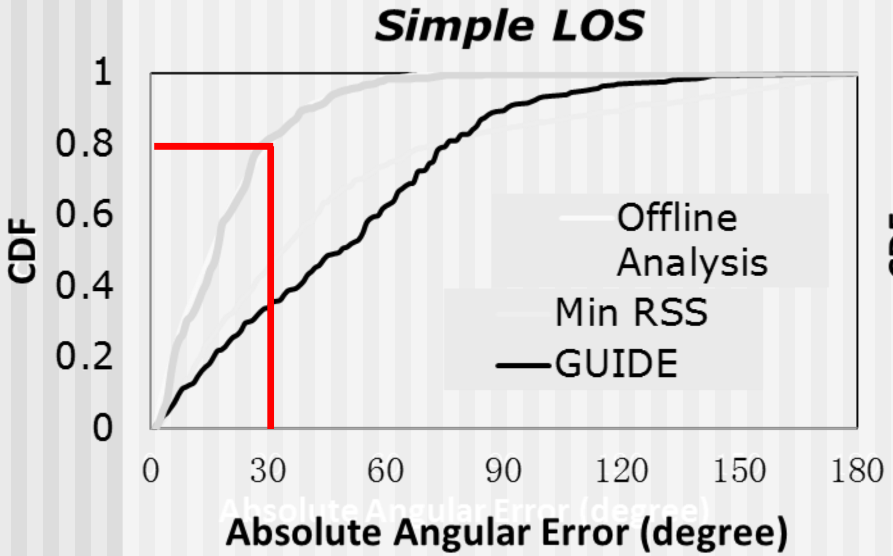
Complex Line of Sight (Complex LOS)

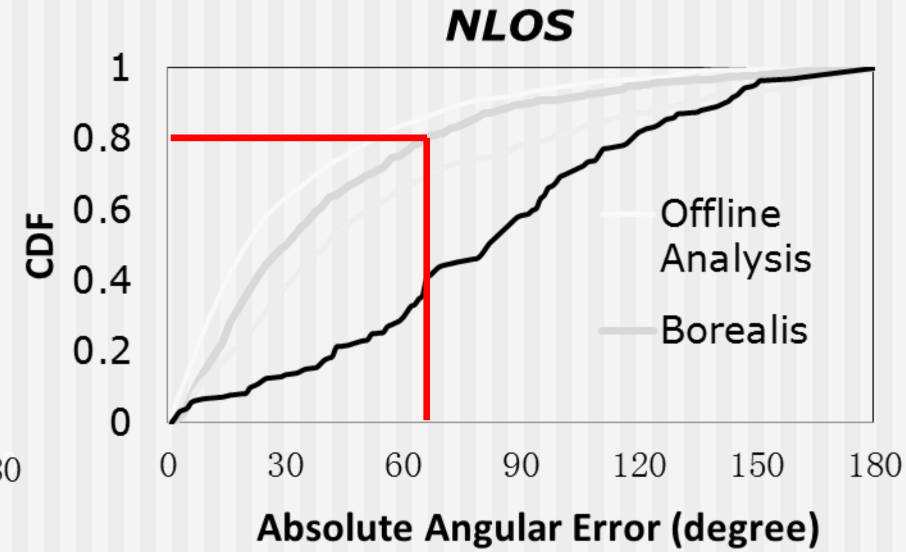
Non Line of Sight (NLOS)



Accuracy of Directional Analysis

- We compared Borealis to
  - Offline Analysis: clustering-based ML method
    - Optimized by training set, can be upper bound of directional analysis
  - GUIDE: RSS gradient based
  - Min RSS: minimum RSS direction based



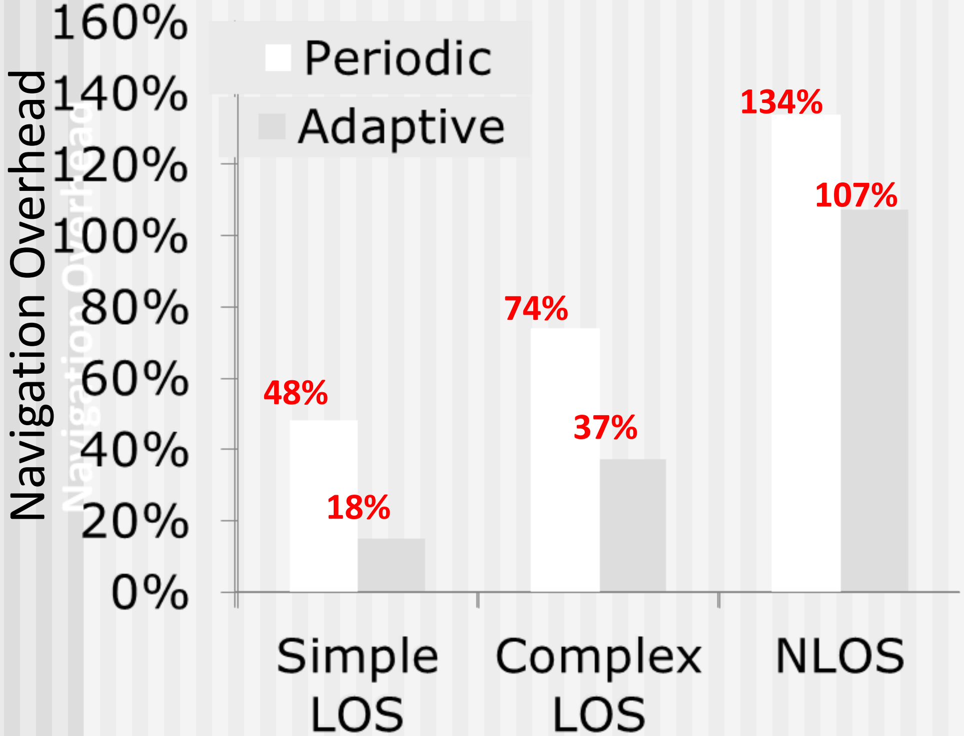


Error < 30˚ for 80%+ cases in Simple LOS

Error < 65˚ for 80%+ cases in NLOS

Navigation Efficiency

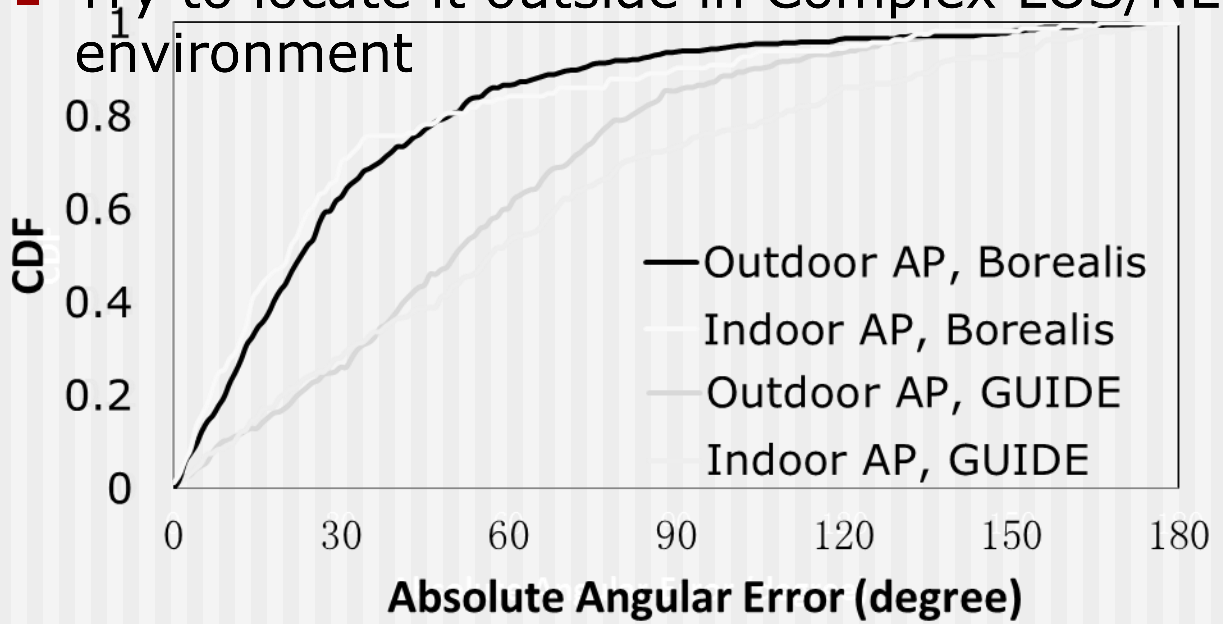
- Navigation Overhead: $\frac{Traveled\ distance - Real\ distance}{Real\ distance}$
  - Defined as the normalized extra distance a user needs to travel



NLOS Examples

Locating Indoor APs?

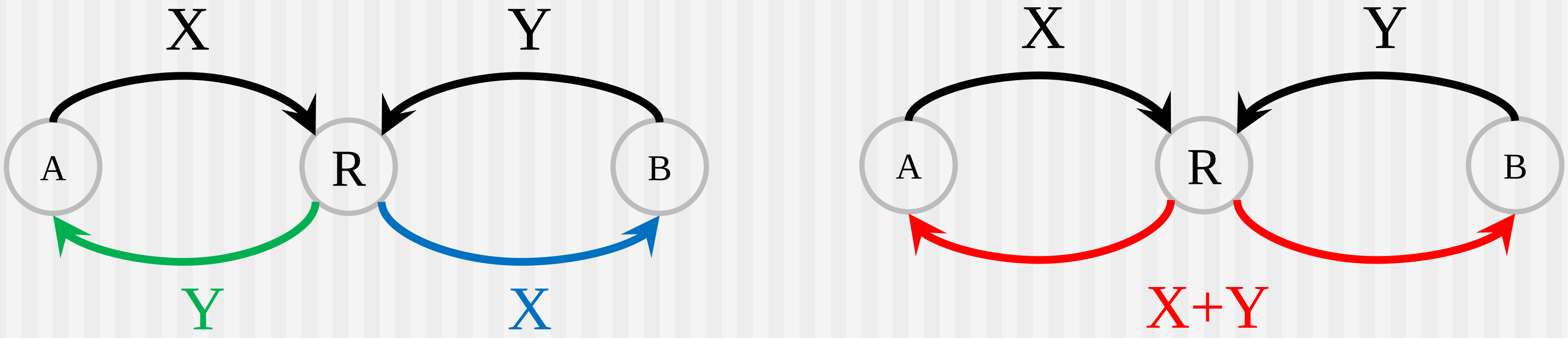
- Most APs are mounted inside buildings
- We mounted the AP on a table in our lab
  - Try to locate it outside in Complex LOS/NLOS environment



Borealis is fully capable of finding Indoor APs

Network Coding (NC)

- A technique to improve a network's throughput, efficiency and reliability.
- Mathematical approach to combine the packets.
- Example:
  - Using the wireless nature of medium in reducing the number of transmissions.

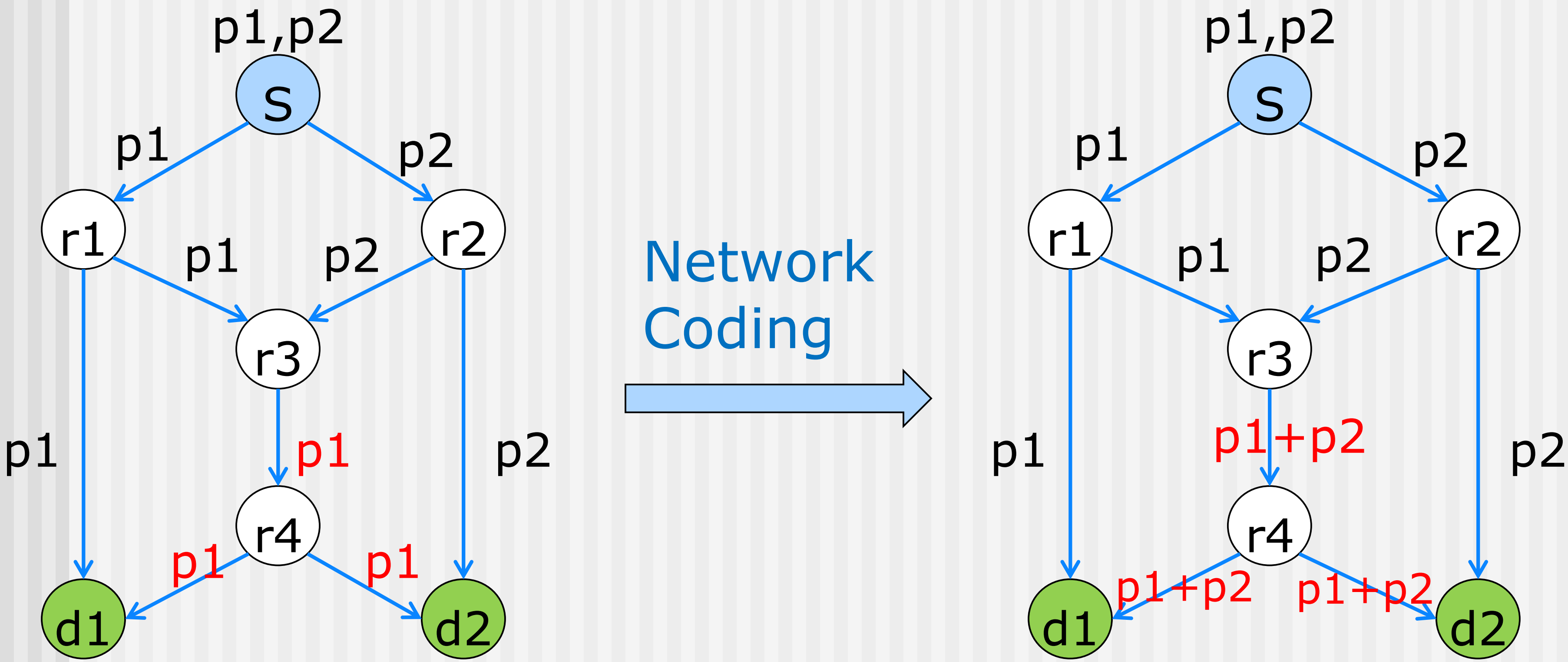


4 transmissions

3 transmissions

Bottleneck Problem

- Capacity of the links are equal to 1.



Max flow=1

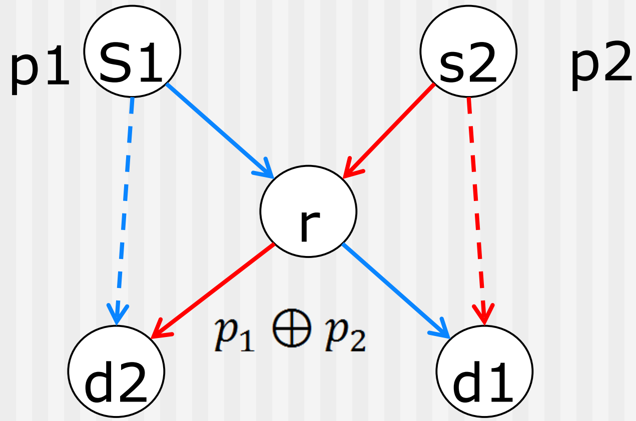
Max flow=2

Classification

- XOR
  - Binary XOR operations: $p_1 \oplus p_2 \oplus p_3$
- Random Linear NC (RLNC)
  - $\alpha_1 p_1 + \alpha_2 p_2 + \alpha_3 p_3$
  - $\sum_{i=1}^{n} \alpha_i p_i$
  - Decoding: Gaussian elimination
- RLNC
  - Advantage: more efficient and easier protocols.
  - Disadvantage: more complex encoding & decoding

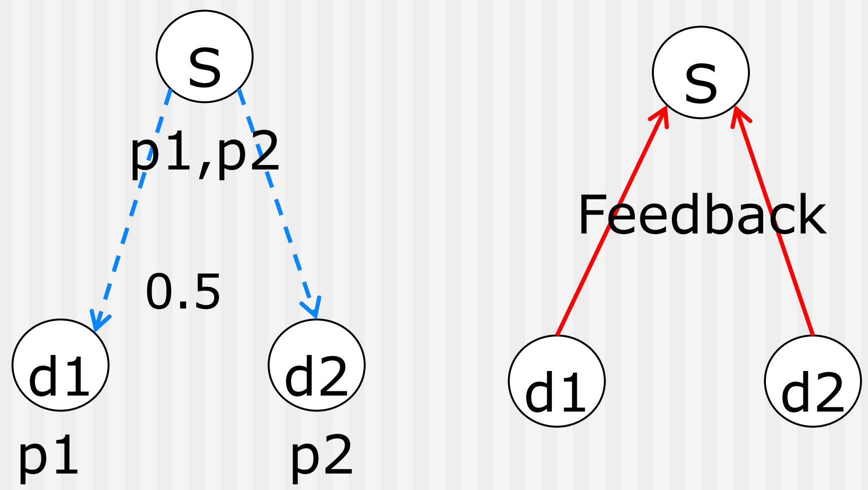
Inter Session

- Increasing throughput
- Reducing number of transmissions
  - Using the broadcasting nature of wireless medium. (overhearing)



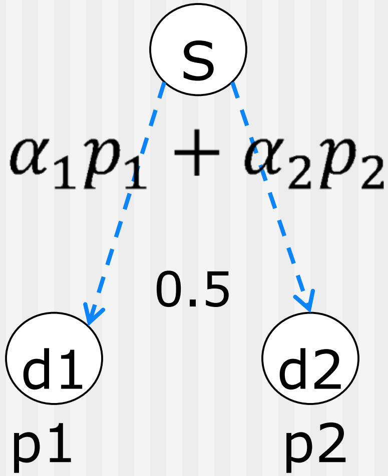
Reliable Transmission

- No coding
  - Needs feedback after each transmission
  - Retransmission of lost packets



Intra Session

- Providing reliability without feedback
- Linear coding
  - Each coded packet contributes the same amount of information.
  - Transmit random linear coded packets until receiving ACK from all destinations.



Network Capacity

- We extensively study the asymptotically capacity of random multihop wireless networks.
- How much information can be transferred through a given randomly deployed network?
- How will the network capacity scale with network size, deployment size, transmission radius?

Why Important?

Possible uses of Wireless Network Information Theory:

How good are present solutions? Which component investments are going to have the biggest impacts?

Network Planning and Design: tradeoffs concerning deployment options

architecture

transmission strategy, topology, heterogeneity,

capacity/latency/delay/energy/mobility

Capacity Definition

Given a fixed network $G = (V, E)$, with fixed

1. node positions of all nodes V,
2. set of receivers U_i for each source node v_i,
3. multicast data rate λ_i for each source node v_i

Definition (Feasible Rate Vector)

A multicast rate vector $\lambda = (\lambda_1, \lambda_2, \cdots, \lambda_{n-1}, \lambda_n)$ bits/sec is *feasible* if there is a spatial and temporal scheme for scheduling transmissions such that by operating the network in a multi-hop fashion and buffering at intermediate nodes when awaiting transmission, every node v_i can send λ_i bits/sec average to its chosen $k - 1$ destination nodes.

Capacity Definition

Definition (Capacity of Random Networks)

We say that the *multicast capacity per flow* of a class of random networks is of order $\Theta(f(n))$ bits/sec if there are deterministic constants $c > 0$ and $c < c' < +\infty$ such that

$$\lim_{n\to\infty} \Pr \lambda_k(n) = cf(n) \text{ is feasible} = 1$$

$$\liminf_{n\to\infty} \Pr \lambda_k(n) = c'f(n) \text{ is feasible} < 1$$

Capacity Definition

Given a fixed network $G = (V, E)$, with fixed node positions of all nodes V, each source node randomly select set of k receivers.

Question: What is the asymptotic network capacity for multicast?

1. Total Capacity: $\sum_{v_i \in S} \lambda_i$
2. Minimum Capacity: $\min_{v_i \in S} \lambda_i$
3. Average Capacity: $\sum_{v_i \in S} \lambda_i / n_s$

Related Works

Unicast Capacity

$\Theta(\frac{W}{\sqrt{n \log n}})$ random

A Scare, 00-01 Gupta, Kumar: Per-flow unicast throughput for a randomly chosen destination is $\Theta(W/\sqrt{n \log n})$

Related Works

Unicast Capacity

$$\Rightarrow \Theta(W)$$

Mobility Matters, 2002 Grossglauser and Tse, $\Theta(W)$ via mobility and power-adjustment, large delay.

Related Works

Unicast Capacity

$$\Rightarrow \Theta\left(\frac{W}{\sqrt{n \log n}}\right) \text{ NC}$$

Network Coding Does Not Matter, 2006 Li, Goeckel and Towsley:

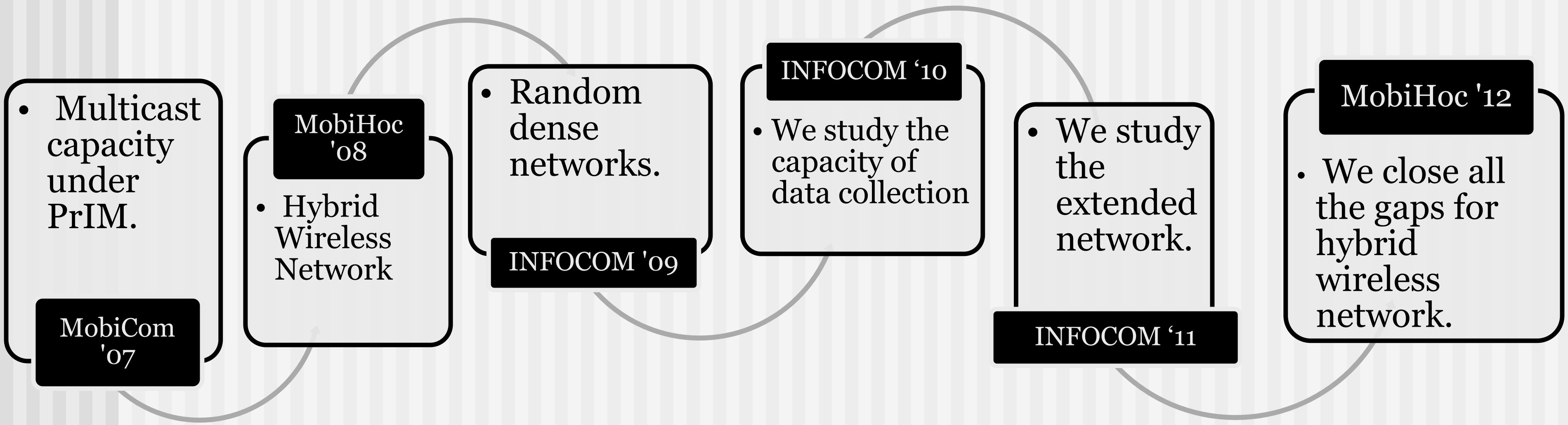
$\Theta(1/\sqrt{n \log n})$ with NC & PrIM.

Related Works

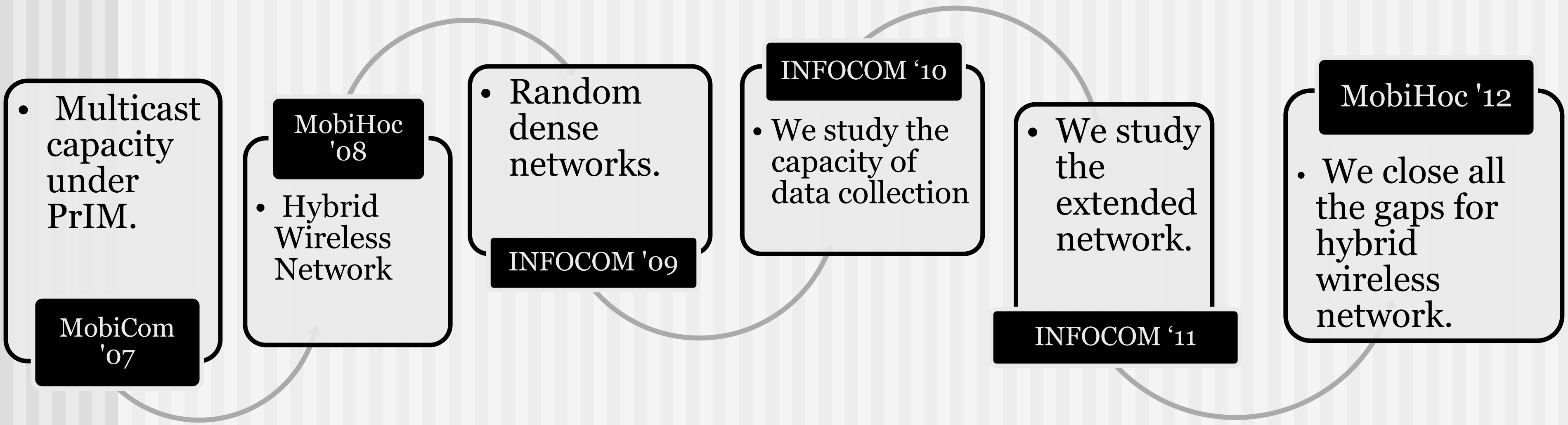
Unicast Capacity

$\Rightarrow \Theta(\frac{W}{\sqrt{n}})$ GC

Channel Model Does Matter Franceschetti *et al.* 2007, $\Theta(W/\sqrt{n})$ when using Gaussian Channel.


• Multicast capacity under PrIM.
MobiCom '07
MobiHoc '08
• Hybrid Wireless Network
• Random dense networks.
INFOCOM '09
INFOCOM '10
• We study the capacity of data collection
• We study the extended network.
INFOCOM '11
MobiHoc '12
• We close all the gaps for hybrid wireless network.

Multicast Capacity for Large Scale Wireless Ad Hoc Networks (ACM MobiCom 2007) X.-Y. Li, Shaojie Tang, Ophir Frieder



Multicast Capacity for Hybrid Wireless Networks
(ACM MobiHoc 2008) X.-F. Mao, X.-Y. Li, Shaojie Tang

MobiCom '07
- Multicast capacity under PrIM.

MobiHoc '08
- Hybrid Wireless Network

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Scaling Laws on Multicast Capacity of Large Scale Wireless Networks (IEEE INFOCOM 2009) Wang, Shaojie Tang etal.

MobiCom '07
- Multicast capacity under PrIM.

MobiHoc '08
- Hybrid Wireless Network

INFOCOM '09
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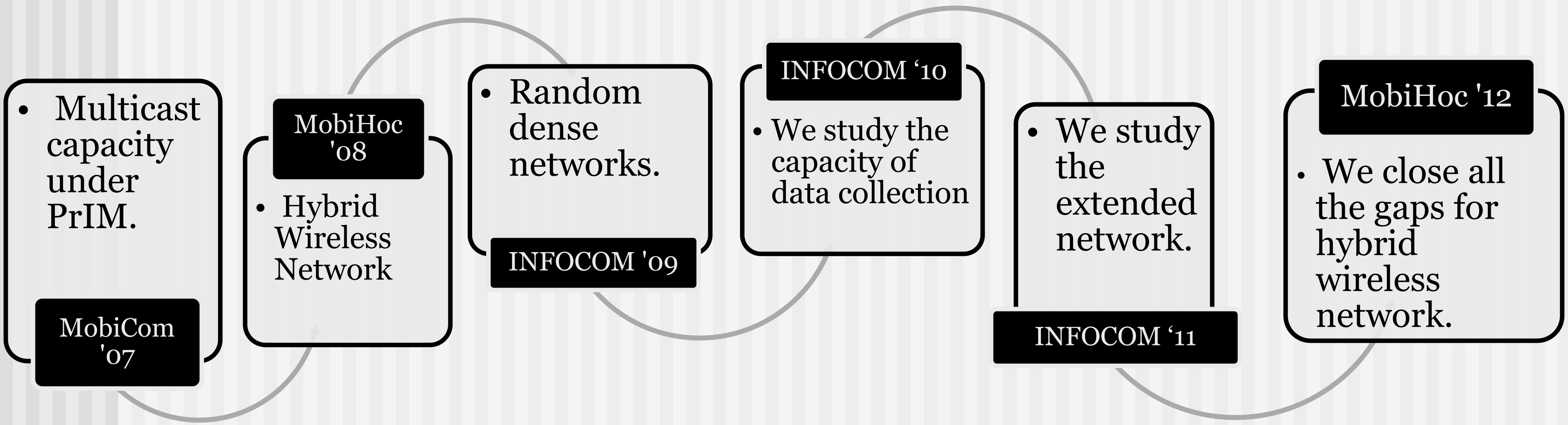
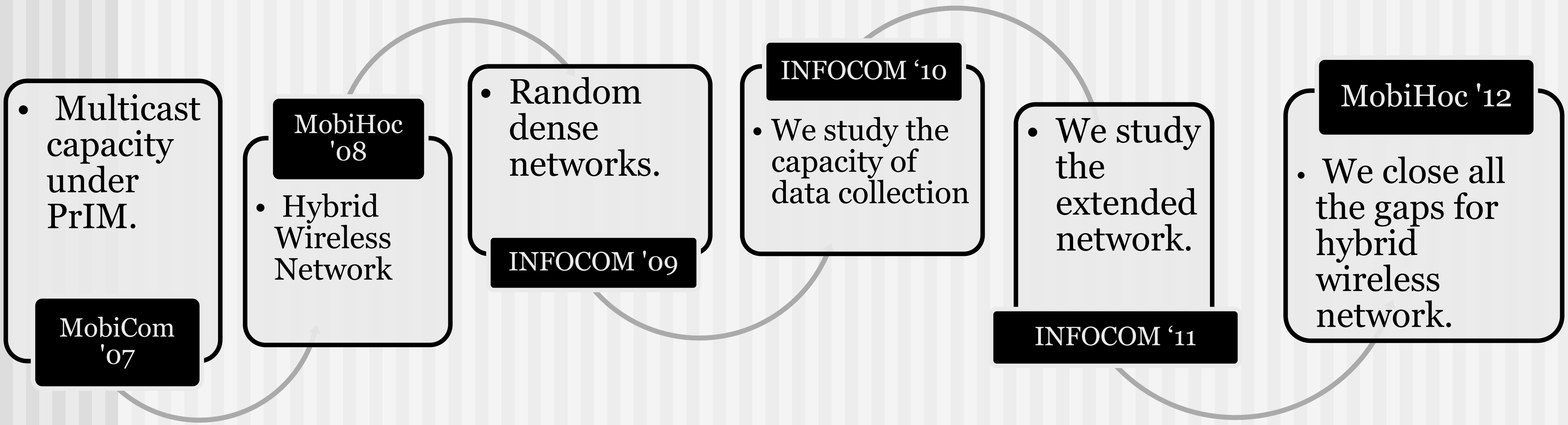
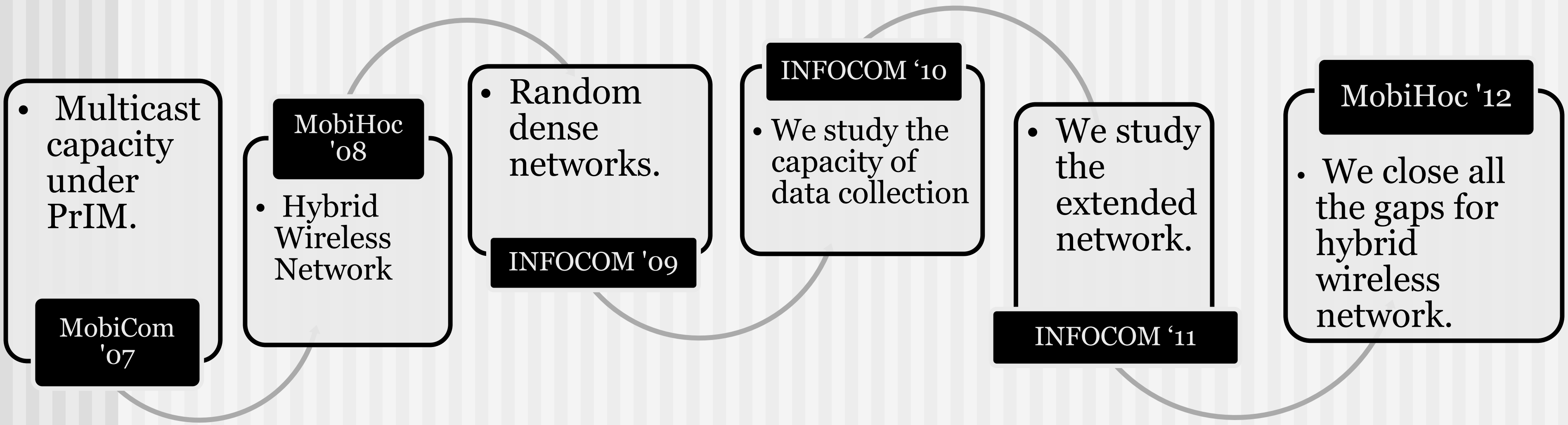
Capacity of Data Collection in Arbitrary Wireless Sensor Networks (IEEE INFOCOM 2010) Chen, Shaojie Tang etal.



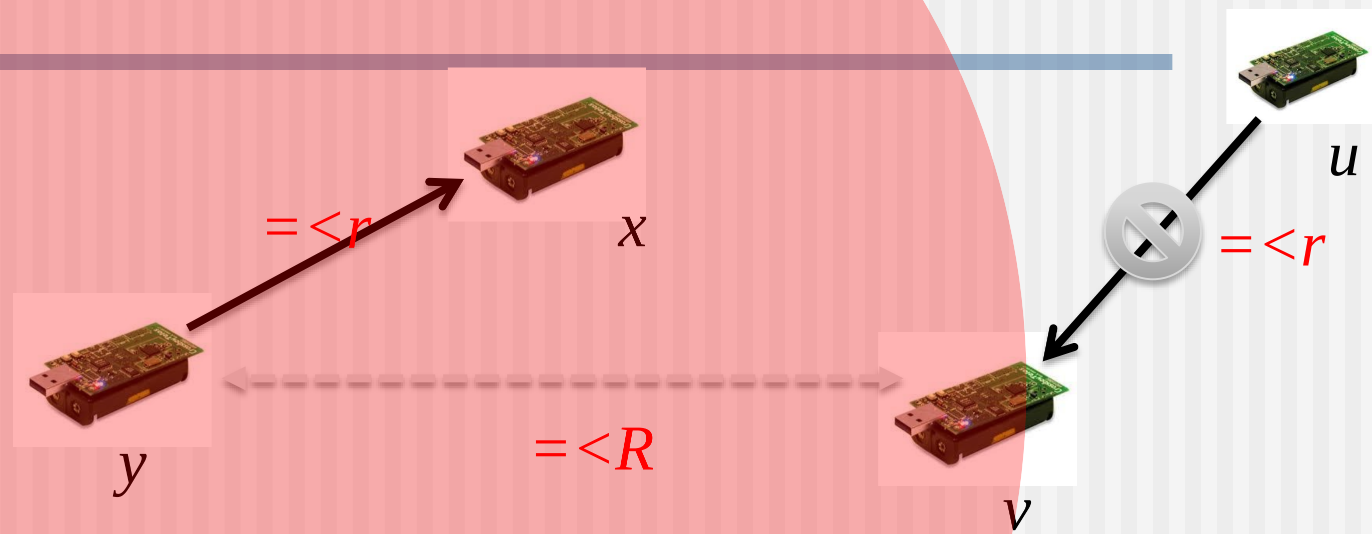
Aggregation Capacity of Wireless Sensor Networks: Extended Network Case (IEEE INFOCOM 2011) Wang, Shaojie Tang etal.



Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks
(ACM MobiHoc 2012) Shaojie Tang etal.

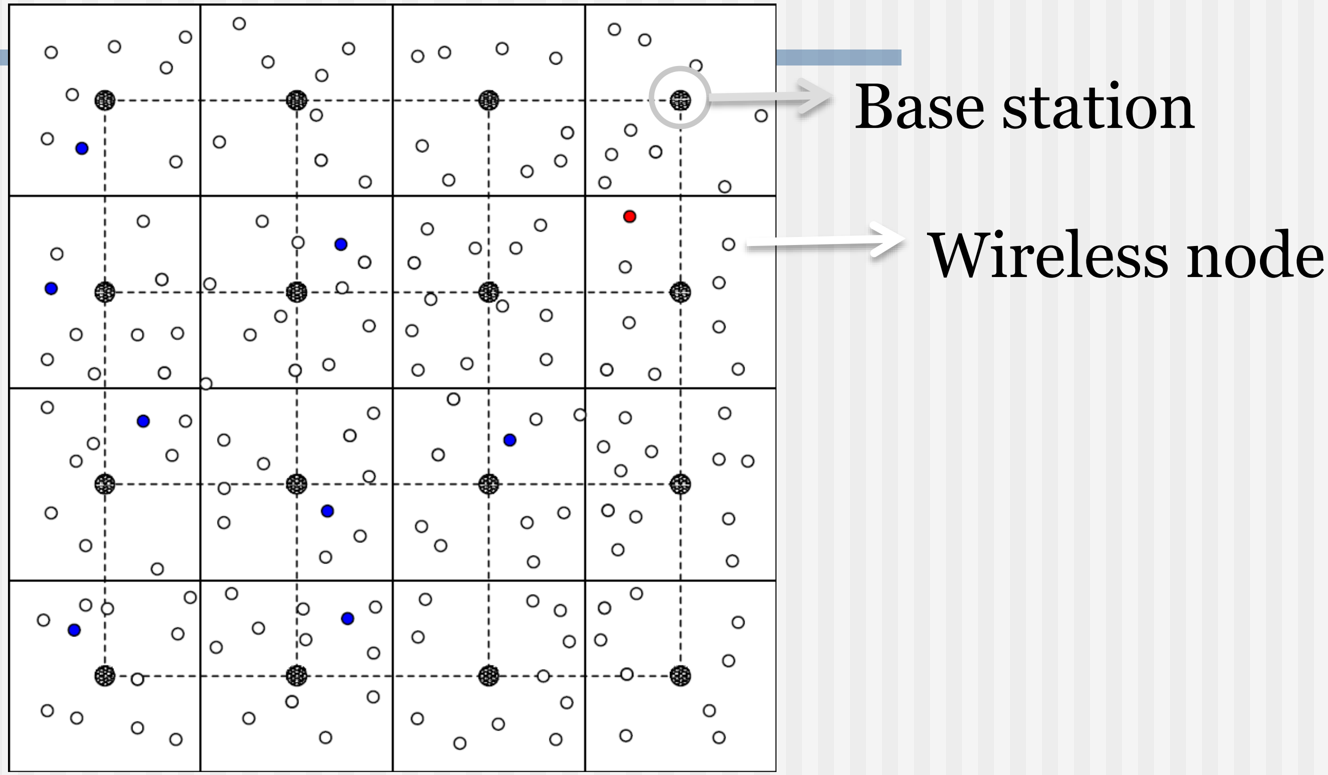


Protocol Interference Model



- Data Rate of each link is: W bps
- Transmission Range r
- Interference Range R
- Receiver v is not inside the interference range of another sender

Hybrid Wireless Networks

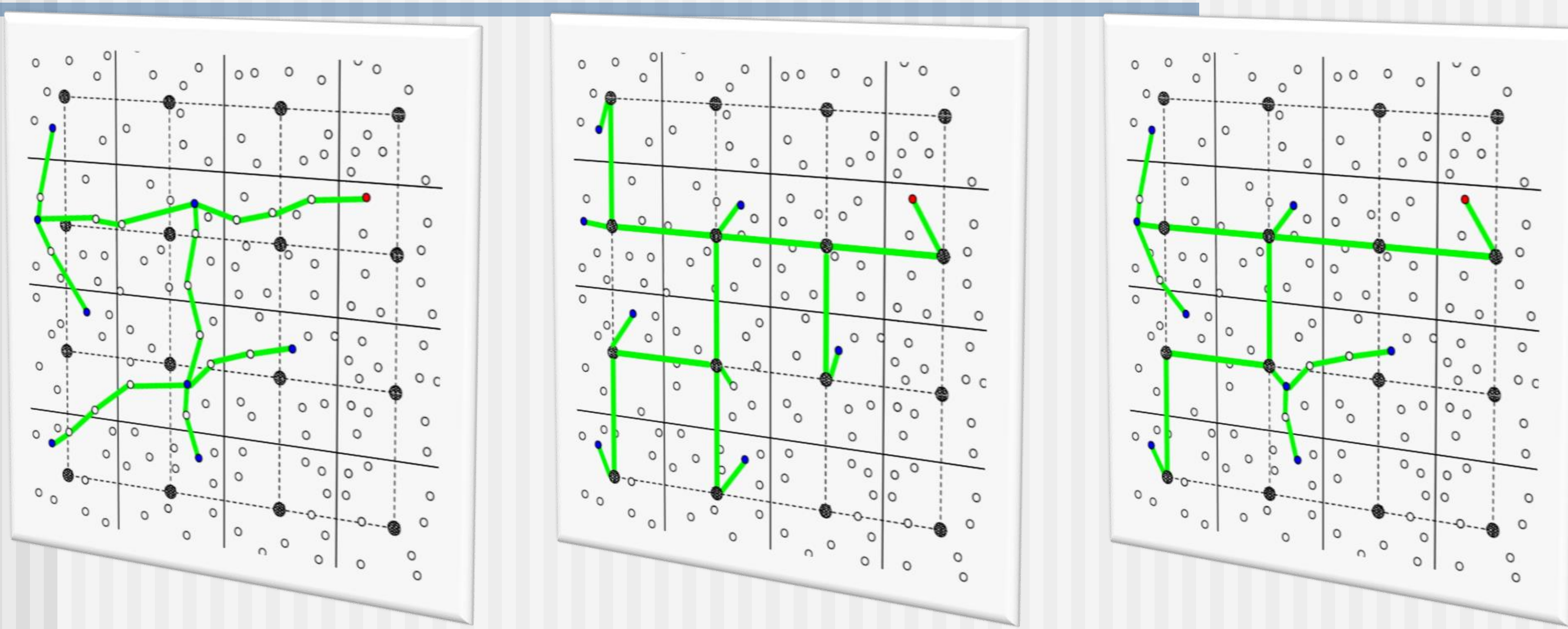


- *n* randomly placed *ordinary wireless nodes* and
- *m* regularly placed *base stations* in a square region.

Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

Shaojie Tang etal. (ACM MobiHoc 2012)

Possible Routing



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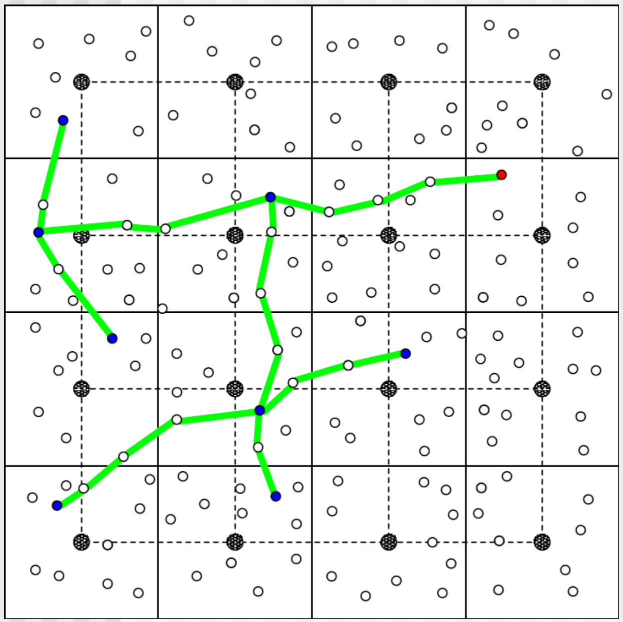
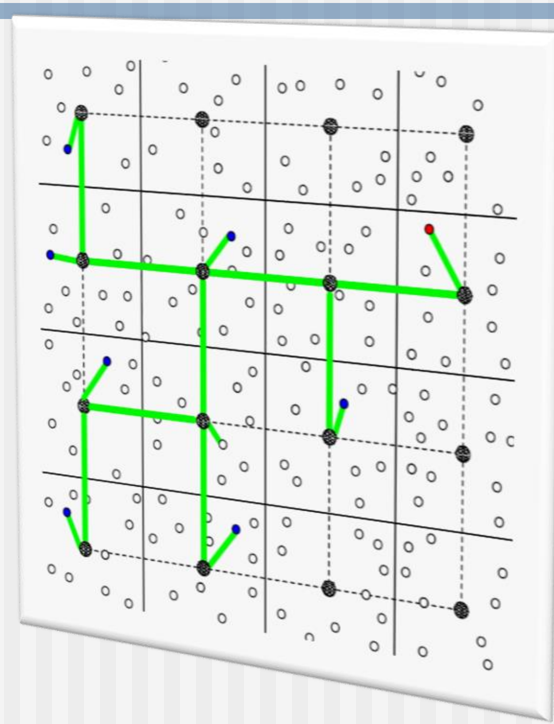
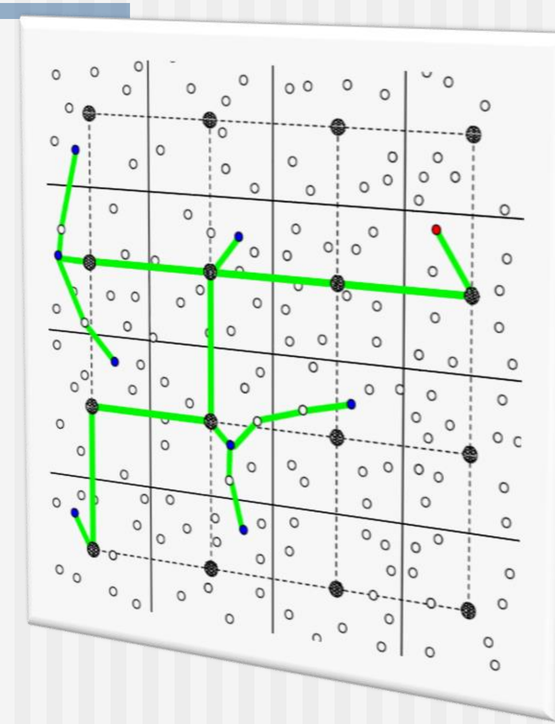


Ad Hoc
Routing





Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

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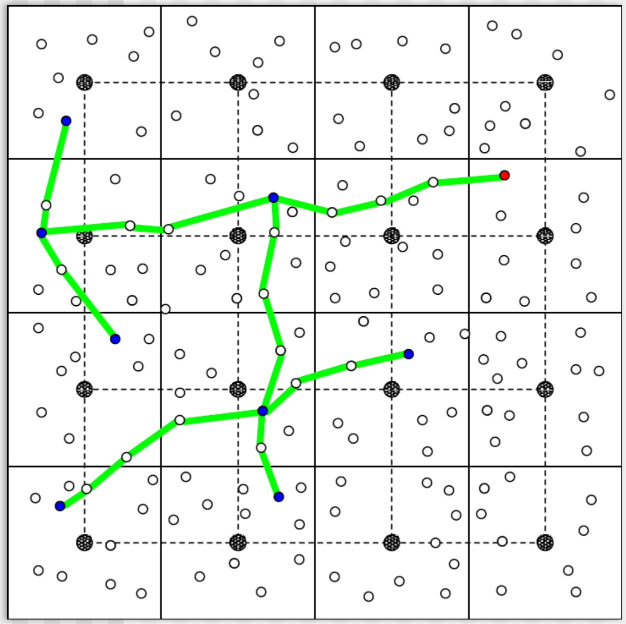

Ad Hoc
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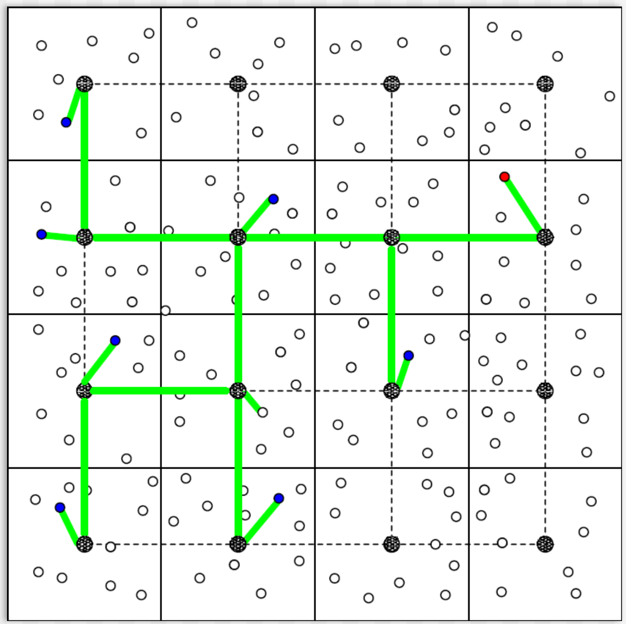
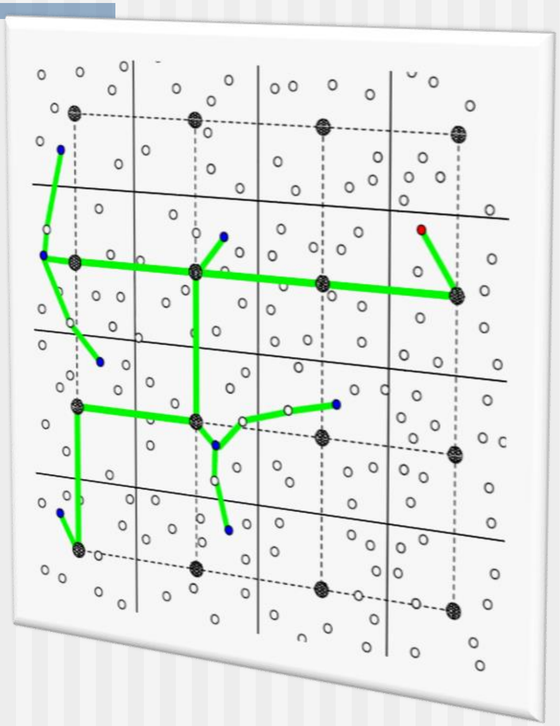


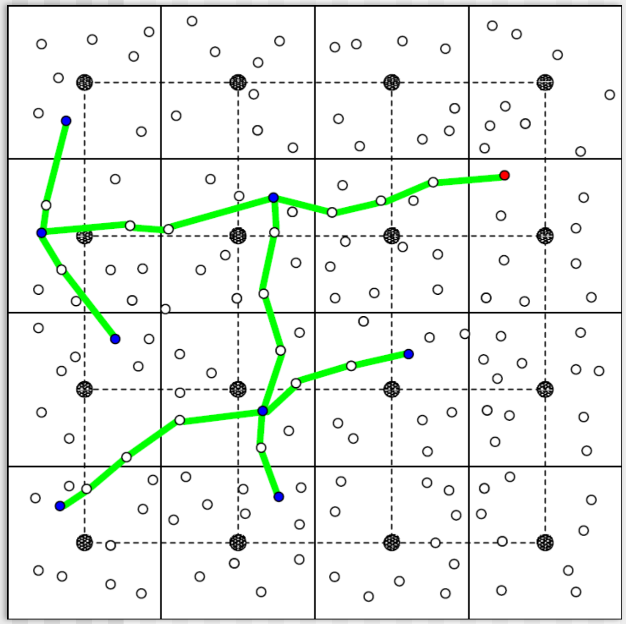
Cellular
Routing



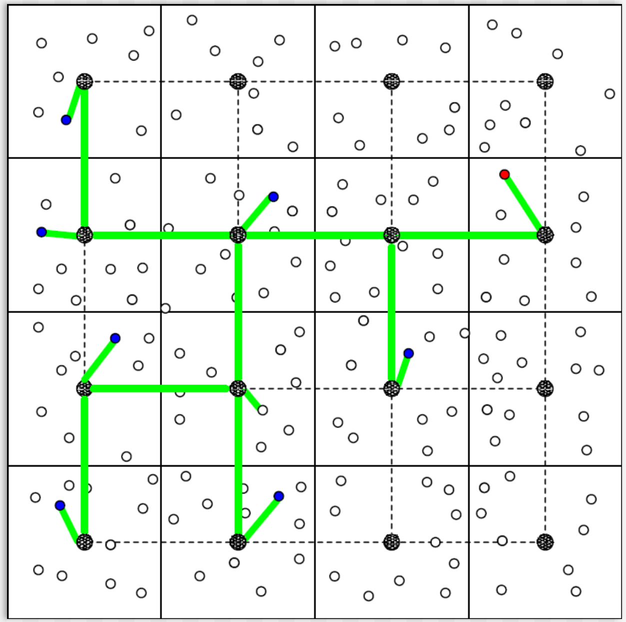
Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

Shaojie Tang etal. (ACM MobiHoc 2012)

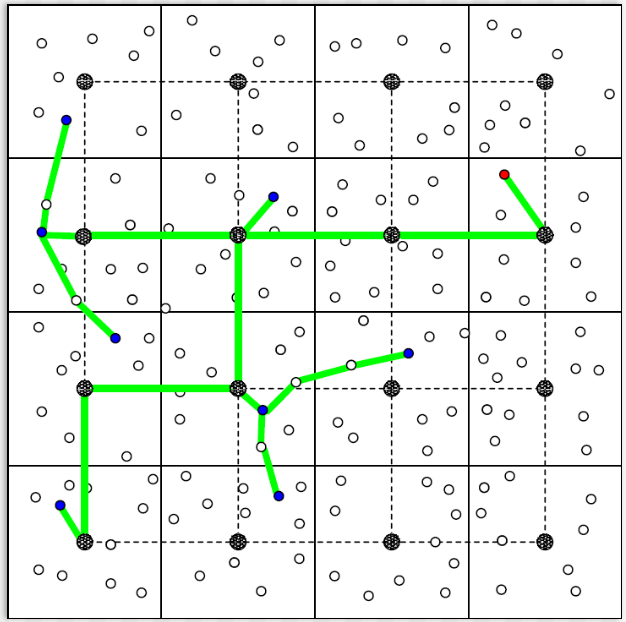
Possible Routing



Ad Hoc Routing



Cellular Routing



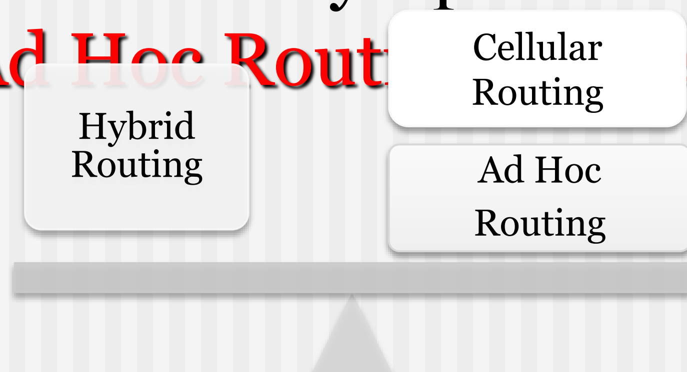
Hybrid Routing

Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

Shaojie Tang etal. (ACM MobiHoc 2012)

Main Results

We prove that Hybrid Routing strategy will achieve a network capacity at most the larger one of the asymptotic capacity achieved by **Cellular Routing strategy** and the asymptotic capacity achieved by the **Ad Hoc Routing strategy**.



Main Results

Multicast Capacity of Cellular Routing

$$\begin{cases} \Theta(\min(\frac{W_B\sqrt{m}}{n_s\sqrt{k}}, \frac{W_c m}{n_s k}, \frac{W_a m}{n_s k})) & \text{if } k = O(m) \\ \Theta(\min(\frac{W_B}{n_s}, \frac{W_c}{n_s}, \frac{W_a}{n_s})) & \text{if } k = \Omega(m) \end{cases}$$

Multicast Capacity of Ad Hoc Routing

$$\begin{cases} \Theta(\sqrt{\frac{n}{\log n}} \cdot \frac{W}{\sqrt{k}}) & \text{when } k = O(\frac{n}{\log n}) \\ \Theta(W) & \text{when } k = \Omega(\frac{n}{\log n}) \end{cases}$$

Main Results

Multicast Capacity of Hybrid Routing

$$\begin{cases} \Theta\left(\max\left[\min\left(\frac{W_B\sqrt{m}}{n_s\sqrt{k}}, \frac{W_c m}{n_s k}, \frac{W_a m}{n_s k}\right), \frac{W_a}{n_s\sqrt{k}}\frac{a}{r}\right]\right) & \text{if } k = O(m) \\ \Theta\left(\frac{a}{r}\cdot\frac{W_a}{n_s\sqrt{k}}\right) & \text{if } k = \Omega(m), k = O\left(\frac{a^2}{r^2}\right) \\ \Theta\left(\frac{W_a}{n_s}\right) & \text{if } k = \Omega\left(\frac{a^2}{r^2}\right) \end{cases}$$

Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

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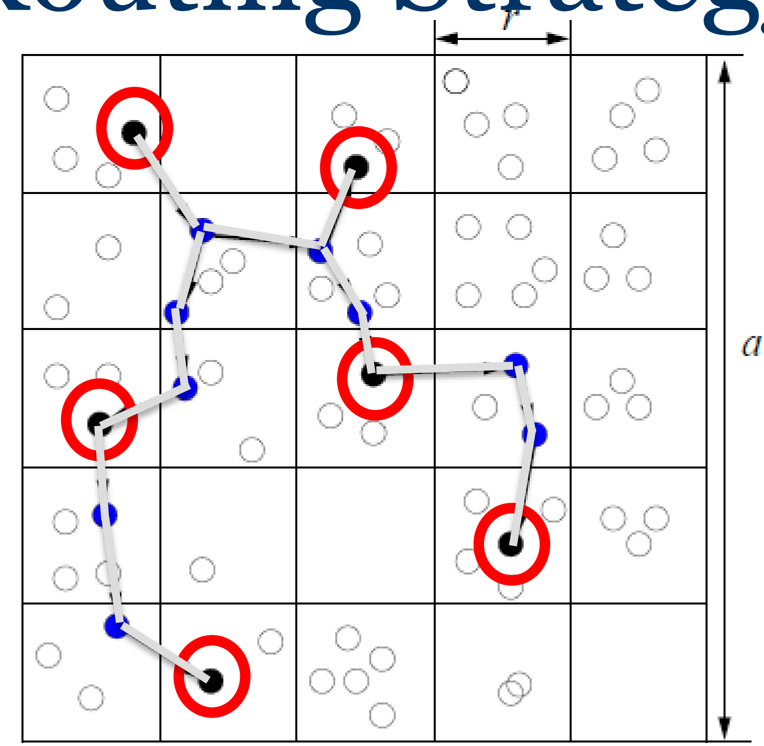
Ad Hoc Routing Strategy



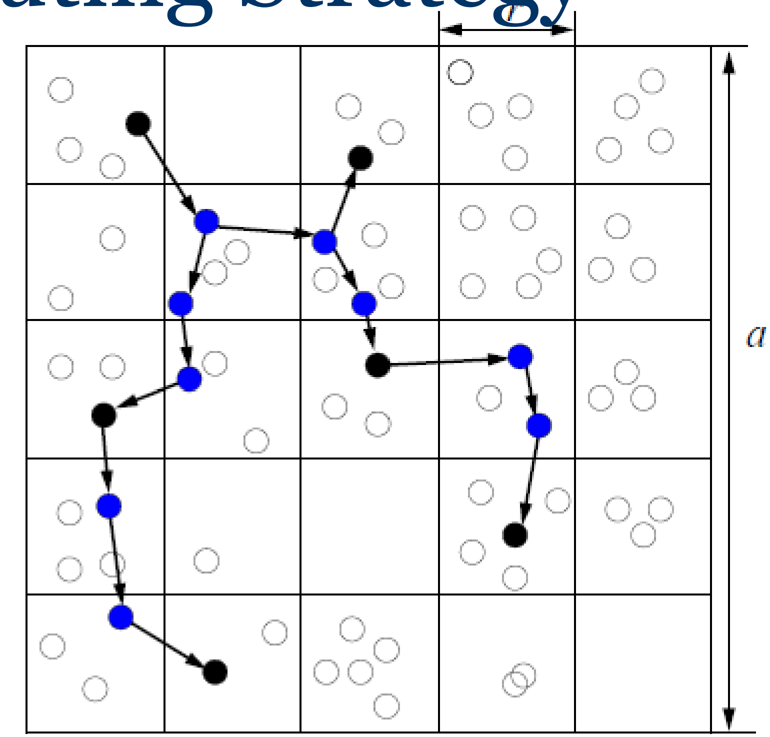
Consider only multicasts where

- There are n_s sources S.
- Each source node randomly selects $k-1$ ($k=2$ for unicast) points and closest nodes as receivers
- Each source node v_i generates data at rate λ_i bits/second.

Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

Shaojie Tang etal. (ACM MobiHoc 2012)

Ad Hoc Routing Strategy



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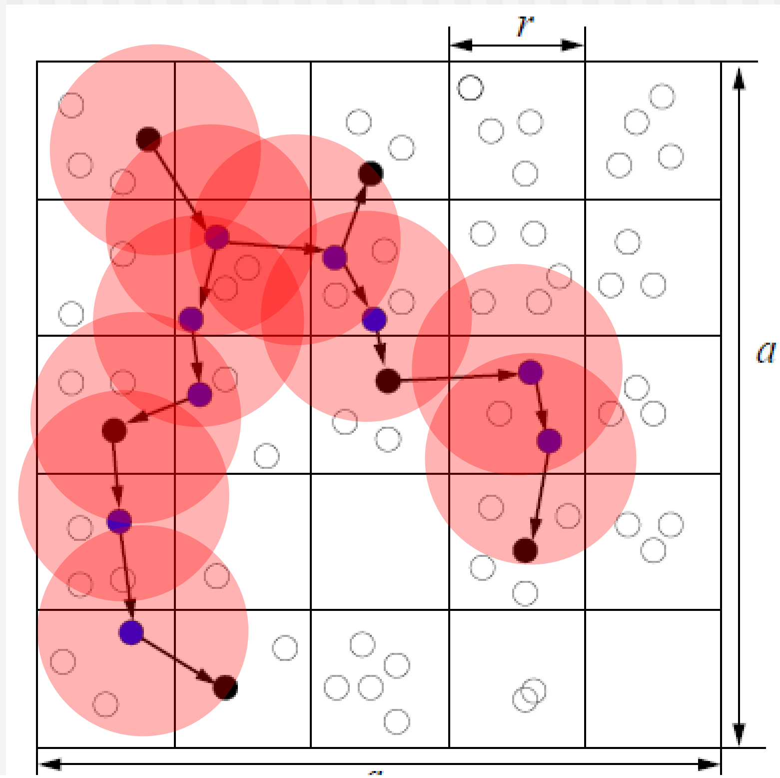
Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

Shaojie Tang etal. (ACM MobiHoc 2012)

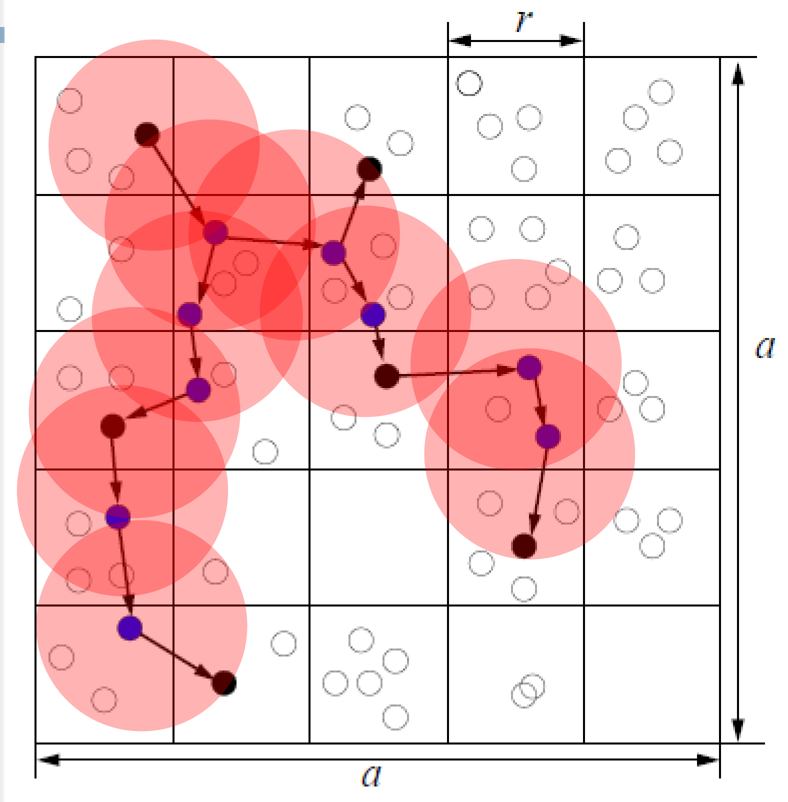
A Capacity Upper Bound



- **Data Copies Argument**:
  Estimate the expected (or asymptotic lower bound) number of nodes $N(b)$ that received (or listened) a bit b.
  Capacity at most $\frac{n \cdot W}{N(b)}$ since all nodes receive at rate at most $n \cdot W$.

Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks
Shaojie Tang etal. (ACM MobiHoc 2012)

A Capacity Upper Bound



Area covered by transmitting disks with high probability is at least

$$\frac{\tau\sqrt{k}a\cdot r}{c_0}$$

when the number of receivers/source nodes

$$k \leq \theta_1 \frac{a^2}{r^2},$$

Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

Shaojie Tang etal. (ACM MobiHoc 2012)

A Capacity Upper Bound

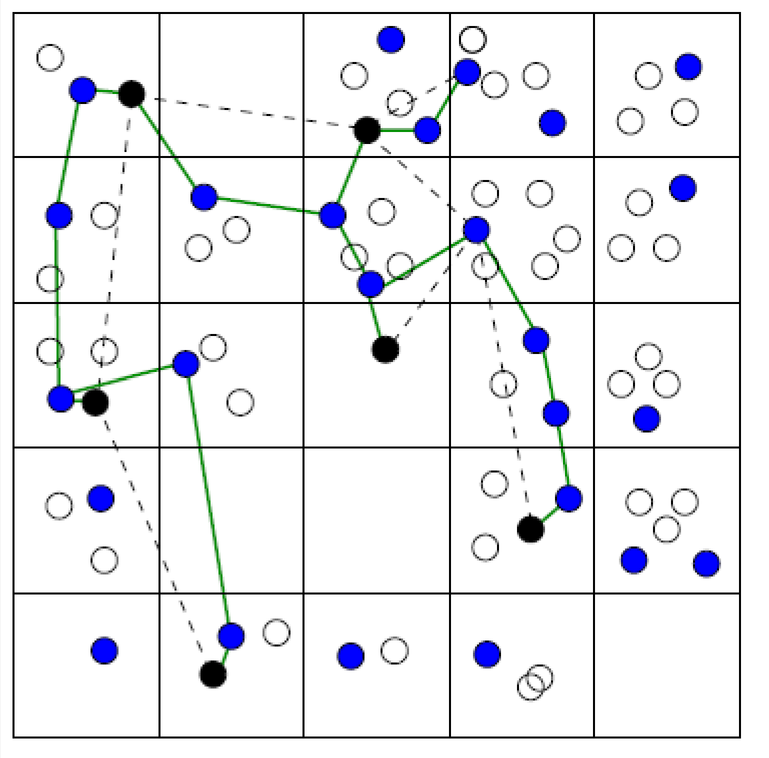
$$\sum_{i=1}^{n} C_i \cdot \lambda_i \leq nW$$

and, with high probability, $C_i \geq \frac{\tau \cdot r \cdot \sqrt{k} \cdot n}{2c_0 a}$ when $k < \theta_1 \cdot a^2 / r^2$. Thus, the multicast capacity $\Lambda_k(n)$ is at most

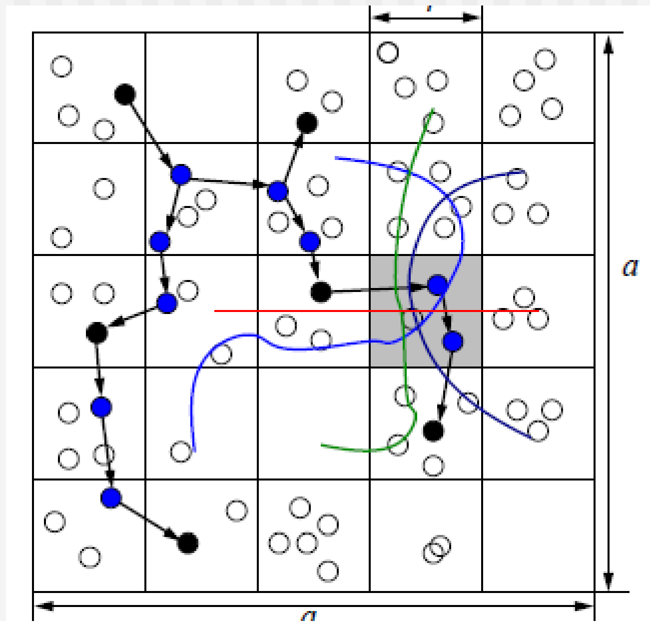
$$\Lambda_k(n) = \sum_{i=1}^{n} \lambda_i \leq \frac{nW \cdot 2c_0 a}{\tau \cdot r \cdot \sqrt{k} \cdot n} = \boxed{c_1 \cdot \frac{aW}{r\sqrt{k}}}$$

for a constant $c_1 = \frac{2c_0}{\tau}$.

A Capacity Lower Bound



A Capacity Lower Bound



Lemma

Given n_s multicast sessions, the expected number of multicast routing flows that use a specific squarelet **s** *is at most*

$$c_6\sqrt{k} \cdot \frac{r}{a} \cdot n_s$$

Shaojie Tang etal. (ACM MobiHoc 2012)

A Capacity Lower Bound

Theorem

Assume that there are N random multicast sessions. There is a sequence of $\delta(n) \to 0$ such that

$$\begin{aligned} & \mathbf{Pr}\{\forall \text{ squarelet } \mathbf{s}, \# \text{ of flows using } \mathbf{s} \leq \frac{3\sqrt{c_6}N}{2}\sqrt{k}\frac{r}{a}\} \\ \geq \ & 1 - \delta(n) \end{aligned}$$

The proof of this need the VC-Theorem (Vapnik and Chervonenkis).

A Capacity Lower Bound

Theorem

Assume $k \leq \theta_1 \frac{a^2}{r^2}$, there are n_s random multicast sessions and

$$n_s \geq \frac{4d\sqrt{c}}{c_6}\sqrt{\frac{n \log n}{k}}.$$

With probability at least $(1-\frac{2}{n})^2 \geq 1-\frac{4}{n}$, the achievable per-flow multicast capacity is at least

$$\lambda_k(n) = \frac{W}{3\sqrt{c_6}\Delta} \cdot \frac{a}{n_s r\sqrt{k}} = \Theta\left(\frac{W}{n_s\sqrt{k}} \cdot \frac{a}{r}\right). \quad (6)$$

Multicast Capacity of Ad Hoc Wireless Network

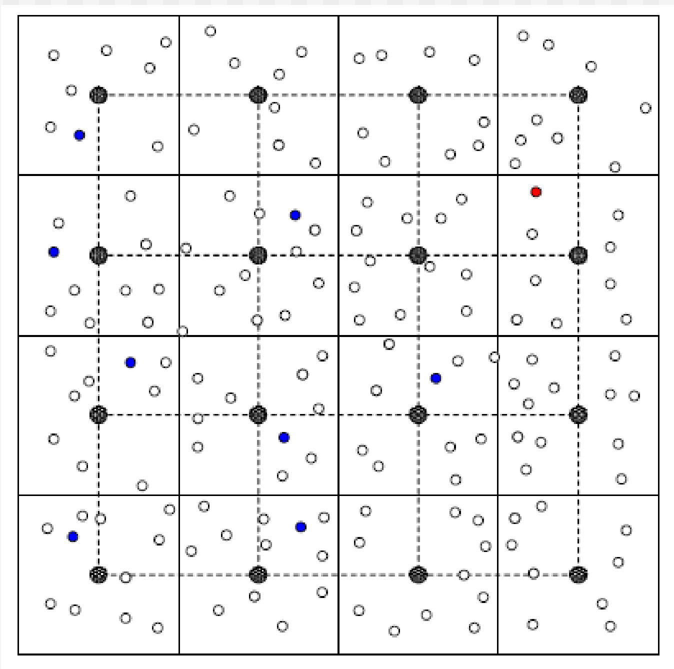
The aggregated multicast capacity of n multicast sessions is

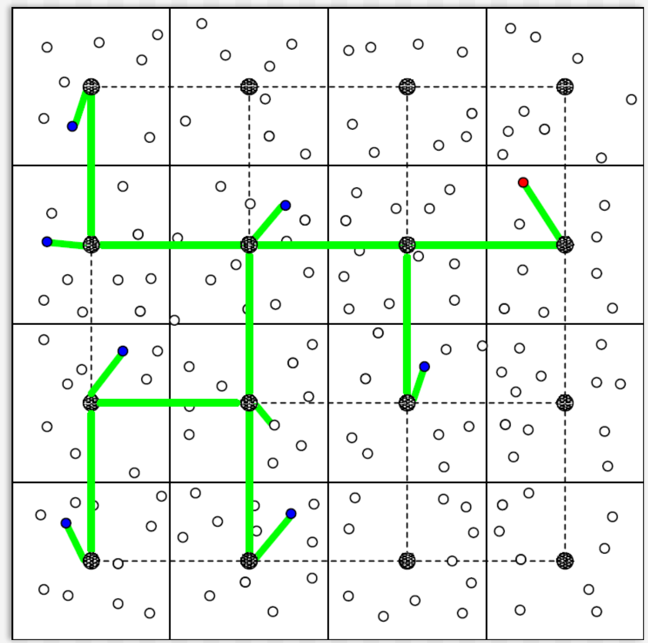
$$\Lambda_k(n) = \begin{cases} \Theta\left(\sqrt{\frac{n}{\log n}} \cdot \frac{W}{\sqrt{k}}\right) & \text{when } k = O\left(\frac{n}{\log n}\right), \\ \Theta(W) & \text{when } k = \Omega\left(\frac{n}{\log n}\right) \end{cases}$$

Our bounds unify the previous capacity bounds

1. Unicast (when $k = 2$): $\Theta\left(\sqrt{\frac{n}{\log n}} \cdot W\right)$ by Gupta and Kumar
2. Broadcast (when $k = n$): $\Theta(W)$ by Keshavarz-Haddad *et al.*, MobiCom'06.

Multicast Capacity of Cellular Network

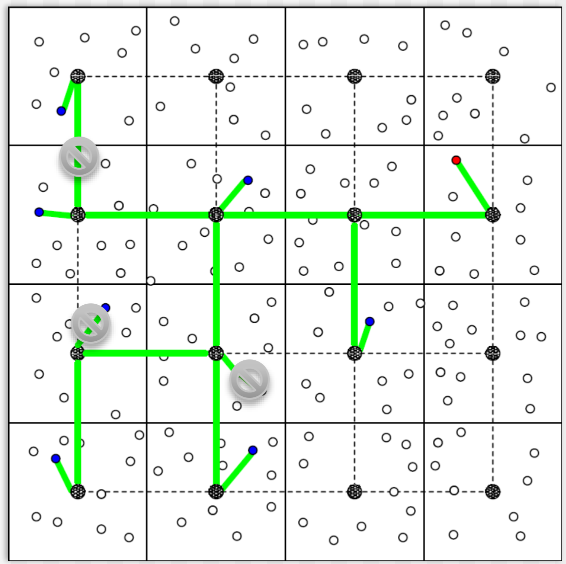




Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

Shaojie Tang etal. (ACM MobiHoc 2012)

Multicast Capacity of Cellular Network



When *Cellular Routing* is used, the capacity for a hybrid network can be constrained due to three different congestion scenarios:

1. the backbone formed by the links E_B is congested;
2. the cellular links E_c are congested; and
3. the ad hoc links $E_a \setminus E_d$ in some cell are congested.

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Multicast Capacity of Cellular Network

The per-flow capacity $\vartheta_k(n)$ of n_s multicast sessions, when *Cellular Routing* strategy is used, is

$$\begin{cases} \Theta(\min(\frac{W_B\sqrt{m}}{n_s\sqrt{k}}, \frac{W_c m}{n_s k}, \frac{W_a m}{n_s k})) & \text{if } k = O(m) \\ \Theta(\min(\frac{W_B}{n_s}, \frac{W_c}{n_s}, \frac{W_a}{n_s})) & \text{if } k = \Omega(m) \end{cases}$$

Closing the Gap in the Multicast Capacity of Hybrid Wireless Networks

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Main Results

Multicast Capacity of Cellular Routing

$$\begin{cases}\Theta\left(\min\left(\frac{W_B\sqrt{m}}{n_s\sqrt{k}}, \frac{W_c m}{n_s k}, \frac{W_a m}{n_s k}\right)\right) & \text{if } k = O(m)\end{cases}$$

$$\begin{cases}\Theta\left(\max\left[\min\left(\frac{W_B\sqrt{m}}{n_s\sqrt{k}}, \frac{W_c m}{n_s k}, \frac{W_a m}{n_s k}\right), \frac{W_a}{n_s\sqrt{k}}\frac{a}{r}\right]\right) & \text{if } k = O(m)\\ \Theta\left(\frac{a}{r}\cdot\frac{W_a}{n_s\sqrt{k}}\right) & \text{if } k = \Omega(m), k = O\left(\frac{a^2}{r^2}\right)\\ \Theta\left(\frac{W_a}{n_s}\right) & \text{if } k = \Omega\left(\frac{a^2}{r^2}\right)\end{cases}$$

$$\begin{cases}\Theta\left(\sqrt{\frac{n}{\log n}}\cdot\frac{W}{\sqrt{k}}\right) & \text{when } k = O\left(\frac{n}{\log n}\right)\\ \Theta(W) & \text{when } k = \Omega\left(\frac{n}{\log n}\right)\end{cases}$$