CIS 5636 Ad Hoc Networks (Part II)

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Ad Hoc Wireless Networks (Infrastructureless networks)

- An ad hoc network is a collection of wireless mobile host forming a temporary network without the aid of any centralized administration or standard support services regularly available on the wide area network to which the hosts may normally be connected (Johnson and Maltz)

Ad Hoc Wireless Networks (Infrastructureless networks)

- Manet (mobile ad hoc networks)
- Mobile distributed multihop wireless networks
- Temporary in nature
- No base station and rapidly deployable
- Neighborhood awareness
- Multiple-hop communication
- **Unit disk graph**: host connection based on geographical distance

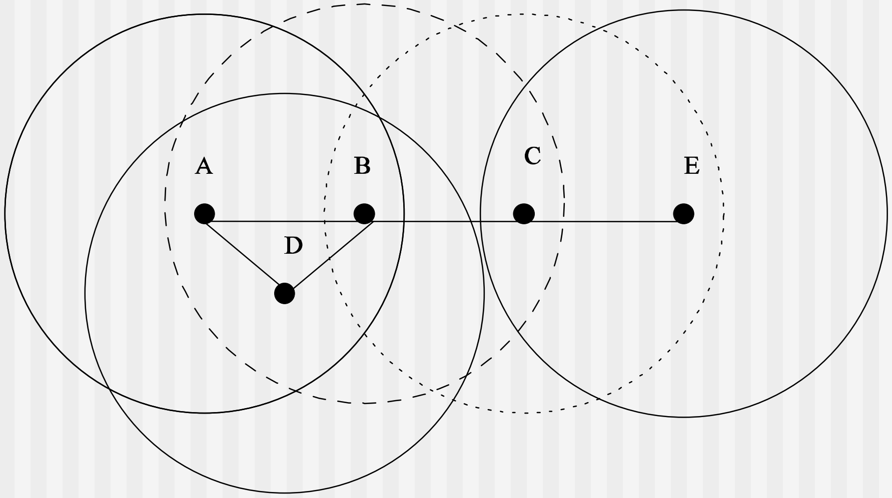
Sample Ad Hoc Networks

- Sensor networks
- Indoor wireless applications
- Mesh networks
- People-based networks
  - “small world” that are very large graphs that tend to be sparse, clustered, and have a small diameter.
  - “six degree of separation”

Characteristics

- Self-organizing: without centralized control
- Scarce resources: bandwidth and batteries
- Dynamic network topology

Unit Disk Graph



A simple ad hoc wireless network of five wireless mobile hosts.

Applications

- Defense industry (battlefield)
- Law enforcement
- Academic institutions (conference and meeting)
- Personal area networks and Bluetooth
- Home networking
- Embedding computing applications
- Health facilities
- Disaster recovery (search-and-rescue)

Major Issues

- Mobility management
  - Addressing and routing*
- Location tracking
  - Absolute vs. Relative, GPS
- Network management
  - Merge and split
- Resource management
  - Networks resource allocation and energy efficiency
- QoS management*
  - Dynamic advance reservation and adaptive error control techniques

Major Issues (Cont'd.)

- MAC protocols*
  - Contention vs. contention-free
- Applications and middleware
  - Measurement and experimentation
- Security*
  - Authentication, encryption, anonymity, and intrusion detection
- Error control and failure
  - Error correction and retransmission, deployment of back-up systems
- Network coding
  - Reduce number of transmissions

Issues to be Covered

- Wireless Media Access Protocols (MAC)
- Ad Hoc Routing Protocols
- Multicasting and Broadcasting
- Power Optimization
- Security
- Network Coding

Wireless MAC

- A MAC (Media Access Protocol) is a set of rules or procedures to allow the efficient use of a shared medium.
  - Contention vs. contention-free
  - Sender-initiated vs. receiver-initiated

Wireless MAC: Major Issues

- Distributed operations
- Synchronization
- Hidden terminals
- Exposed terminals
- Throughput
- Access delay
- Fairness
- Real-time traffic
- Resource reservation
- Ability to measure resource availability
- Power and rate control
- Directional antennas

Wireless MAC

Contention-based

- ALOHA: no collision avoidance
  - Pure: transmitted at arbitrary time
  - Slotted: transmitted at start of a time slot
  - *p*-persistent: slotted and transmitted with a probability *p*

Wireless MAC

- Carrier Sense Multiple Access (CSMA): listen to determine whether there is activity on the channel
  - Persistent: continuously listens
  - Nonpersistent: waits a random amount of time before re-testing
  - *p*-persistent: slotted, continuously listens, and transmits when idle with a probability of *p*
  - 1-persistent: when $p = 1$.

Wireless MAC

Contention-free protocols

- Bit-map protocol: each contention period consists of N slots.
- Binary countdown: use binary station address in bidding.

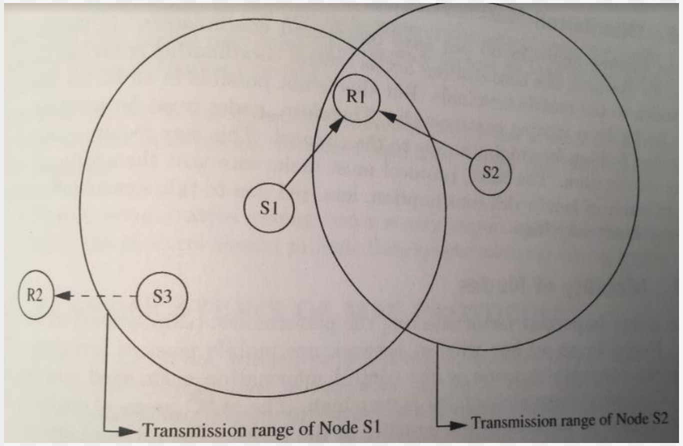
Hybrid

- Mixed contention-free with contention

Wireless MAC

- Hidden Terminal Problem
  - Two nodes, hidden from one another (out of transmission range), attempt to send information to the same receiving node.
  - Packet collisions.
- Exposed Node Problem
  - A node is inhibited from transmitting to other nodes on overhearing a packet transmission.
  - Wasted bandwidth.

CSMA/CA using RTS and CTS



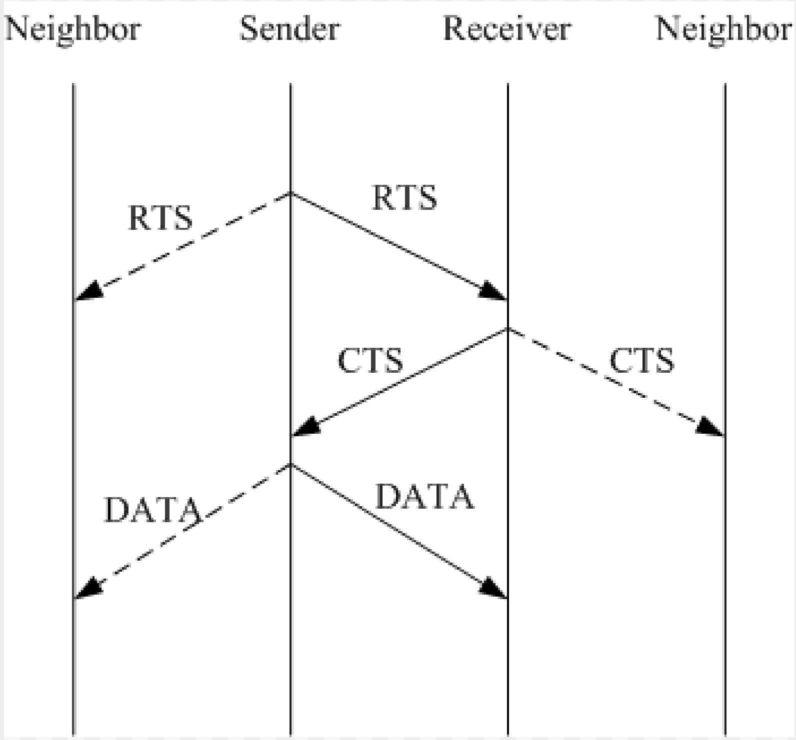
Wireless MAC

- Sender-initiated
  - MACA (Multiple Access with Collision Avoidance) (RTS-CTS-data)
  - MACAW (MACA with Acknowledgement)
  - BTMA (Busy Tone Multiple Access)
  - DBTMA (Dual BTMA)
- Receiver-initiated
  - MACA-BI (By Invitation)
- Other extensions
  - March and PAMAS

MACA (P. Karn)

- No carrier-sensing for channel at all
- Two special signals
  - RTS: request-to-send
  - CTS: clear-to-send

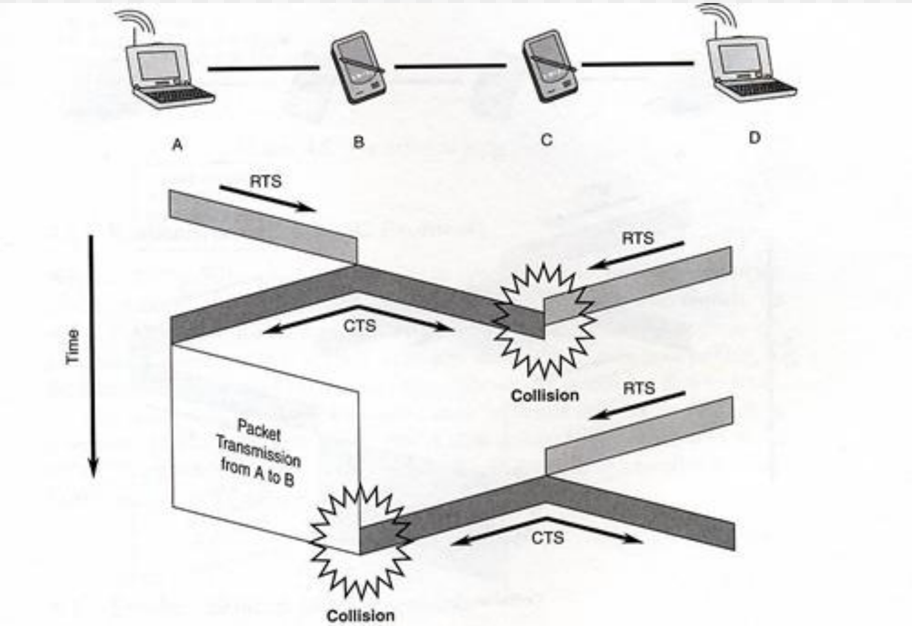
  (virtual carrier sensing)
- Packet lost
  - Binary exponential back-up
- Overcomes the hidden terminal issue



Karn, "MACA-A New Channel Access Method for Packet Radio", Sept. 1990

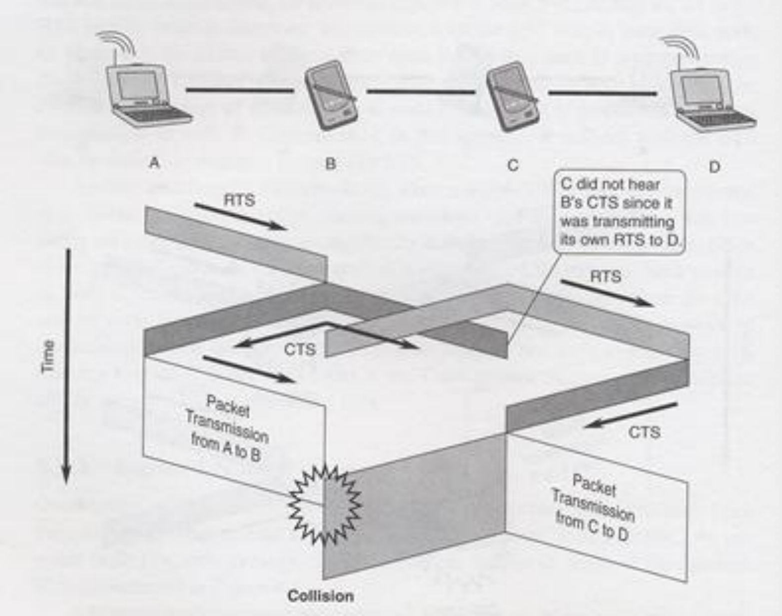
Sample collision for MACA

- RTS-CTS problem 1



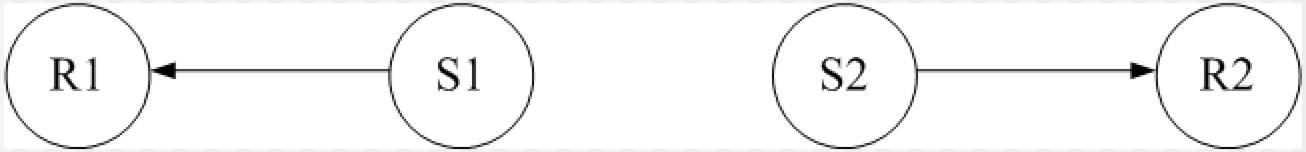
Sample collision for MACA

RTS-CST problem 2



MACAW (V. Bharghavan et al)

- RTS+CTS+DS+DATA+ACK
  - DS: data-sending (avoid unnecessary back-off counter build up), DS (from s1) carries duration information for S2 to act

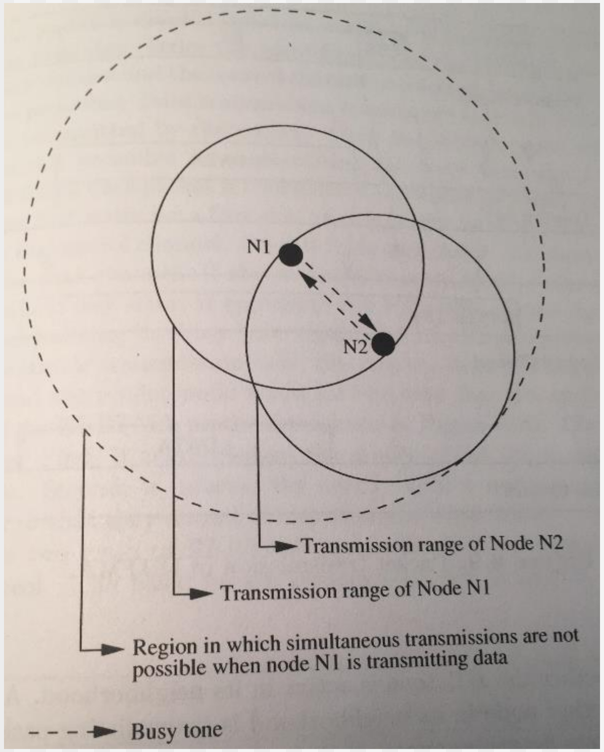


- RRTS: request-for-request-to-send
  - R2 acts on S2 once S1 to R1 is done, as DS does not help

Bharghavan et al, "MACAW: A media Access Protocol for Wireless LAN's," SIGCOMM'94

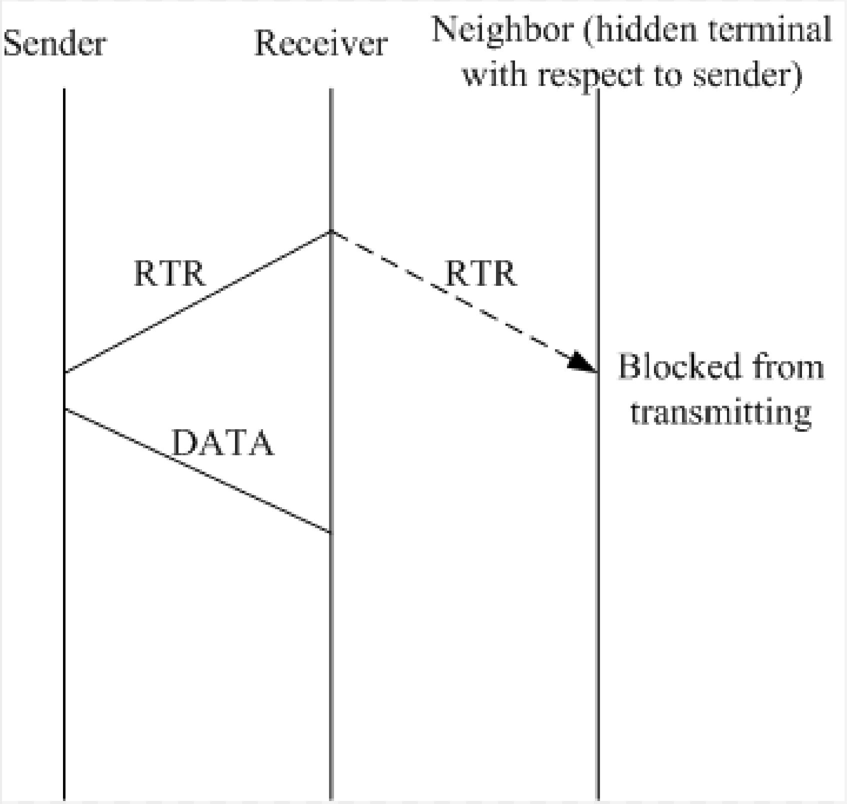
DBTMA (Z. Haas)

- BTMA (Busy Tone Multiple Access)
  - Separate control and data (busy tone)
  - Busy tone goes for two hops: nodes sense data carry also send busy tone
  - Too restrictive (disable two-hop)
- Dual BTMA
  - RTS
  - Receive busy tone + CTS
  - Transmit busy tone + Data



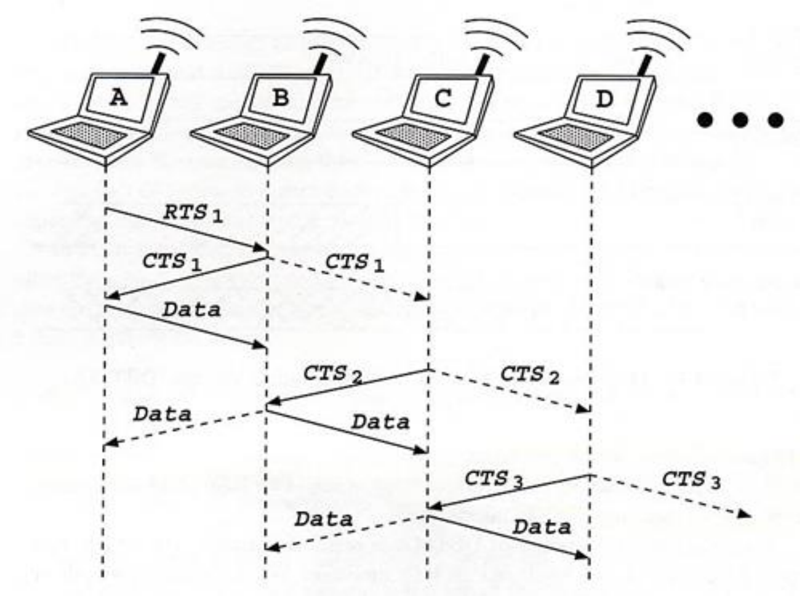
MACA-BI (M. Gerla)

- Receiver-initiated
  - RTR: ready-to-receive
  - Data: data transmission



MARCH (C. T. Toh)

Media Access with Reduced Handshake (MARCH)



PAMAS (C. S. Raghavendra)

Power-Aware Multi-Access Protocol with Signaling (PAMAS)

- Temp. reducing transmitter range
- Turn off

Others (N. H. Vaidya)

- Different ranges
  - TR: transmission range, IR: interference range, SR: sensing range (TR < IR < SR)
  - Different ranges for RTS, CTS, Data, and Ack
- Directional antennas
  - DO (sender: omni (O) and receiver: directional (D))
  - Other models: OO, OD, and DD

Others (M. Fang)

- Impact of MAC on communication
  - Intra-flow contention
  - Inter-flow contention
- Physical layer related issues
  - Rate-adaptation (varying the data rate)
  - Other options: varying the transmission power or the packet length
  - Link Diversity: Multi-output link diversity and multi-input link diversity

Power Saving (Y. –C. Tseng)

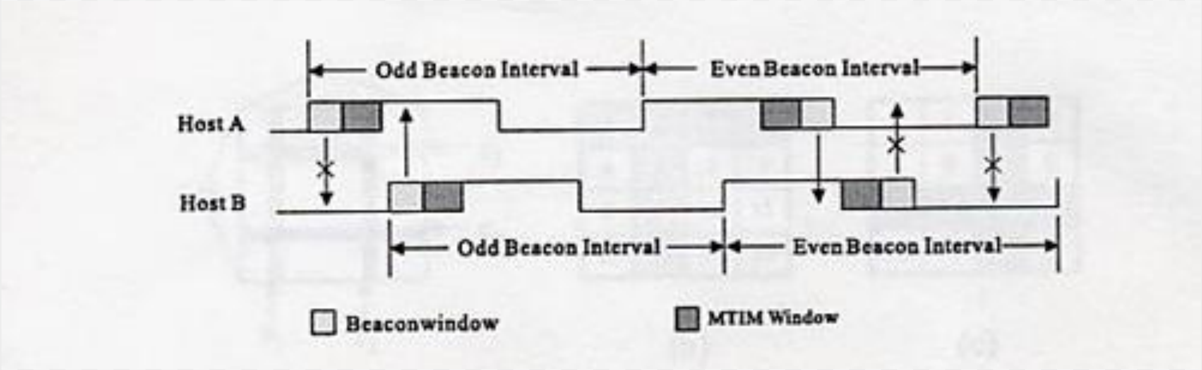
Tseng's Power-saving Protocols:

Use periodic active window to discover neighbors

- Overlapping Awake Intervals
- Wake-up Prediction

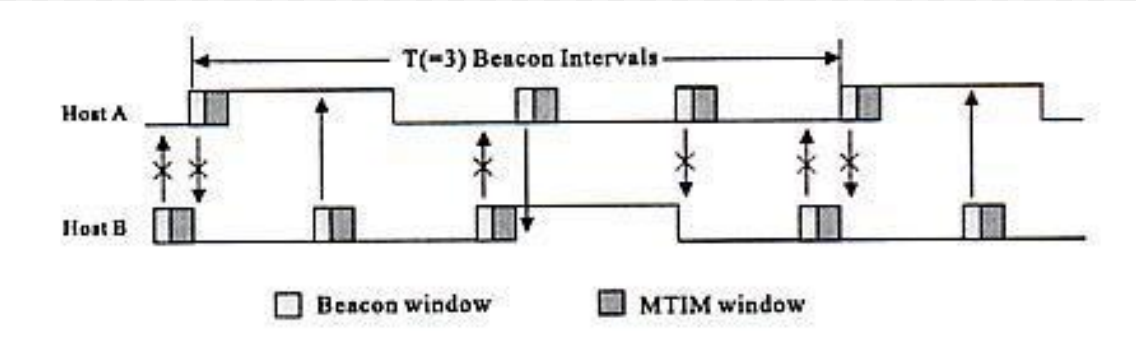
Power Saving

- Dominating-Awake-Interval Protocol



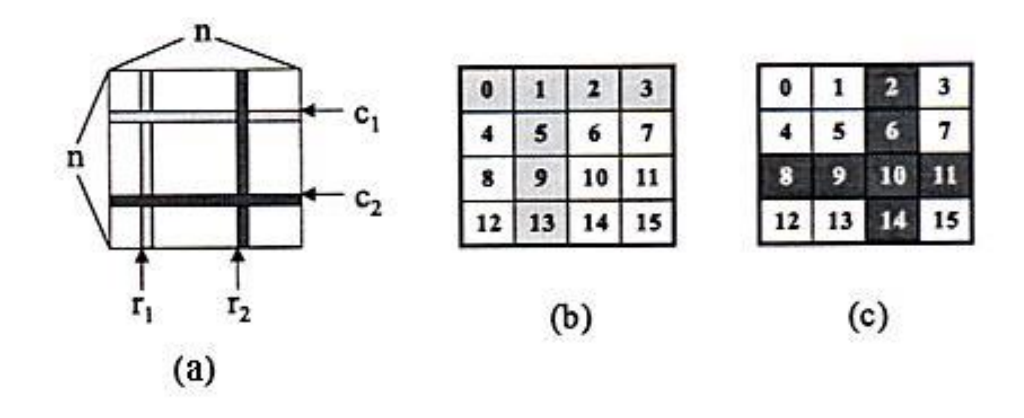
Power Saving

- Periodically-Fully-Awake-Interval



Power Saving

- Quorum-Based Protocols



IEEE 802.11

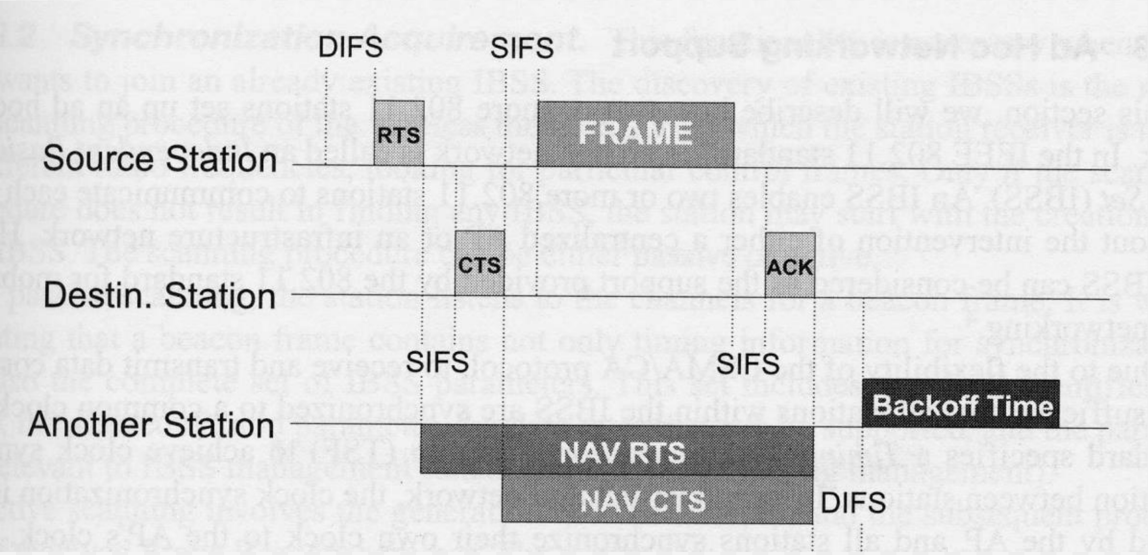
- Two operational modes
  - Infrastructure-based
  - Infrastructureless or ad hoc
- Two types of service at the MAC layer
  - Contention-free service by Distributed Coordination Function: DCF

    (based on CSMA/CA)
  - Contention-free service by Point Coordination Function: PCF

    (based on a polling scheme using a point coordinator)

IEEE 802-11

- RTS-CTS handshake



(Distributed InterFrame Space: DIFS)
(Short InterFrame Space: SIFT)

IEEE 802.11

- RTS-CTS handshake
  - RTS (request to send)
  - CTS (clear to send)
  - Data trasmission
  - Ack
- Other items
  - Network Allocation Vector (NAV)
  - Distributed InterFrame Space (DIFS)
  - Short InterFrame Space (SIFS)
  - Backoff time

IEEE 802.11

- RTS-CTS: contention
- Data transmissionL contention-free
- NAV setup cannot work properly when there are collisions
- All packets: RTS, CTS, Data, Ack are subject to collisions
- SIFS < DIFS to increase the priority
- Backoff time: an integer from (0, CW-1), where CW (contention window) is doubled at each retransmission

Routing in Ad Hoc Networks

Types: (n: network size)

- Unicasting: (1, 1) = (source, destination)
- Multicasting: (1, k), $1 < k < n$
- Broadcasting: (1, n)
- Geocasting: (1, k in a region)
- Gossip: (n, n)
- Gathering: (k, 1)
- Fusion: a special type of gathering (with simple data processing at intermediate nodes)

Routing in Ad Hoc Networks

Qualitative properties:

- Distributed operation
- Loop-freedom
- Demand-based operation
- Proactive operation
- Security
- Sleep period operation
- Unidirectional link support

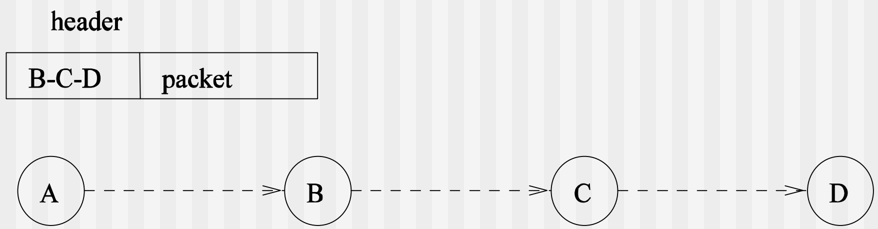
Routing in Ad Hoc Networks

Quantitative metrics:

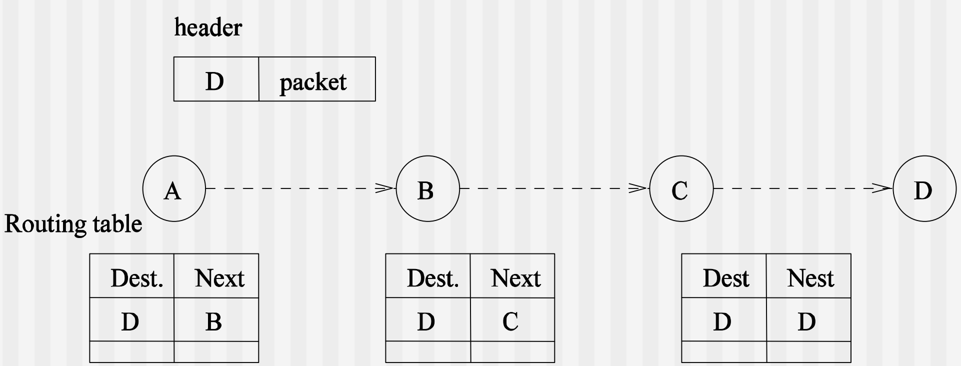
- End-to-end data throughput and delay
- Route acquisition time
- Percentage out-of-order delivery
- Efficiency

Basic Routing Strategies in Internet

Source Routing vs. Distributed Routing



A sample source routing



A sample distributed routing

Classification

- Proactive vs. reactive
  - proactive: continuously evaluate network connectivity
  - reactive: invoke a route determination procedure on-demand.
  - Right balance between proactive and reactive
- Flat vs. hierarchical

Proactive: Data Forwarding

- Source routing: centralized at the source
- Distributed routing: decentralized
- Multiple paths

Proactive: Route Maintenance

- Source routing vs. distributed routing.
- Global re-construction vs. local fix
- Single path vs. multiple path

Sample Protocols

- Proactive Protocols
  - Destination sequenced distance vector (DSDV)
- Reactive Protocols
  - Dynamic source routing (DSR)
  - Ad hoc on-demand distance vector routing (AODV)
  - Temporally ordered routing algorithms (TORA)

Sample Protocols

- Hybrid:
  - Zone routing
- Hierarchical
  - Cluster-based
  - Connected-dominating-set-based

Proactive: DSDV

- Based on Bellman-Ford routing algorithms
- Enhanced with freedom from loops.
- Enhanced with differentiation of stale routes from new ones by *sequence numbers.*

Reactive

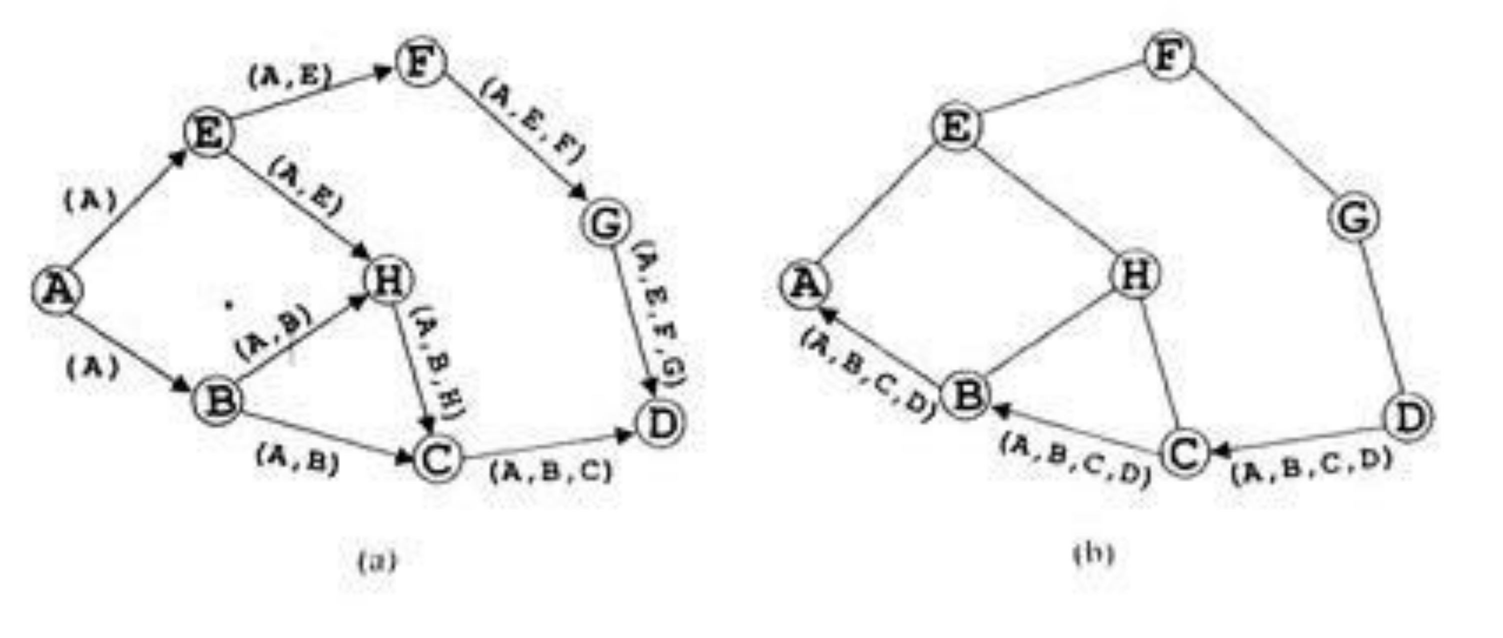
Three steps

- Route discovery
- Data forwarding
- Route maintenance

DSR

- There are no periodic routing advertisement messages (thereby reducing network bandwidth overhead).
- Each host maintains a route cache: source routes that it has learned .
- If a route is not found from route cache, the source attempts to discover one using route discovery.
- Route maintenance monitors the correct operation of a route in use.

DSR Routing (Cont'd.)



A sample DSR route discovery

AODV

- Combination of DSR and DSDV
  - Routing table is constructed on demand.
  - Sequence numbers (issued from different destinations) are used to avoid looping
- The node should respond (ROUTE_REPLY) a request (ROUTE_REQ) if
  - It is the destination node
  - An intermediate node with a route of a destination sequence number no less than that in the request packet.

TORA

- For each destination, a DAG is maintained with destination as the *sink*:
  - Each node has a height metric.
  - A directed link always points to a node with a lower height metric.
- To send a packet, a host forwards the packet to any neighbor with a lower metric.

TORA: route maintenance

- **Destination disoriented**
  - If and only if there exists a node other than the destination that has no outgoing link.
- **Link reversal**
  - Given a destination disoriented DAG, transform it to a destination oriented DAG by reversing the directions of some links (locally).
- **Properties**
  - A finite number of iterations of link reversals
  - DAG at each iteration is acyclic
  - The direction of any link between two nodes that have a direct path to the destination in the initial graph will never be reversed

Gafni and Bertsekas, “Distributed Algorithms for Generating Loop-Free Routes in Networks with Frequently Changing Topology,” IEEE Trans. Comm., Jan. 1981

TORA: route maintenance

- **Full reversal**
  - At each iteration each node other than the destination that has no outgoing link reverses the directions of all its incoming links.
- **Partial reversal**
  - Every node *u* other than the destination keeps a list of its neighboring nodes *v* that have reversed the direction of the corresponding link (*u, v*)
  - At each iteration each node *u* that has no outgoing link reverses the directions of the links (*u, v*) for all *v* which do not appear on its list, and empties the list. If no such *v* exists, node *u* reverses the directions of all incoming links and empties the list.

TORA: route maintenance

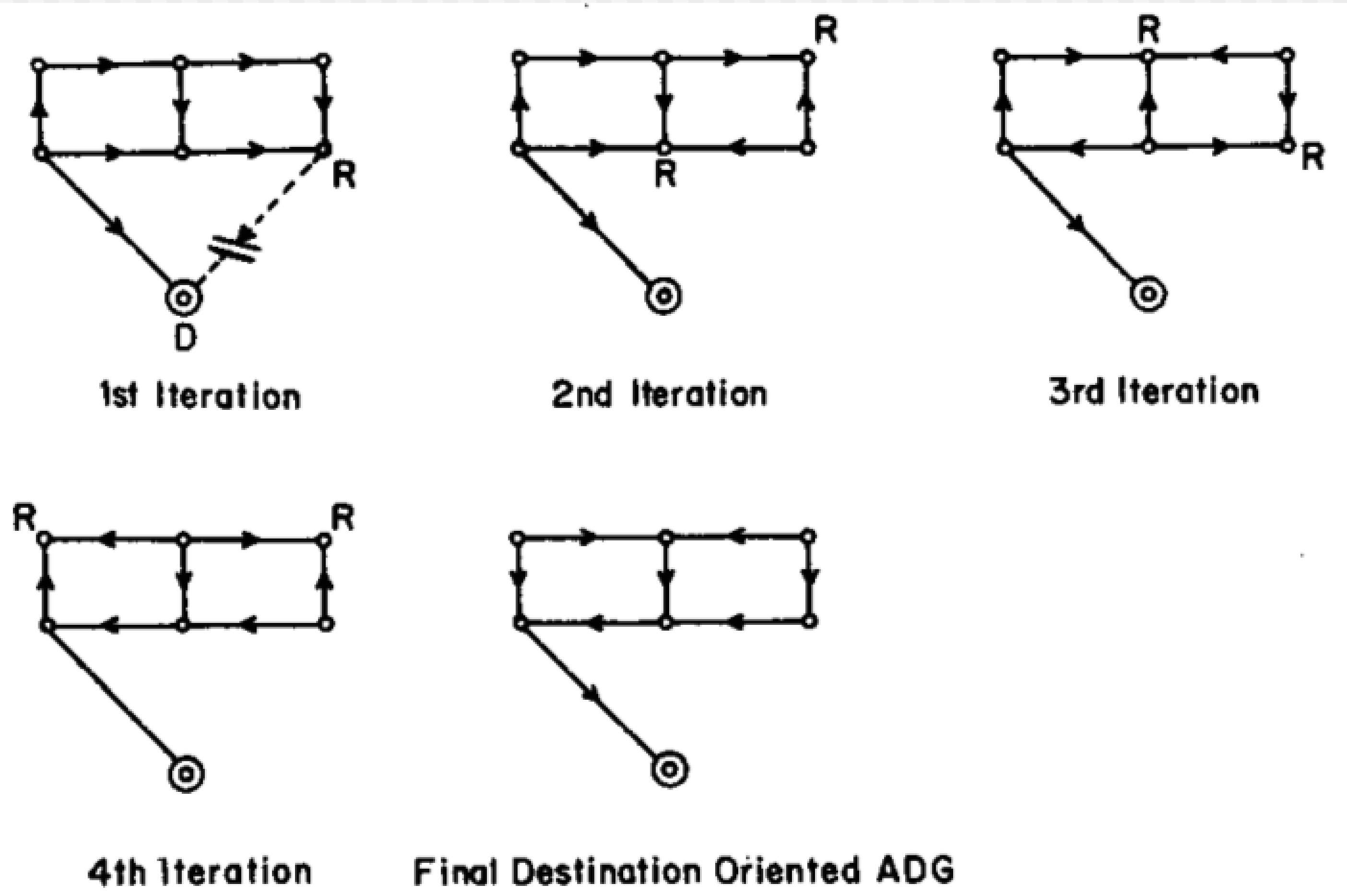


Fig. 1. Full reversal method.

TORA: route maintenance

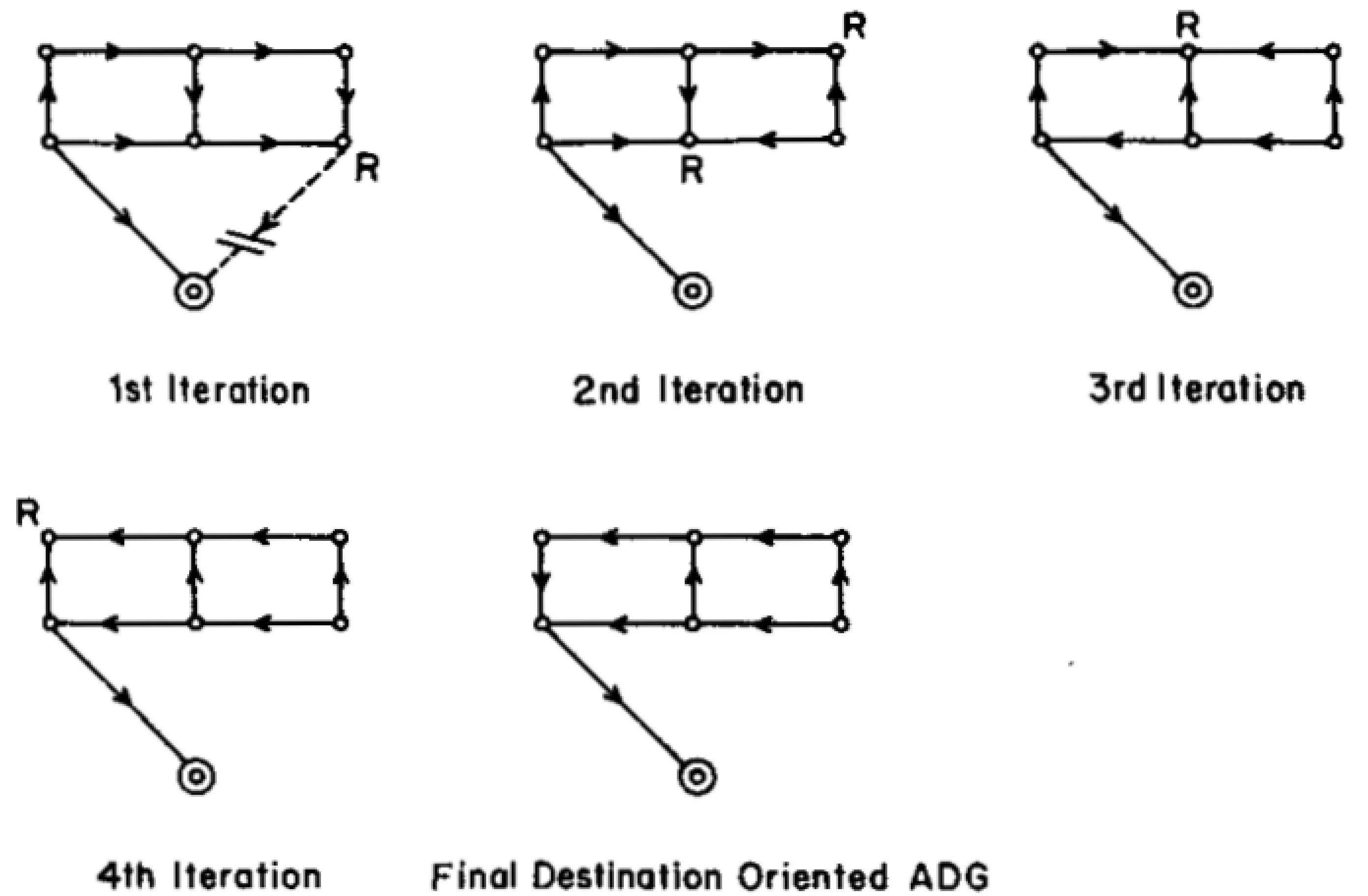


Fig. 2. Partial reversal method.

Watermark Implementation

Full Reversal (FR)

- Can implement FR by having each vertex *v* keep an ordered pair (*c*,*v*), the *height* (or *vertex label*) of vertex *v*
  - *c* is an integer counter that can be incremented
  - *v* is the id of vertex *v*
- View link between *v* and *u* as being directed from vertex with larger height to vertex with smaller height (compare pairs lexicographically)
- If *v* is a *sink* (node without outgoing link) then *v* sets *c* to be 1 larger than maximum counter of all *v*'s neighbors

(*c* can be calculated through a topological sort order)

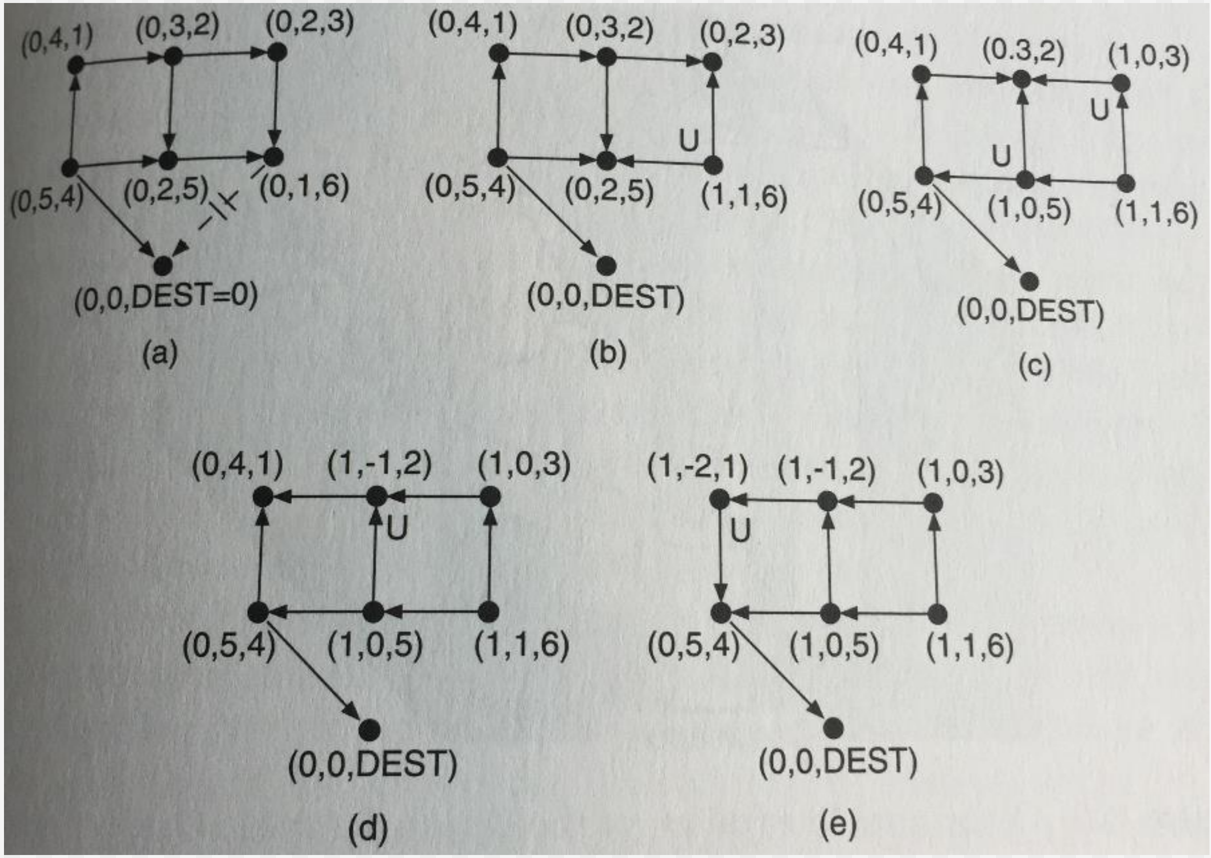
Watermark Implementation

Partial Reversal (PR)

- Can implement PR by having each vertex v keep an ordered triple (*a*,*b*,*v*), the *height* (or *vertex label*) of vertex *v*
  - *a* and *b* are integer counters
  - *v* is the id of node *v*
- View link between *v* and *u* as being directed from vertex with larger height to vertex with smaller height (compare pairs lexicographically)
- If *v* is a sink then *v*
  - sets *a* to be 1 greater than smallest a of all its neighbors
  - sets *b* to be 1 less than smallest *b* of all its neighbors with the same new value of *a* (if none, then leave *b* alone)

Watermark Implementation

Partial Reversal



Link Reversal Complexity

Overall: $O(n^2)$ rounds

General link reversal by Charron-Bost et al

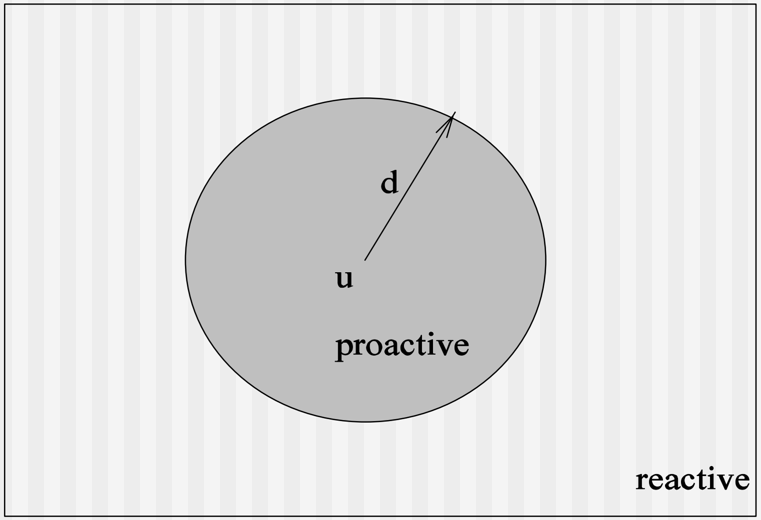
- Full and partial link reversals as special cases
- Binary link labels instead of unbounded watermark
- A more in-depth complexity analysis for different types of graphs

B. Charron-Bost et al, Time Complexity of Link Reversal Routing

Hybrid:Zone-based Routing

- Trade-offs: network capacity usage in proactive approaches and the long delay in reactive approaches.
- A routing zone (for a host) includes the nodes within a given number of hops.
- Each host maintains routing information only to nodes within its routing zone.
- Information outside the routing zone is obtained through on demand.

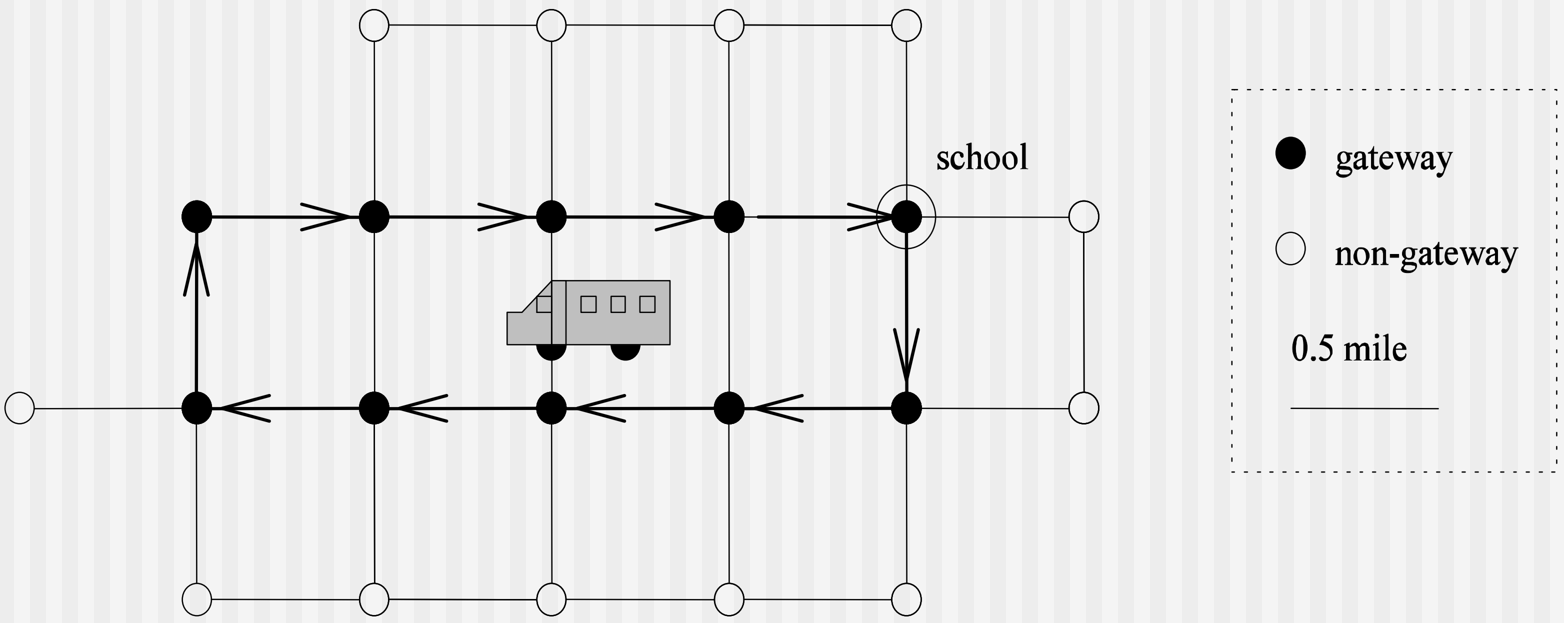
Zone-based Routing (Cont'd.)



Z. Haas, A New Routing Protocol for the reconfigurable Wireless Networks

Hiearchical: Domination-set-based

School bus routing



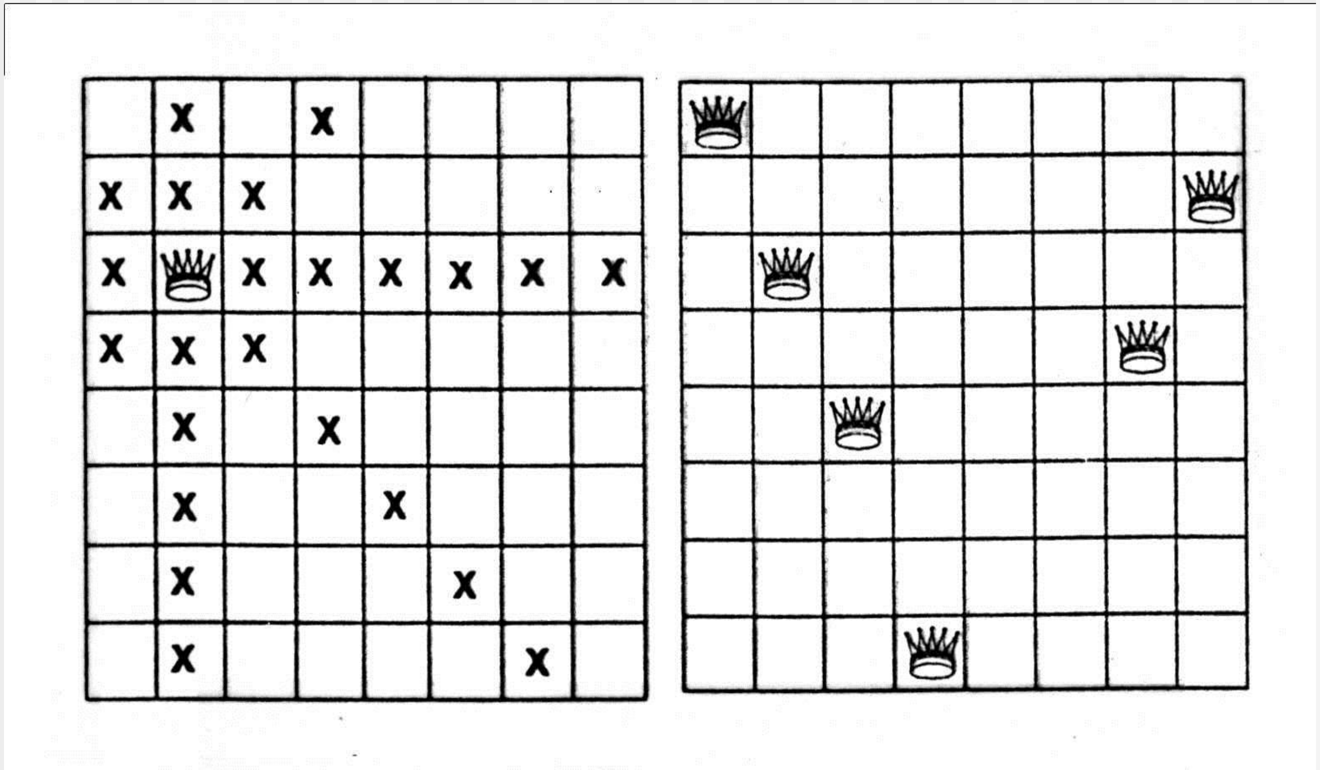
Graph-theoretic Definition

A set in G(V, E) is dominating if all the nodes in the system are either in the set or neighbors of nodes in the set.

Minimum Dominating Set (DS)

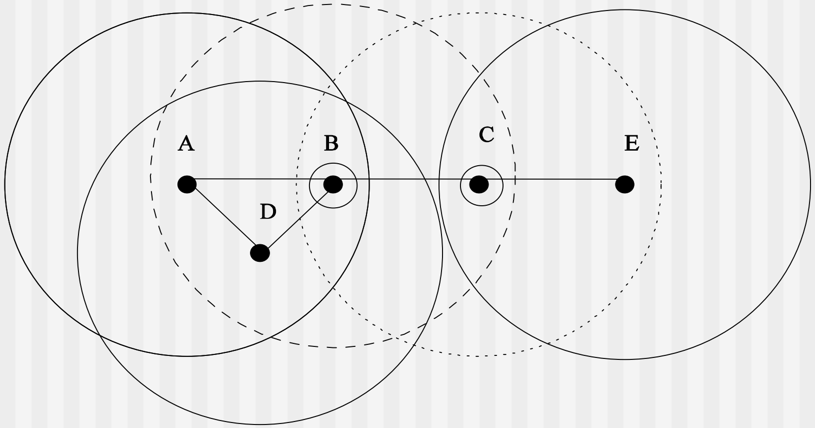
Minimum Connected Dominating Set (CDS)

Five-Queen Problem (1850's)



Desirable Features

- Simple and quick
- Connected dominating set



A simple ad hoc wireless network of five wireless mobile hosts.

Independent Set

- Independent set (IS) S is a subset of nodes such that no two nodes are neighbors in G
- S is a maximal independent set (MIS) if any node not in S has a neighbor in S, i.e., S forms a dominating set (DS)
- Maximal independent set is an MIS with maximum cardinality

Existing Approaches

- Graph theory community:
  - Bounds on the *domination number* (Haynes, Hedetniemi, and Slater, 1998).
  - Special classes of graph for which the domination problem can be solved in polynomial time.

Existing Approaches (Cont'd.)

- Ad hoc wireless network community:
  - **Global**: MCDS (Sivakumar, Das, and Bharghavan, 1998).
  - **Quasi-global**: spanning-tree-based (Wan, Alzoubi, and Frieder, 2002).
  - **Quasi-local**: cluster-based (Lin and Gerla, 1999).
  - **Local**: marking process (Wu and Li, 1999).

Complexity for DS

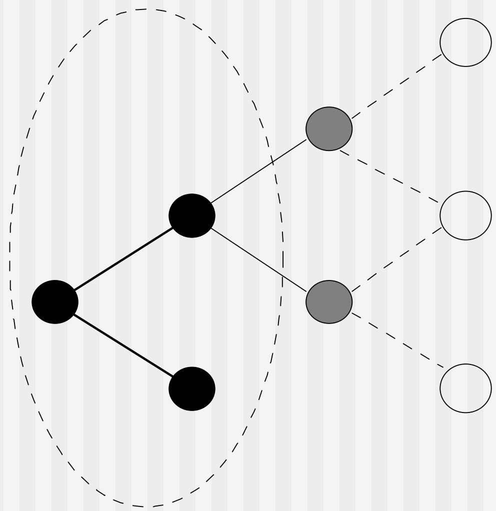
- General graph
  - NP-hard, but ln Δ in approximation, Δ is highest node degree
- Unit disk graph
  - NP-hard, but has a PTAS (polynomial time approximation scheme)
  - Suppose OPT is a minimum DS and S is an IS, then S $\leq 5\,|OPT|$

MCDS (Sivakumar, Das, and Bharghavan, UIUC)

- All nodes are initially colored white.
- The node with the maximum node degree is selected as the root and colored black. All the neighbors of the root are colored gray.
- Select a gray node that has the maximum white neighbors. The gray node is colored black and its white neighbors are marked gray.
- Repeat step (3) until there is no more white node.

MCDS (Cont'd.)

black nodes = CDS (connected dominating set)



MCDS as an approximation of CDS

Spanning-tree-based (Wan, Alzoubi, and Frieder, IIT)

- A spanning tree rooted at *v* (selected through an election process) is first constructed.
- Nodes are labeled according to a topological sorting order of the tree.
- Approximation under unit disk graph: 4 |OPT| + 1.

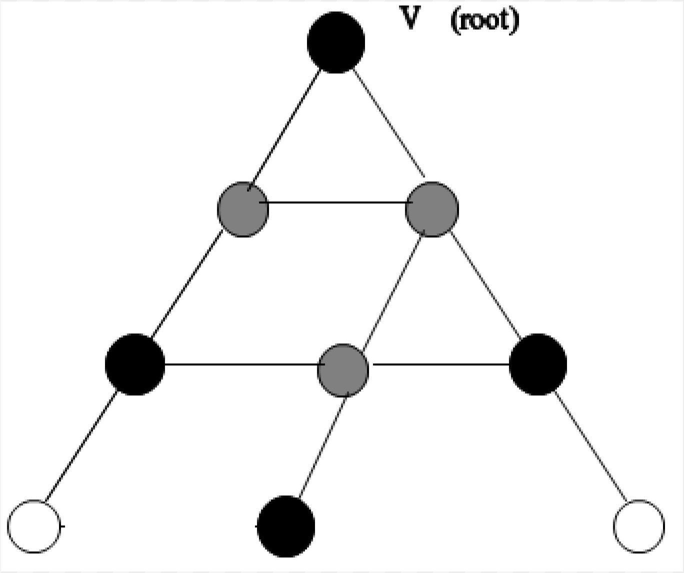
Spanning-tree-based (Cont'd.)

- Nodes are marked based on their positions in the order starting from root *v*.
  - All nodes are white initially.
  - *V* is marked black and each subsequential node is labeled black unless there is a black neighbor.
- Each black node (except root *v*) selects a neighbor with the largest label but smaller than its own label and mark it gray.

Spanning-tree-based (Cont'd.)

black nodes = DS

black nodes + gray nodes = CDS



Selecting CDS in a spanning tree

Cluster-based (Lee and Gerla, UCLA)

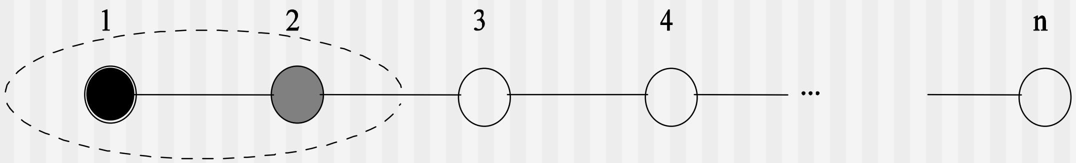
- All nodes are initially white.
- When a white node finds itself having the lowest id among all its white neighbors, it becomes a cluster head and colors itself black.
- All its neighbors join in the cluster and change their colors to gray.

Cluster-based (Cont'd.)

- Repeat steps (1) and (2) until there is no white node left.
- Special gray nodes: gray nodes that have two neighbors in different clusters.

Cluster-based (Cont'd.)

black nodes = DS
black nodes + special gray nodes = CDS



Sequential propagation in the cluster-based approach.

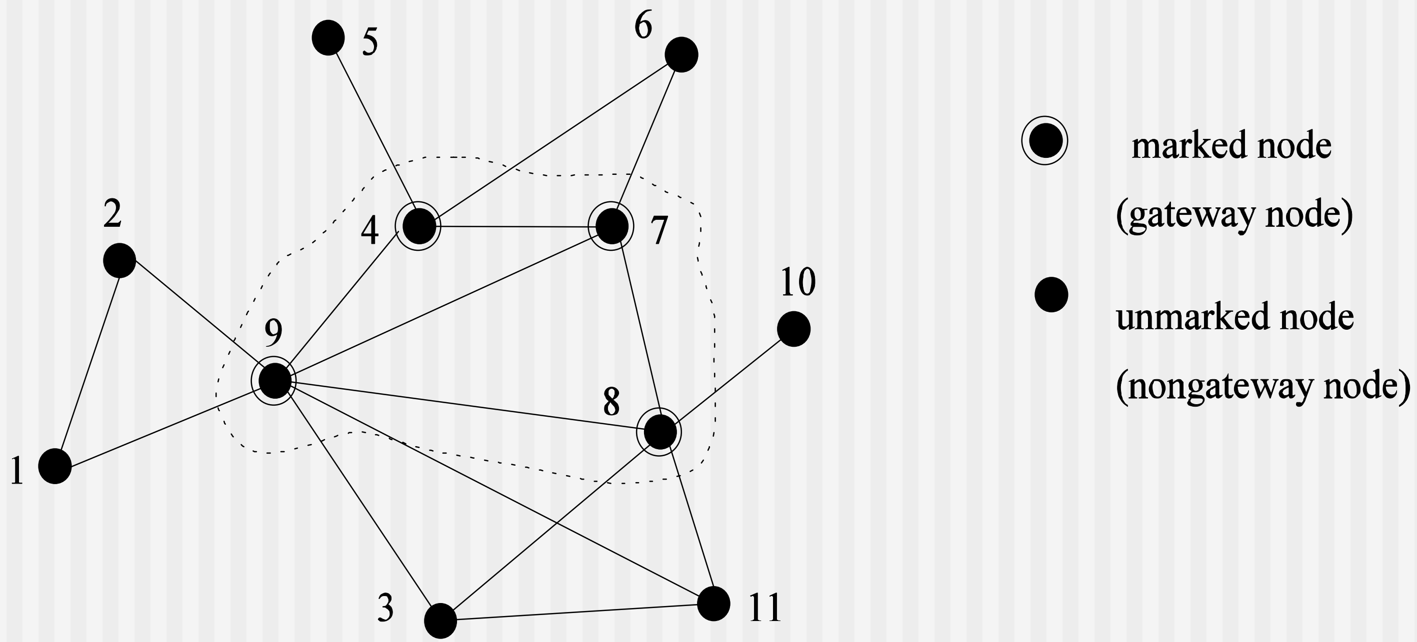
Localized Algorithms

- Processors (hosts) only interact with others in a restricted vicinity.
- Each processor performs exceedingly simple tasks (such as maintaining and propagating information *markers*).
- Collectively these processors achieve a desired global objective.
- There is **no sequential propagation** of information.

Marking Process (Wu and Li, 1999)

- A node is marked true if it has two unconnected neighbors.
- A set of marked nodes (gateways nodes) V’ form a connected dominating set.

Marking Process (Cont'd.)



A sample ad hoc wireless network

Dominating-set-based Routing

- If the source is not a gateway host, it forwards packets to a source gateway neighbor.
- This source gateway acts as a new source to route packets in the induced graph generated from the connected dominating set.
- Eventually, packets reach a destination gateway, which is either the destination host itself or a gateway of the destination host.

Dominating Set Reduction

- Reduce the size of the dominating set.
- Role of gateway/non-gateway is rotated.

Dominating Set Reduction (Cont'd.)

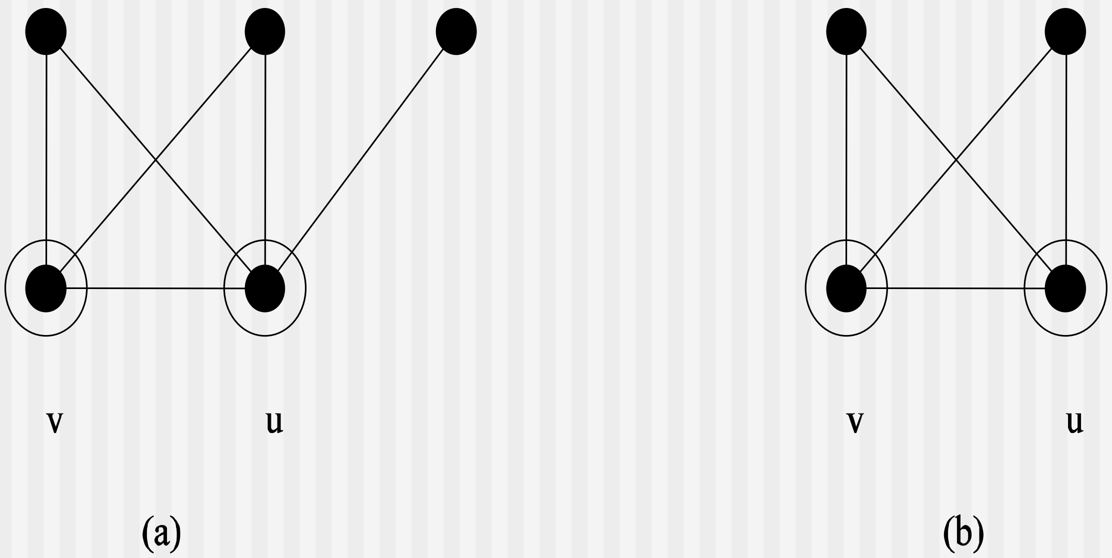
N [v] = *N (v)* U {*v*} is *v*'s *closed neighbor set*

- *Rule 1: If N [v]* $\subseteq$ *N [u] in G and id(v) < id(u), then unmark v.*
- Rule 2: *If N (v)* $\subseteq$ *N (u)* U *N (w) in G and id(v)* = min{*id(v), id(u), id(w)*}, *then unmark v.*

- *Rule k:* coverage by any number of nodes, based on 2- or 3-hop neighborhood.

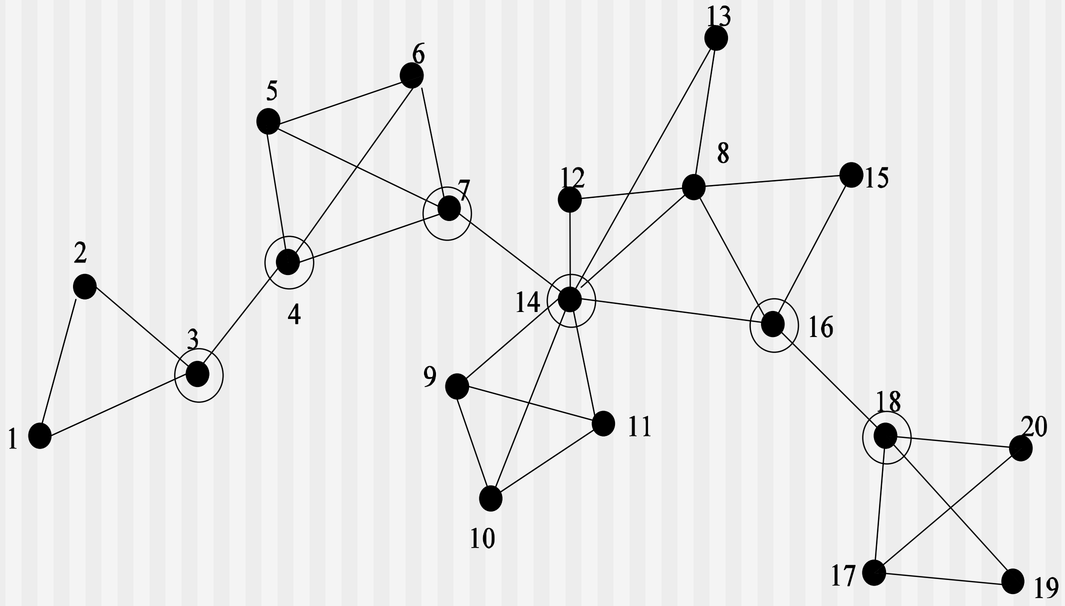
F. Dai and J. Wu, An Extended Localized Algorithm for Connected Dominating Set Formation in Ad Hoc Wireless Networks

Dominating Set Reduction (Cont'd.)



Two sample examples

Example



(a) Dominating set from the marking process (b) Dominating set after dominating set reduction

Directed Networks: *dominating node* and *absorbant node*

Dominating and absorbant nodes

J. Wu, Extended Dominating-Set-Based Routing in Ad Hoc Wireless Networks with Unidirectional Links

Directed Networks (Cont'd.)

Finding a subset that is both dominating and absorbant

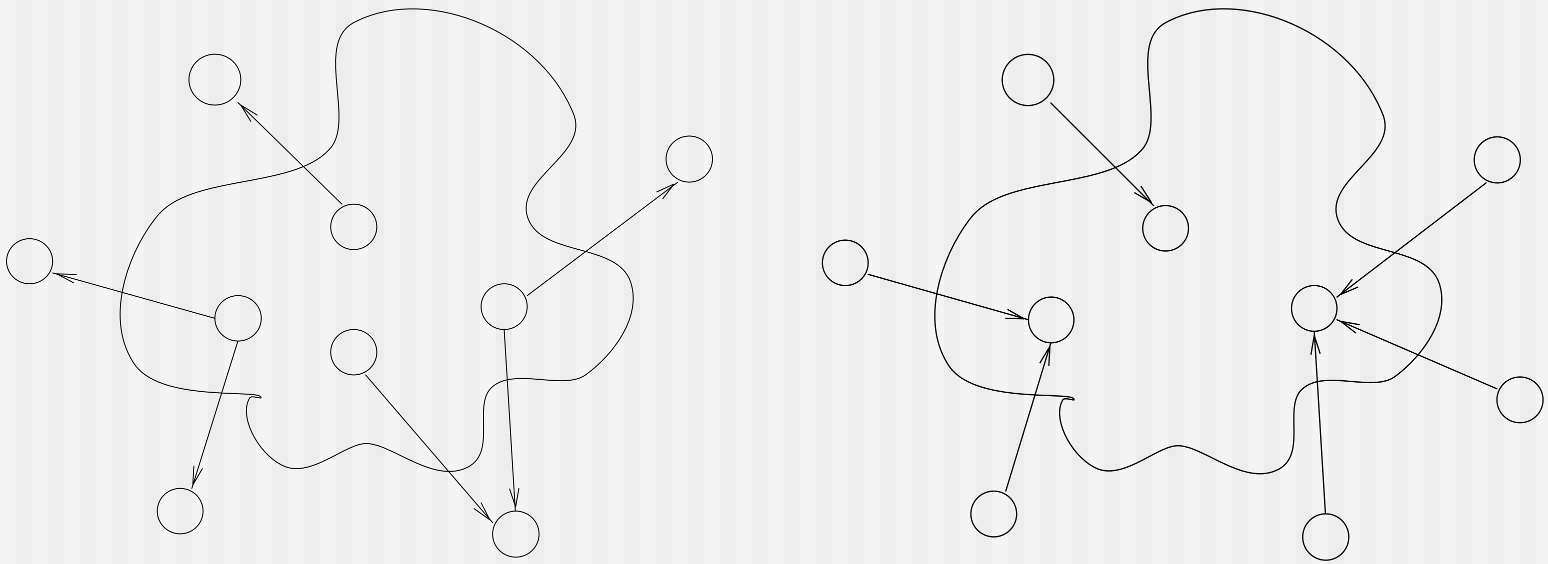


Figure 16: An absorbant set and a dominating set

Mobility Management

- Update/re-calculation
  - on/off
  - movement
    - recognizing a new link
    - recognizing a broken link
- Localized maintenance (update)

Other Algorithms for DS

- Core extraction (for clusterheads)
  - Each node *v* selects the largest node (including itself) as dominating node in its 1-hop neighborhood: N[v]
- Constant approximation to minimum DS
  - Partition the 2-D plane by a grid into squares of side length $\frac{1}{\sqrt{2}}$. Select one head from each square
  - Need location information

R. Sivakumar et al, CEDAR: a Core-Extraction Distributed Ad Hoc Routing Algorithm

QoS routing

- Wireless link’s bandwidth may be affected by the transmission activities of adjacent links.
- Unlike one-hop network (cellular), one must guarantee the quality of multiple hops in a path.
- Existing links may disappear and new links may be formed as mobile hosts move.

QoS: Signal stability-based adaptive (SSA)

- Each node maintains a signal stability table.
- A receiving node propagates a request if
  - The request is received over a strong link.
  - The request ha not been forwarded previously
- The level of qualify can be lowered at the source if the source fail to receive a reply within a time-out period.

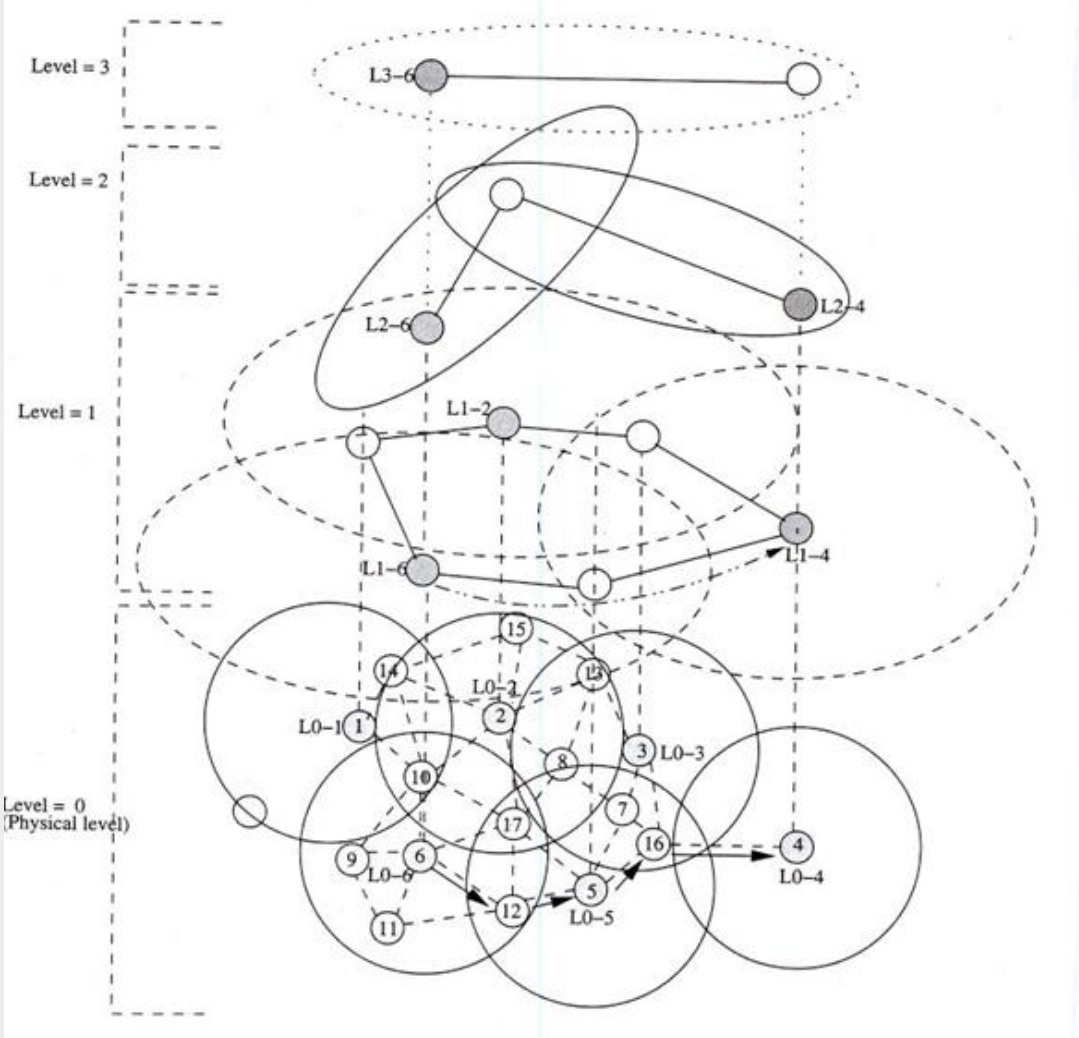
QoS: Ticket-based routing

- Each probing packet carries a number of tickets.
- The number of route-searching packets is confined to avoid blind flooding.

S. Chen and K. Nahrstedt, Distributed QoS Routing with Imprecise State Information

Hierarchical routing protocols

- Hierarchical state routing (HSR)
  - Multi-level clustering
  - A node can be a head at different levels



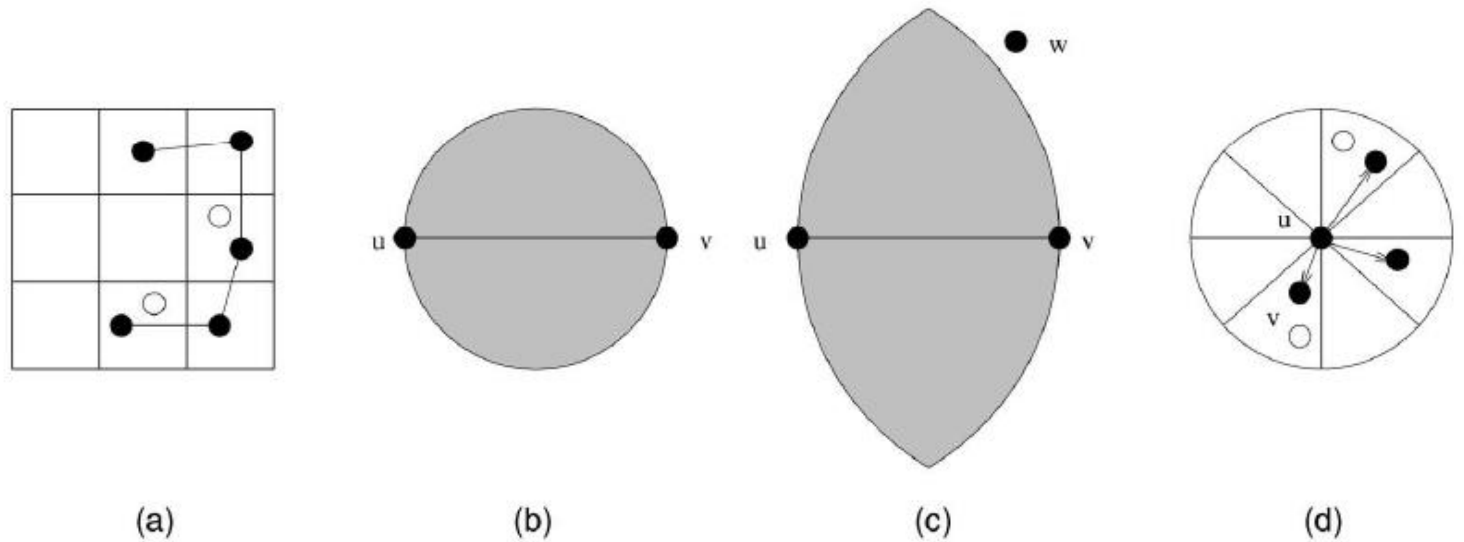
Hierarchical routing protocols

- Zone-based Routing Protocol (ZRP)
  - Proactive intra-zone and reactive inter-zone.
- Fisheye State Routing Protocol (FSR)
  - A fish’s eye that can capture pixel information with greater accuracy near its eve’s focal point.
  - The frequency of exchanges decreases with an increase in scope.

Geometric Routing

- GPS-based routing
  - The space is partitioned into a 2d grid
  - One clusterhead is selected in each grid point.
- Sparse a graph
  - **GG (**Gabriel graph**)**: link uv exists iff the open disk with diameter uv contains no other nodes.
  - **RNG** (relative neighborhood graph): link exists if $d(u,v) \leq d(u, w)$ and $d(u,v) \leq d(v, w)$.
  - **Yao graph**: For each node u, any k ($k \geq 6$) equal-separated rays originated at u define k cones. In each cone, choose the closet v (if any) within the transmitter range of u and add a directed link (u,v).

Samples

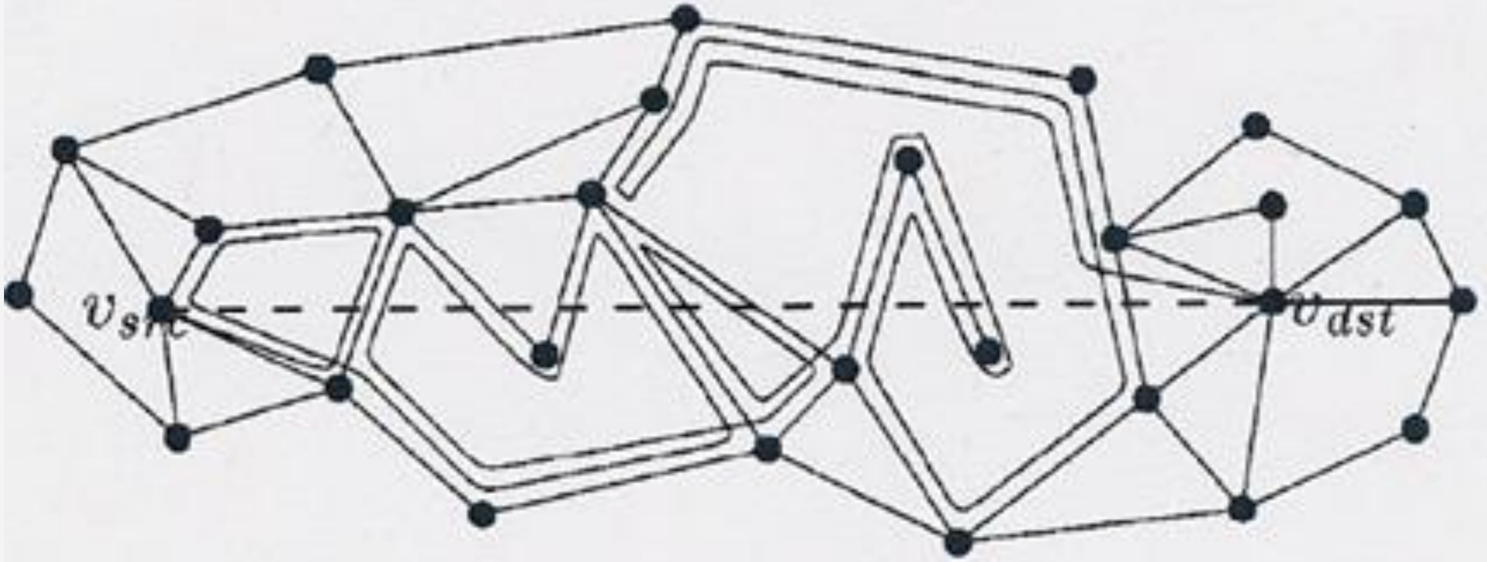


(a) 2D grid. (b) Gabriel graph. (c) RNG graph. (d) Yao graph.

Geometric Routing

- Greedy algorithm
  - Closer to the destination
  - Different greedy: most forwarding progress within radius
- Face routing
  - Route on a face in Gabriel graph
  - Alternate between right-hand and left-hand rule at intersection (of the line connected source and dest.)
- Greedy-Face-Greedy
- GFG on CDS

Sample Greedy-Face-Greedy

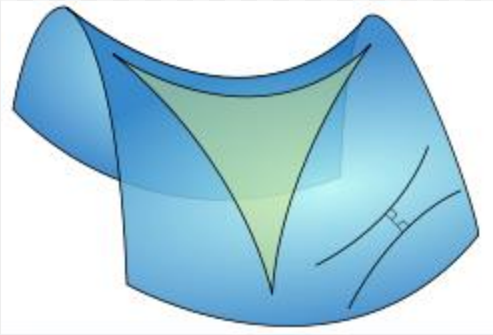


Topology control to Gabriel graph (GG) first: (1) computed Locally and (2) GG is a constant-stretch spanner

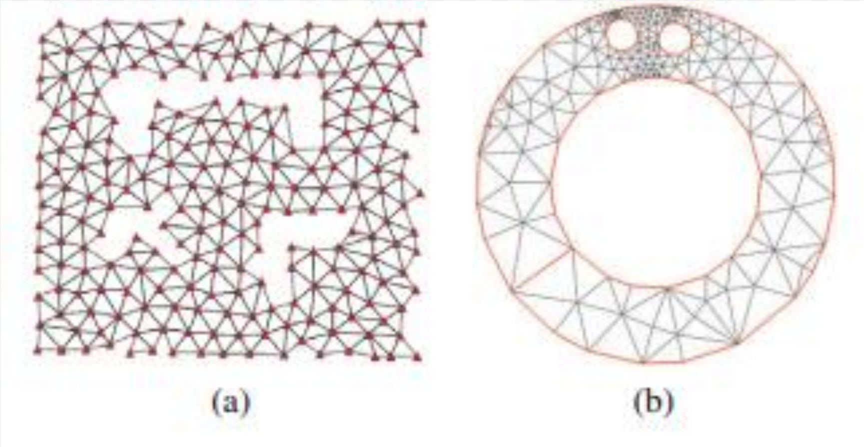
I. Stojmenovic: Position-based routing in Ad Hoc Networks
F. Kuhn, Geometric Ad Hoc Routing: of Theory and Practice

Virtual Coordinates

- Geographic greedy routing becomes easy under hyperbolic space (left figure)
- Conformal mapping using Ricci flows (right figure)



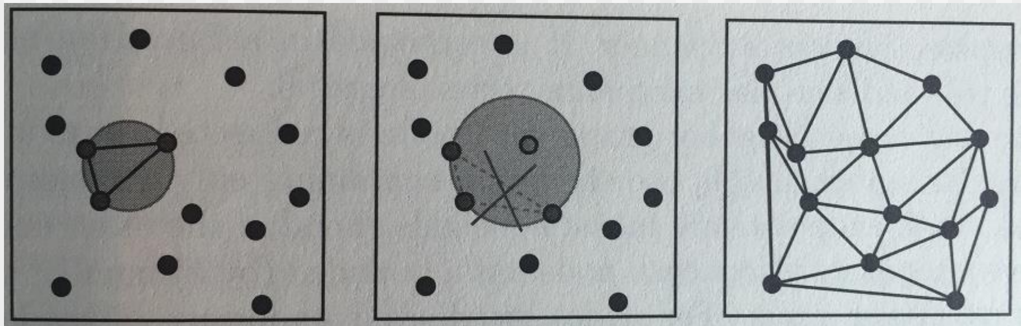
A triangle immersed in a saddle-shape plane (a hyperbolic paraboloid), along with two diverging ultra-parallel lines



R. Kleinberg:Geographic Routing Using Hyperbolic Space
R. Sarkar et al, Greedy Routing with Guaranteed Delivery Using Ricci Flows

Topology control (TC)

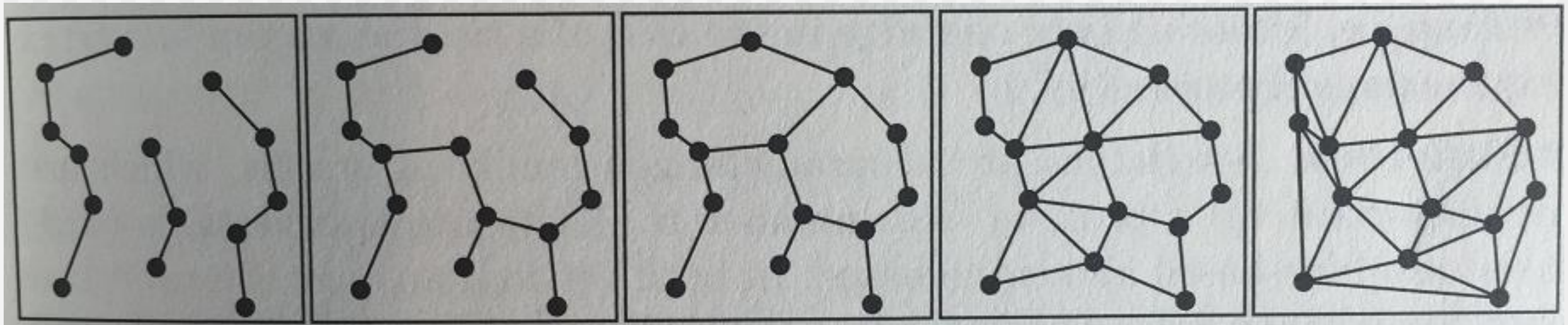
- Select a subgraph while ensuring:
  - Connectivity, symmetry (for links), and stretch factors: energy, hop, and distance
- A few more samples:
  - Delaunay Triangulation (DT): two nodes are connected if there exists any empty circle through the two vertices.



(a) triangle (b) not a triangle (c) resulting graph

Topology control (TC)

EMST: Euclidean minimum spanning tree
NNG: nearest neighbor graph



(a) NNG (b) EMST (c) RNG (d) GG (e) DT

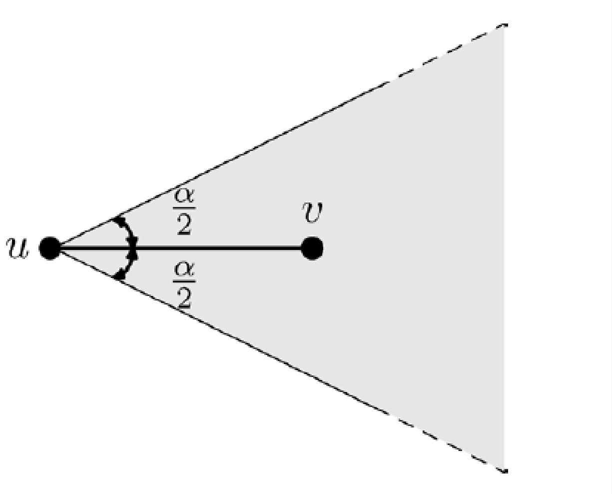
RNG contains EMST as a subgraph
DT is not locally constructible as the empty area is not necessarily close to the points

Sample TC Algorithm

- Core-based, at each node u
  - Increase transmission range to cover the next nearest neighbor of v
  - Add an *a-cone centered at u and v (see below)*

  Until range reaches max or any *a-cone* contains a node

- Property
  - Connectivity if a ≤ 5Π/6
  - EMST as a subgraph



L. Li et al, A Cone-based Distributed Topology Control Algorithm for Wireless Multi-Hop Networks

Sample TC Algorithm

Local MST-based

- At each node v, do the following
  - Build its local minimum spanning tree (LMST) to cover all its 1-hop neighbors
  - Keep only 1-hop on-tree nodes as neighbors
- Properties
  - Network connectivity
  - Degree of any node is bounded by 6
  - Topology can be converted into one with only bidirectional links (after removing unidirectional links)

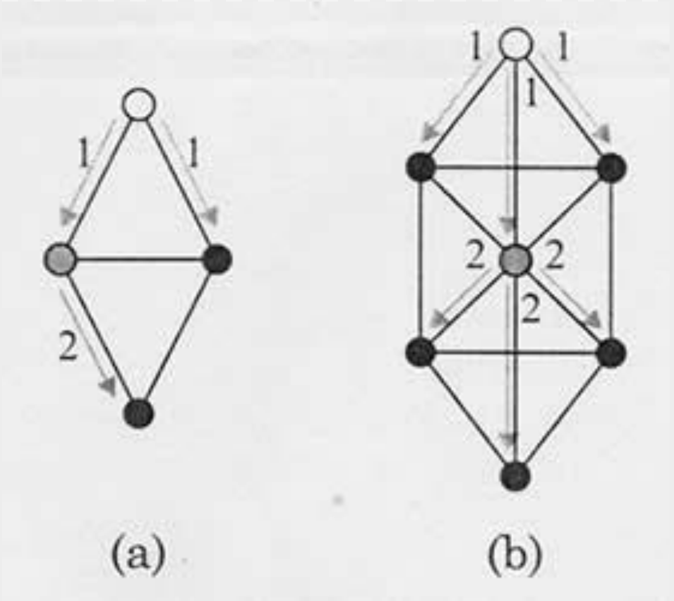
N. Li and J. Hou, Design and Analysis of an MST-based Topology Control Algorithm

Collective Communication

- Broadcast: one source and all destinations.
- Multicast: one source and many destinations.

Broadcast: Blind Flooding

Redundant transmission may cause contention and collision



Ni et al, The Broadcast Storm Problem in a Mobile Ad Hoc Network

Broadcast

- Static vs. dynamic
  - Forwarding status determined before or after the broadcast process)
- Self-pruning vs. neighbor-designating
  - Forwarding status determines by each node itself or by neighbors.

Broadcast

- Connected-dominating-set-based
  - Only dominating nodes forward the broadcast packet.
- Cluster-based (independent set)
  - Only clusterheads forward the packet, some gateways (that connect two adjacent clusters) are selected to relay the packet.

Broadcast

- Dominant pruning (multipoint relays)
  - Select a subset of 1-hop neighbor to cover all 2-hop neighbors

Qayyum et al, Multipoint Relaying for Flooding Broadcast Messages in Mobile Wireless Networks

Broadcast

- A generic rule:
  - Node v has a non-forwarding status if any two neighbors are connected by a path consists of visited nodes and nodes with a higher priorities.

J. Wu and F. Dai, A Generic Distributed Broadcast Scheme in Ad Hoc Wireless Networks

Multicast

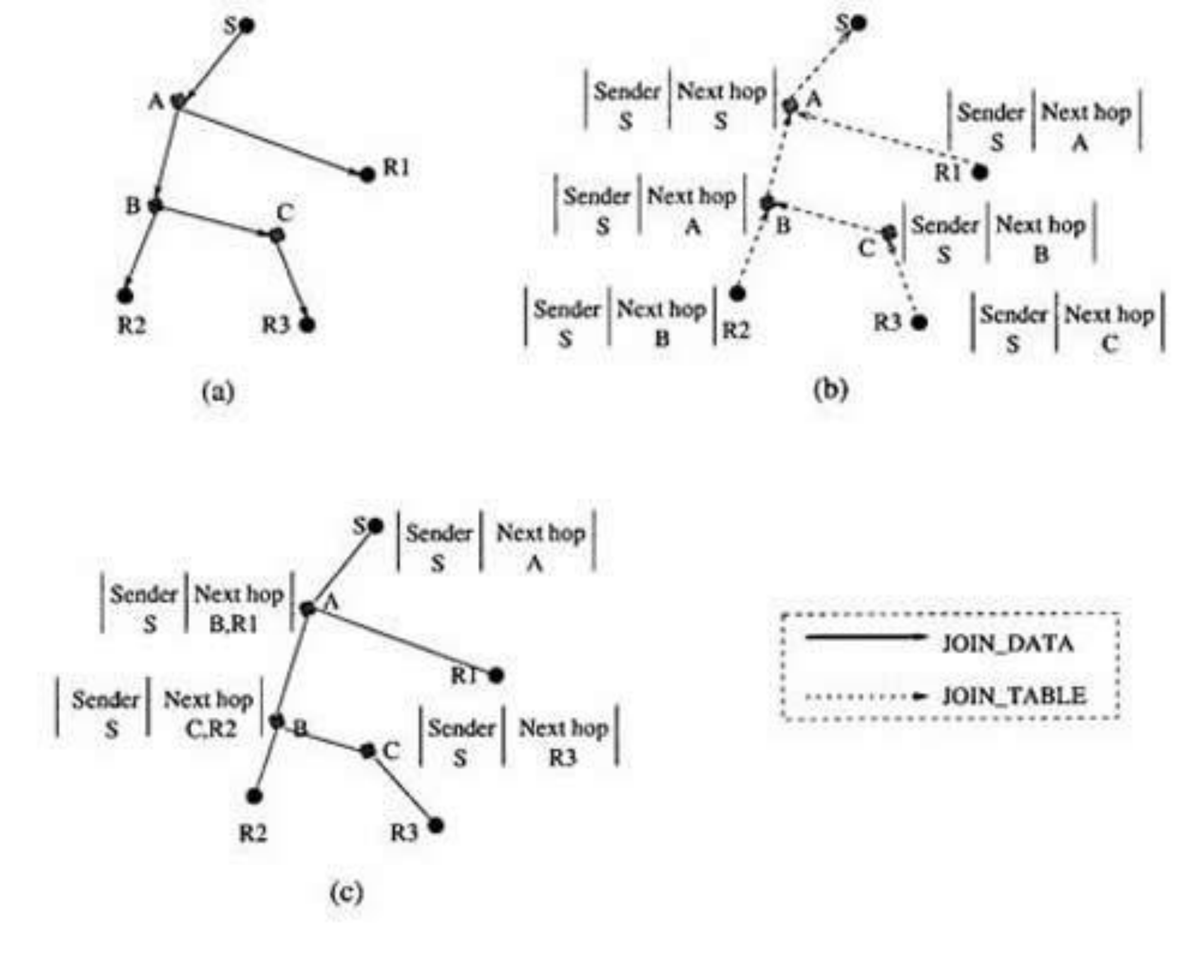
- Source-initiated protocols
  - JoinReq and JoinReply
- Receiver-initiated protocols
  - JoinReq and JoinAck
- Tree-based vs. mesh-based
- Soft-state vs. hard-state

Multicast

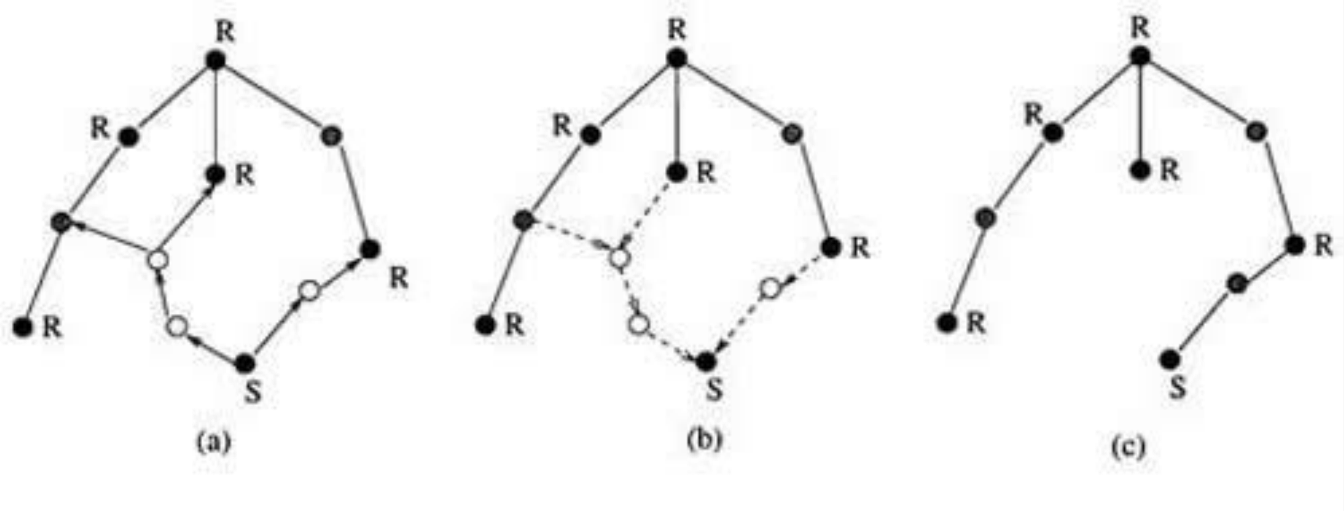
- Shortest path tree: for a particular multicast
- Core tree: shared tree for all multicast

Multicasting: ODMRP

- On-demand multicast routing protocol

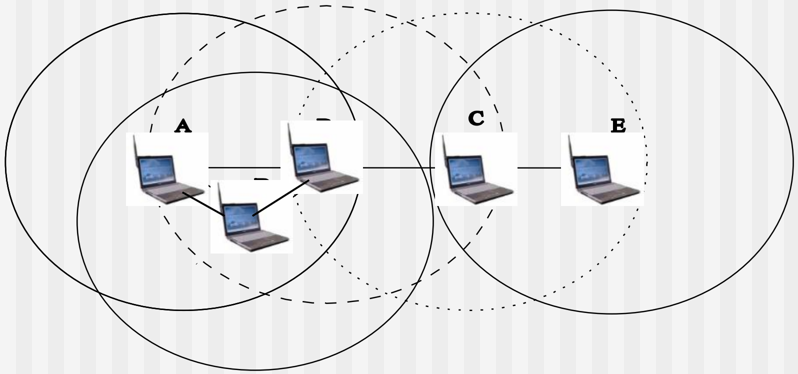


Multicasting: Multicast AODV



Dealing with Mobility

- Node mobility is considered to be undesirable in MANETs using a connection-based model
- Recovers from and tolerates "bad" effects caused by mobility
- Nodes are assumed to be relatively stable



J. Wu and F. Dai, Mobility Control and Its Applications in Mobile Ad Hoc Networks

Two Schemes

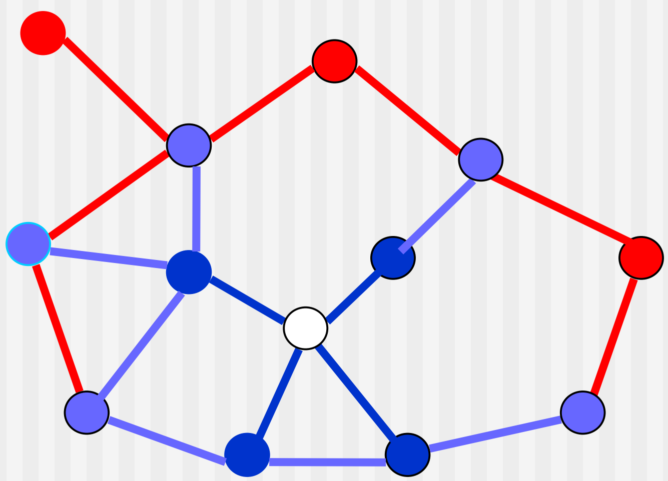
- Recovery Scheme
  - If a routing path is disrupted by node mobility, it can be repaired quickly
  - E.g., route discovery and route repair
- Tolerant Scheme
  - Masks the bad effects caused by node mobility
  - E.g., transmission buffer zone and view consistency

Mobility as a Serious Threat

- Mobility threatens *localized protocols* that use local information to achieve certain global objectives
- "Bad" decisions occur because of
  - Asynchronous sampling of local information
  - Delays at various stages of handshake
  - Mobile node movement

Local Information

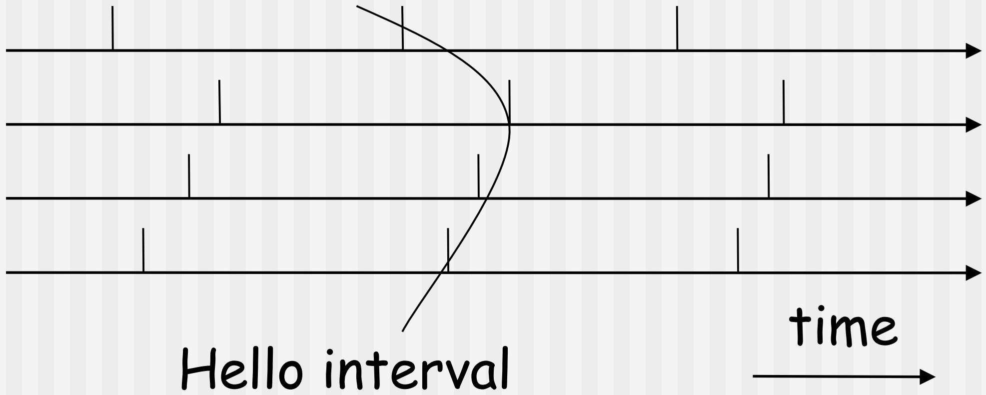
- 1-hop information
- 2-hop information
- 3-hop information



- *k*-hop information
  - Discovered via *k* rounds of Hello exchanges
  - Usually *k* = 1, 2, or 3
- Neighborhood vs. location information

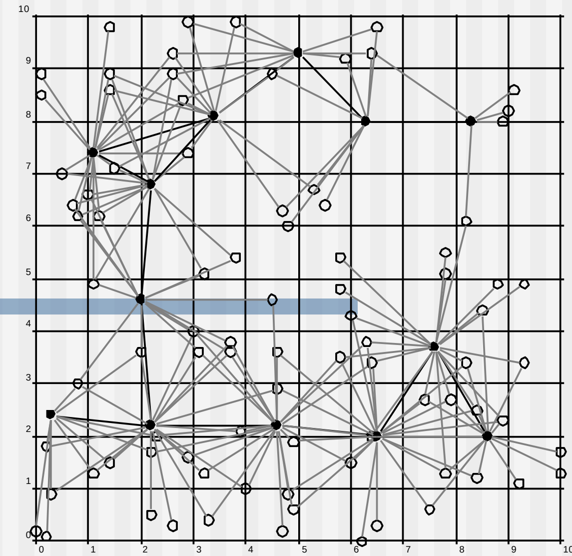
Time-Space View

- Snapshot: a global state in time-space view

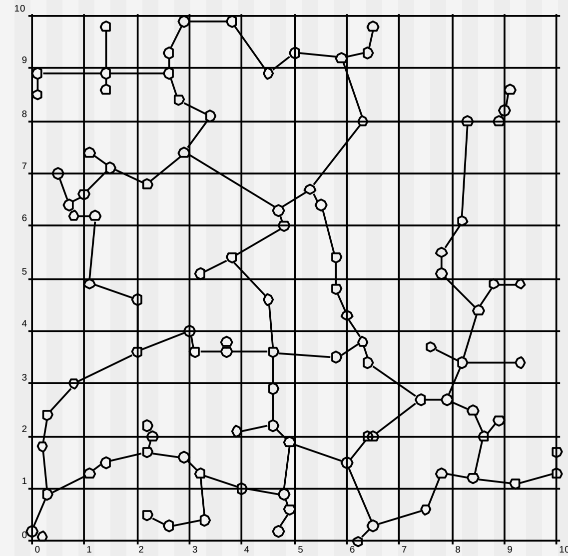


Applications

- Energy saving:
  - Sleep mode
    - Connected dominating set (CDS)
    - Wu and Li's 2-hop neighborhood solution
  - Adjustable transmission range
    - Topology control (TC)
    - Li, Hou, Sha's 1-hop location solution



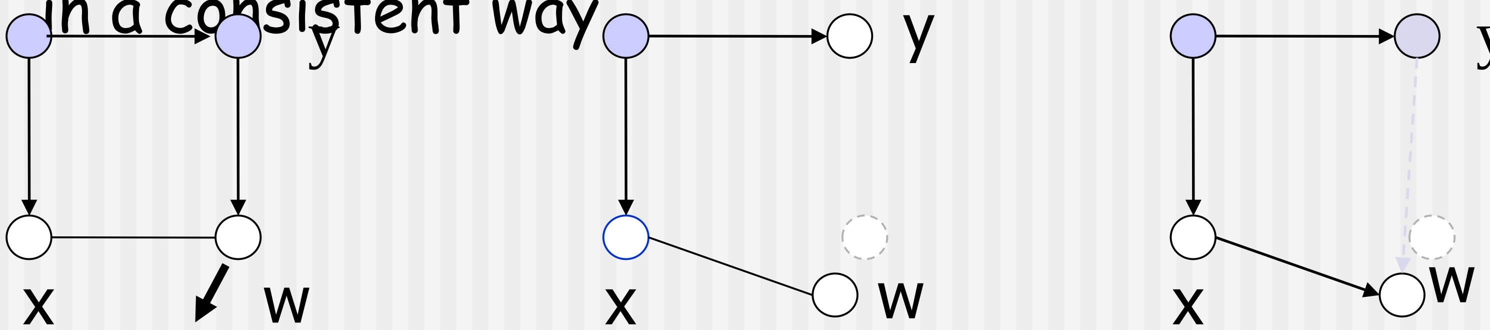
Virtual backbone (CDS)



Topology control (TC)

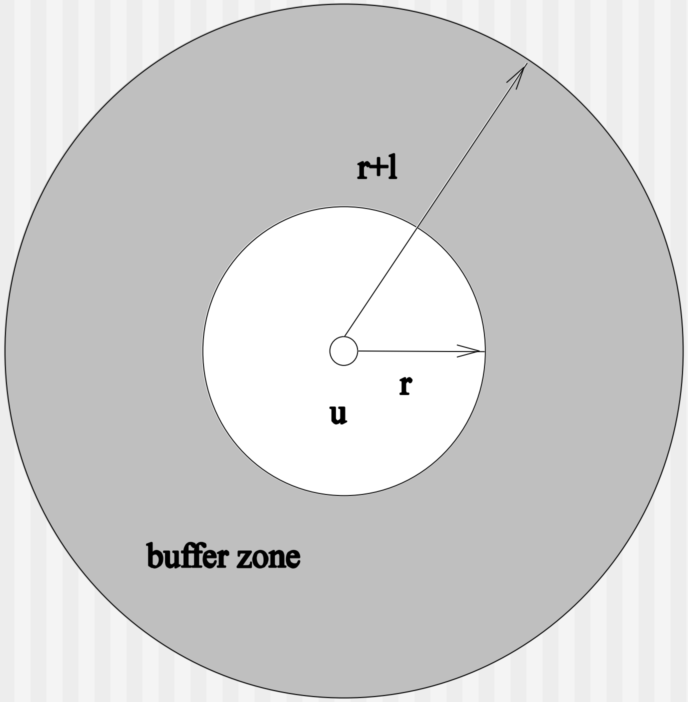
Two Technical Issues

- Link Availability
  - How protocols deal with imprecise neighborhood information caused by node mobility and delays
- Inconsistent Local Views
  - How each node collects and uses local information in a consistent way



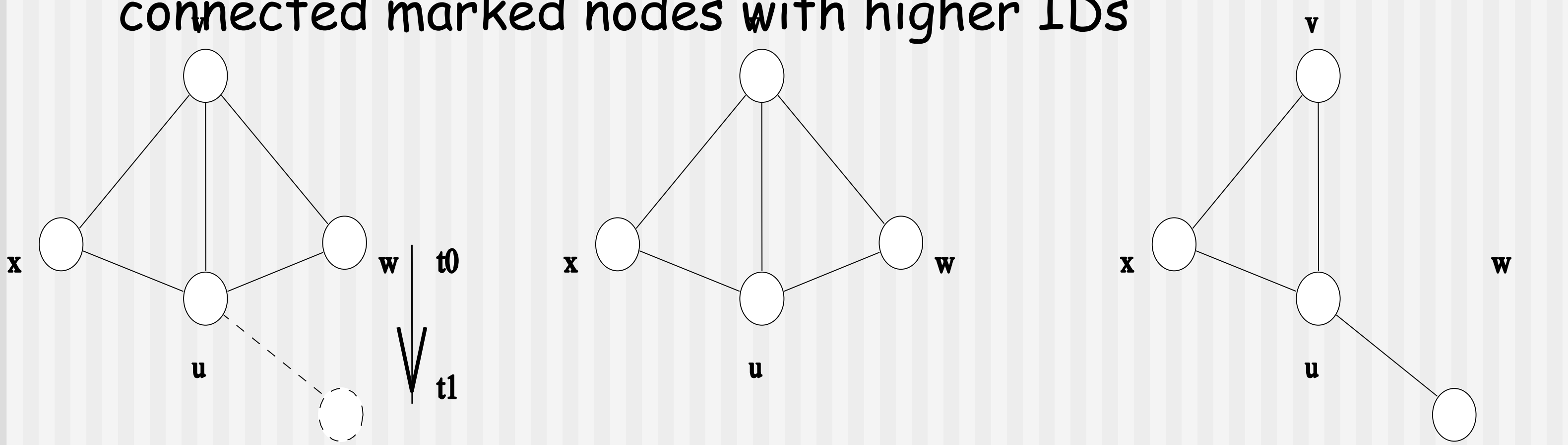
Tolerant Scheme I (link availability)

- *A buffer zone* is used in existing protocols without having to redesign them.



Sample I (inconsistent local view)

- Wu and Li's marking process (for CDS construction)
  - Node *u* is marked if there are two unconnected neighbors
  - Node *u* is unmarked if its neighbor set is covered by several connected marked nodes with higher IDs



(a) w's position at t0 and t1 (a) u's decision as an unmarked node at t1 (a) v's decision as an unmarked node at t1

Tolerant Scheme II (inconsistent local view)

- Consistent Local View
  - Each view keeps a version by using a timestamp
- Conservative Local View
  - Maintaining a window of multiple views
  - New-view(i)= F(view(i), view(i-1), …view(i-k))

    where F: {union, max, min, …}

(More information on tolerant schemes: Wu and Dai, IEEE IPDPS 2004, IEEE INFOCOM 2004, IEEE TMC 2005, IEEE TPDS 2006)