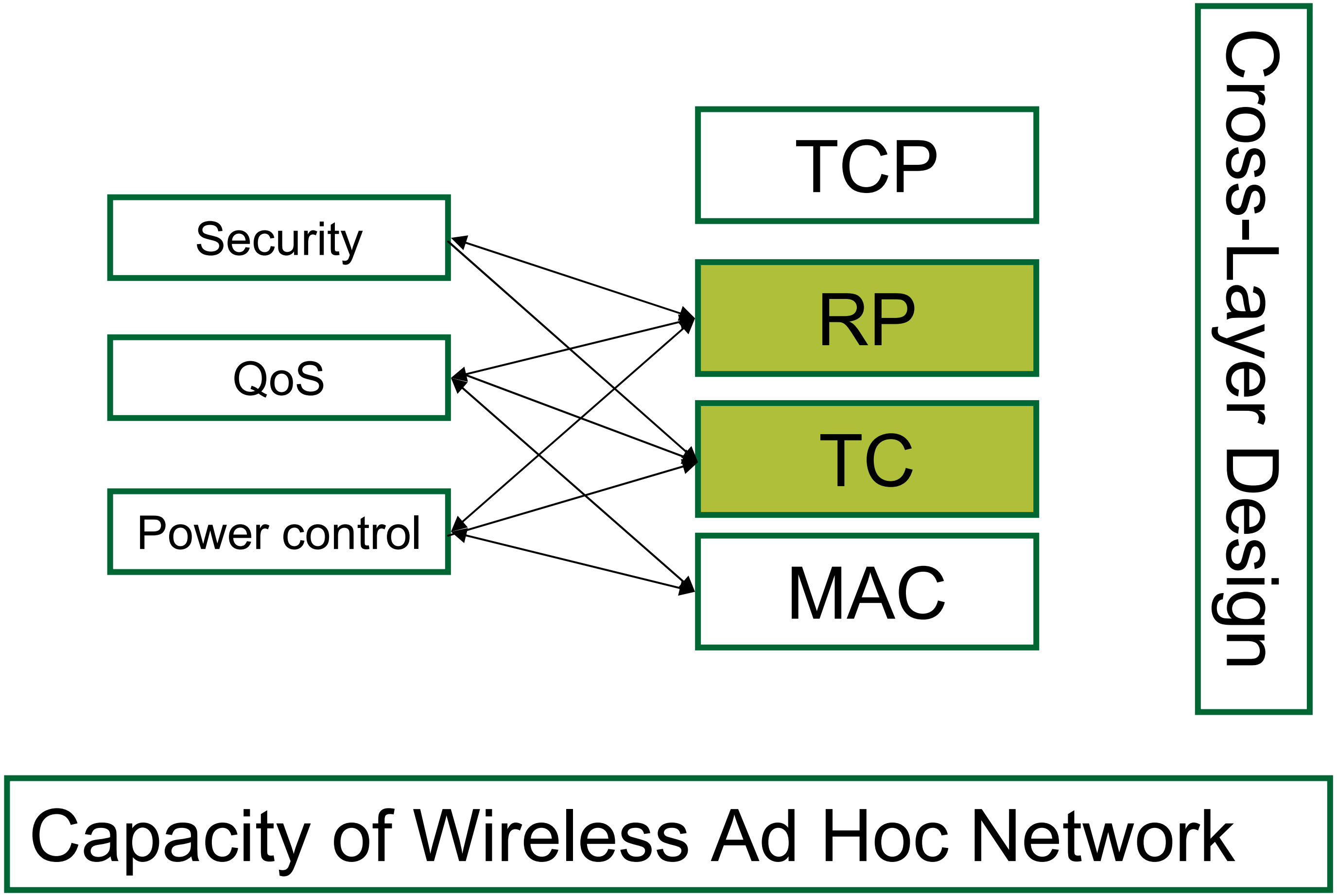
Routing and Topology Control in Mobile Ad Hoc Networks

Navid Nikaein
Institut Eurecom
http://manet.eurecom.fr

Outline



Security
QoS
Power control
TCP
RP
TC
MAC
Cross-Layer Design
Capacity of Wireless Ad Hoc Network

Ad Hoc Networks

- A collection of nodes forming one or several dynamic autonomous networks
  - Nodes may be mobile or fixed
  - Nodes communicate
    - using wireless medium
    - without necessarily the intervention of any fixed infrastructure, i.e. AP/BS
    - potentially in *multi-hop* (store-and-forward) fashion due to the lack of any infrastructure, limited transmission range, channel utilization considerations, power saving
  - Nodes acts as a host, and may act as a router
- Ad Hoc :: Multi-Hop :: Packet Radio Networks

Routing & Topology Control: Classification

- Ad hoc routing can be broadly classified into topology- and position-based routing strategy
  - Broadcasting, one-to-all
  - Unicasting, one-to-one
  - Multicasting, one-to-some
  - Geocasting, one-to-region
- Topology control
  - Neighborhood discovery
  - Network discovery
  - Backbone formation

Routing Definition

- A mechanism by which traffic is directed and transported through the network from a source to a destination [steenstrup]
- Core routing functionalities:
  - Route generation
  - Route selection
  - Data forwarding
  - Route maintenance

- Why is routing in ad hoc networks different?

Topology Control Definition

- Adjust network topology according to some given criteria as environment changes to achieve certain properties
- Such criteria are:
  - K-Connectivity
  - Energy efficiency
  - Scalability
  - Network efficiency
- Why topology control in ad hoc networks?

Routing and topology control Issues

- Routing: topology- / position- based
  - Broadcasting, one-to-all
  - Unicasting, one-to-one
  - Multicasting, one-to-some
  - Geocasting, one-to-region

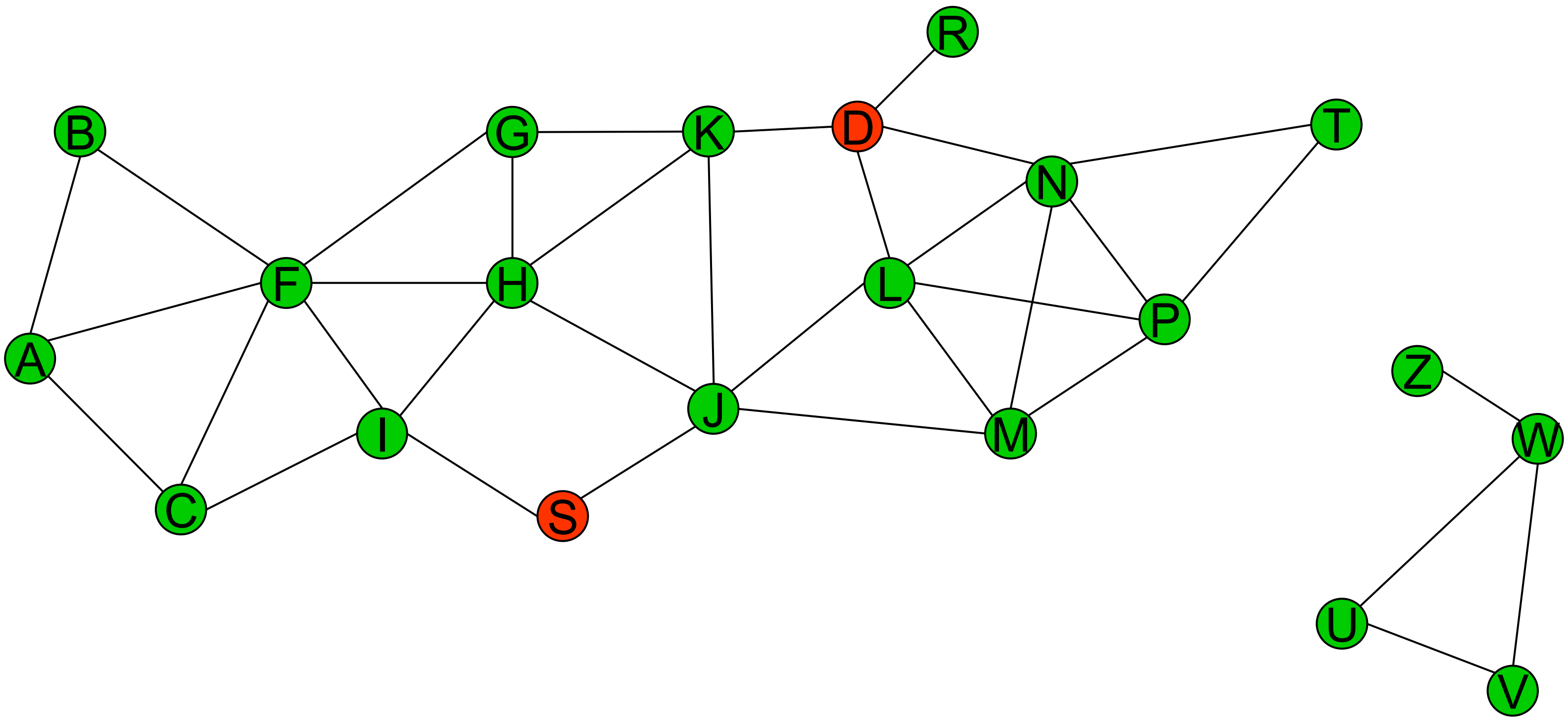
- Topology control
  - Neighborhood discovery
  - Network discovery
  - Backbone formation

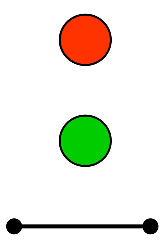
Broadcasting

- Network wide broadcasting "flooding" is one of the building block of ad hoc routing
  - Each node retransmits a copy of the same received data packets to its neighbors
  - Sequence numbers are used to dump the process of packet generation and duplication

- Why flooding?
- What are the advantages and drawbacks of flooding?

Flooding



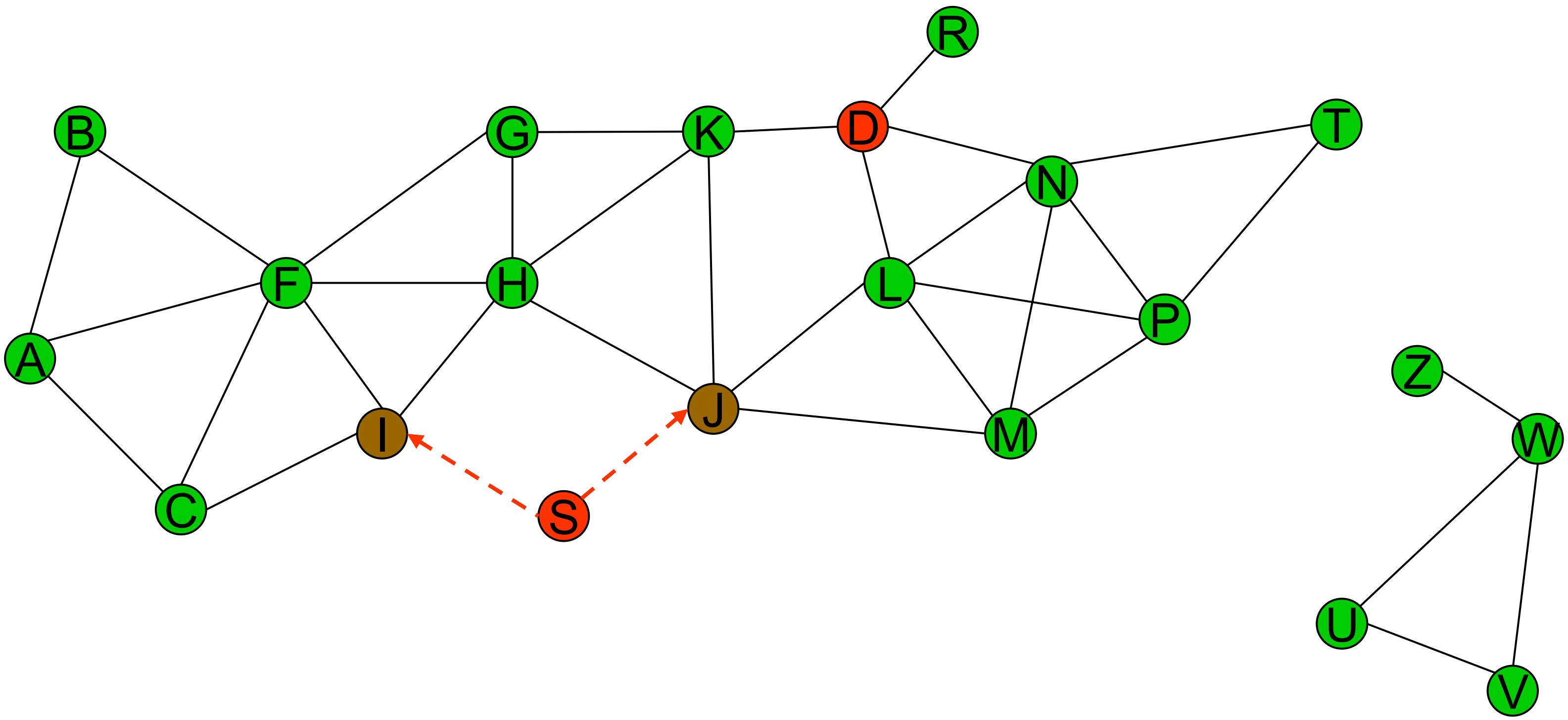


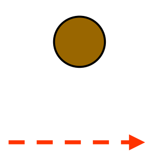
Represents source and destination nodes

Represents the network nodes

Represents the network connectivity

Flooding

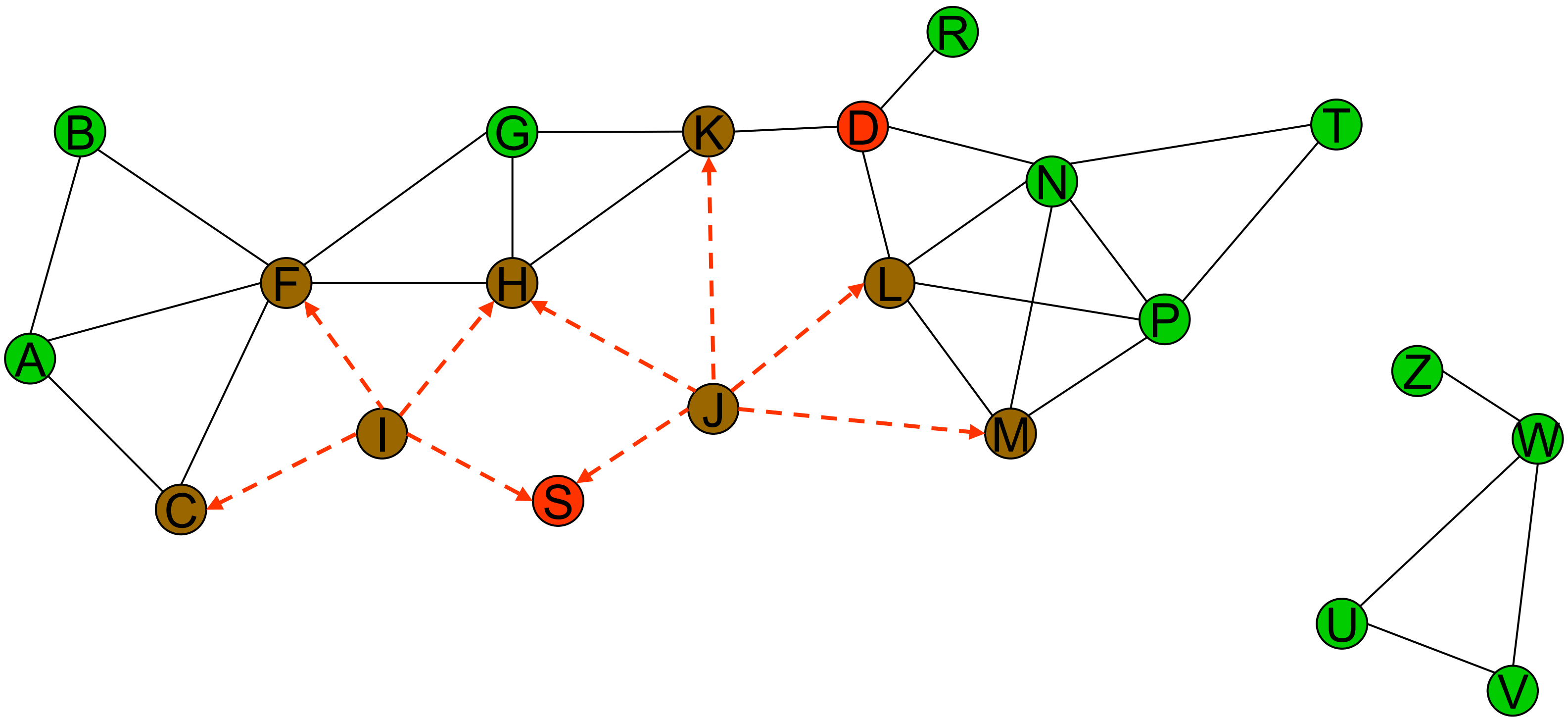




Represents a node that receives packet P for the first time

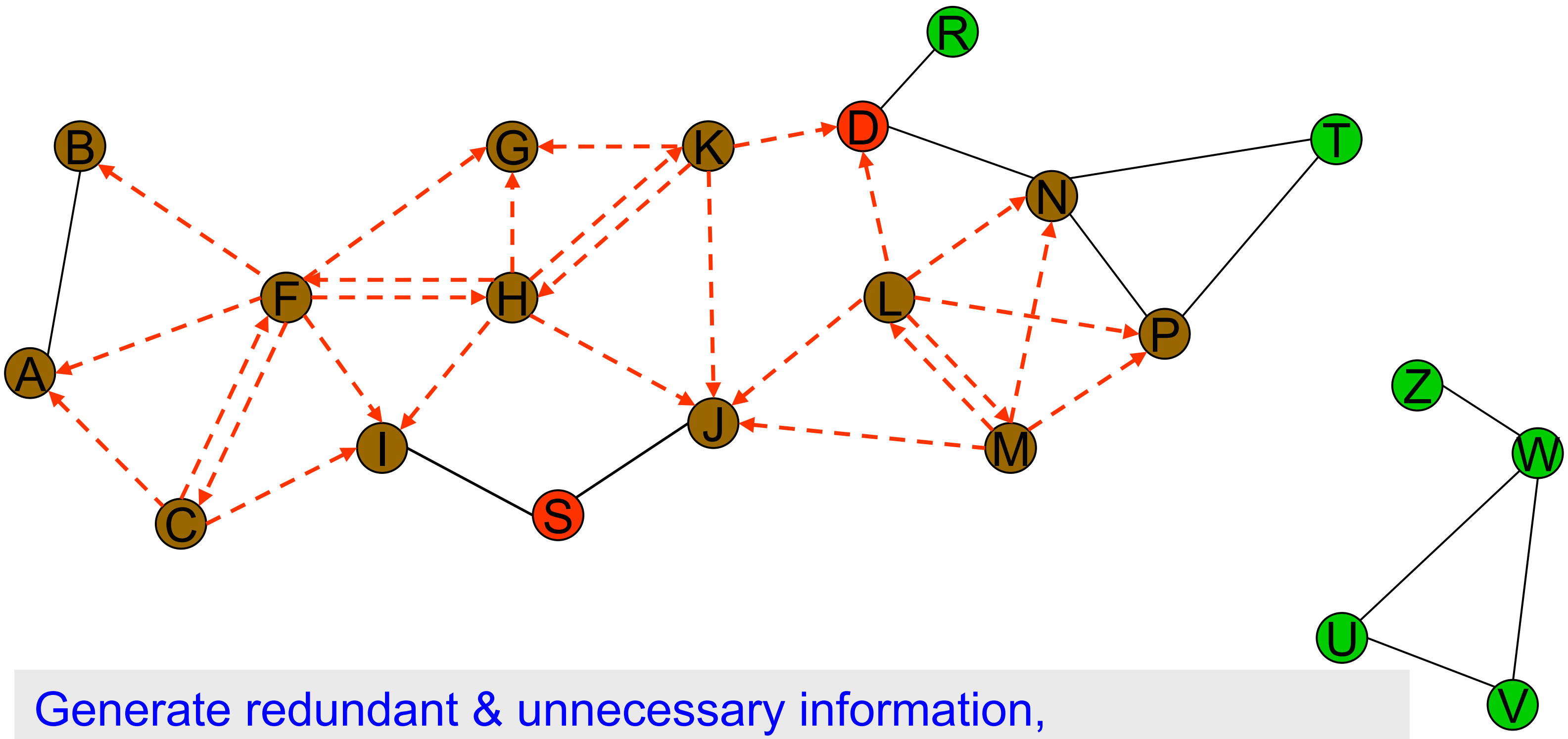
Represents transmission of packet P

Flooding



Potentially generates collision <u>under random access channel</u>,
e.g. at node H,
Note that I & J are hidden from each other

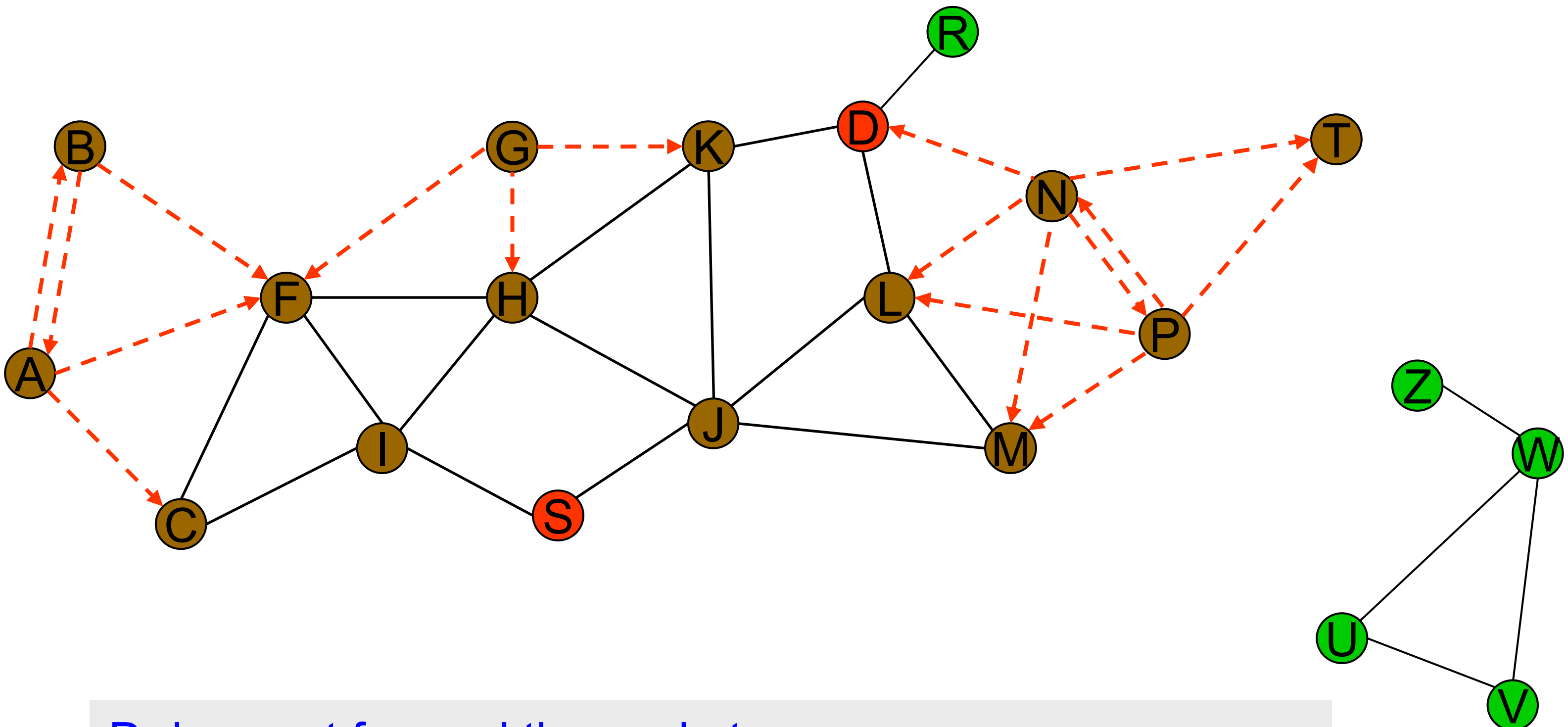
Flooding



Generate redundant & unnecessary information,
e.g. node G receives multiple copies of the same message
Note that node H does not forward the packet P again due to SN

Transmission may collide at D:
Packet P may not be delivered to the destination

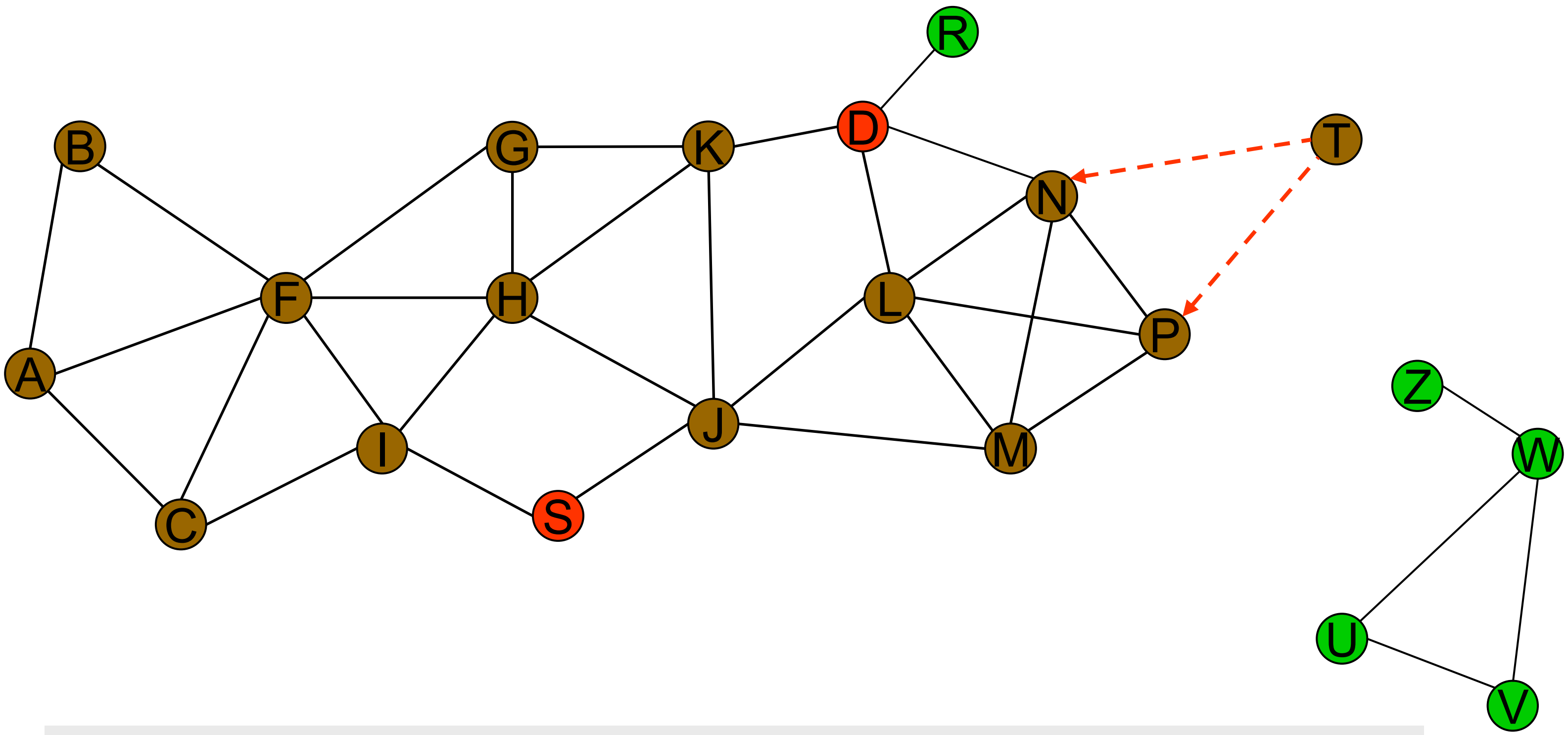
Flooding



D does not forward the packet
Flooding is omni-directional (blind)
e.g. node A & B receive the packet P

Flooding may not converge to the shortest path (hop #)
e.g. P<s,d>=(S, J, L, N, D)

Flooding



Flooding range is network diameter (TTL)
e.g. node T receives the packet P

Note: unreachable nodes (e.g. Z) or nodes for which destination is the only upstream node (e.g. R) do not receive the packet P

Flooding: pros and cons

- Simple
- Multiple path to destination: path diversity
  - Not necessarily the shortest path

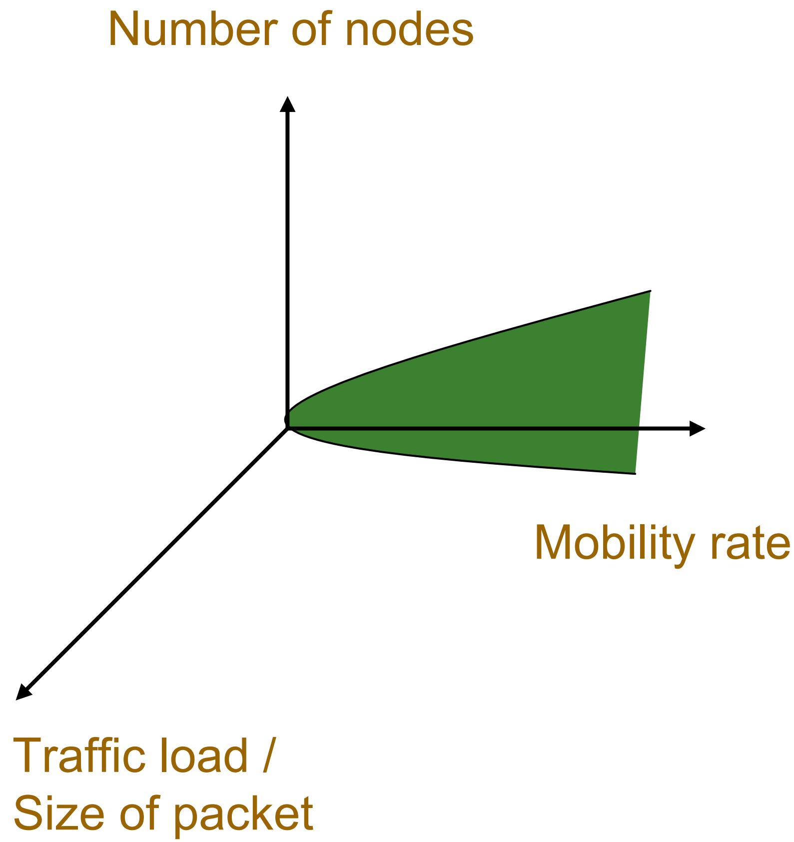
- High redundancy, contention, and collision
- High overhead
  - Omni-direction: angle
  - Network diameter: scope

Protocol scalability [santivanez02]

- The ability of a network to maintain the performance when its limiting factors grow
- Main limiting factors:
  - Mobility rate
  - Traffic load
  - Number of nodes
- Other limiting factors:
  - Packet size
  - Network density

Flooding scalability

- Is flooding more appropriate for data packet or for control packet?
  - e.g. control packets used for route discovery
  - Depends on the overhead of control packets over data packets transmitted
- How flooding can be improved?



Flooding

- How to limit the scope of flooding?
  - Query localization technique[Castenada99]
  - Relative distance estimation RDMAR [Aggelou99]
  - Expanding ring search [hassan04]
- How to reduce the angle of flooding?
  - Location aided routing LAR [ko00]
  - Distance routing effect algorithm for mobility [basagni98]
  - Relative movement estimation RME [nikaein03]
- How to reduce the redundancy ?
  - Broadcast storm problem [ni99]
  - Broadcasting techniques [camp02]
  - Topology control [rajaraman02]

Routing and topology control Issues

- Routing: topology- / position- based
  - Broadcasting, one-to-all
  - Unicasting, one-to-one
  - Multicasting, one-to-some
  - Geocasting, one-to-region

- Topology control
  - Neighborhood discovery
  - Network discovery
  - Backbone formation

Topology-based Routing: Uniscasting

- Use the information about the sequence of nodes towards destination for forwarding
  - Without location information
- Dilemma at a node:
  - Do I keep track of routes to all destinations, or instead keep track of only those that are of immediate interest?
    - Proactive: keep track of all, e.g. LS, DV(DBF), OLSR
    - Reactive: only those of immediate interests, DSR/AODV
    - Hybrid: partial proactive/partial reactive, e.g. ZRP
- Is there any alternative forwarding strategy?

Example: Dynamic Source Routing

- Source node initiates a route generation procedure by flooding a route request (RREQ)
- Each intermediate nodes append its own ID during the path generation phase
- Upon receiving the first RREQ by the destination node, a route reply (RREP) is sent back through the reverse path to the source node
  - RREP piggybacks the route traversed by RREQ
  - Note: The metric used for route selection depends on the traffic load and its distribution
  - Observation: packet size is a function of source-destination distance and nodes' ID size (larger header w.r.t. payload)
  - Question: What happens if the link is unidirectional?

Example: Dynamic Source Routing

- Source node caches the route included in RREP
  - Optimization: all intermediate nodes or the nodes that overhears the RREQ/RREP can cache the route to react to future RREQs
    - Speedup RREQ, and reduce the overhead
  - But beware:
    - Stale or invalid cached routes can pollute the network and hence affecting the routing performance
    - Reply storm problem
- Source node routes all it data packets by tagging them with the complete route to be traversed
  - Routing is done by the source: Source Routing
  - All intermediate nodes determine the next hop based on the tag information

Example: Ad Hoc On-Demand Distance Vector Routing

- RREQ procedure in AODV is similar to DSR
- Instead of source routing, AODV routes a packet on hop-by-hop basis
  - During RREQ propagation, several reverse routes towards the source node are set up
  - RREP then activates only one of the reverse path by re-reversing the route toward the destination
  - Note: routing information is stored at each hop
    - Packets do not need to contain routing information
- Neighborhood discovery using hello message
- Reducing flooding overhead using destination sequence number

Example: Optimized Link-State Routing

- Neighborhood discovery (2-hop)
  - Each node periodically transmits a hello messages
- Multi-Point Relay (MPR) formation
  - Set of nodes over which a broadcasting message propagates
- Link state information (LSI) propagation
  - Each node broadcast the LSI to its neighbors
  - Each neighbor that belongs to the set of MPR re-broadcasts the received LSI
    - Note: In original LS algorithm, all neighbors rebroadcasts the LSI
- Routing table construction
  - Create the network topology and assign a weight for each link
  - Apply shortest path algorithms, such as Dijkastra
  - Determine the next hop for each destination

- Does OLSR adapt its reaction to traffic load / mobility rate ?

Example: Zone Routing Protocol

- Intra-zone routing: Pro-actively maintain state information for links within a short distance from any given node
  - Routes to nodes within short distance are thus maintained proactively (using, link state or distance vector protocol)

- Inter-zone routing: Use a route discovery mechanisms for determining routes to far away nodes
  - Route discovery is similar to DSR with the exception that route requests are propagated via peripheral nodes

Trade-offs

- Delay before data forwarding
  - Proactive protocols may experience lower delay than that of reactive subject to the frequency of topology changes since all routes are generated in advance
- Overhead of route generation/maintenance
  - Reactive protocols may produce lower overhead than that of proactive subject to the frequency of E2E connections because routes are generated on-demand
- Trade-offs depend on the mobility model and traffic pattern
- Note: all of the aforementioned routing protocols apply flooding in one way or another

Routing Design Choice

- Whether each node has to perform the same routing functionalities or instead perform some extra functionalities of interest?
  - Flat structure: perform same functionalities
  - Hierarchical structure: extra functionalities of interest
    - Essentially, in heterogeneous environments where some nodes have some extra capabilities/responsibilities
      - Capability: processing, transmission range, battery life
      - Responsibility: position in the network, speed of movement
    - Can be logical or geographical.
    - What are the examples of hierarchical structure?
    - What are the trade-offs?

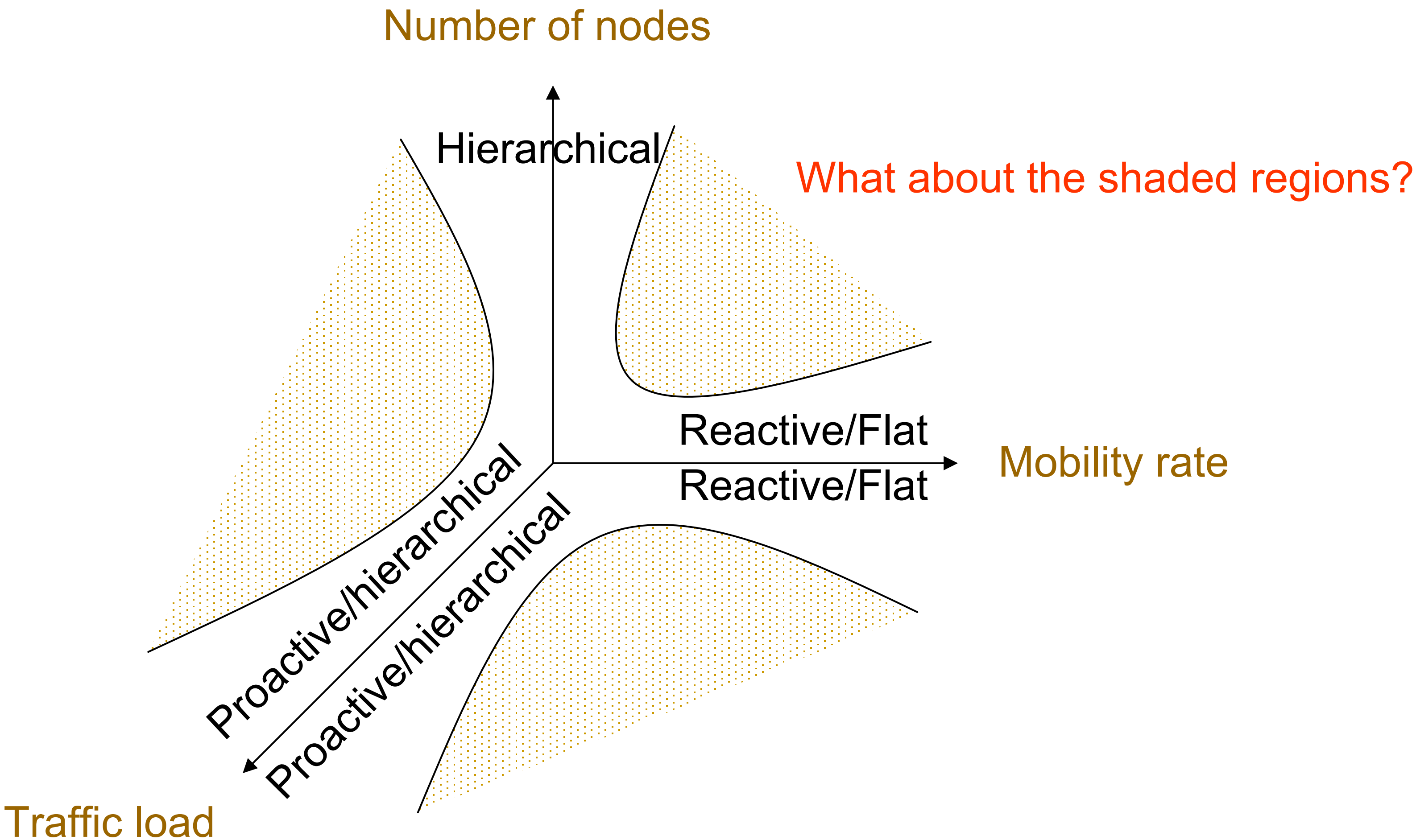
Trade-offs

- Complexity
  - Hierarchical structures are more complex than that of flat
- Overhead
  - Hierarchical structures produce significant configuration overhead at the expense of efficient communication overhead; while
  - Flat structures produce no configuration overhead at the expense of significant communication overhead
- Scalability
  - Hierarchical structure are more scalable than that of flat as the number of nodes increases
- What about storage requirement? Fairness?

Other Issues

- Route caching
- Source routing vs. hop by hop routing
- Local route repair
- Periodical Beaconing and battery life
- Unidirectional link
- Shortest path is not enough!
  - Power-aware routing
  - Stability-based routing
- Load balancing and traffic shaping
- Effect of mobility model and traffic pattern on protocol performance

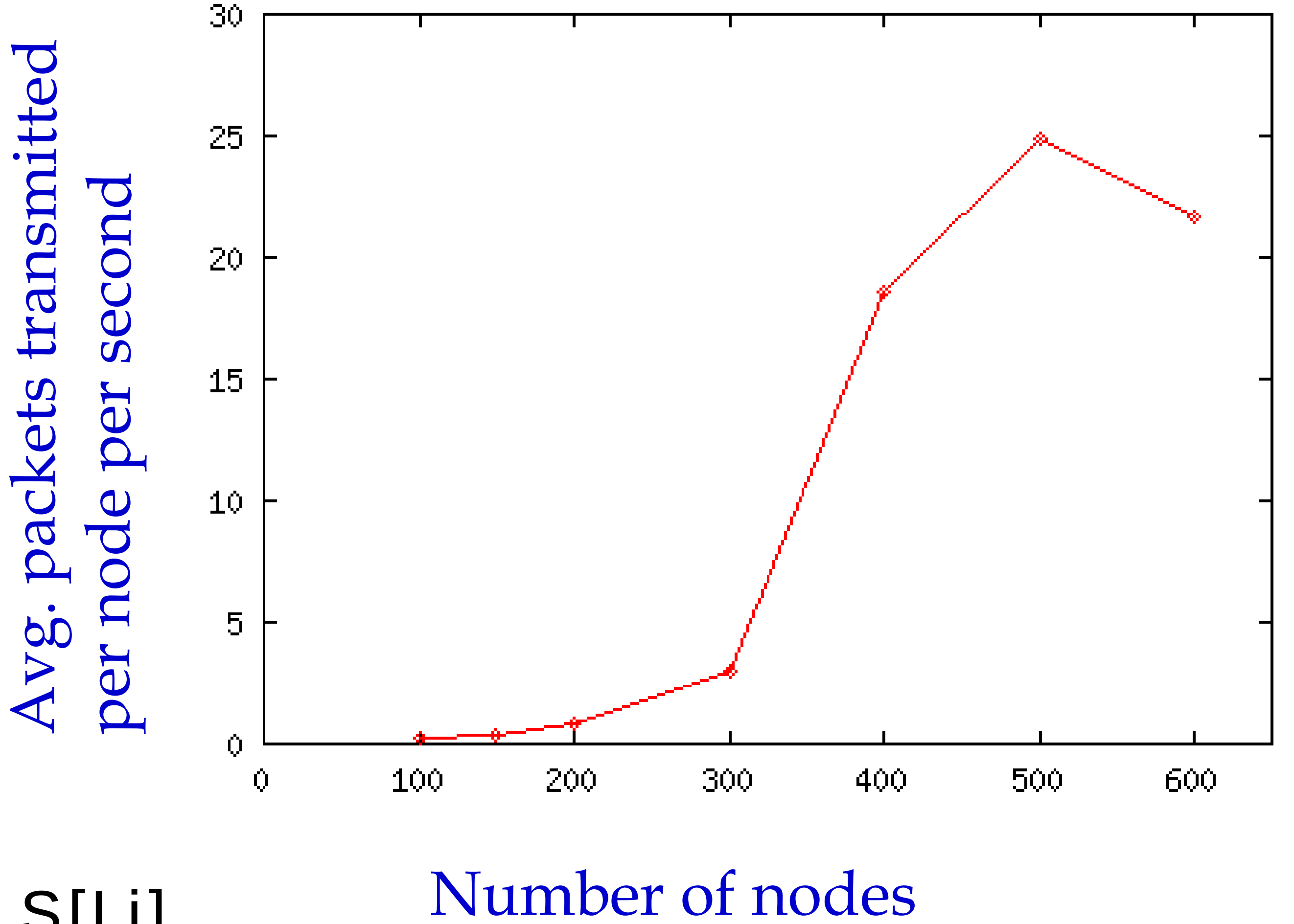
Protocol scalability



Motivation of Position-based Routing

- Determining relative/absolute positions of nodes in indoor/outdoor becomes practical
  - Relative: distance estimation on the basis of incoming signal strength or time delay in direct communication [bulusu00,capkun01]
  - Absolute: using global positioning system (GPS) through a satellite communication
  - Such position information can either be:
    - Physical (47º39’17’’ N by 122 º18’23” W)
    - Symbolic (in the kitchen, next to a mailbox)
- Lack of scalability
  - Communication overhead for route generation due to node mobility is quadratic as the network size increases[stoj02]

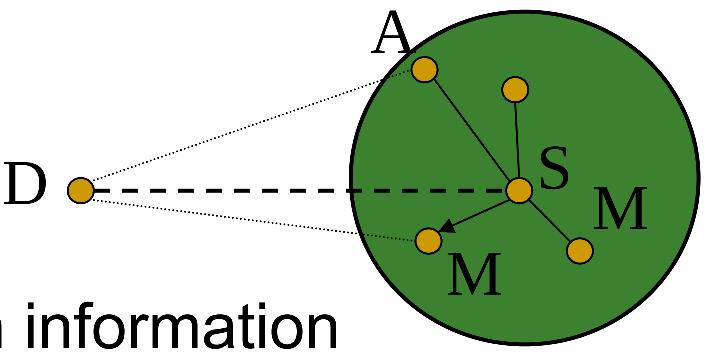
Motivation: Flooding Overhead



Ref. GLS[Li]

Motivation

- Large network with high mobility and traffic load
  - Localized algorithm (distributed in nature)
    - Local behavior achieves global objectives [stojm02]
    - Think globally, act locally [streenstrup02]



  - Require accurate local location information
  - Approximation of the position of destination
  - The source (S) forwards a data packet to at least one neighbor (A or M or both) closest to the destination (D)

Position-based Routing [finn,mauve01,stoje02]

- Requires location-sensing techniques[hightower01]
  - Triangulation:
    - Lateration measures multiple distances between known points
    - Angulation measures angle to points with known separation
  - Proximity: measures nearness to known set of points
  - Scene analysis: examines a view from a particular point
- Incorporates three fundamental building blocks:
  - Location service: determines the position of destination
  - Forwarding strategy: determines the next hop
  - Recovery procedure: determine the next hop in case of failure
  - The first two blocks can either be performed jointly (DREAM, LAR) or separately

Location Service

- A process that enables the network to *track* and *locate* the current position of a node
- Operating on location server/directory/database
- Location service is a combination of:
  - Location update
    - in charge of tracking
    - occurs when a node changes location
  - Location search (location request/reply)
    - in charge of locating
    - occurs when a host wants to communicate with a mobile node whose location is unknown to the requesting node
- What are the different design choices of location service?

Location Service Design Choice

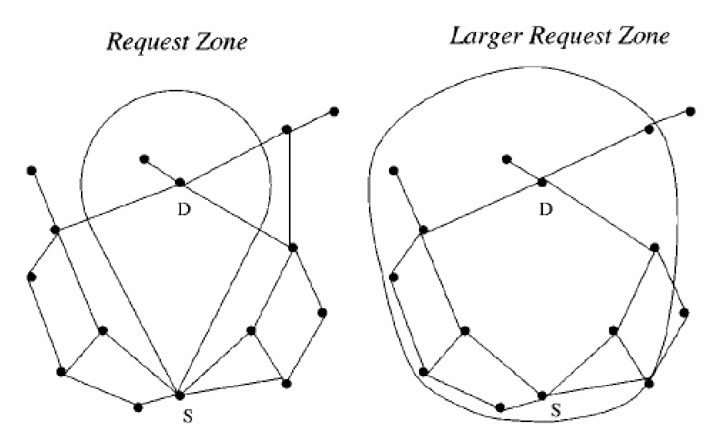
- Do I keep *track* of positions to all destinations, or instead *locating* only those of immediate interests?
  - Proactive: full location update and no location search, DREAM
  - Reactive: no location update and full location search, LAR
  - Hybrid: moderate location update and location search
    - How many nodes host the service?
    - How many positions are maintained by the location server?
- Trade-offs exist between the delay performance of location search and communication overhead of location update

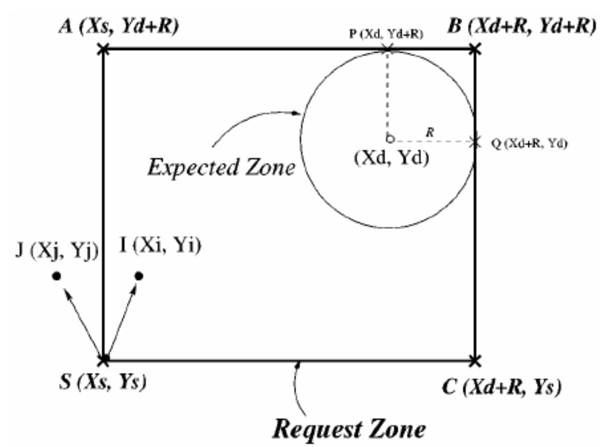
Location-aided routing (LAR)

- Idea: using location information to limited flooding
  - Node S knows that
    - Node D was at location L at time t_0
    - Traveling with average speed v
    - The current time is t_1
- Determine the expected zone
  - By a circle centered at $L_D(t_0)$ with radius $v \times (t_1 - t_0)$
  - Refine the expected zone if some trajectory information is available (D is traveling towards north)
- Determine the request zone for route request
    - Greater or equal than the expected zone
    - Other regions around the expected zone
    - Note: request zone affects the probability of successful route request

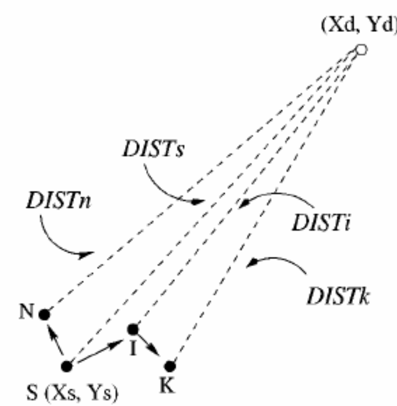
Location-aided routing

- No guarantee that a path can be found consisting only of the hosts in a chosen request zone
  - timeout
  - expanded request zone
- Trade-off between latency of route determination and the message overhead





LAR Scheme 1



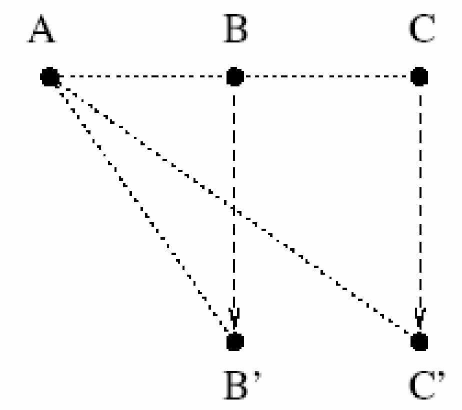
LAR Scheme 2

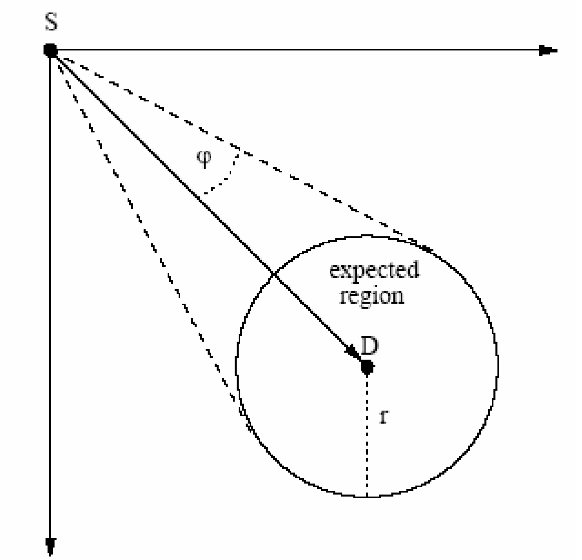
A distance routing effect algorithm for mobility

- Proactively disseminate location information
  - Each node maintains a location table of all nodes
  - Flood if no entry for destination in table, otherwise
  - Forward to the neighbors in the direction of the destination
  - If no one-hop neighbor is found in the required direction, run the recovery procedure (not specified in DREAM!)
- Direction is the line between S and D with the angle φ
  - The angle φ is determined by an expected region
  - Expected region centered at $L_D(t_0)$ with radius $r = v_{max} \times (t_1 - t_0)$

DREAM

- Distance Effect
  - The farther away a nodes gets, the slower it appears to move
  - Update more frequently the closed by nodes (packet age)
- Mobility Effect
  - The faster a node moves, the higher is the update rate
  - Adjust the frequency of update as a function of mobility rate
  - No bandwidth wastage for no movement

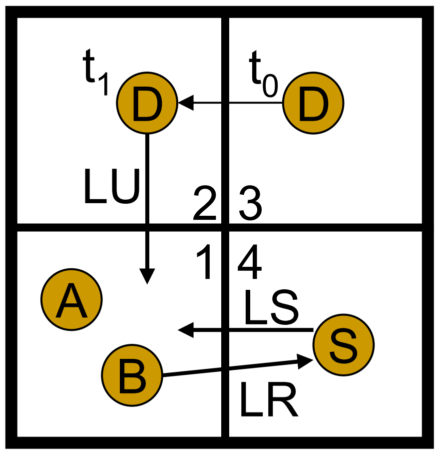




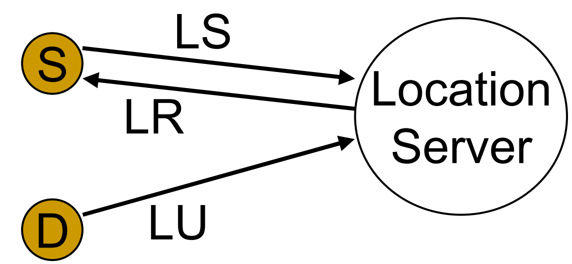
Hybrid Location Server

- Single home zone: e.g. Mobile IP, virtual home region
  - Define as a set of nodes, in a rectangular or a circle with radius R, close to a known position
  - This position is determined based on a <u>well-known hash function</u>
  - All for some if home zones are uniformly distributed
- Quorum system: e.g. uniform QS, double circle,
  - Replicates location information at multiple nodes that are acting as location servers
  - Location updates (write operation) are sent to a subset of nodes (quorum)
  - Location search (read operation) requests potentially a different subset
  - Such subsets are designed such that their intersection is non-empty
  - Can be configured to be all-for-all, all-for-some, or <u>some-for-some</u>
- Multi home zone: e.g. grid based, graph-based
  - Replicates location information at multiple positions in the area of ad hoc networks

Hybrid Location Server

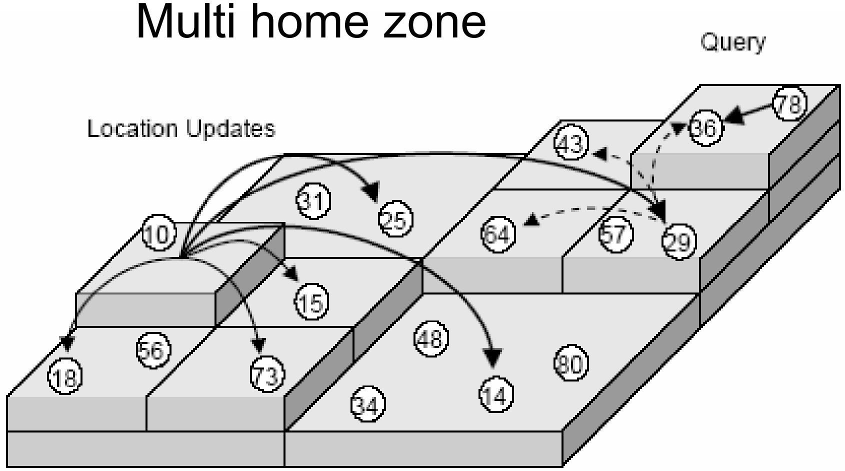


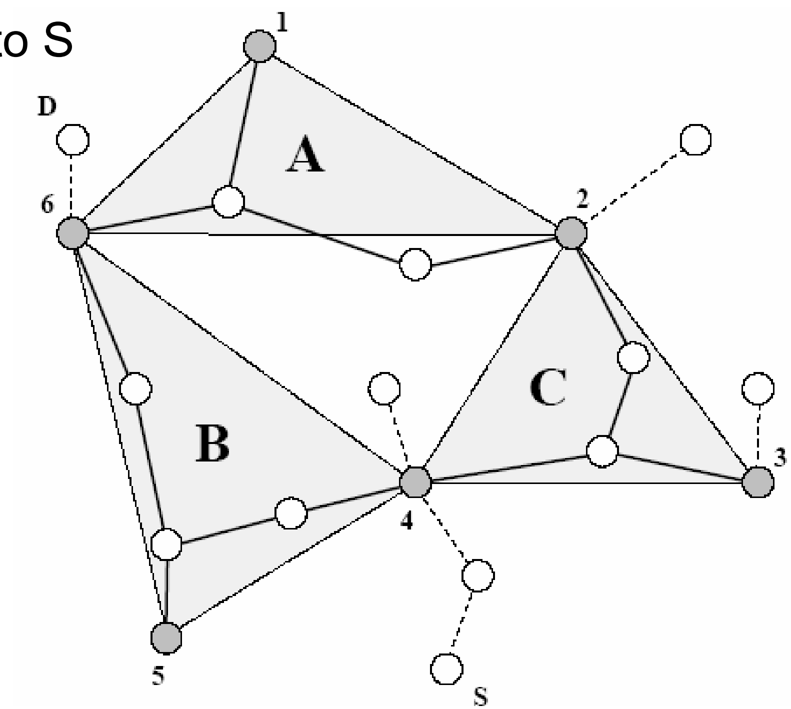
1. LS(D) = zone 1
2. D(t_0) @ zone 3
3. D (t_1) @ zone 2
4. LU(D) @ LS(D)
5. LS(S) @ LS(D)
6. B sends LR(D) to S



Single home zone

Multi home zone





GRID: Multi home zone
Least ID greater than a node's own ID

Quorum System

Complexity metrics [mauve03]

- Type indicates how many nodes host the location information and for how many nodes they maintain location information
- Communication complexity describes the average number of hops required to update or search a node's location
- Time complexity measures the average time it takes to perform a location update or search
- State volume represents the amount of state required in each node to maintain the location information represents state volume
- Localized information means that a higher density or a better quality of the location information is maintained near the position of the node
- Robustness indicates the failure of how many nodes can render the location of a given node inaccessible
- Implementation complexity describes how well the location service is understood and how complex it is to implement and test it

Complexity comparison [mauve03]

Criterion	DREAM	Quorum System	GLS	Homezone
Type	All-for-All	Some-for-Some	All-for-Some	All-for-Some
Communication Complexity (Update)	$O(n)$	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$
Communication Complexity (Lookup)	$O(c)$	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$
Time Complexity (Update)	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$
Time Complexity (Lookup)	$O(c)$	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$
State Volume	$O(n)$	$O(c)$	$O(log(n))$	$O(c)$
Localized Information	Yes	No	Yes	No
Robustness	High	Medium	Medium	Medium
Implementation Complexity	Low	High	Medium	Low
Abbreviations: n=Number of Nodes c=Constant				

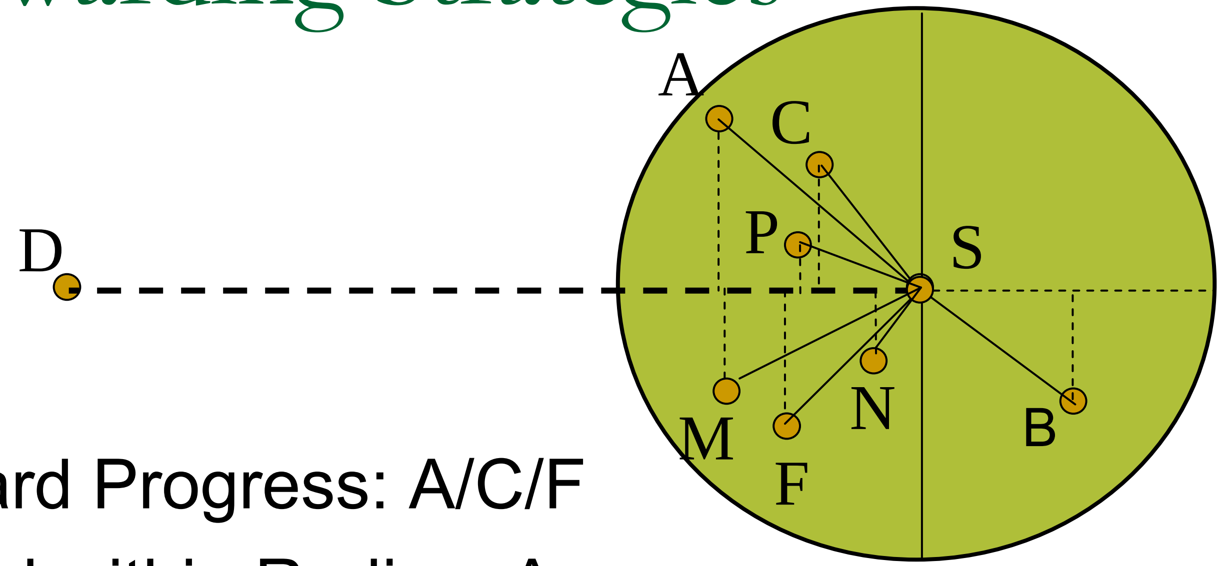
Location Update/Search Schemes

- Temporal resolution: frequency at which a location update/search is sent
  - Timer-based: periodic, threshold
  - (predictive) Distance-based: (velocity) location, threshold
  - Profile, movement, state (a combination)
- Spatial resolution: where/how far a location update/search should travel before it is discarded
  - Blanket polling
  - Shortest distance first
  - Sequential (group) paging
- [aky99,tabbane97,wong00, zhang04]
- Note:route discovery can be used for location search

Forwarding Strategy

- To which node(s) should I forward packet P?
  - Greedy forwarding: forwards P to exactly one neighbor closer to the destination than the forwarding node itself, e.g. MFP, NFP
  - Restricted directional flooding: forwards P to more than one neighbor, e.g. DREAM, LAR
  - Hierarchical forwarding: forwards P through a set of known positions (e.g. anchor, location proxies) that lead to the final destination, e.g. Terminodes, Grid
    - Apply topology-based routing (mainly proactive) for short distance and position-based (mainly greedy) for long

Greedy Forwarding Strategies



- Random Forward Progress: A/C/F
- Most Forwarded within Radius: A
- Nearest Forward Progress: N
- Geographic distance: M
- Nearest Closer: N
- Compass (directional) routing: P
- Are all of these approaches loop-free?

Terminodes [blazovic00]

- Combines topology- and position-based routing
- Routing is done at two levels:
  - For short distance routing (# of hops): route the packets according to a proactive distance vector algorithm
  - For long term distance routing, a greedy forwarding is used
  - Note: once the packet gets close to its final destination, it switches to the short distance routing
- To prevent <u>local maximum</u>, the sender includes a list of anchor nodes into the header through which the packet should visit during forwarding
  - Packet forwarding is greedy between two anchor nodes
  - Could also be named as position-based source routing
  - Note: the sender should know the sequence of anchor nodes that lead to the final destination

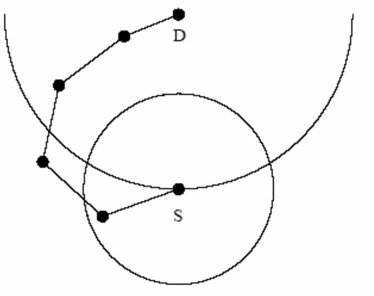
Complexity comparison

Criterion	Greedy	DREAM	LAR	Terminodes	Grid
Type	Greedy	Restricted Directional Flooding	Restricted Directional Flooding	Hierarchical	Hierarchical
Communication Complexity	$O(\sqrt{n})$	$O(n)$	$O(n)$	$O(\sqrt{n})$	$O(\sqrt{n})$
Tolerable Position Inaccuracy	Transmission Range	Expected Region	Expected Region	Short-Distance Routing Range	Short-Distance Routing Range
Requires All-for-All Location Service	No	Yes	No	No	No
Robustness	Medium	High	High	Medium	Medium
Implementation Complexity	Medium	Low	Low	High	High

- Tolerable position inaccuracy: degree of inaccuracy w.r.t. the position if the receiver
- Robustness: if the failure of a single intermediate node does not prevent the packet form reaching its destination

Recovery procedures

- Deals with the situation where forwarding strategies may fail if there is no one-hop neighbor closer to the destination than the forwarding node itself (occurs in sparse networks)



  - Packet reaches a local maximum
  - Local route discovery
  - Closest neighbor in backward (least negative BW)
  - Planner sub-graph, e.g. Gabriel graph
    - There is an edge between two nodes *u*,*v* iff the disk(*u*,*v*) including boundary contains no other points
  - Reinitiate from source with a random selection of the forwarding node

Other issues

- How to avoid empty location server
- How to adjust the size of location server
- What happens if no location reply is received?
- Who determines the next hop?
  - Sender or receiver
- Location privacy?

Routing and topology control Issues

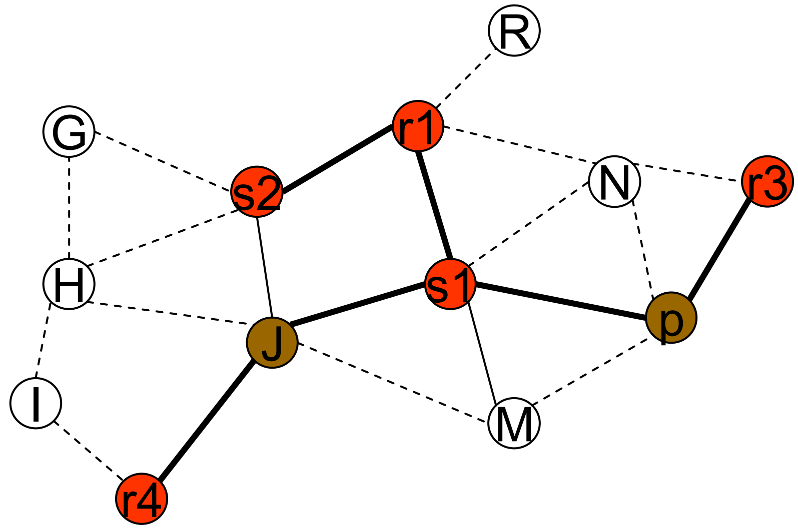
- Routing: topology- / position- based
  - Broadcasting, one-to-all
  - Unicasting, one-to-one
  - Multicasting, one-to-some
  - Geocasting, one-to-region
- Topology control
  - Neighborhood discovery
  - Network discovery
  - Backbone formation

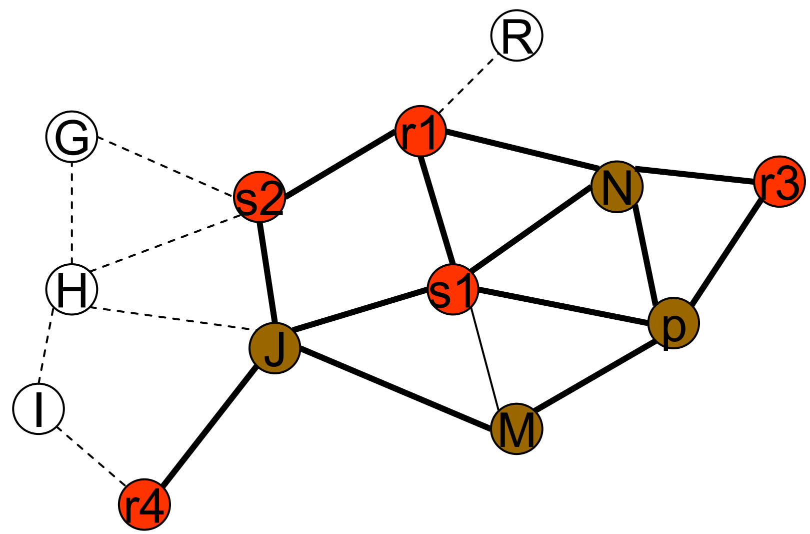
Multicasting [li04]

- Potential applications in MANET require one-to-one, one-to-many, and many-to many communication models.
- One-to-many and many-to-many require efficient multicasting to support group-oriented computing
  - Community centric: multi-player on-line gaming
- There exists three ways to transmit packet P to multiple receivers:
  - Unicasting: sends a separate copy of P to each receiver
  - Broadcasting: floods a copy of P throughout the network
  - Multicasting: transmits P to a group of hosts identified by a single destination address [cordeiro 03]
- Which approach is the best?

Multicast Issues [wu]

- Operation
  - Group-demand
  - Traffic-demand
- Group membership management (dynamic join/leave)
  - Tree-structure
    - Source-based (figure above↗)
    - group-shared
  - Mesh-structure (figure below↘)
    - Multiple path between any source and receiver pair
  - State-less
    - Explicitly mention the list of receivers
- Forwarding strategy
  - On tree
  - Unicasting
  - Boadcasting





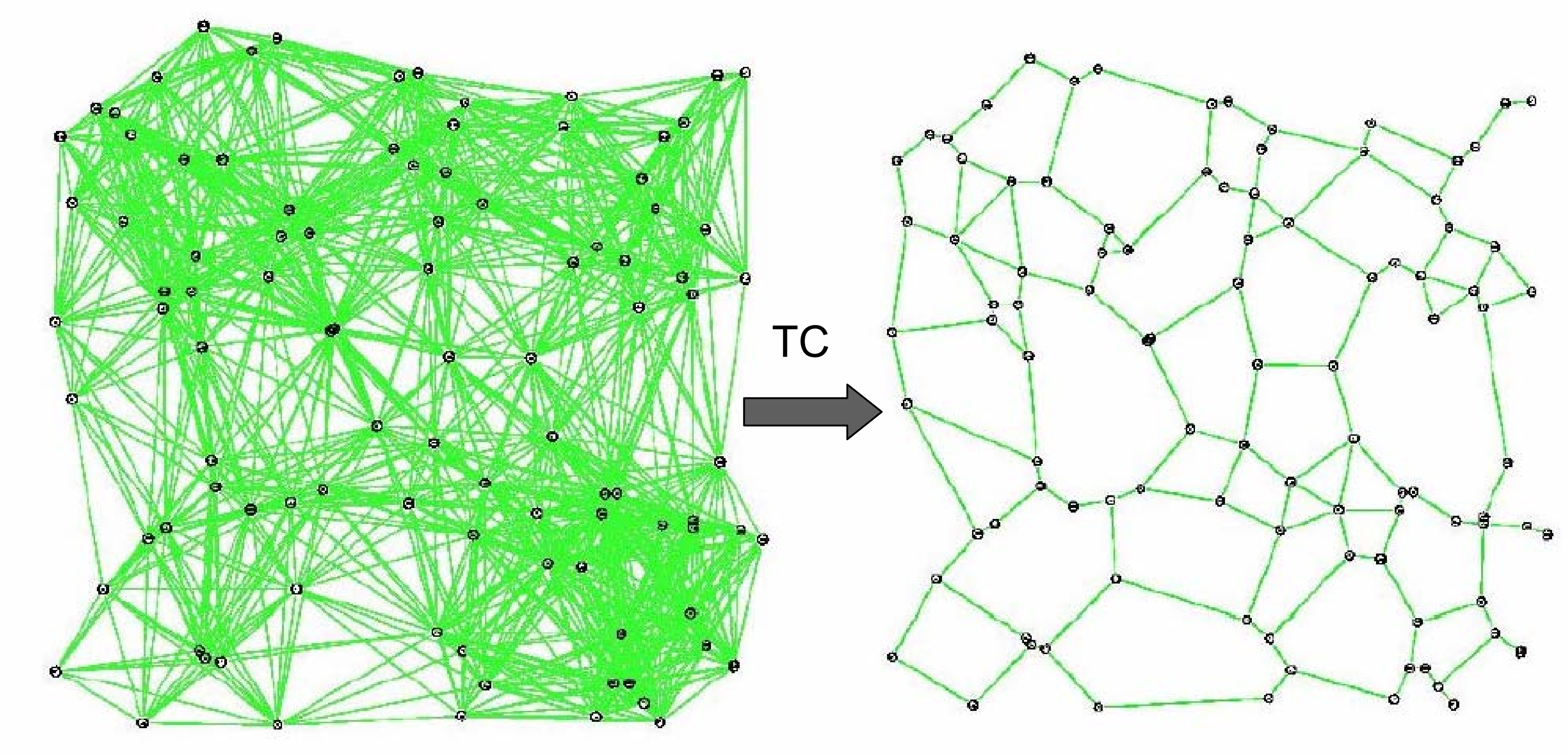
Geocasting [jiang02, maihöfer04]

- Deliver packet P to a group of nodes located within a specific geographical location: called geocast region
  - Public safety applications, Fire, accident
    - Geocast emergency information within a given radius
  - Finding nearby friends, or geographical advertising
- A variant of multicasting problem
- Group membership is implicitly defined as the set of nodes within a geocast region at a given time
- Protocols differ in how they transmit information from a source to the geocast region:
  - Broadcasting or Unicasting
- Could multicasting be used instead of geocasting?
- How to distinguish between different groups within a geocast region?

Topology Control

- Inappropriate topology can significantly reduce the network capacity and performance
  - Too dense network limits spatial reuse factor, and drains battery life
  - Too sparse network risks of partitioning
- To adjust the network topology as nodes move and environment changes subject to certain constraints
- Network topology, G(V, E)
  - Link: range assignment problem → power control
  - Node: dominating set problem → clustering scheme
  - Both approaches make the graph G sparser, same objective
- Constraints:
  - Link: power consumption, and network capacity
  - Node: load reduction, and load balancing

Topology Control



Power Control [santi04]

- Whether all nodes have the same radii?
  - Homogeneous:
    - Given *n*, what is the minimum value of the transmitting range that ensures connectivity? or
    - Given a transmitter technology, how many nodes must be distributed in order to obtain a connected network?
    - Min connectivity range is called critical transmission range
  - Non-homogeneous:
    - Given n, determine a connecting (potentially asymmetric) range assignment set with minimum energy cost ?
    - Given a graph *G*, determine a so called routing subgraph *G*' of *G* such that the power of the path connecting any two vertices is minimized

Homogenous Power Control

- Whether nodes' position are known?
  - Position-based:
    - CTR is the longest edge of the Euclidean MST
  - Non-position-based:
    - Probabilistic approaches
      - Given n, determine the transmission range such that the network is connected with a high probability
      - Applied probability theories are used as a tool:
        - Continuum percolation
        - Occupancy theory
        - Geometric random graph

Non-Homogenous Power Control

- Main properties of subgraph G':
  - Connected
  - Energy efficient
  - Localized
  - Low stretch factor

$$Max \frac{C_G(u,v)}{C_{G'}(u,v)}, \forall u \neq v \in V$$

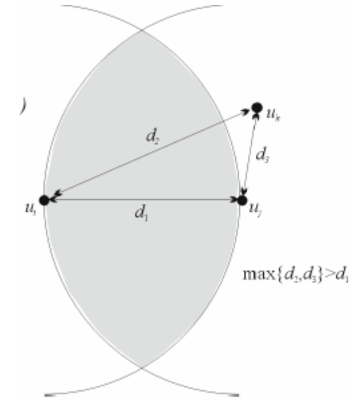
    - Measure of the increase in cost function, C, due to communicating through G' instead of G
    - Cost function can be energy, hop, distance
    - [rajaraman]

Non-Homogenous Power Control

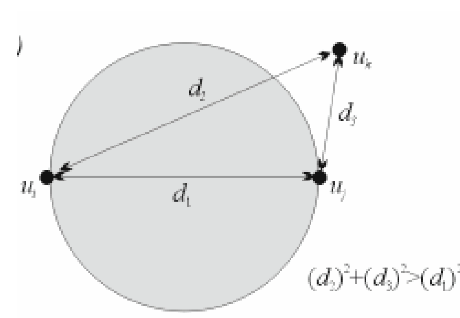
- Spanner subgraphs best describes the problem of designing topology with low stretch factor
  - A spanner is a subgraph G' of G such that the distance between any two nodes is within a constant factor, i.e. *O(1)*, of the distance between two nodes in G
  - Topology with a *O(1)* distance stretch factor has a *O(1)* energy stretch factor
    - The power attenuates as distance raised to an exponent (α)
  - Examples of routing proximity subgraphs:
    - Relative Neighbor Graph (RNG)
    - Gabriel Graph
    - Yao Graph
    - (Restricted) Delaunay triangulation

Proximity Graphs

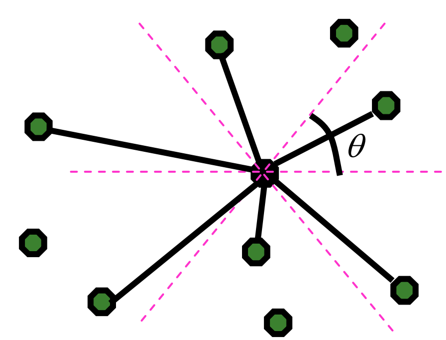
- RNG Graph
  - An edge between u and v exists if for any node w *max { d(u,w), d(v,w)} > d(u,v)*



- Gabriel Graph
  - An edge between u and v exists if for any node w $d^2(u,w) + d^2(v,w) > d^2(u,v)$

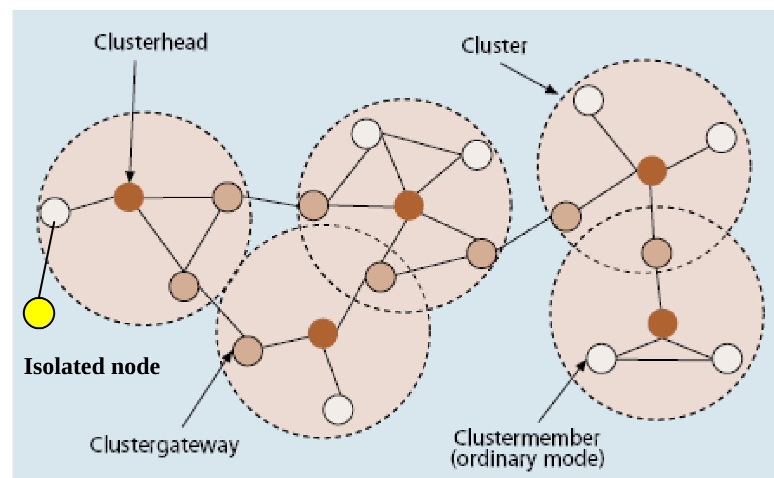


- Yao Graph
  - Partition the space into sectors of a fixed angle φ
  - Connect the node to the nearest neighbor in the sector



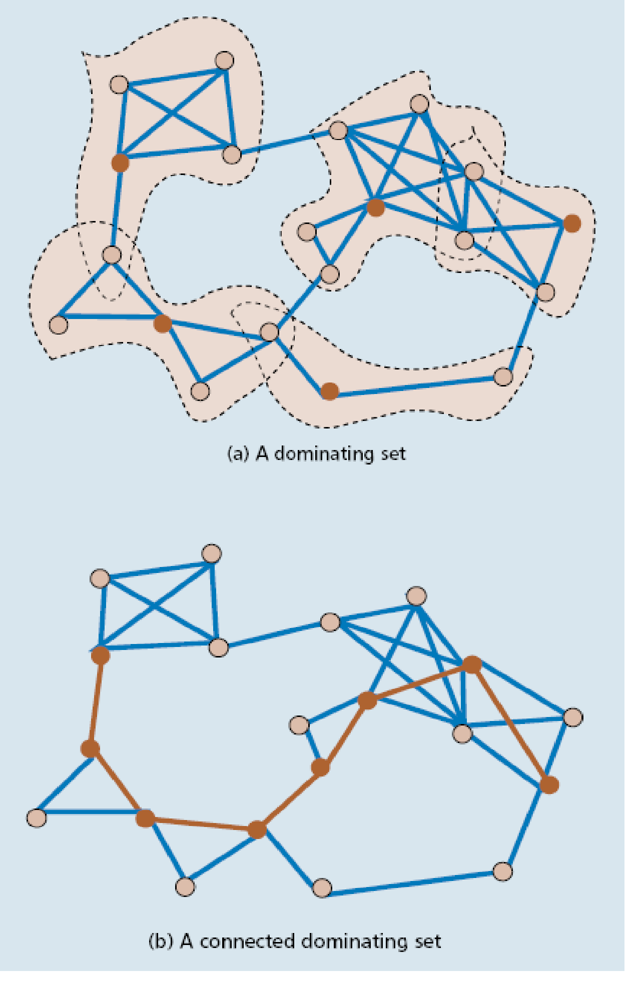
Clustering Scheme [yu05]

- A hierarchical structure is essential for protocol scalability and for performance guarantee
  - Facilitate spatial reuse: improve network capacity
  - Virtual backbone: reduce overhead, improve stability
- Partitioning network into a set of logical / physical groups or zones
- Role assignment:
  - Clusterhead
  - Clustergateway (relay)
  - Clustermember
  - Isolated node



Clustering Scheme

- In graph theory, the Dominating Set problem best describes the clustering scheme
- Determining a subset of nodes such that each node is either a DS or adjacent to DS node
  - $G=(V,E)$, $DS(G)=G'(V', E')$
  - $\{ V' \in V,\ \forall u \in V-V',\ \exists v \in V' \mid (u,v) \in E \}$
- Connected Dominating Set
- Minimum CDS
- M(C)DS is NP-Complete
  - Heuristics approach



Sub-optimal Clustering Schemes

- Find a (C)DS that is "close" to minimum
  - Sub-optimal DS → optimal CDS iterative
  - Sub-optimal CDS → optimal CDS purging
  - Sub-optimal DS → optimal WCDS
  - Sub-optimal MIS → optimal CDS
- Weakly connected dominating set (WCDS)
  - Relax the requirement of direct connection between neighboring dominating set
- Maximum independent set (MIS)
  - No two vertex in the dominating set are adjacent

Clustering Scheme Issues

- Time and communication complexities of clustering: formation and maintenance
- Stability to nodal mobility and traffic load
- Clusterhead existence
- Clusterhead election criteria:
  - Any nodal information: ID, Deg, # of local DS, Mobility,Energy, Load, security-related metric
- One-hop or multihop

Nodal State Information

- ID
- Degree
  - Logical or physical?
- State
  - Load (buffer state)
  - Power level (transmission radii)
- Velocity
- Absolute or relative position
- Trajectory

- Local information
  - Average state of neighboring nodes
  - SNR, signal stability
- Global information
  - Average state of the network