Mobile Systems M

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02 – Mobile Ad Hoc Network (MANET) and Routing

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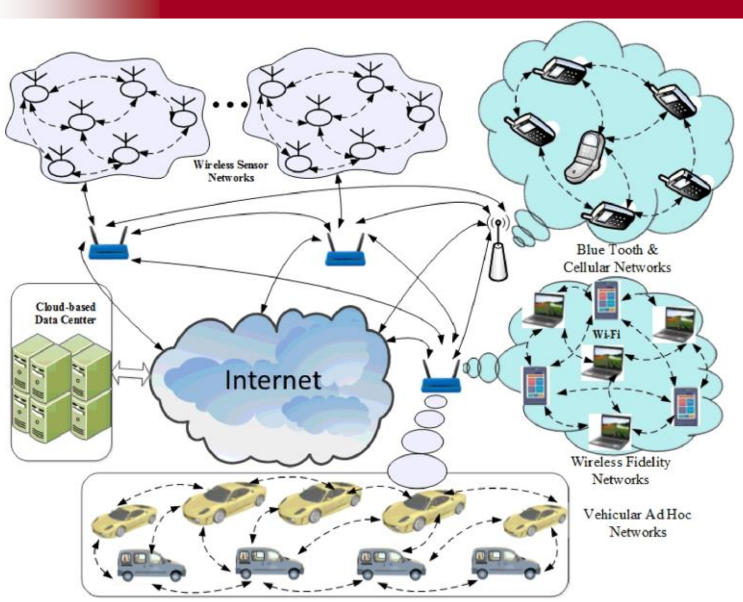
What is exactly an Ad Hoc Network?



Primary Features of Wireless Ad Hoc Networks

- ***Created dynamically*** (on-the-fly) to satisfy needs and reqs that are typically ***temporary***
- ***Immediate and highly reconfigurable deployment*** (NO fixed infrastructure)
- High "volatility"
  - ***Mobility, failures/faults***, node resources that vary over time
- Nodes with very differentiated features (***heterogeneity***)
- Nodes with ***limited energy (battery-operated)***
- Any node can play the ***role of potential router***
  - ***Multi-hop communications***

Tech Challenges for Ad Hoc Networks

- Limited transmission range
- Broadcast nature of the wireless medium (e.g., hidden terminal)
- Packet loss due to transmission errors
- ***Mobility***
  - ***Modifications to routing and established paths due to mobility***
  - ***Packet loss*** induced by mobility
  - ***Network partitioning*** is possibly frequent
- Energy constraints
- Easy "snooping" of wireless transmissions (associated security issues)

Possible Application Areas for MANETs

But a ***vast spectrum*** of possible application areas :

- Personal Area Networking
  - Cellphones, laptops, wrist watches, human body sensors, …
- Civil environments
  - Meeting rooms, stadiums, ships/planes groups, …
- Military environments
  - War scenarios, realization of dynamic coalitions while in the war field, lack of infrastructure in enemy fields/areas
- Rescue/emergency operations
  - Search&rescue, police actions, firemen, …
- Sensor and actuator networks
  - Groups of sensors/actuators embedded in the environment (e.g., smart home) or "scattered" in geographical wide area

Several Variants are Possible…

- Fully ***symmetric*** environments
  - Any node has the ***same capabilities and responsibilities***
- ***Asymmetric capabilities***
  - Different coverage ranges and differentiated ***wireless*** transmission techniques
  - Different ***battery life***
  - Different ***computing capabilities***
  - Different ***mobility degrees*** (e.g., speed ranges)
- ***Asymmetric responsibilities***
  - Only some nodes can perform ***packet routing***
  - Only some nodes play the role of ***leader*** for their neighbors (e.g., clusterheads)
- Differentiated ***traffic characteristics***
  - Bandwidth, latency, reliability; unicast/broadcast/multicast/geocast

Several Variants are Possible…

- They can also ***co-exist and cooperate*** with infrastructure-based networks
- Different ***mobility patterns***
  - People seated in waiting rooms (*limited mobility*)
  - Taxi cabs (*high mobility*)
  - Military movements (most of them are *clustered*?)
  - Personal area networks (also in this case, most movements are *clustered*?)
- ***Mobility features***
  - Speed
  - ***Predictability*** (direction, pattern, triggers, …)
  - ***Uniformity or lack of uniformity*** in the mobility of different cooperating nodes

Routing in MANETs: Overview

First issue: ROUTING

- Why MANET routing is specifically hard and challenging?
  The answer to you ☺…
- ***3 routing protocols***, described below
  - Dynamic Source Routing (***DSR***)
  - Ad hoc On-demand Distance Vector routing (***AODV***)
  - Greedy Perimeter Stateless Routing (***GPSR***)

And, in addition, some elements of ***the more sophisticated TORA***

How to Properly Perform Routing in MANETs?

- Usually ad hoc networks ***involve mobile nodes***
  - Most relevant exception (only partial): Wireless Sensor Networks (WSN)
  - Thus, mainly Mobile Ad hoc NETworks (MANETs)
- ***Several routing protocol proposals in the related literature***
  - Some of them specifically designed for MANETs
  - Other ones adapted from existing protocols, previously proposed for usage in wired networks
- ***No single protocol has demonstrated to be optimal*** in any possible deployment environment and scenario
  - Some proposals also towards the development of ***adaptive protocols***

Why Routing is Different in MANETs?

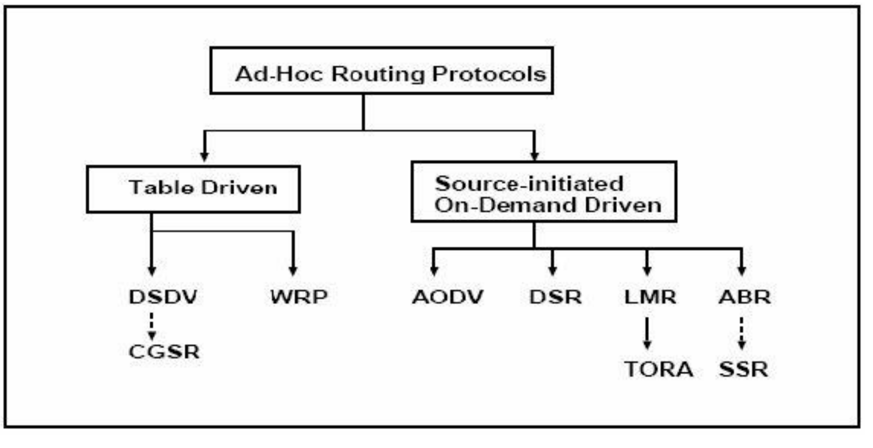
- ***Host mobility***
  - Link failure/repair operations in response to mobility may have different characteristics if compared with management operations reacting to other problems
- ***Frequency*** (*rate*) of ***link failure/repair operations*** may be high in the case of high mobility
- Need of exploiting ***new criteria for performance evaluation***, for example
  - ***Stability*** of routing paths ***depending on mobility***
  - ***Energy consumption***

MANET Routing Protocols

- ***Proactive protocols***
  - ***Maintain valid routes independently on ongoing traffic***
  - Generally, minor latency and greater overhead
  - Traditional routing solutions such as link-state and distance-vector are proactive
- ***Reactive protocols***
  - ***Maintain valid routes only if needed*** (on-demand)
- ***Geographic protocols***
  - Usage of knowledge of destination ***location*** to perform forwarding
- ***Hybrid protocols***

Which is the best approach? ***It depends on traffic and mobility patterns***

Just for curiosity, other taxonomies are more than possible



Trivial Solution: Flooding

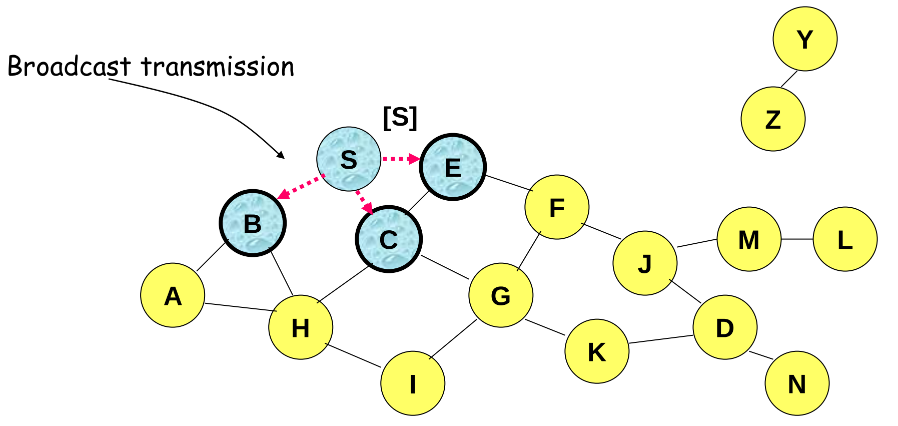
- ***Advantages***
  - Simplicity
  - More efficient when ***transmission frequency is very low*** (no need of discovery/maintaining valid routes or paths)
  - ***Potentially higher reliability*** (exploitation of *multiple paths*)
  - More suitable for ***high mobility patterns***
- ***Disadvantages***
  - Potentially high overhead
  - Potentially low reliability (broadcast exploitation, ***no reliable broadcast*** always available at low-layers of the employed wireless connectivity protocol)

Some protocols use ***flooding for control packets***, typically for routing discovery (overhead mortgaged over the successive longer sequence of data transmissions)

Dynamic Source Routing (DSR) (Johnson&Maltz, CMU, 1996)

- ***Source routing***: it is the source that tries to establish and embeds ***the whole path*** (from source to destination) in the exchanged packets
- How does the source determine the valid path in DSR?
  - When a node S is willing to send a packet to node D, but it does not know yet a valid route to D, ***S starts an operation of route discovery***
    - S performs ***flooding of a Route Request*** (RREQ) packet
    - Any node ***appends its own identifier*** to the packet header when forwarding the received RREQ packet

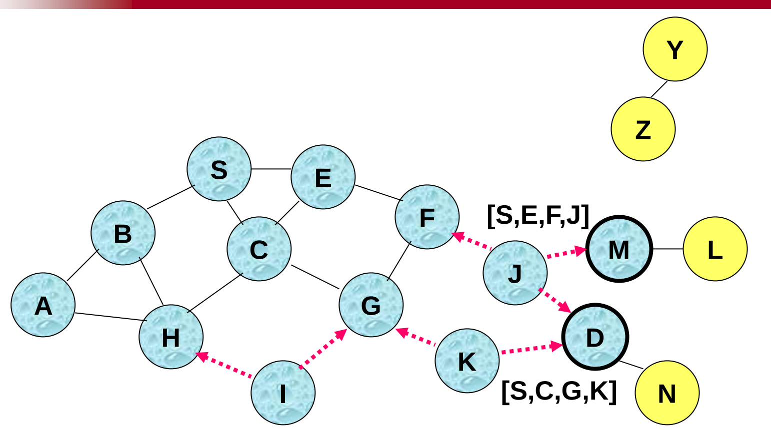
Route Discovery in DSR (1)



Represents RREQ transmission

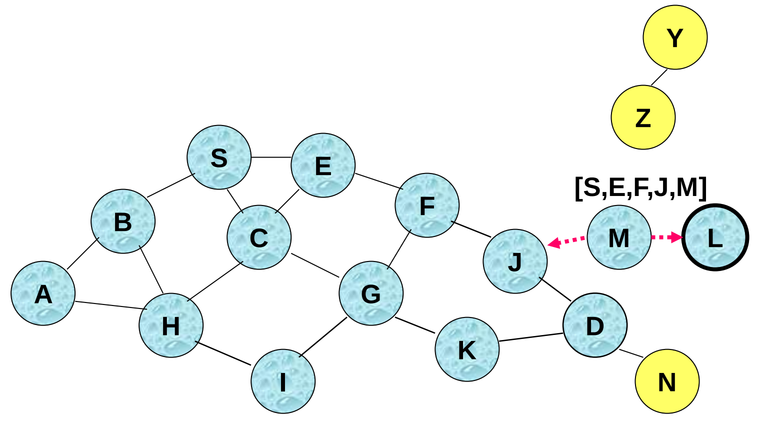
[X,Y] Represents the list of identifiers appended to RREQ

Route Discovery in DSR (2)



- Nodes J and K both perform RREQ broadcast to node D
- Since nodes J and K may be ***hidden nodes*** the one of the other, their ***trasmissions may be colliding***

Route Discovery in DSR (3)

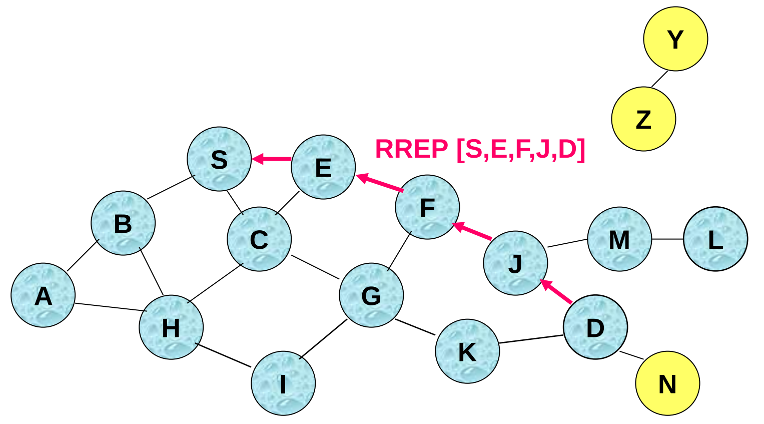


Node D ***does not perform forwarding*** of the RREQ packet because it realizes to be the ***desired destination*** for the route discovery operation

Route Reply in DSR

- Destination D, once received the first RREQ packet, sends a reply packet called ***Route Reply (RREP)***
- RREP is sent on the ***inverse path*** wrt the one contained in the received RREQ packet
- RREP ***includes data about the path*** from S to D, i.e., the one used by RREQ to reach D

Route Reply in DSR: Example

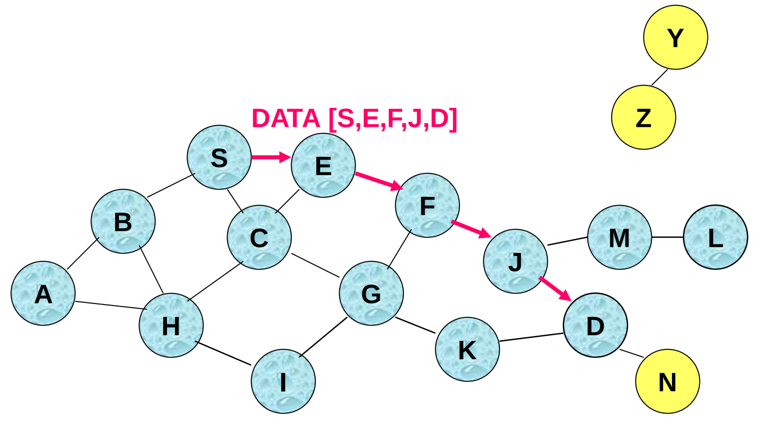


Represents the RREP control message

How to Perform Data Routing in DSR?

- Node S, after receiving RREP, can ***cache the path*** included in the RREP message
- When node S is willing to send a data packet to D, ***the whole routing path is included in the packet header*** (this is the reason why this is called source routing)
- ***Intermediary nodes use the source route*** included in the data packet to ***determine to which node the packet has to be forwarded***

Data Messages in DSR

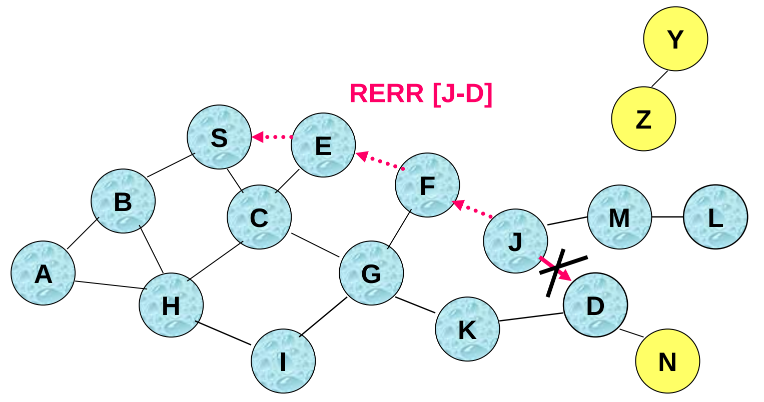


The packet header size grows with the path length

Path Caching in DSR

- ***Path caching*** (or *route caching*) is an add-on optimization
- Any node can perform caching of new paths that it happens to discover, in any possible way
- Advantages
  - ***Accelerates*** the route discovery process
  - ***Reduces*** the ***RREQ propagation*** process
  - Helps the exploitation of additional alternate paths
- Disadvantages
  - ***Invalid caches*** (*stale caches*) may negatively affect on the overall performance
    - How to invalidate the distributed caches?

Route Error (RERR)



- ***J sends an RERR packet to S*** along the JFES path when its forwarding of a data packet from S to D fails, e.g., due to node mobility
- Nodes that listen to the RERR packet can update their path cache and ***remove the JD link***

DSR: Pros and Cons

- ***Advantages***
  - Paths are maintained only among nodes that need to communicate (reduced overhead)
  - Caching can reduce the overhead associated with routing discovery
  - Each discovery can lead to the determination of ***multiple paths*** to destination because of intermediaries that reply based on local caches
- ***Disadvantages***
  - ***Growth of packet header size***
  - ***RREQ flooding***
  - Necessary mechanisms to avoid RREQ collisions among neighbors
  - Increase of channel conflicts when sending RREP (*RREP storm issue*; overhearing and local decision based on shortest path)
  - RREPs that use ***stale cache*** (affecting other caches in cascading)
    - Static timeout for caching, or
    - Adaptive timeout based on expected mobility, statistics about link usage, probability of link failure

Ad hoc On-demand Distance Vector (AODV)

(Perkins&Royer, Sun&UCSB, 1999)

DSR may lead also to ***large-size headers*** and consequent performance degradation

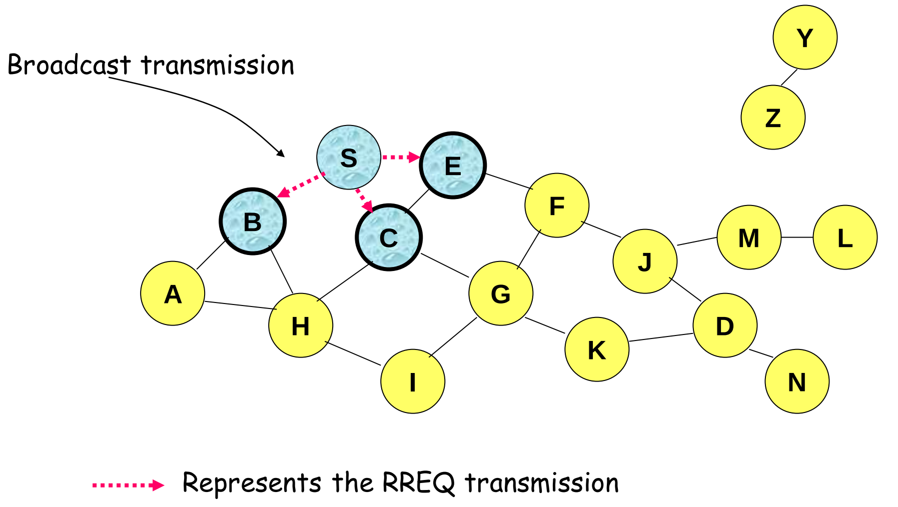
- In particular, when typical payloads are small

- ***AODV*** tries to improve the DSR efficiency ***by maintaining lightweight routing tables, suitable for MANET nodes***
  - Data packets do not include path info at all
- AODV maintains the positive feature of DSR that ***paths are stored only on the nodes that need to communicate*** (by need)

AODV: Basic Idea

- ***Route requests (RREQ) are forwarded similarly*** to analogous packets in ***DSR***
- When a node performs re-broadcasting of a RREQ packet, it initializes and starts an ***inverse path that is directed*** to the source node
- When the target destination receives an RREQ, it replies with a ***Route Reply (RREP) packet***
- ***RREP travels along the inverse path that is configured during the forwarding chain*** of RREQ and ***consequently configures the entries of the routing tables*** only of the ***traversed nodes***

RREQ/Reverse Path Setup in AODV (1)



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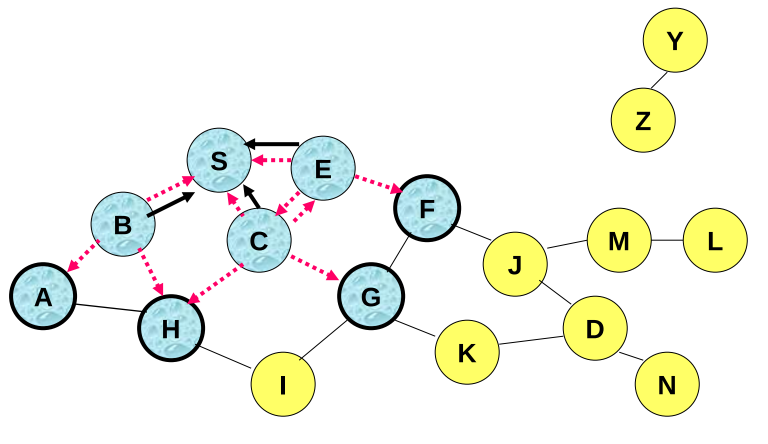
RREQ/Reverse Path Setup in AODV (2)



Represents the links for the inverse path
Backpointers are stored over the path nodes

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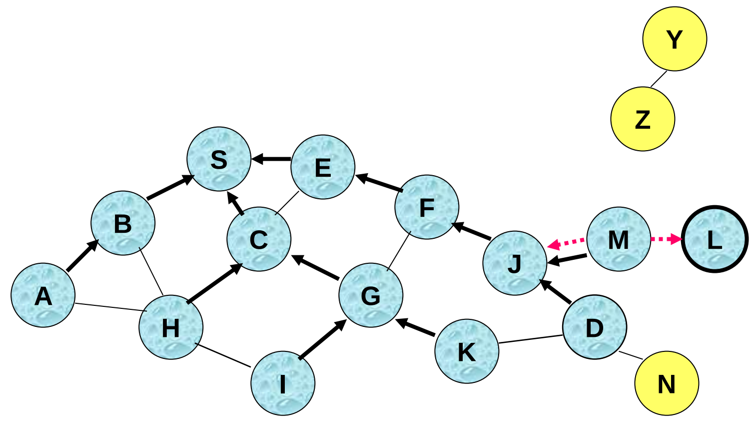
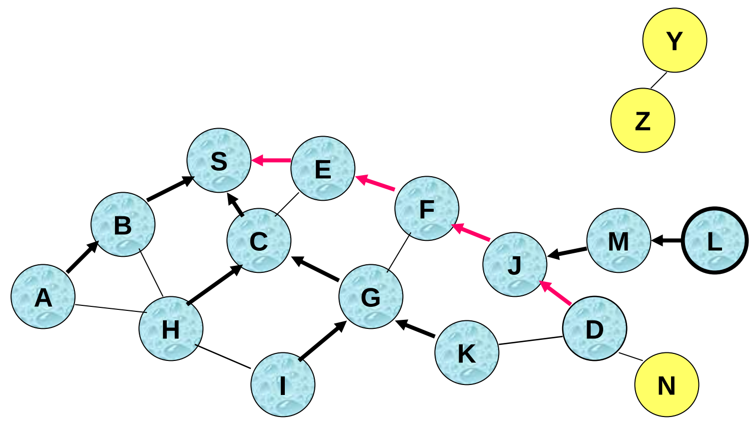
RREQ/Reverse Path Setup in AODV (3)



D does NOT perform RREQ forwarding because it is THE destination of RREQ

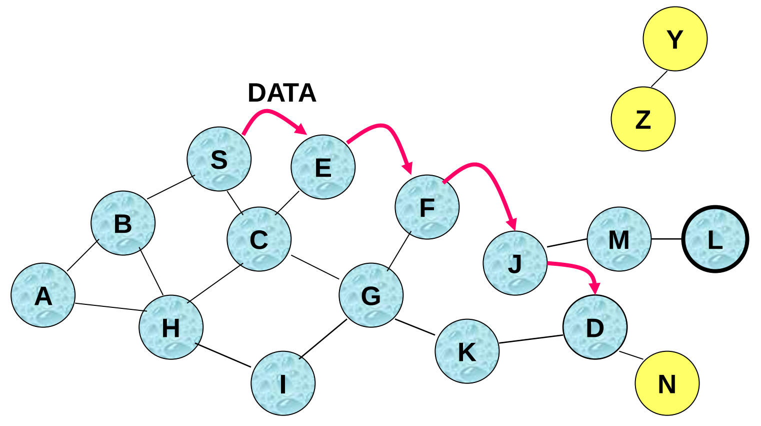
Route Reply in AODV



← Represents the link on the path used by RREP

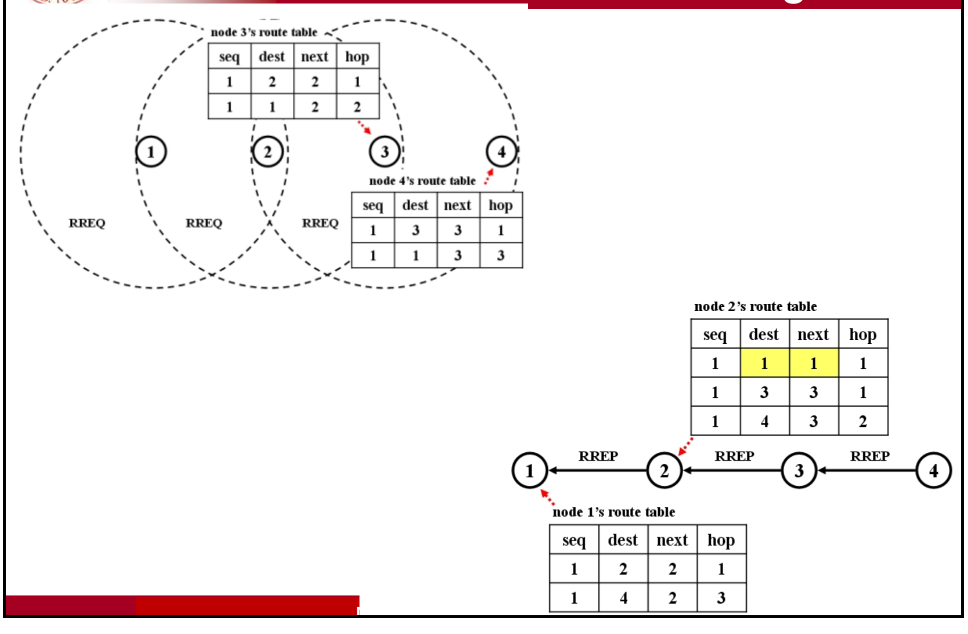
Forward links are configured when the RREP packet passes through the inverse path

Data Transmission in AODV



- The entries of the local routing tables are used to perform forwarding of data packets
- Differently from DSR, the path is not included in the header

Examples of AODV Routing Tables



node 3's route table

seq	dest	next	hop
1	2	2	1
1	1	2	2

node 4's route table

seq	dest	next	hop
1	3	3	1
1	1	3	3

node 2's route table

seq	dest	next	hop
1	1	1	1
1	3	3	1
1	4	3	2

node 1's route table

seq	dest	next	hop
1	2	2	1
1	4	2	3

Timeout

- Any entry of a routing table that includes an ***inverse path is discarded after a given timeout***
  - Why? If ***RREQ did NOT get to reach its destination, or if RREP did NOT correctly return back***, the related entry would occupy local memory in a completely useless way
  - ***Timeout must be sufficiently long*** to allow ***RREP packets to return back***
- Any entry of a routing table that includes a ***forward path*** is removed if not used for a given interval called active_route_timeout (longer than the timeout for inverse paths)
  - Why? The path may ***become invalid in short time*** in highly mobile networks

Reporting of non-usable Links

- ***A neighbor node is considered active*** for one entry in the routing table if ***one of its packets has been forwarded by using that entry*** in the last active_route_timeout time interval
- When a ***link*** towards a next node included in the routing table ***fails***, all ***active neighbors are informed***
- A node generates ***RERR in response to a broken path*** to destination D
  - When S receives RERR, it starts a ***new route discovery process*** towards D

In addition: Link Failure Detection

- ***Hello messages***: ***neighbor nodes periodically exchange alive messages***
- ***Lack of hello messages*** is used as an indication of possible ***fault/failure of a link***
- Alternatively, ***the lack of a series of received ACKs at the MAC layer*** can be used as an indication of probable link failure *(cross-layer monitoring)*

How to Limit Flooding during the Phase of Route Discovery?

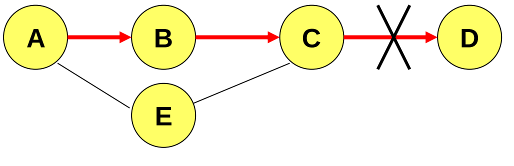
- Optimization: ***gradual expansion of the search, ring shaped***
- RREQ messages are sent initially with ***limited TTL***, in order to limit their propagation
  - DSR also may exploit (and several versions of it do that) a similar optimization
- If no RREP message is received, then the approach is to ***try again with larger TTL***
  - Sending of a new RREQ

Therefore, we are looking for a more balanced ***tradeoff among which factors***?

AODV – Optimization

- ***Possible additional optimization***: an intermediate node with a route to D can reply to RREQ
  - Faster operation
  - Decreases the issue of route request flood
- This optimization can cause loops in presence of link failures

AODV: Routing Loops

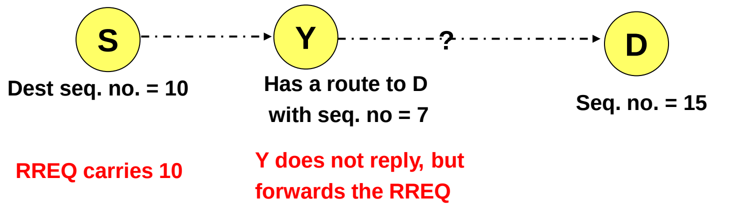


- Assume that link C-D fails and node A does not know about it (RERR packet from C is lost)
- C performs a route discovery for D
- Node A receives the route request (via path C-E-A)
- Node A replies, since A knows a route to D via node B
- ***Results in a loop: C-E-A-B-C***

AODV: Sequence Numbers

- Each node X maintains a ***sequence number***
  - acts as a time stamp
  - incremented every time X sends any message
- Each route to X (at any node Y) also has X's sequence number associated with it, which is Y's latest knowledge of X's sequence number
- ***Sequence number relates to 'freshness' of the route*** – higher the number, more up to date is the route

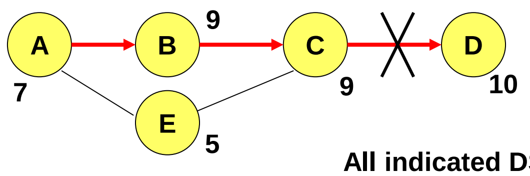
Use of Sequence Numbers in AODV



Loop freedom: intermediate node replies with a route (instead of forwarding request) only if it has a route with a higher associated sequence number

AODV: Avoidance of Loops

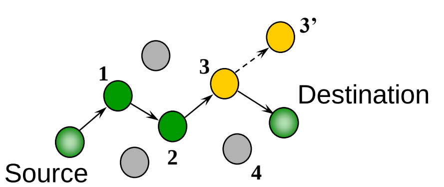
DSN = Destination Sequence Number

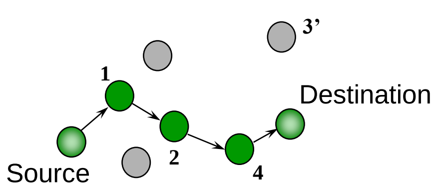


All indicated DSNs are for D

- Link failure increments the DSN at C (now is 10)
- If C needs route to D, RREQ carries the DSN (10)
- A does not reply as its own DSN is less than 10

Mobility-related Path Maintenance





- Movement not along the active path triggers no action
  - If source moves, reinitiate route discovery
- When destination or intermediate node moves
  - upstream node of break broadcasts RERR messages
  - RERR contains list of all destinations no longer reachable due to link break
  - RERR propagated until node with no precursors for destination is reached

Greedy Perimeter Stateless Routing (GPSR; Karp&Kung, Harvard, 2000)

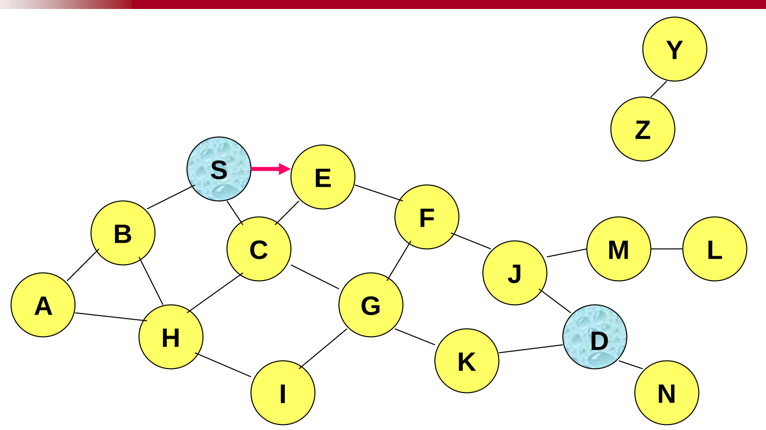
Geographic routing exploits location information to facilitate reaching the destination

- Assumption#1: ***source node knows the destination location***
- Assumption#2: nodes maintain ***lists of neighbor nodes and their locations***
    - Need to include ***location info in hello messages*** (beacons) that are periodically exchanged

Two schemes for data forwarding:

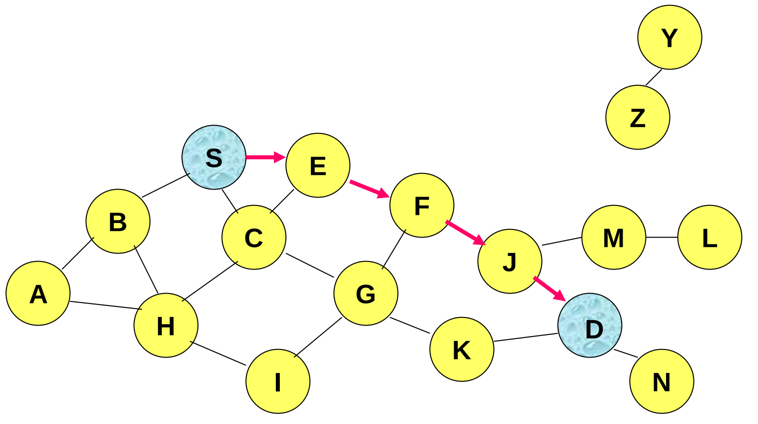
- ***Greedy forwarding***: data are sent to the neighbor node that is estimated as the closest one towards the destination (usage of only the location info of neighbor nodes for data forwarding)
- If ***greedy forwarding fails***, switch to a different scheme, i.e., ***perimeter forwarding***

Greedy Forwarding (1)



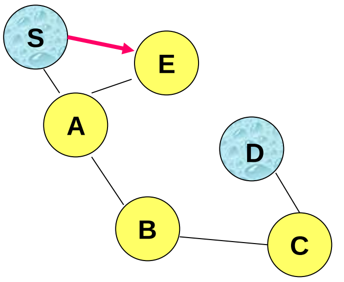
E is the S's neighbor that is closest to D
("closest" in terms of Euclidean distance)

Greedy Forwarding (2)



F is the E's neighbor node closest to D
J is the F's neighbor node closest to D

Possible Failures in Greedy Forwarding



In the case that E is not in the coverage range of D (assumption of the figure)

No node among the E's neighbors is closer to D than E
Forwarding failure!
But a useful path would exist: [S, A, B, C, D]

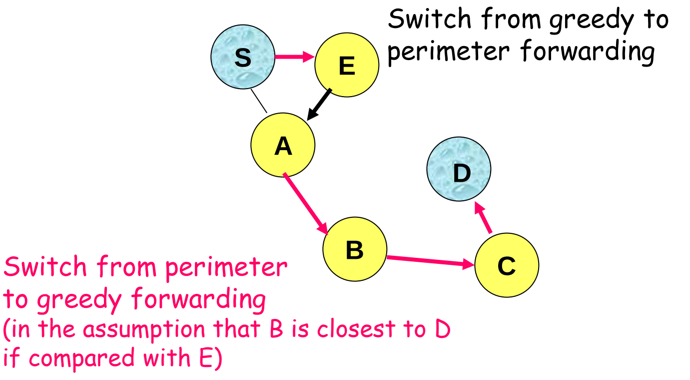
Perimeter (Face) Forwarding

- It can ***always reach a destination if a useful valid path exists***
  - Route ***around the so-called "holes"***
- Each node calculates ***Relative Neighborhood Graph (RNG) or Gabriel Graph (GG)***
  - RNG is a ***non-directed graph*** defined on a set of points in the Euclidean plane that are compliant with this constraint: connecting two points A and B with an arc ***if and only if there is no point C that is closest to both A and B (C-to-A and C-to-B distances minor than A-to-B distance)*** - G. Toussaint, 1980
- ***RNG is traversed*** by using the right-hand rule
  - Basically, the idea is of ***visiting the nodes that determine the perimeter*** around a hole

Perimeter (Face) Forwarding

- During graph traversing, if a packet meets a node that is closest to destination if compared with the node where greedy forwarding had failed, ***the decision is to operate a new switch towards greedy forwarding***
- ***We can have loops*** if perimeter forwarding is used and whenever the destination is not reachable
  - GPSR is capable of detecting the situation and of discarding the involved packet

Example



Temporally Ordered Routing Algorithm (TORA)

TORA is proposed to operate in a ***highly dynamic*** mobile networking environment

- ***Highly adaptive, loop-free, highly distributed***
- Based on the concept of ***link reversal***

Key design concepts of TORA:

- ***Localization of control messages*** to a very small set of nodes ***near the occurrence of a topological change***
- To this purpose, nodes need to maintain ***routing info about neighbors***
- The ***height metric*** is used to model the routing state of the network

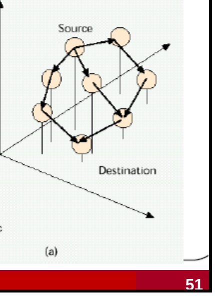
Three basic functions:

- ***route creation***
- ***route maintenance***
- ***route erasure***

Temporally Ordered Routing Algorithm (TORA)

During route creation and maintenance, nodes establish a Directed Acyclic Graph (DAG)

- ***A logical direction*** is imposed on links towards destination
- ***Source-initiated***
- Provides ***multiple routes*** for any desired source/destination pair
- Starting from any node in the graph, a destination can be reached by ***following the directed links***
- ***Highly adaptive, efficient, scalable, distributed algorithm***
- ***Multiple routes from source to destination***



TORA Major Tasks

Three major tasks

- Route creation – query (QRY) and update (UPD) packets
- Route maintenance
- Route erasure – broadcast of clear packet (CLR)

Using ***unique node ID and unique reference ID for packets***

1) Route creation: demand-driven «query/reply»

Performed only when a node requires a path to a destination but does not have any directed link

- A QRY packet is flooded
- An UPD packet propagates back if routes exist

2) Route maintenance: «link reversal» algorithm

- React only when necessary
- Reaction to link failure is ***localized in scope***

3) Route erasure

A CLR packet is flooded to erase invalid routes

TORA Metrics

- ***Assigns a reference level (height) to each node***
- ***A local DAG is maintained for each destination***
- ***Synchronized clock*** is relevant, accomplished via GPS or a dedicated protocol such as Network Time Protocol (NTP)

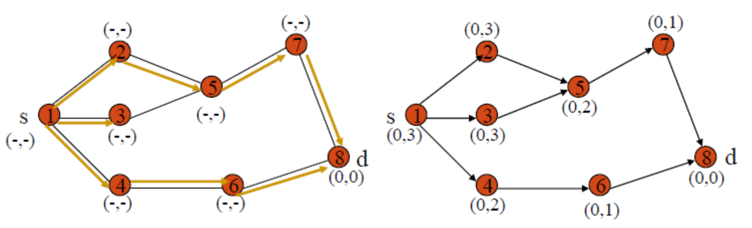
Timing is an important factor in TORA because the «height» metric is dependent on the logical time of a link failure

- Logical time of a link failure
- The unique ID of the node that defined the new reference level
- A reflection indicator bit
- A propagation ordering parameter
- The unique ID of the involved node

Adjust reference level to restore routes on link failure

Temporally Ordered Routing Algorithm (TORA)

- Route creation of TORA

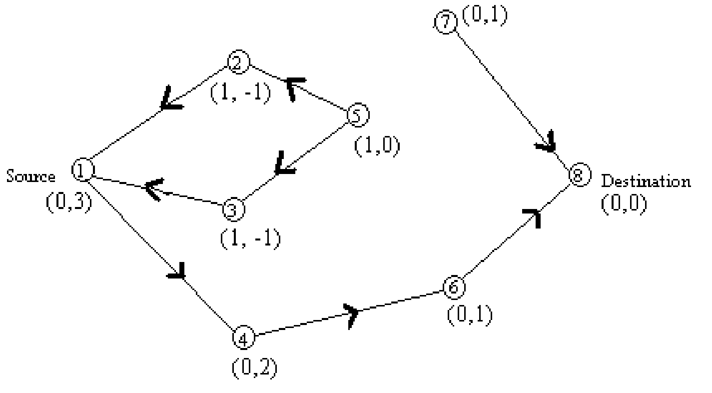


Propogation of QRY (reference level, height)

Height of each node updated by UPD

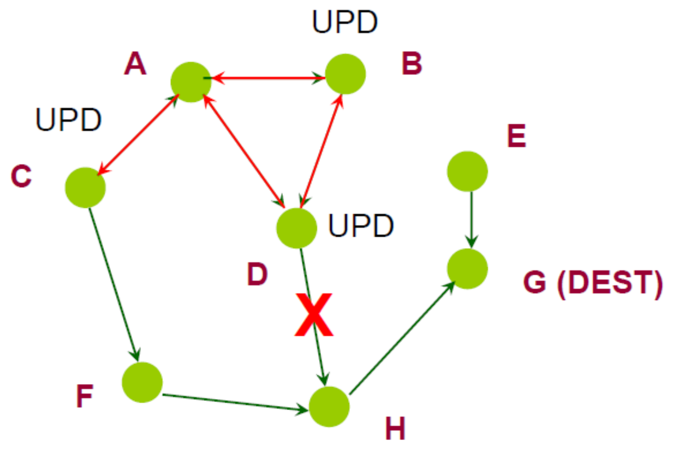
Temporally Ordered Routing Algorithm (TORA)

Route creation

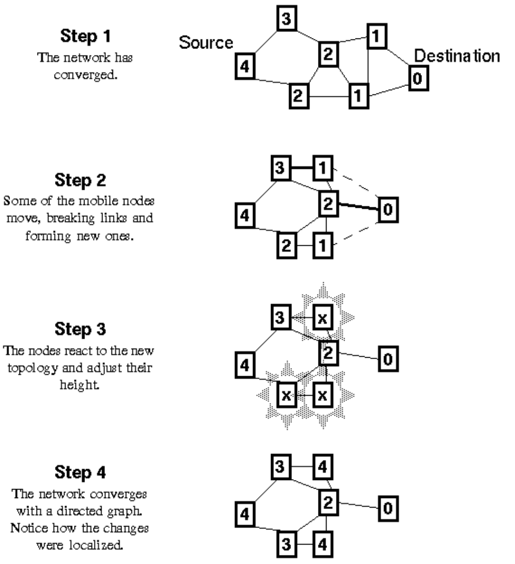


Temporally Ordered Routing Algorithm (TORA)

- Route maintenance



Temporally Ordered Routing Algorithm (TORA)



Temporally Ordered Routing Algorithm (TORA)

In summary…

Advantages:

- ***Less control overload*** – by limiting the control packets for route ***reconfiguration to a small region***

Disadvantages:

- Local reconfiguration of paths ***results in non-optimal routes***
- Concurrent deduction of partitions and subsequent deletion of routes could ***result in temporary oscillations and transient loops***

Moreover, many other MANET routing algos in the literature…

Think about optimizations that stem from

- Application requirements
- Most probable characteristics of deployment scenarios
- Rate between mobility&dynamicity vs communication rate
- Which information assumed to be known at participating nodes?
- Which node coordination and associated overhead?
- How much proactive? How much reactive?
- How much optimistic? How much pessimistic?

For instance: Multi-hop Routing vs. Energy Consumption

- Energy consumption to transmit a packet:
  - Constant cost to power on the circuitry
  - Proportional to packet size
  - Proportional to distance * distance

- Multi-hop routing can ***reduce the consumption*** of energy (the consumed energy is basically proportional to distance * distance) but this can generate non-negligible ***latencies***

- Which per-hop distance?
  - Too short => the dominant part of the energy cost is for powering on the circuitry
  - Too large => the dominant part is for packet transmission; ***reduction of re-usability of bandwidth in space***; overhead for scheduling because the number of nodes at 1-hop-distance grows

A short Parenthesis on Clustering

Clustering (grouping) to ***decrease resource consumption***

- Split the network in ***clusters (groups)***, each of them including an "analogous" number of nodes
- ***Clusterheads*** are the ***natural backbone*** also in order to perform routing
- ***Optimal clustering is an NP-complete problem***
- Very relevant: anyway mobility tends to ***degrade the optimality of the determined clustering***

Specific usefulness for sensor networks: to combine "cluster-level readings" into a single data packet (*data aggregation*)

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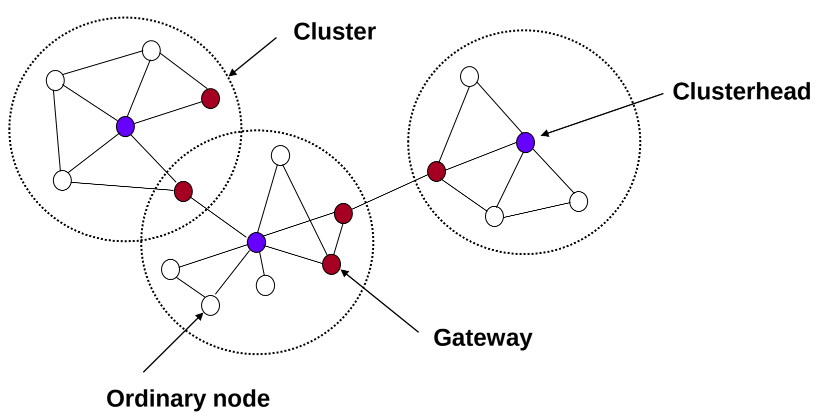
Clustering as a Routing Backbone



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Very shortly: Clustering Examples

LEACH

- ***Local decision*** if a node should serve as clusterhead or not (random number choice and completely local election)
- Any non-clusterhead node performs overhearing and ***selects the closest clusterhead***
- The clusterhead role ***is periodically re-assigned (node rotation)*** to balance energy consumption
- ***Communication is first to clusterhead, then to cluster members***
- ***No guarantee of optimality in clustering determination***

HEED

- ***Residual energy*** to consider in the clusterhead election
- Clusterheads are elected after an iterative protocol:
  - A node announces its ***intention and cost*** as a clusterhead
  - Any non-clusterhead node selects its candidate with minor cost by following a probabilistic metric, possibly choosing itself

Weighted Clustering Algorithm (WCA)
(Chatterjee et al., 2002)

- A clusterhead can ***ideally support n nodes***
  - Ensures efficient MAC functioning
  - Minimizes delay and maximizes throughput
- A clusterhead uses ***more battery power***
  - Does extra work due to packet forwarding
  - Communicates with more nodes
- A clusterhead should be ***less mobile***
  - Helps to maintain same configuration
  - Avoids frequent WCA invocation
- A ***better power usage with physically closer nodes***
  - More power for distant nodes due to signal attenuation

Is Wi-Fi Direct a MANET technology?

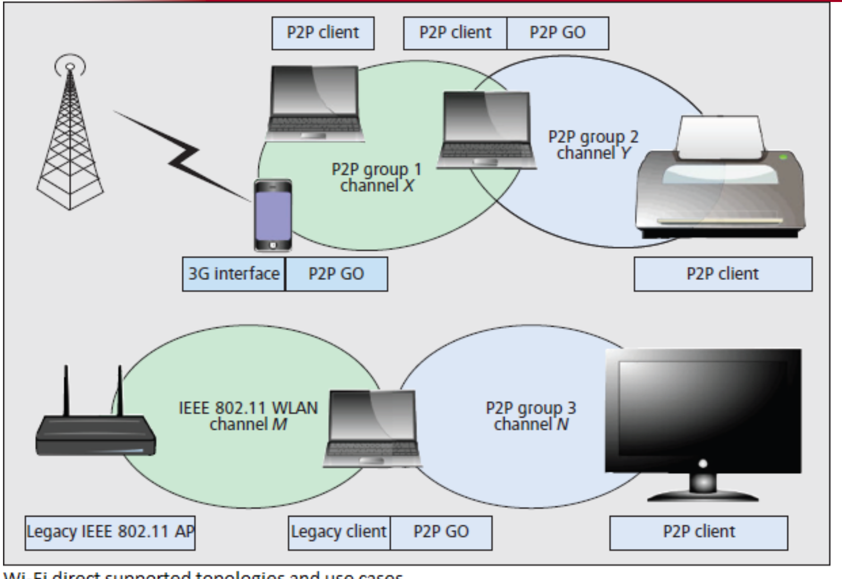
Given our current understanding of MANET, let us go back to Wi-Fi Direct…

- In a typical Wi-Fi network, client scans and associate to wireless networks available, which are created and announced by Access Points (AP)
- ***Wi-Fi Direct allows specifying these roles as dynamic***, and hence a Wi-Fi Direct device has to implement both the role of a client and the role of an AP
- These roles are therefore ***logical roles that could even be executed simultaneously by the same device***, this type of operation is called ***Concurrent mode***

Wi-Fi Direct Architecture

- Wi-Fi Direct devices communicate by ***establishing a P2P group***
- The ***device implementing AP-like functionality*** in P2P group is referred to as the ***P2P Group Owner (P2P GO)***, and device acting as client are known as P2P clients
- Once P2P group is established, other P2P clients can join the group as in a traditional Wi-Fi network
- When the device acts as ***both as P2P client and as P2P GO, the device will typically alternate between the two roles by time-sharing the Wi-Fi interface***
- Like a traditional AP, a P2P GO announces itself through beacons, and has to support power saving for its associated clients

Wi-Fi Direct Architecture



Wi-Fi direct supported topologies and use cases.

Wi-Fi Direct Architecture

- Only ***the P2P GO is allowed to cross-connect*** the devices in its P2P group to ***an external network*** (e.g., mobile in the previous figure)
- ***This connection must be done at network layer***, typically implemented using Network Address Translation (NAT)
- ***Wi-Fi direct does not allow transferring the role of P2P GO within the group***
- If P2P GO leaves the P2P group then the group is broken down and has to re-established

Parallel and comparison with Bluetooth scatternets?

Wi-Fi Direct Group Formation

Three types of group formation techniques: ***Standard, Autonomous, and Persistent cases***

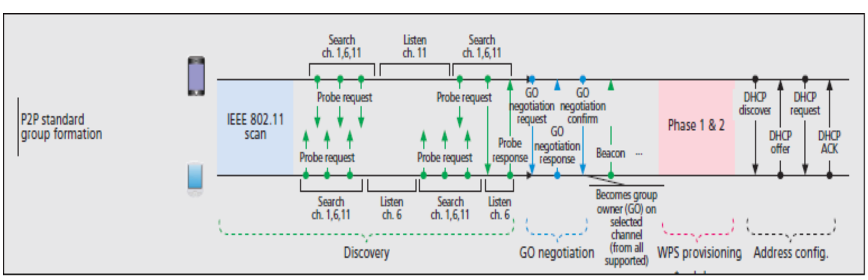
Group Formation procedure involves two phases:

- Determination of P2P GO
  - ***Negotiated*** - Two P2P devices negotiate for P2P GO based on desires and capabilities
  - ***Selected*** - P2P GO role established at formation or at an application level
- Provisioning of P2P Group
  - Establishment of ***P2P group session*** using appropriate credentials
  - Using Wi-Fi simple configuration to exchange credentials

Wi-Fi Direct Group Formation

Standard: P2P devices have to discover each other, and then negotiate which device will act as P2P GO

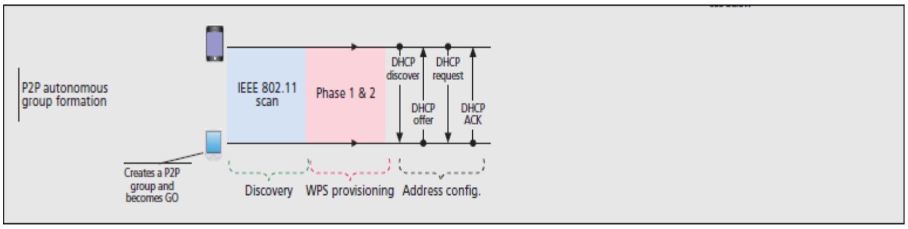
- Its starts by performing a traditional Wi-Fi scan, by means of which they can discover existing groups and Wi-Fi networks



- To prevent conflicts when two devices declare the same GO Intent, a tie-breaker bit is included in the GO Negotiation Request, which is randomly set every time a GO Negotiation Request is sent

Wi-Fi Direct Group Formation

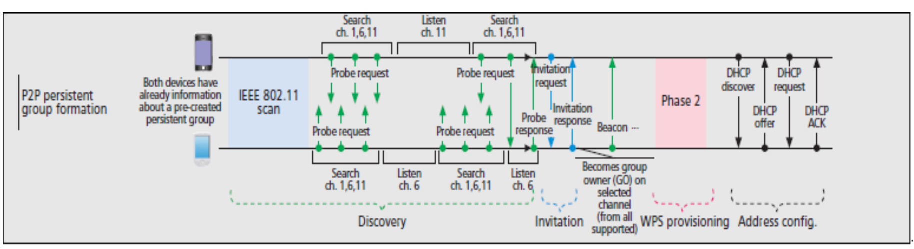
Autonomous: a P2P device may autonomously create a P2P group, where it immediately becomes the P2P GO, by sitting on a channel and starting a beacon



- ***Other devices can discover the established group*** using traditional scanning mechanisms
- As compared to previous case, ***discovery phase is simplified*** in this case as the device establishing the group does not alternate between states, and indeed no GO negotiation phase is required

Wi-Fi Direct Group Formation

Persistent: a P2P device can declare a group as persistent, by using flag in the P2P capabilities attribute present in beacon frames



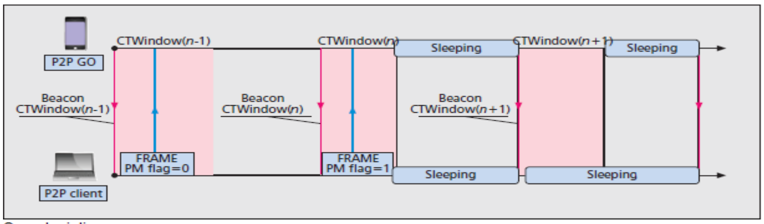
After the discovery phase, if a P2P device recognizes to have formed a persistent group with the corresponding peer in the past

any of the two P2P devices can use the ***Invitation Procedure to quickly re-instantiate the group***

Wi-Fi Direct Power Saving

Wi-Fi Direct defines ***two new power saving mechanisms***: the Opportunistic Power Save protocol and the Notice of Absence (NoA) protocol

Opportunistic Power Save protocol (OPS) allows a P2P GO to save power when all its associated clients are sleeping

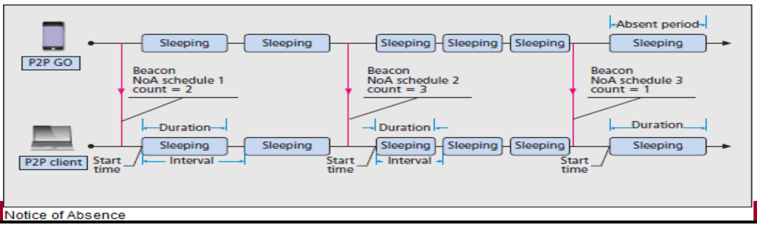


Opportunistic power save

Wi-Fi Direct Power Saving

Notice of absence protocol (NoA) allows a P2P GO to announce time intervals, referred to as ***absence periods***, where P2P Clients are not allowed to access the channel

- P2P GO defines a NoA schedule using four parameters:
  - Duration that specifies the length of each absence period
  - Interval specifying time between consec absence periods
  - Time that specifies the start time of the first absence period after the current Beacon frame
  - Count that specifies how many absence periods will be scheduled during the current NoA schedule



Notice of Absence

Wi-Fi Direct Security

- Wi-Fi Direct devices are required to implement ***Wi-Fi Protected Setup (WPS)*** to support a secure connection with ***minimal user intervention***
- WPS allows establishing a ***secure connection by introducing a PIN*** in the P2P Client, or ***pushing a button in the two P2P devices***
- Following WPS terminology, P2P GO is required to implement an internal Registrar, and the P2P Client is required to implement an Enrollee
- WPS operations consist of two parts
  - In the first part, the internal Registrar is in charge of generating and issuing the network credentials, i.e., security keys, to the Enrollee
  - In the second part, the Enrollee (P2P Client) disassociates and reconnects using its new authentication credentials

Wi-Fi Direct: some Refs to Additional Material

Optional additional readings:

- IEEE 802.11-2013 Standard, Device-To-Device communication with Wi-Fi direct: Overview and experimentation, 2007
- Wi-Fi Alliance, P2P Technical Group, Wi-Fi Peer-to-Peer (P2P) Technical Specification v1.0, December 2009
- Wi-Fi Alliance, Wi-Fi Protected Setup Specification v1.0h, Dec. 2006
- IEEE 802.11z-2010 - Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 7: Extensions to Direct-Link Setup (DLS)

Other more Innovative Routing/Clustering Modes?

Under some ***simplifying assumptions***, which can significantly facilitate how to solve the problem

Again ***cross-layer*** or ***possible static assumptions*** about given and determined deployment environments

For example, ***content sharing*** scenarios in sport events with very large pubic of attendants (Olympic stadium in Turin 2006) and widespread distribution of pictures/videos recorded by spectators

- to provide an ***entertainment service***, e.g., small multimedia contents, dynamically discovered, to a ***large public*** of users ***concentrated in space and in time***
- to maintain ***content availability*** notwithstanding ingress/exit of spectators from the targeted physical locality

Dense MANET Assumption and Interaction with Application Layer

- Assumptions
  - ***Dense MANET***
    - ***Large number of devices co-located*** in a physical area that is relatively small
    - ***Node density*** that is almost ***invariant*** over relatively long time intervals
  - ***Replication and read-only replicas***

- Non-functional requirements
  - Low ***overhead*** → Lightweight and approximated protocols
  - High ***scalability*** → Complete decentralization
  - Sufficient ***accuracy*** → Protocol ending based on heuristics

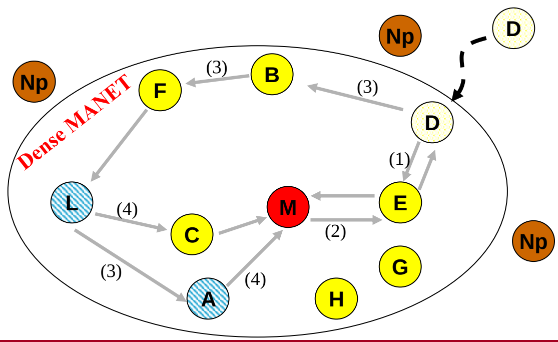
Replication in Dense MANETs (REDMAN)

Basic idea: to ***disseminate replicas*** of resources of common interest and to ***maintain the desired replication degree*** independently from node mobility (unpredictable) in/out the targeted dense area

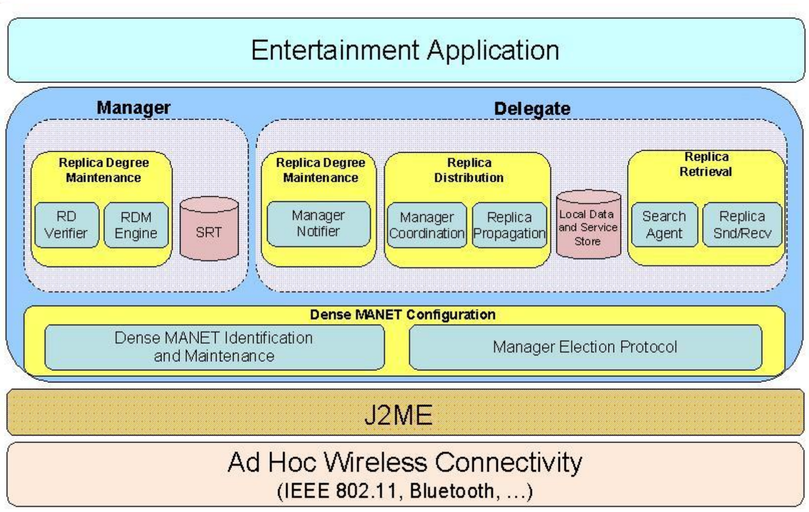
- ***Delegates host replicas***, reply to retrieval requests, participate to dissemination
- ***Managers***: responsible for maintaining the proper and desired replication degree

Shared Resource Table

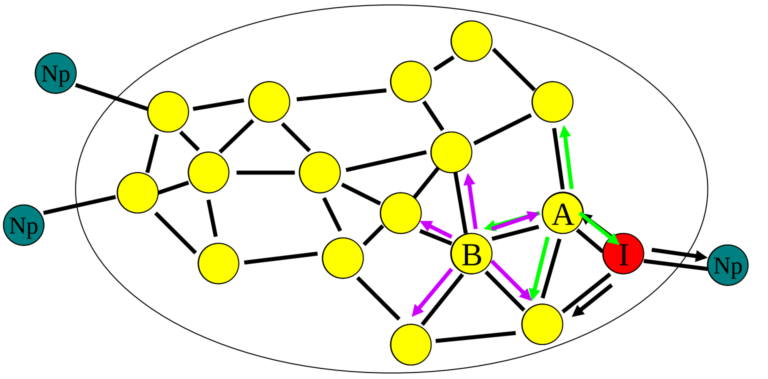
Resource Name	Replication Degree	Probable Replica Placement
Alberto Tomba's Picture1	3	D, L, A



Middleware Approach: Application-layer Management

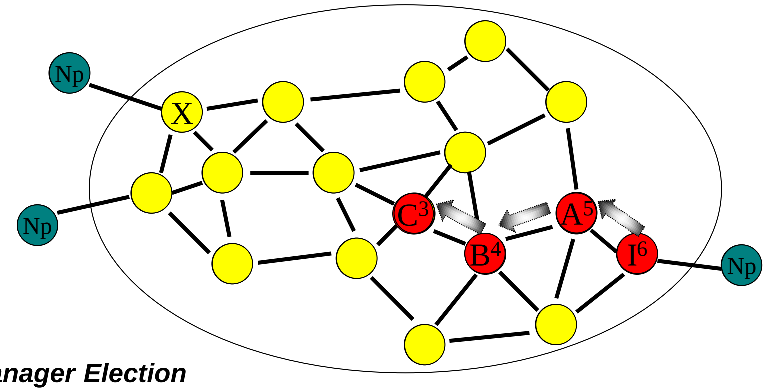


Issue: Identifying a Dense MANET



- Dense MANET if and only if #*Neighbors > Threshold*
- ***Decentralized and lightweight protocol*** in which any node ***autonomously decides*** its own belonging condition
- ***Dynamicity***: lazy updates based on hello messages

Issue: Manager Election



Manager Election

- Role is assigned to a node that is ***topologically central***
- Lightweight solution, ***no optimal placement*** (priority is avoiding exhaustive search)
- Exploration strategy based on heuristics

Dynamicity

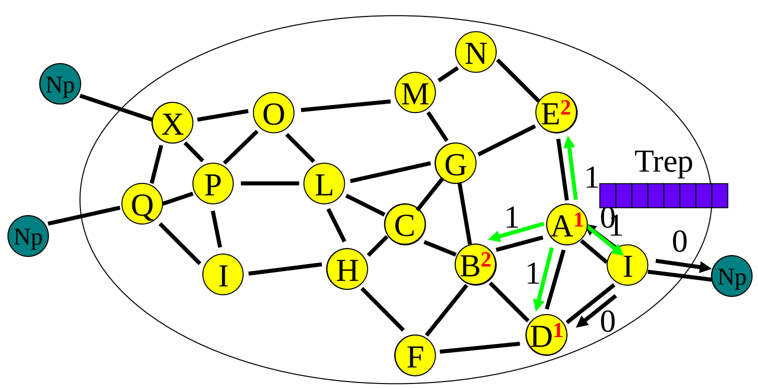
- Reactive response: new determination of farthest nodes every *Tr*
- Proactive response: new election every *Tp* >> *Tr*

Ending the Election Process

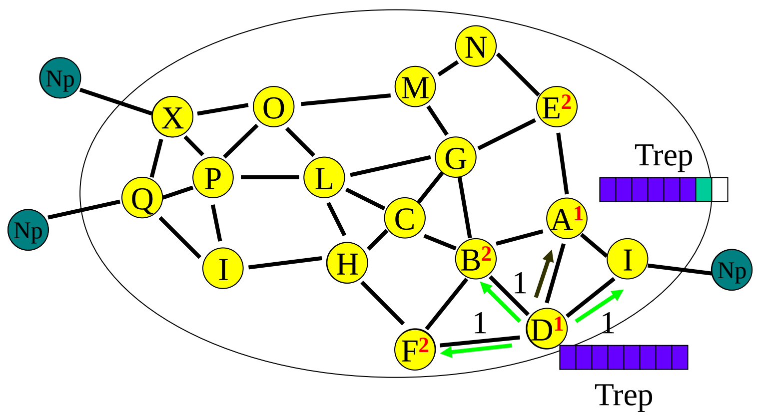
- ***Optimal solution is considered to be found iff***:
  1. *currentINvalue* = $\lceil$*worstExploredValue* / 2$\rceil$
- Alternatively, ***heuristics***:
  2. *currentINvalue ≤ worstExploredValue* * ***DesiredAccuracy***
  3. ***maxConsecutiveEqualSolutions*** have been explored without improving the current *bestValue*

Of course, ***DesiredAccuracy*** and ***maxConsecutiveEquals*** determine (approximatively) the quality of the solution achieved (quantitatve indicator)

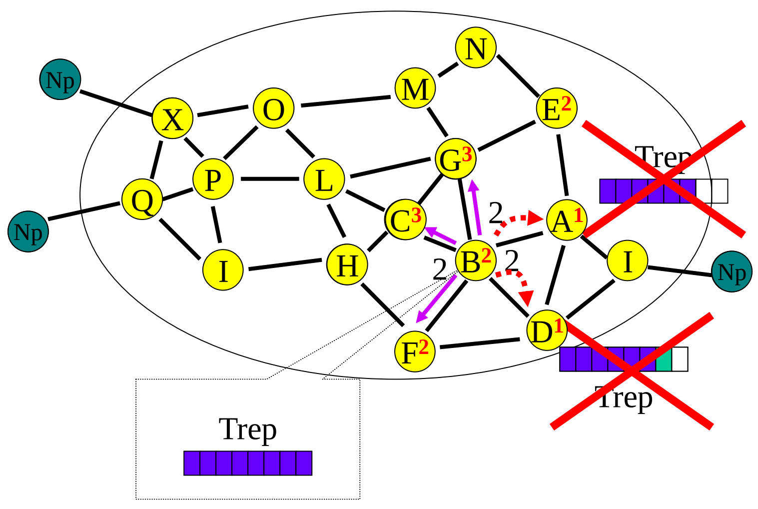
Identifying the Farthest Nodes



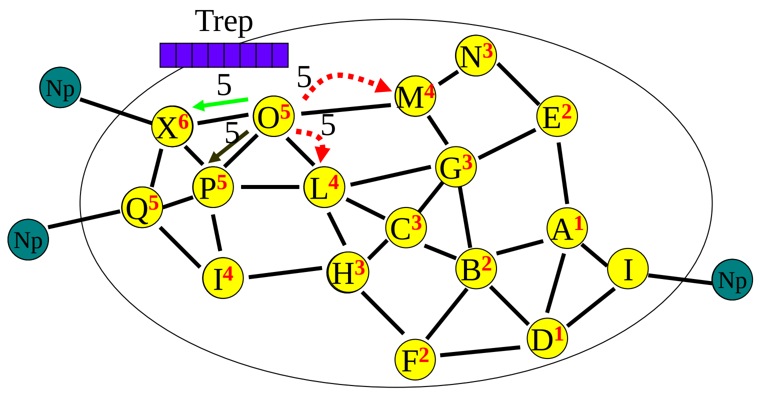
Identifying the Farthest Nodes



Identifying the Farthest Nodes



Identifying the Farthest Nodes



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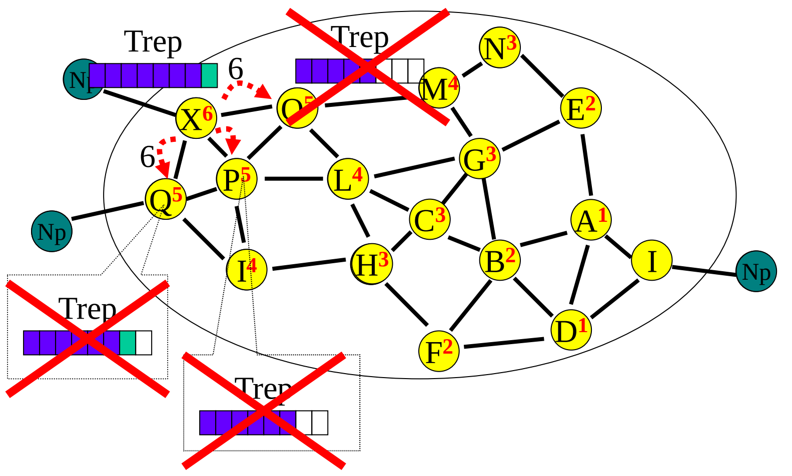
Identifying the Farthest Nodes



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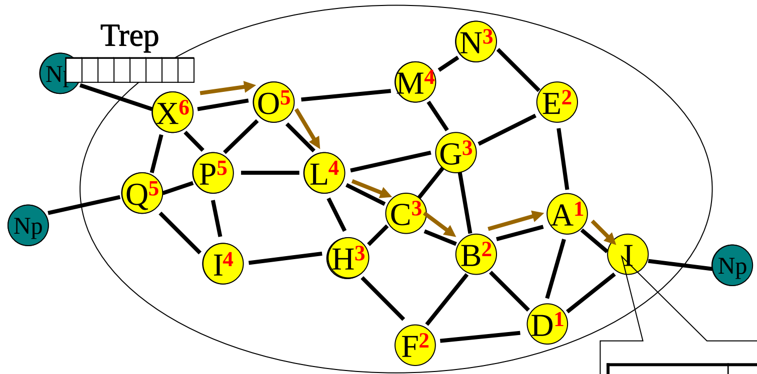
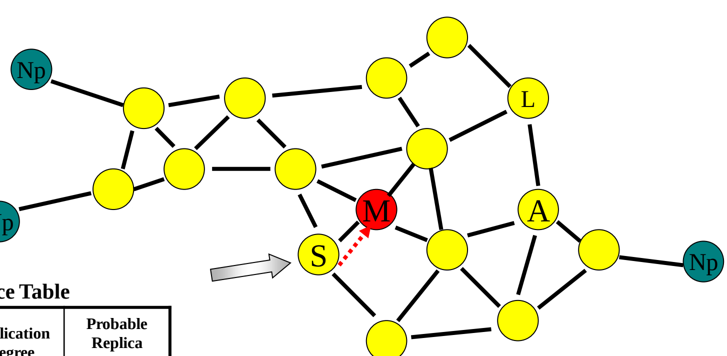
Identifying the Farthest Nodes



Farthest Node	Forwarder
X	A

Degree of Replication: Approximated Consistency

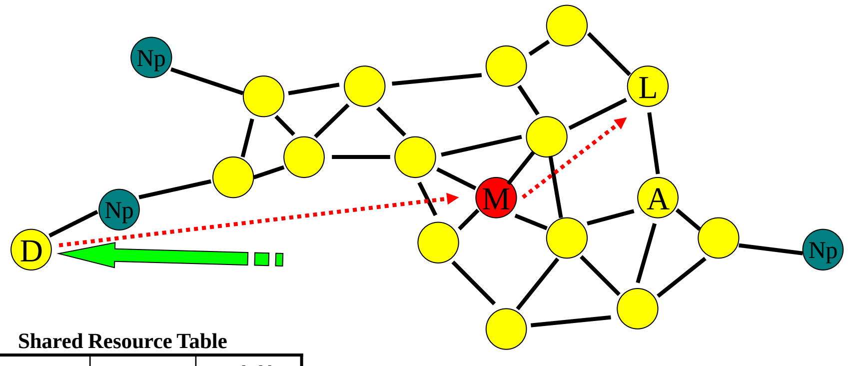
It relaxes the constraint of ***anytime perfect consistency*** for the number of available replicas



Shared Resource Table

Resource Name	Replication Degree	Probable Replica Placement
AlbertoTomba Picture1	3	L, A, S

Degree of Replication: Approximated Consistency



Shared Resource Table

Resource Name	Replication Degree	Probable Replica Placement
AlbertoTomba Picture1	3	~~D~~, L, A

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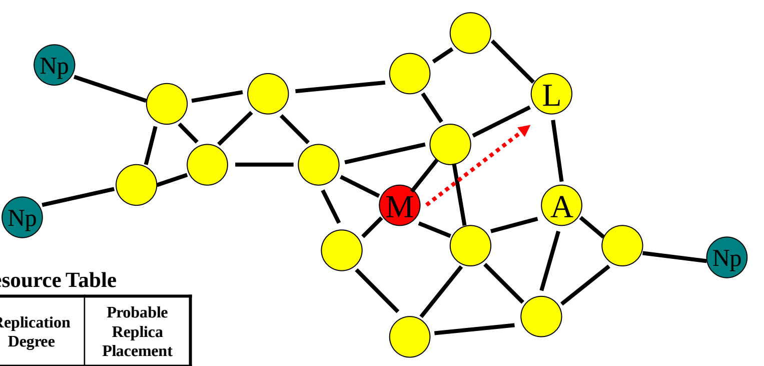
Degree of Replication: Approximated Consistency



Shared Resource Table

Resource Name	Replication Degree	Probable Replica Placement
AlbertoTomba Pic1	3	~~D~~, L, A

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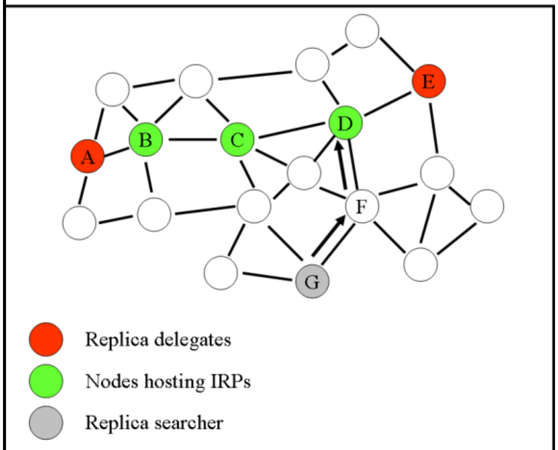
Strategies for Replica Dissemination

Different possible strategies:

- ***Random*** distribution
- ***Spatially uniform*** distribution
- …



REDMAN: distribution along ***"straight lines"*** (approxim.)

- No positioning equipment
- Straight lines: neighbors with the ***lowest number of neighbors shared*** with the previous nodes

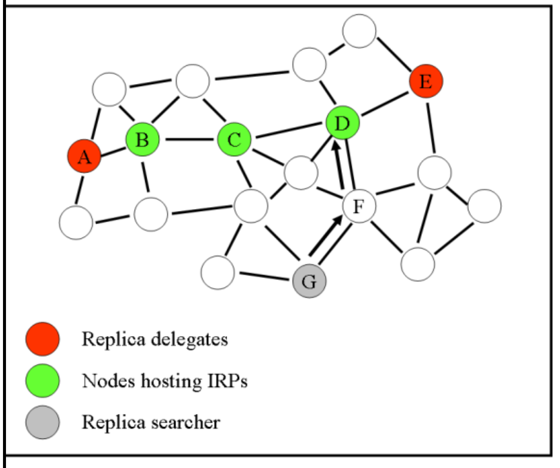
Strategies for Replica Retrieval

Different possible strategies for ***replica retrieval***:

- ***Query*** flooding (QF)
- Flooding of ***Information about Replica Placement*** (IRP)
- ***k-hop Distance IRP Dissemination (k-DID)***

REDMAN exploits ***Straight IRP Dissemination (SID)***

Strategies for Replica Retrieval



IRP are distributed along the ***same approxim. straight lines*** used for replica dissemination

Retrieval along straight lines (***non parallel*** to the lines used for dissemination)

Duality between replica distribution and retrieval