Dipartimento di
Elettronica e Informazione

Politecnico
di Milano

Multi-Hop Wireless Networks: Fundamentals and Protocols

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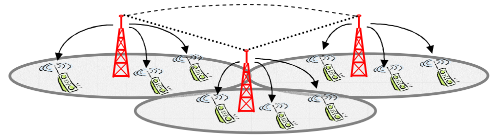
Summary

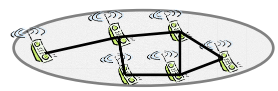
- Wireless Networks: classification
  - On a transmission technology basis, or "technology generation" (analog TACS, digital GSM, GPRS, EDGE, UMTS, and more)
  - On a organizational basis: networks with base-stations, infrastructure-less (ad-hoc)
  - On a coverage basis (IEEE802.16 Metropolitan Access Networks, IEEE802.11 Local Area Networks, Personal Area Networks)

Main Topic: Ad-hoc

- Infrastructured network:
  - Wired *cum* wireless



- Ad-hoc, infrastructure-less network:



- Focus on Infrastructure-less networks
- Purposes:
  - simple resource-sharing
  - networking in emergencies
  - intervehicular networking
  - sensor networking

- Ad-hoc Routing Performance Evaluation: criteria, scenarios

Wireless Scenarios: Issues

- Wireless networks lead to new network design problems respect to wired

- Trasmission errors are very likely to occur (in comparison, error probability in wired networks is lower by many orders of magnitude)
  - Large distances between nodes play fundamental role, so
  - Modern receivers used can handle radio signals with power covering a span of many orders of magnitude

- The medium is intrinsically broadcast; even high-technology receivers don't allow carrier sense while transmitting
  - Collision Avoidance is not simply feasible for safe radio access due to possible saturation in acquisition stage
  - Communication can be worsened by interfering agents

- Difficult to isolate malicious users

- Node mobility can lead to link disconnections

Wireless Communications: Propagation

- When a node S transmits a radio wave with power P_{tx}, energy conservation imposes a maximum reception power level inversely proportional to the square of the distance from S
  - Theoretical maximum limit valid only in free-space, but…
  - Interesting framework for more general scenarios

Fading

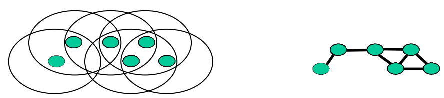
- One of the most important family of propagation models for wireless communication is the Pathloss Model family
- The received power is assumed to be proportional to:
  - The transmitted power
  - Transmitter/receiver distance *d*, raised to ρ

$$P_{rx} = A\frac{P_{tx}}{d^{\rho}} \qquad \rho \geq 2\,(typ.4)$$

- The presence of absorbing surfaces reduces power

Isotropic Propagation?

- For wireless communication protocol evaluation, it is important to determine figures of merit of channel *quality*, affected also by propagation
- The CTR (Critical Transmission Range) is used as a means of evaluating the reachability of a mobile node
- According to the previous model, CTR is independent on direction. The reach of a node is a circle:



Shadowing

- *Experimental measures don't agree with this models!*
- We have not considered the phenomenon of multiple receptions / random *fading*
- Result:

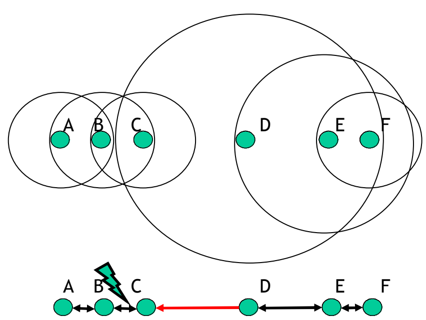
$$\left[\frac{p_r(d)}{p_t}\right]_{dB} = -10\log_{10}\frac{d}{d_0} + X$$

where X is a gaussian random variable
(X's variance is a parameter of the model)

Capture Effect

- Problems arise when multiple users are present, eventually with different power levels:
  - Different users share the same radio channel: the interference level requires accurate modeling
  - If users in the same channel use different transmission powers, one may “capture” the other with no possible notification

Capture Effect: An Example

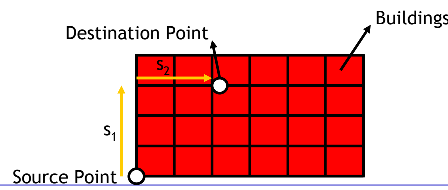


- In this example, node C is captured by node D, so link BC can fail
- The system suffers poor fairness
- One node should notify the problem to D (which one?)

Propagation: Alternative Models

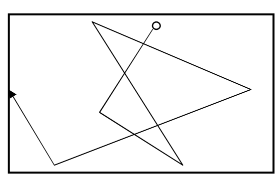
- Different propagation models have been developed for free-space as well as more realistic environments
- Many models have counterpart in mobility models
- Manhattan Model (as in UMTS specifications):
  - Grid of roads
  - Obstacles bteween parallel roads
  - Pathloss: $L = 20\log_{10}(4\pi d_n / \lambda) \qquad k_n = k_{n-1} + d_{n-1}c \qquad d_n = k_n s_{n-1} + d_{n-1}$

    $s_n : length\ of\ straigth\ propagation\ subpath\ 'n'$



Other Mobility Models

- The most widely used mobility model to compare ad-hoc protocol performance is Random Waypoint Model (RWM)



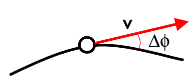
- RWM implies alternating time periods (t_P) in which a node is still with others in which it moves towards a point uniformly chosen in simulation field (uniform straight motion)
  - t_P is tipically kept constant
  - In every "epoch", v_{node} is chosen uniformly between v_{min} and v_{max}

Other Mobility Models (2)

- With RWM, the spatial distribution of nodes has an asymptotic peak in the center of the simulation field, even if nodes are chosen uniformly at their birth
- In RWM, the average speed of nodes tends to *zero* when v_{min}=0; in general, the asymptotic value is less than $(v_{min}+v_{max})/2$
- RWM does not reproduce in a realistic way node mobility in many intersting scenarios; for example, vehicular traffic with continous speed variation

Other Mobility Models (3)

- Alternative mobility model: Modified Brownian Motion [Haas]
  - v_{node} uniformly distributed between 0 and v_{max}
  - direction of motion: any (angle ϕ)
  - every time interval Δt , node speed has a variation Δv, uniformly distributed between $-\alpha\,\Delta t$ and $\alpha\,\Delta t$; the direction varies between $-\Delta\phi$ and $\Delta\phi$
- Improvement: $\Delta\phi$ can be assumed to be inversely proportional to v_{node}



Infrastructure-less Approach

- Ad-Hoc networking: the network topology is built step-by-step by peer nodes
- No base stations available for
  - Synchronization (levels 1-2)
  - Radio access grant distribution (level 2)
  - Connection routing (level 3)
  - Connection maintenance (levels 3-4)
  - Key distribution (applicative levels)
  - Service availability information, DNS information distribution (appl. levels)
  - Power adjusting
- Cross-layering required for optimizing performance!

Existing "Ad-Hoc" Technologies

- Network initialization and self-configuration (maintenance) must be implemented
- Technologies:
  - Bluetooth (IEEE802.15)
    1) Personal Area Networks
  - IEEE802.11 -> different services
    1) Wideband communication (even for fixed-rooftop networks)
    2) Network can scale to many users

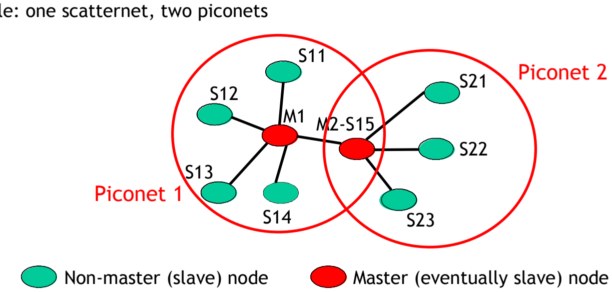
Bluetooth

- Radio interface with one-chip (low-cost) design
- Originally designed to be a "cable-replacement" technology
  - Low scalability design (not many nodes in the elementary cell)
  - Small radio-range
- Piconet-organization
  - Non-peer system: Master-Slave principle
  - Master is *the* provider of synchronization, bandwidth allocation, flow control in the piconet
  - A master handles inter-piconet communications

Bluetooth: Master-Slave Principle

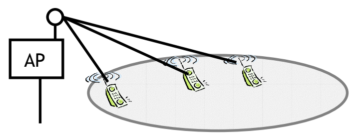
- Piconet-scatternet organization
- A piconet can be composed (at maximum) of 1 master+7 slave nodes
- A slave node in a piconet can be master of another

Example: one scatternet, two piconets

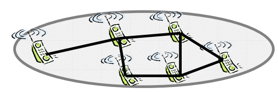


Fully Distributed Ad-Hoc: IEEE802.11

- The standard IEEE802.11 deals with Wireless Local Area Networks
- Two running modes for IEEE802.11 nodes:
  - Infrastructured
    - intra-network and inter-network communications are handled by a fixed access point (AP)

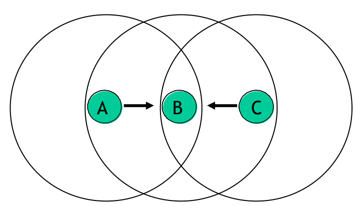


  - *Ad-hoc* mode: peer-to-peer communications between nodes are possible



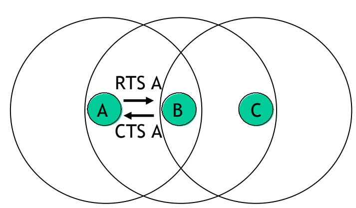
IEEE802.11 Ad-Hoc Mode and the "Hidden Terminal" Problem

- If nodes A and C (using the same channel) have to send data to node B, collision can occur
- A node can start transmitting without information about an incoming collision



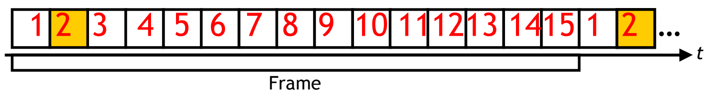
Collision: B cannot receive clear signal

- IEEE802.11 solves the problem with Request To Send/Clear To Send mechanism
- Before transmitting data, a node must ask and obtain permission



Access: TDMA Scheme

- The MAC protocol can allow radio channel sharing between nodes
- One possible way: time-sharing (Time Division Multiple Access)
- Time axis is subdivided into *frames*, and each frame into *K slots*



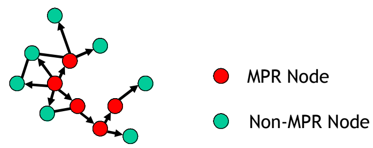
- Each station, before transmitting:
  - Listens to an entire frame
  - Eventually makes a “booking” of an empty slot *j (j<K)*
  - If no collision is reported by other nodes, acquires *j*

Routing Protocols for Ad Hoc Networks

- Traditional routing protocols (i.e. OSPF) are not practical in mobile, variable topology networks
  - Large bandwdth would be used to obtain rapidly-changing (expired…) information
  - Frequent looping
- Possible metrics:
  - Route(s) stability
  - Minimum bandwidth/energy consumption in an almost-fixed scenario
- Two families of *topological* (table-driven) routing:
  - Proactive
  - Reactive (*on-demand*)

Example of Proactive Scheme: OLSR

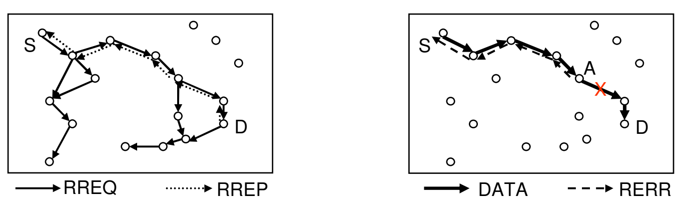
- Proactive protocol: every node tries to collect overall topology information
- Link State Approach is used in Optimized Link State Routing – OLSR (IETF RFC3626 - proposed standard)
- Some nodes are designed as MultiPoint Relays (MPR):



- Strengths:
  - Only MPRs are allowed to retransmit packets
  - Link state information is generated only by MPRs
  - A node advertises only the links between itself and neighbor MPRs

Example of Reactive Scheme: AODV

- Reactive protocol: routes are created/maintained only on demand, i.e. as needed
- One of the most widely known reactive protocol is the Ad hoc On-demand Distance Vector (AODV - proposed standard IETF RFC3561)
- Many implementations and extensions (Secure AODV, Multipath AODV etc.) have been developed
- AODV scheme:



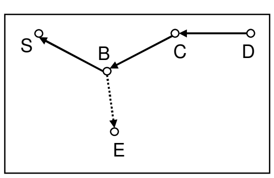
AODV Improvements

- ❑ AODV, as described in RFC3561, is considered a general-purpose protocol
  - The *broadcast* nature of radio medium is not considered
  - The direct integration with other *wired*-network protocols is considered mandatory

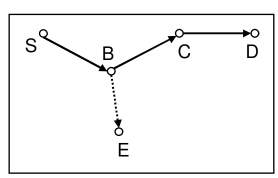
- ❑ Consequence: standard AODV is not optimized gor wireless
  - Complete IP packet parsing is not made but by the only IP destination node
  - The overhead caused by the hard-layered structure of wired protocols is high (e.g. UDP ports are always specified…)

Use of Overhearing in AODV

- ❑ Routing tables are kept up-to-date if every node analyzes each received packet (*overhearing*):
  - No additional bandwidth
  - Without *misbehaving nodes*, important information is collected (hypothesis: bidirectional links)



RREP forwarding:
A path E→B→D exists



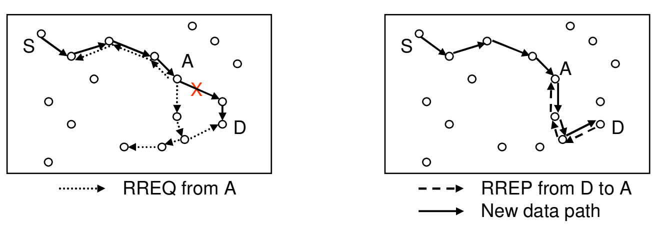
data forwarding:
A path E→B→S exists

AODV Improvement: Real-Time Traffic

- Standard voice traffic transport requires some modifications to be applied to standard AODV:
  - Flooding should be limited during RREQ
  - The scarce radio resources should be kept into account while configuring the protocol
    - Real MAC: a few low-bandwidth channels
  - Efficient *local repair* procedures should be implemented to face link/node failures

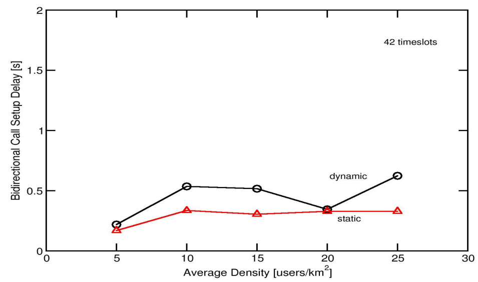
AODV Improvement: *Local Repair*

- If an intermediate link fails during data transmission, the preceding node tries a *path local repair* before sending a RERR



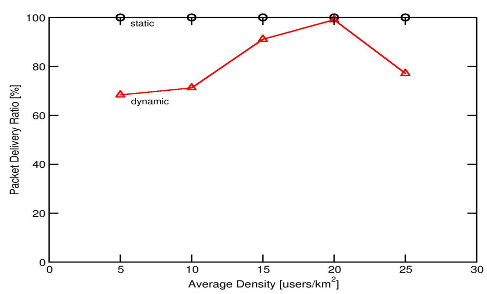
- This approach has advantages if the link is near the destination
  - Not too high values of Time To Live (TTL) are used
  - Timeout expiration produces a RERR

Call Setup Delay



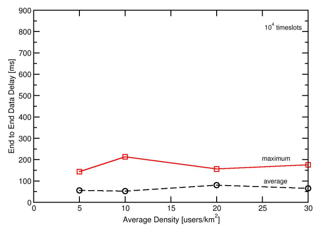
- ❑ Call Setup time is less than one second
  - Good performance even in case of a timeout expiration (dynamic case – high disconnection frequency)
  - Analysis performed with a ratio edge/radius=6 (maximum path length is 9 hops)

Fraction of Delivered Packets

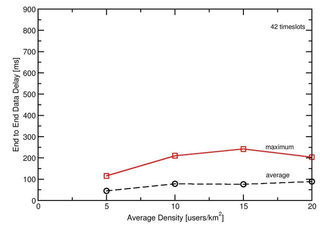


- ❑ In static case, the protocol converges; no packet loss
- ❑ With mobile nodes, the Packet Delivery Ratio is lower:
  - At **low densities** the connectivity degree of the network is reduced
  - At **high densities** some nodes lose their radio channel due to collisions

Voice Packets End-to-End Delay



Ideal MAC



Real MAC

- Integration real MAC-Routing AODV:
  - Intermediate nodes lose the access to the radio channel; the re-routing is required
  - With at least some tens of timeslots, the end-to-end delays of voice packets are kept below 250 milliseconds
- The maximum delay is less than 100ms if only short paths are accepted (maximum 3 hops)

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GPSR: Geographical Routing in Ad-Hoc Networks

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Routing for Mobile Ad-Hoc Networks
Some Issues

- Ad-Hoc Networks: no pre-existent network infrastructure
- Node mobility provoking rapidly changing topology
  - High control overhead required to keep the connectivity among nodes
- Real-time traffic in multihop wireless networks
  - Stringent requirements in terms of delay/jitter
  - Limited bandwidth available
  - Control overhead should be low
- Necessary to study interactions among protocols at different levels of the ISO-OSI stack

Geographical routing

- A way of reducing control overhead:
  - Avoid flooding as much as possible
  - All nodes may not be aware of overall topology if not useful
- If each mobile node is equipped with a running GPS system, it knows/can make its neighbors know its current position
- Geographic routing protocols use this feature
- Control traffic for topology discovery is greatly reduced, but…
- Geographic routing protocols require dissemination of additional information about node positions
- Information must be supplied more frequently when nodes move faster

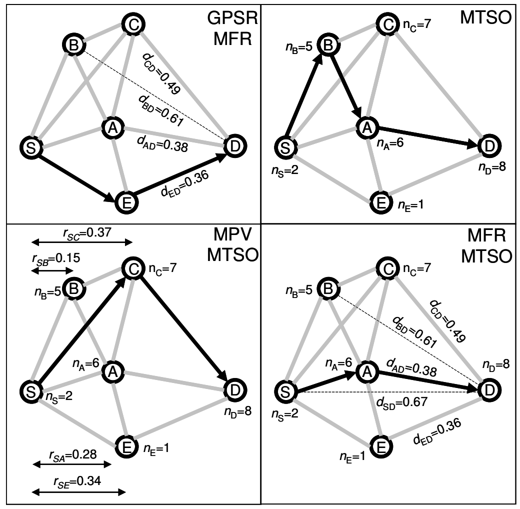
Basic GPSR Functionality

- Whenever possible, packets are routed in Greedy mode
- *Greedy* means simply that next hop is approaching destination
- The next hop is usually chosen as the neighbor that is nearest to the destination node (Most Forward within Radius, MFR)
  - This approach tends to minimize the number of hops, i.e. the number of potentially congested nodes
- Other approaches are possible
- When power consumption is an issue, NFP (Nearest with Forward Progress) approach can be used

Optimizing Greedy Mode in TDMA Context

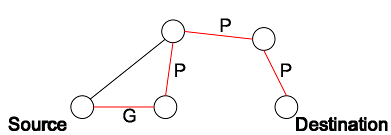
- If the access to channel is TDMA (i.e. each node has a time slot in which it can transmit control/data), different approaches (metrics) lead to better Greedy performance
- In every case, the same Perimeter Mode is used
- Three new metrics:
  - Minimum Time Slot Offset (MTSO)
  - Maximum Speed in Destination Direction approach (Maximum Projection Vector, MPV-MTSO)
  - Maximum absolute speed approach (MFR-MTSO)

Optimizing Greedy Mode in TDMA Context



Perimeter Mode

- ❑ Even in connected networks with still nodes, Greedy mode is not guaranteed to reach destination node
- ❑ Local minima in distance from destination are critical for GPSR-MFR
  - “Voids” due to dishomogeneity in node spatial distribution
- ❑ GPSR switches to *Perimeter Mode*, a topological approach for bypassing (turning around) a void



Location Service

- How can a source node be aware of the destination position?
- A location service must be available
- Simple solution, good for medium-density and hop-limited networks: one (fixed) location server in the geographical center of the topology
- Location server should be given more MAC resources than mobile nodes and (eventually) privileged power control management
- Issue: case of no connectivity between node and location server, partitioned network
- Solution: minimizing the probability of partitioning using:
  - network of LS's,
  - Other approaches (distributed location service made available by GLS protocol with suitable power control)

Location Server Functionality

- Providing information to LS: can be done (in small/medium size networks) via *Hello* packets
- LS position is well-known to all nodes
- At the beginning of a call, source node queries the LS with a *REQ* packet
- LS unicasts to the source a *RESP* packet with destination node location information
- In our approach, if no congestion is reported, the RESP is sent with Source Routing technique

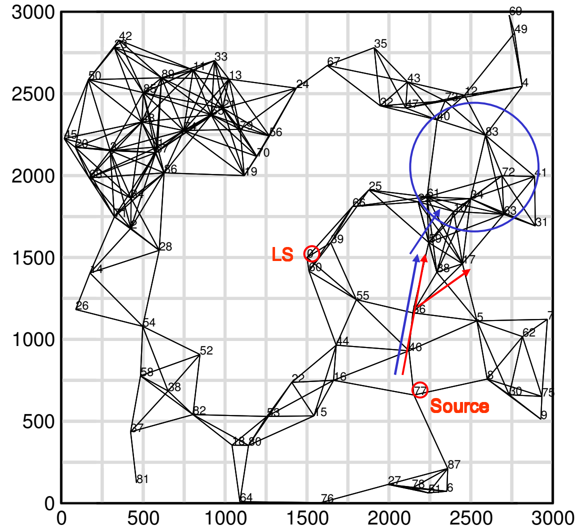
Mobility Handling with GPSR

- How can I obtain continously endpoints' positions in a (high) mobility context?
- Frequently, it is not practical to send multiple queries to Location Server
  - LS's neighbors: likely to be congested with control traffic
- A good solution is forcing *position piggybacking*
- No problem for bidirectional Voice Traffic: a minimum data rate is maintained for voice packets
- Unidirectional streaming (typical for multicasting): each destination node polls the source with ACKs containing their own position
  - If a timeout has elapsed without ACK from a destination, source can either query the LS or declare lost connectivity

GPSR Multicast Extensions

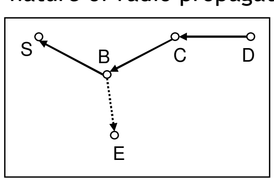
- In our scheme, Hello forwarding by each node is untouched
- The sender of a flow towards a Multicast Group queries the Location Server for the position of all the Destination Nodes (resilient, unclustered approach)
- Location Server replies with known information
- The sender chooses a next hop for each destination, and broadcasts one multicast packet
- Packet is retransmitted *only* by designated next hops (multicast splitting)
- Simple approach to be used when, e.g. each node has random mobility (Random Waypoint)
- Respect to Mauve's approach, we carry on a clustering estimation
  - Packet forwarding is done in two steps: reaching clusters and local flooding
  - Traffic can be largely reduced

GPSR Multicast Extensions



GPS Signal Unavailability

- Sometimes, nodes can be unaware of their position, e.g. for GPS failure (people in buildings, vehicles in tunnels etc.)
- Necessary to implement a non-GPSR recovery procedure to maintain connectivity
- The availability of a non-position-based protocol (e.g. AODV) can be useful
- How to guarantee a fast switching GPSR-AODV?
- In our approach, AODV routing tables are being maintained *even during GPSR operation*
- AODV tables are updated using *overhearing* too, exploiting broadcast nature of radio propagation



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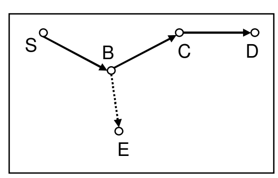

data forwarding:
A path E→B→S exists

Conclusions

- Geographical routing guarantees scalability even in high mobility, low radio bandwidth context
- Greedy mode can be configured in different ways, e.g. according to access protocol used
- Flexibility: fast-switching between geographical and topological protocols
- Multicast extensions are straightforward, it is possible to exploit clustering concept