http://www.kom.tu-darmstadt.de

Advanced Topics in Distributed Systems (Spring/Summer 2006)

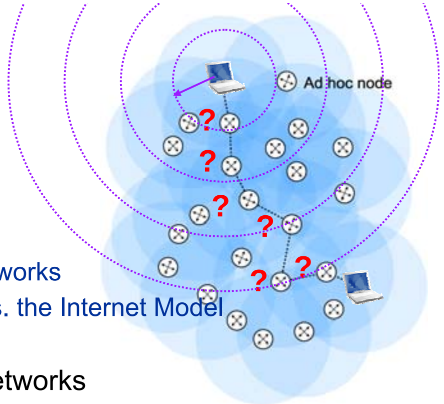
Mobile Ad hoc Networking

Dr.-Ing. Matthias Hollick, Prof. Dr.-Ing. Ralf Steinmetz

Technische Universität Darmstadt,
Fachbereich Elektrotechnik und Informationstechnik, Fachbereich Informatik (Zweitmitglied),
Fachgebiet Multimedia Kommunikation – KOM, Tel.+49 6151 166158, Fax. +49 6151 166152
Merckstr. 25, D-64283 Darmstadt, Matthias.Hollick@KOM.tu-darmstadt.de

http://www.kom.tu-darmstadt.de

Outline (1)



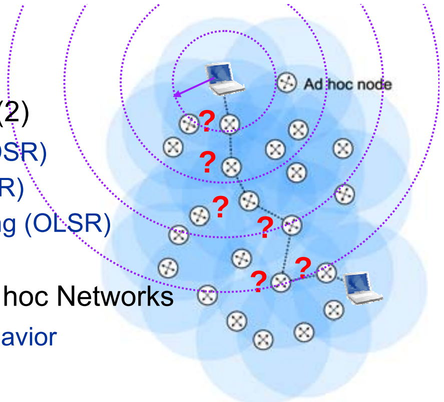
Introduction and Motivation
- Terminology and Basics
- Applications for Ad hoc Networks
- Ad hoc vs. Mesh vs. P2P vs. the Internet Model

Routing in Mobile Ad hoc Networks
- Characteristics of Ad hoc Networks
- Ad Hoc Routing Paradigms

Selected Routing Protocols (1)
- Ad Hoc On-demand Distance Vector Routing (AODV)

http://www.kom.tu-darmstadt.de

Outline (2)



Selected Routing Protocols (2)
- Dynamic Source Routing (DSR)
- Location Aided Routing (LAR)
- Optimized Link State Routing (OLSR)

Routing Dependability in Ad hoc Networks
- The Effects of Node Misbehavior
- Modelling Ad hoc Networks

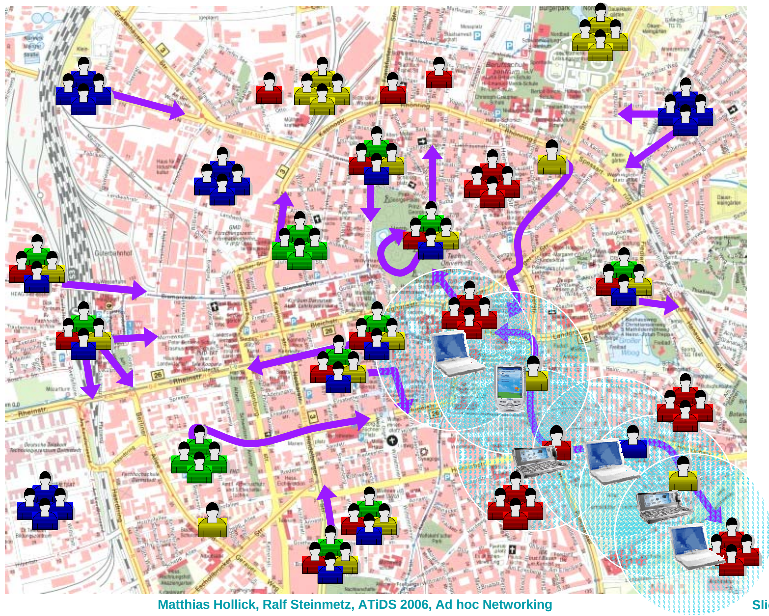
Performance Evaluation of Ad hoc Networks
- The Art of Performance Evaluation
- Analyzing Ad hoc Network Performance

Research Challenges, Summary and Conclusion

Appendix

http://www.kom.tu-darmstadt.de

Motivation for Mobile Ad hoc Networks



Terminology and Paradigms

"Ad hoc"

- often improvised or impromptu; *„an ad hoc committee meeting"*
  Wordnet
- formed or used for specific or immediate problems or needs;
  „ad hoc solutions"
- fashioned from whatever is immediately available: improvised;
  „large ad hoc parades and demonstrations"

Encyclopædia Britannica

"Spontaneous"

- arising from a momentary impulse
- controlled and directed internally; *„self-acting"*
- produced without being planted or without human labor;
  „indigenous"
- developing without apparent external influence, force, cause, or treatment

Encyclopædia Britannica

Basics

(Mobile) Ad Hoc Communication Networks - MANET

- Historical successor of packet radio networks
- Self-organizing, mobile and wireless nodes
- Absence of infrastructure, multi-hop routing necessary
- Systems are both, terminals (end-systems) and routers (nodes)
- Constraints (dynamics, energy, bandwidth, link asymmetry)

Applications

Military applications

- Battlefield communication (soldiers, tanks, planes, …)
- Smart dust (sensor networks to detect chemical, biological threats)

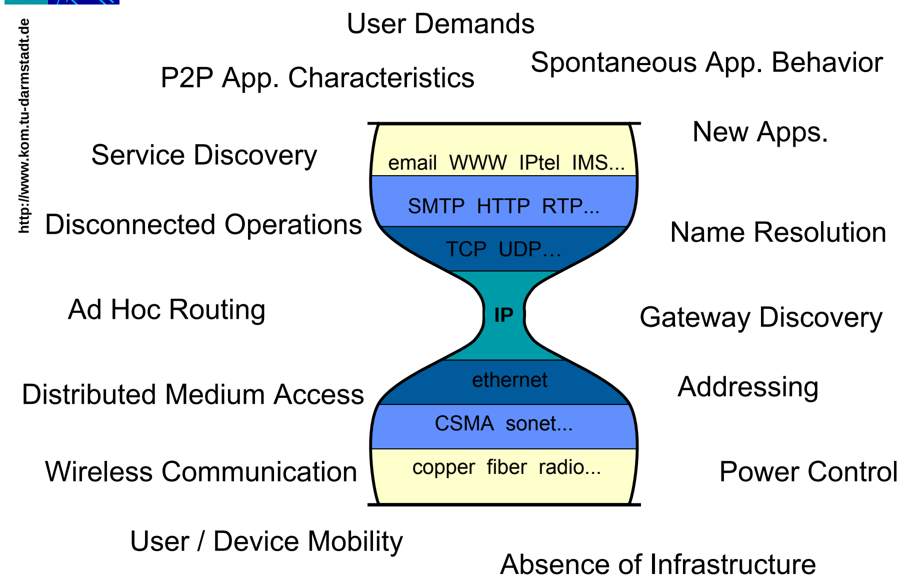
Civilian applications

- Vehicular environment (telematics, car to car communication, taxi cab network, …)
- Entertainment (filesharing, gaming, ... in train, car, plane, school, …)
- Event support (conferences, sport-events, exhibitions, meetings, lectures)
- Home networking / Personal Area Networking (VCR, DVD, home entertainment, remote control, cell phone, laptop, watch, …)
- Disaster recovery (emergency services, ambulance, police, …)
- Smart dust (sensor networks for civilian applications)
- Ubiquitous computers with short-range interactions (embedded systems, smart buildings/artefacts, …)
- Cellular range extension, moveable base stations (UMTS, WLAN, WMAN, …)

Applications (2)

(Source: Daimler Chrysler)

Ad Hoc vs. The Internet Model

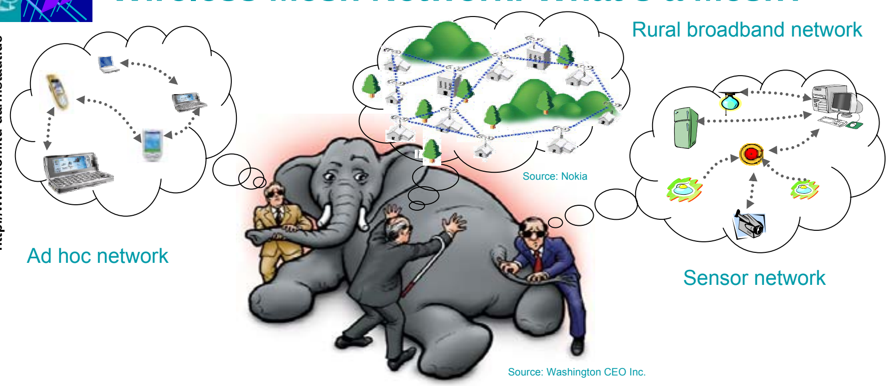


Peer to Peer vs. Ad Hoc

P2P
- Relevant resources located at nodes at the edges ("peers")
- Variable connectivity is the norm
  - e.g. does it support dial-up users with variable IP addresses
- Combined Client and Server functionality
  - for all end system nodes
  - also for intermediate nodes
- Peers with significant autonomy
  - e.g. storage / processing done by autonomous end-systems
- Direct data transfer between peers
  - e.g. more-or-less no central control
- Content locations widely distributed and most often replicated

Ad Hoc and P2P share paradigms
- Ad Hoc focuses on network level and below
- P2P focuses on application level
- Coexistence of Ad Hoc and P2P is possible / synergetic

Wireless Mesh Network: What's a Mesh?



Mesh characterized by:
- Multihop communication
- Self-forming, Self-healing, Self-organizing
- Weak mobility and power constraints

Features additional to "Ad hoc":
- Wireless infrastructure/backbone
- Enable easy integration of different radio technologies
- Additional capabilities ➡ more sophisticated algorithms

Multihop Ad hoc and Mesh Networks

Why?

Wireless Broadband Access/Networks?

Today

The day after tomorrow

What can you get for a €1 in early 2005

Processing

- One PC-day of CPU time

Storage

- 2 GB disk storage
  (> 30h MP3 in 128kbps,
  ~ 3 DivX movies)

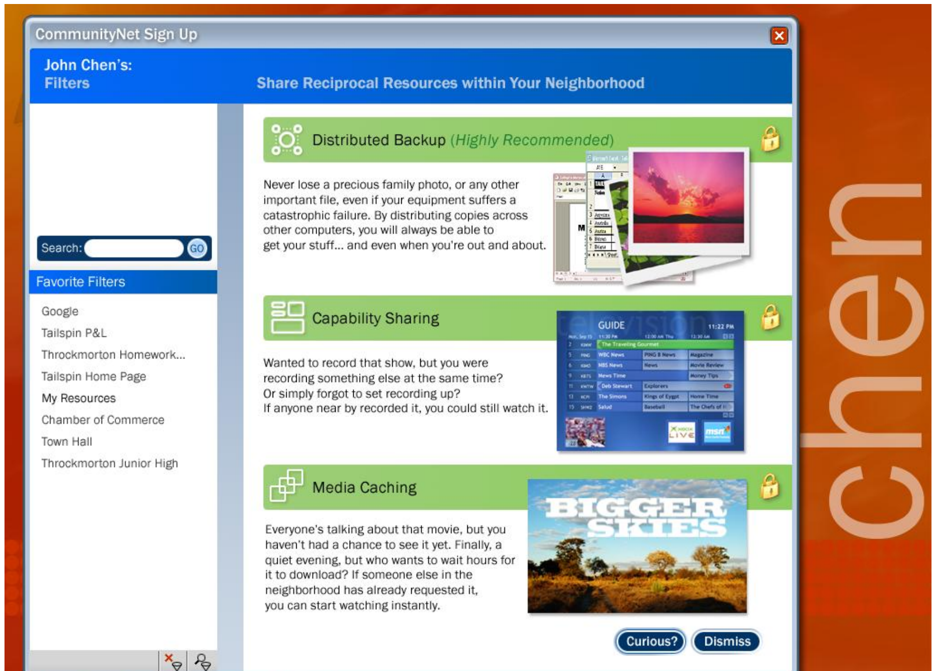
Interconnection

- 400 MB broadband data
  (6 hours of music)
- 20 MB ISDN voice telephony
  (45 minutes talk time)
- 0.8 KB SMS
  (5 messages)

Bits ≠ Value

- Wired
  - Broadband: 0.25¢ per MB
- Wireless
  - GPRS: > €1 per MB
  - SMS: €1250 per MB

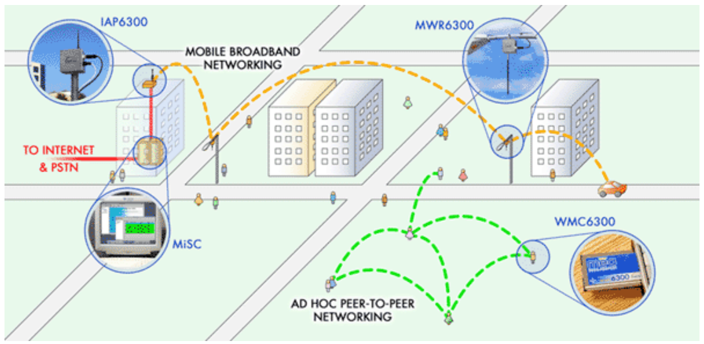
It's the Bandwidth/Spectrum that's expensive
(also missing competition for some services)



(Source: MS-Research)

Vendor Application Demo

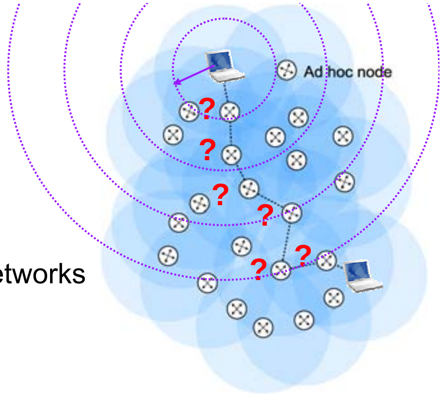
Demo seen at www.meshnetworks.com



Other companies include

- "Flarion", "Moteran", "Wireless-ip", and nearly all major networking technology companies …

Outline



Introduction and Motivation

Routing in Mobile Ad hoc Networks

Selected Routing Protocols

Routing Dependability in Ad hoc Networks

Performance Evaluation of Ad hoc Networks

Research Challenges, Summary and Conclusion

Quiz on Ad Hoc Routing

Why do we need specialized ad hoc routing?

- ❑ (A) To deal with topology dynamics induced by mobility
- ❑ (B) To reach nodes that are no direct neighbors
- ❑ (C) To match the characteristics of wireless communication
- ❑ (D) To support spontaneous formation of the network
- ❑ (E) To operate without fixed infrastructure
- ❑ (F) Because all end-systems are also acting as routers

→ Correct answers are A, B, C, D, E, and F!

→ We discuss these issues with selected protocols in a few minutes

Characteristics of Ad Hoc Communications

Characteristics are dominated by heterogeneity and variability

- Mobility characteristics (speed, predictability, uniformity, synthetic vs. empirical models , …)
- Wireless characteristics (broadcast nature of the net, packet losses due to transmission errors, limited range, hidden and exposed terminals, partitioning)
- Application / traffic characteristics and patterns (P2P, real time, unicast, multicast, geocast, CBR, VBR, self-similar, …)
- System characteristics (distribution, absence of infrastructure, (unpredictable) high dynamics, (a)symmetry …)

Inherent heterogeneity

- Do nodes have identical capabilities, responsibilities, and constraints?
- Transmission ranges and radios may differ, battery life may differ, processing capacity may differ, … (asymmetric capabilities)
- Only some nodes may route packets, some nodes may act as leaders of nearby nodes, e.g. cluster head (asymmetric responsibilities)

Adaptation is crucial

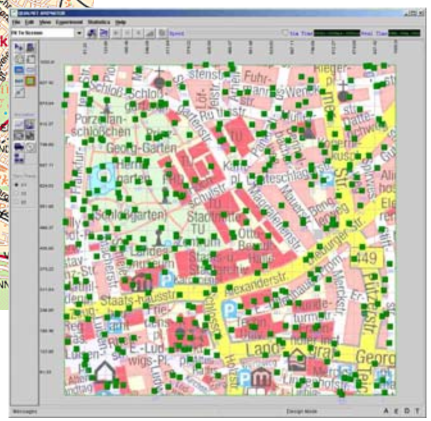
Example User Mobility: What is Realistic?

10 nodes?
100 nodes?
1000 nodes?
10000 nodes?

4000m x 3000m

1000m

1 m/s → 1000s
5 m/s → 200s
20m/s → 50s



1000m x 1000m, 333 nodes

Node Density Quiz: Street Lamps

Moving from mobile to stationary, more mesh like multihop scenarios:

What do you think:

How many street lamps
are operated in Frankfurt (am Main)

(1) Please provide your first guess

Node Density Quiz: Street Lamps

Moving from mobile to stationary, more mesh like multihop scenarios:

What do you think:

How many street lamps
are operated in Frankfurt (am Main)

(1) Please provide your first guess

Consider the following Information:
- ~ 650.000 Residents (with ~330.000 cars)
- ~ 248 square-km
- ~ 1000 km streets

(2) Please provide your second guess

Macroscopic Workload / Mobility Model

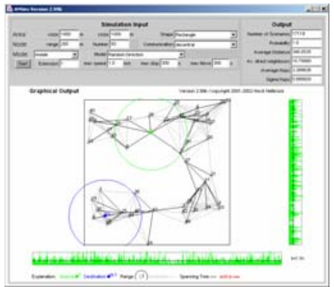
Synthetic mobility models (see demo)
- Easy to use
- Strict separation from traffic models
- Unrealistic for large scenarios (e.g. random waypoint)

Empirical workload / mobility models
- Data is hard to obtain
- Can often not be separated in mobility vs. traffic
- Available for past scenarios (may not be generalized easily)

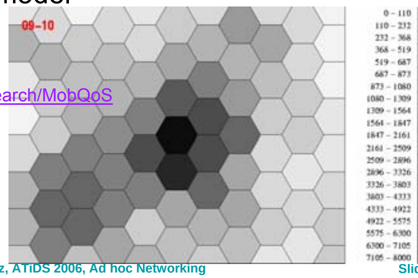
Hybrid workload / mobility model (synthetic traffic, empirical mobility) (see demo)
- Pros: flexibility, realism
- Cons: lots of parameters, data is hard to obtain
- Trade-off

Demo of Mobility Models

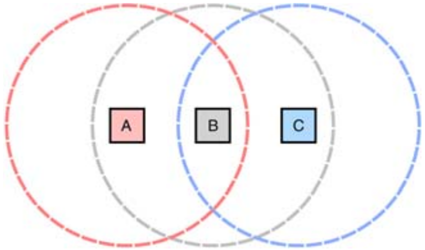
Synthetic mobility model
- e.g. random walk, random waypoint
- Demo: ANSim, see
  http://www.i-u.de/schools/hellbrueck/ansim



Hybrid workload / mobility model
- Demo: MobQoS Model
- See
  http://www.kom.tu-darmstadt.de/Research/MobQoS
- Developed together with Siemens Corporate Technology, Munich



Why specialized Ad Hoc Routing



Within MANETs

- Some nodes may be out of range of others
- Must use other peer nodes as routers to forward packets
- Need to find new routes as nodes move or conditions change (highly dynamic and unpredictable)

- Routing protocol captures and distributes state of network
- Routing strategy (algorithm) computes shortest paths

Requirements for Ad Hoc Routing

The routing protocol needs to

- Converge fast
- Minimize signaling overhead

The routing strategy (algorithm) may include

- Shortest distance
- Minimum delay
- Minimum loss
- Minimum congestion (load-balancing)
- Minimal interference
- Maximum stability of routes or maximal signal strength
- Minimum energy (power aware routing)

Standard Internet routing cannot fulfill these requirements

- Assumes infrastructure, assumes symmetrical conditions, assumes plenty of resources, to slow, misses metrics, …

Ad Hoc Routing Paradigms

Flooding of Data Packets

- Simple approach, extremely high overhead
- Many protocols perform (limited) flooding of control packets
  - To discover routes
  - Overhead of control packet flooding is amortized over data packets transmitted between consecutive control packet floods

Uniform Protocols

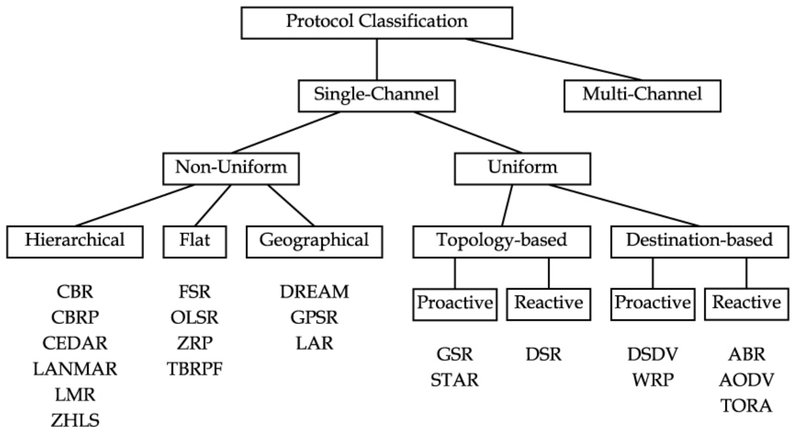
- Topology-based (e.g. source routing)
- Destination-based (usually distance vector paradigm)
- Proactive (table-driven) vs. reactive (on-demand) paradigms
  - Trade-off latency vs. overhead

Non-Uniform Protocols

- Hierarchical protocols, Cluster-based, flat protocols
- Geographical protocols
- Hybrid protocols (e.g. combination of proactive and reactive)

There is no silver bullet to ad hoc routing

Taxonomy of Routing Protocols



- The above mentioned protocols are only a selection!
- AODV, DSR, OLSR, and TBRPF are currently moved towards Experimental RFC (within IETF)

Some Routing Protocols / Frameworks

http://www.kom.tu-darmstadt.de

AODV - Ad Hoc On Demand Distance Vector (Perkins, NOKIA; Belding-Royer, UCSB; Das, UC)

CEDAR - Core-Extraction Distributed Ad Hoc Routing

DREAM - Distance Routing Effect Algorithm for Mobility

DSDV - Destination-Sequenced Distance Vector

DSR - Dynamic Source Routing (Johnson, CMU)

FSR - Fisheye State Routing

LANMAR - Landmark Ad Hoc Routing

LAR - Location Aided Routing

OLSR - Optimized Link State Routing (Clausen, Jacquet, INRIA)

TBRPF - Topology Broadcast based on Reverse-Path Forwarding (Ogier,Templin, SRI)

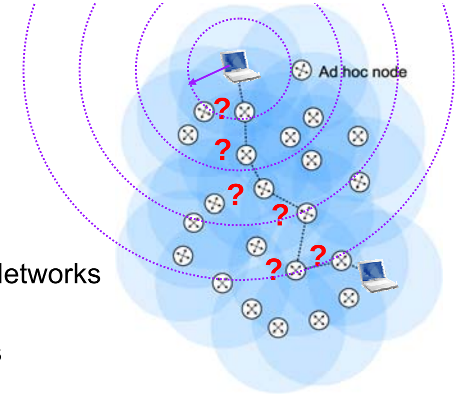
Tora / IMEP - Temporally-Ordered Routing Algorithm / Internet Manet Encapsulation Protocol

ZRP - Zone Routing Protocol (Haas, Cornell)

… see also http://www.wikipedia.org/wiki/Ad_hoc_protocol_list

Outline

http://www.kom.tu-darmstadt.de



Introduction and Motivation

Routing in Mobile Ad hoc Networks

Selected Routing Protocols

Routing Dependability in Ad hoc Networks

Performance Evaluation of Ad hoc Networks

Research Challenges, Summary and Conclusion

Ad hoc On-demand Distance Vector Protocol

http://www.kom.tu-darmstadt.de

AODV (Ad hoc On-demand Distance Vector)

- Reactive routing protocol
- All nodes are treated equal
- Based on distance vector principle
- Route discovery cycle for route finding
  - Flooded / Broadcast Route Request (RREQ)
  - Unicast Route Reply (RREP) along reverse path of RREQ
  - Unicast Route Error (RERR)
- No overhead on data packets
- Loop freedom is achieved through sequence numbers, also solves “count to infinity” problem

Status

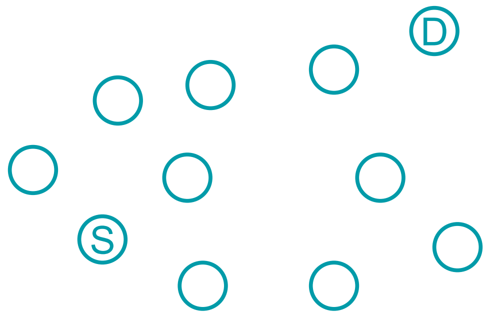
- Implementations available (IPv4, IPv6)
- Interoperability testing (successful)
- Experimental RFC status issued (July 2003)
  - http://ietf.org/rfc/rfc3561.txt

AODV – Route Discovery

http://www.kom.tu-darmstadt.de

Route discovery

- Broadcast flood acquisition using Route Request (RREQ)
- A RREQ must never be broadcast more than once by any node
- Nodes sets up a reverse path pointing towards the source
- Route Reply (RREP) propagation



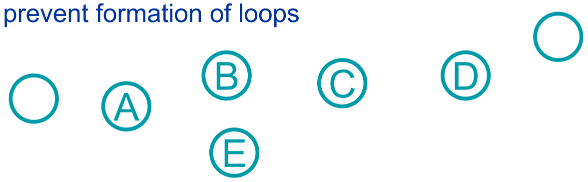
AODV – Route Maintenance

Timers to keep route alive

- A routing table entry maintaining a reverse path is purged after a timeout interval
  - Timeout should be long enough to allow RREP to come back
- A routing table entry maintaining a forward path is purged if not used for a active_route_timeout interval
  - If no data is being sent using a particular routing table entry, that entry will be deleted from the routing table (even if the route may actually still be valid)

Destination Sequence numbers to determine fresh routes

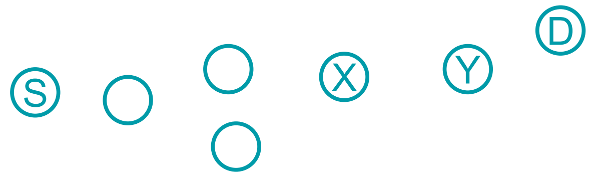
- To avoid using old/broken routes
- To prevent formation of loops



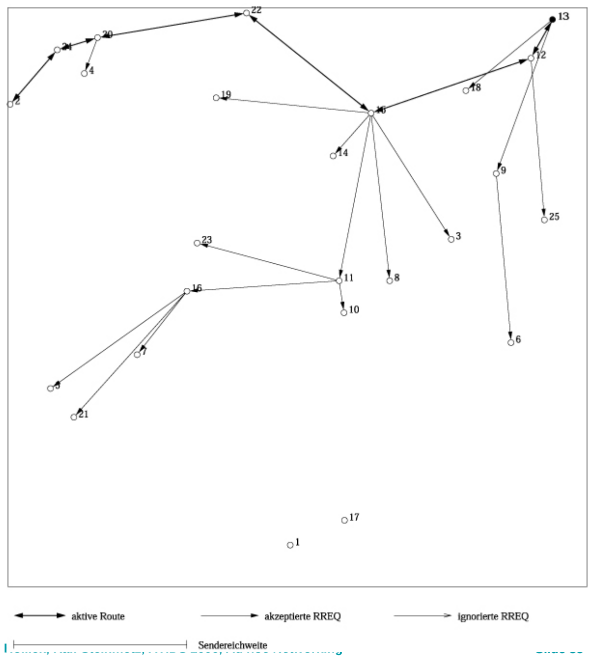
AODV – Route Error

Link failure reporting / repairing routes

- When node X is unable to forward packet P (from node S to node D) on link (X,Y), it generates a Route Error (RERR) message
- Node X increments the destination sequence number for D cached at node X
- The incremented sequence number *N* is included in the RERR, which is sent out based upon precursor lists
- When node S receives the RERR, it initiates a new route discovery for D using destination sequence number at least as large as *N*



Routes



Parameters

- AODV
- 25 nodes
- No Expanding Ring Search
- Area = 836m * 836m
- Radio Range = 250m
- Node Density = 7
- RREQ from #13 to #2

Summary / Other Features of AODV

Target networks

- Where routing churn is high enough that proactively maintaining routes is unproductive, and that can absorb a network wide broadcast rate
- The authors claim scalability up to 10,000 nodes (performance suffers, simulation results)

Multiple optimizations

- AODV-LR - Local Repair
- AODV-ESP - Expanding-Ring Search
- Multi-path extension proposed (AODVM, AOMDV)

Multiple open issues

- Security
- QoS
- …
- Protocol needs operational experience to discover further issues

AODV Optimizations – Gossiping (1)

Flooding is very inefficient, esp. if node density is high

- Probabilistic techniques are expected to better deal with the highly dynamic and mobile characteristics of the network
- Probabilistic techniques may easily be adapted to network density without breaking symmetric conditions

Gossiping as example of epidemiological algorithm

- Assume a large population of *n* people
- A rumor is initially transmitted to one member of the population
- This person passes (forwards) the rumor to a fixed number of confidants with probability *p,* the rumor is kept secret with probability 1- *p* (other modes possible)

Other prominent networking applications of gossiping

- Application level multicasting, content addressable networks

AODV Optimizations – Gossiping (2)

Gossip-variants

- General forwarding probability p_1
- Number of neighbors n; probability p_2 for $n < n_0$, $p_2 > p_1$
- Hop count k; forwarding probability $p = 1$ for $k \leq k_0$
- Number of overheard messaged m; $p = 1$ for $m \leq m_0$

Pseudo-Algorithm for Gossip (p_1, k)

```
upon reception of message m at node n
if message m received for the first time then
  if hop count k less or equal k0 then
    broadcast(m) with probability 1
  else
    broadcast(m) with probability p1
  end if
end if
```

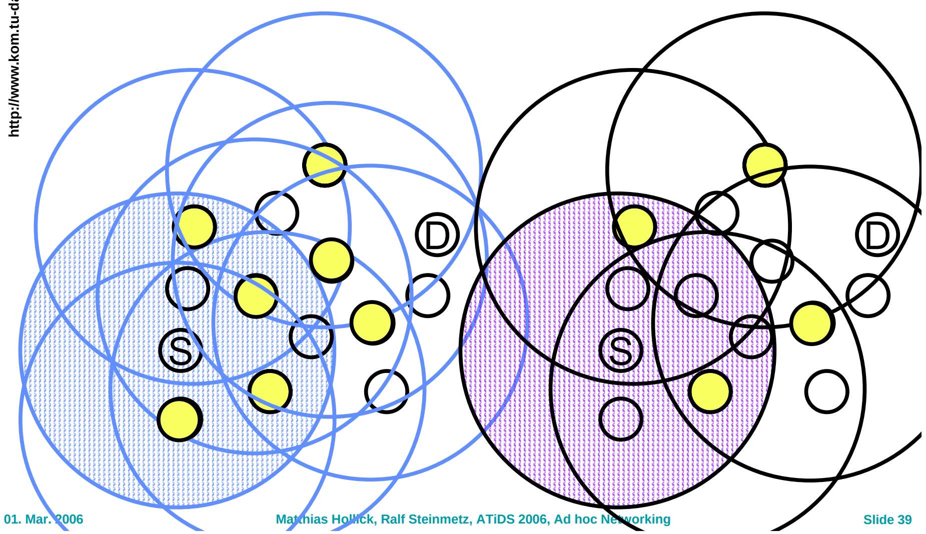
Multiple variants implemented

- Gossip (p_1), Gossip (p_1, k), Gossip (p_1,k,m), Gossip (p_1,k,p_2,n) → proactive behavior, hello messages

AODV Optimizations – Gossiping (3)

Gossiping examples

- Left Gossip (p_1), right Gossip (p_1,k,m)



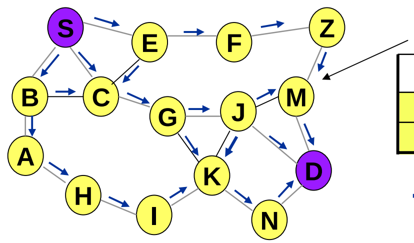
AODV Extension – Multipath (AOMDV)

Multipath variants for multiple protocols

- Easy for source routing algorithms
- Not trivial for optimized protocols like AODV
- "Multipath" should NOT be mixed up with "Multicast"

AODVM

- Ad hoc On-demand Distance Vector Multipath (AODVM) Routing
- Instead of dropping duplicate RREQ packets, AODVM uses an RREQ table to store the redundant RREQ information.



Node M's RREQ table

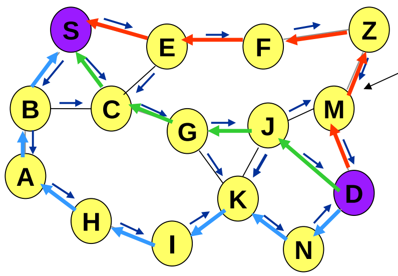
Source	Neighbor	Distance
S	J	3
S	Z	3

(Source: Zhenqiang Ye)

AODVM Explained

Path Discovery Procedure

- Destination initiates an RREP for each RREQ that is received (from different neighbors).
- Nodes overhear the RREP packets
- A node that is assigned to a route is deleted from its neighbors' RREQ tables



Node M's RREQ table

Source	Neighbor	Distance
~~S~~	~~J~~	~~3~~
~~S~~	~~Z~~	~~3~~

Route Request (RREQ)

Route Reply (RREP)

Source: Zhenqiang Ye