Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols

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The MONARCH Project

MOBILE **NET**WORK **ARCH**ITECTURE

- Originated at CMU in 1992
- Moved to Rice w/ Professor Johnson
- Develop networking protocols and protocol interfaces
- Research scope includes protocol design, implementation, performance evaluation, and usage-based validation
- The goal is to enable mobile hosts to communicate with each other and with stationary or wired hosts, transparently, seamlessly, efficiently using the best network connectivity available

Purpose of This Paper

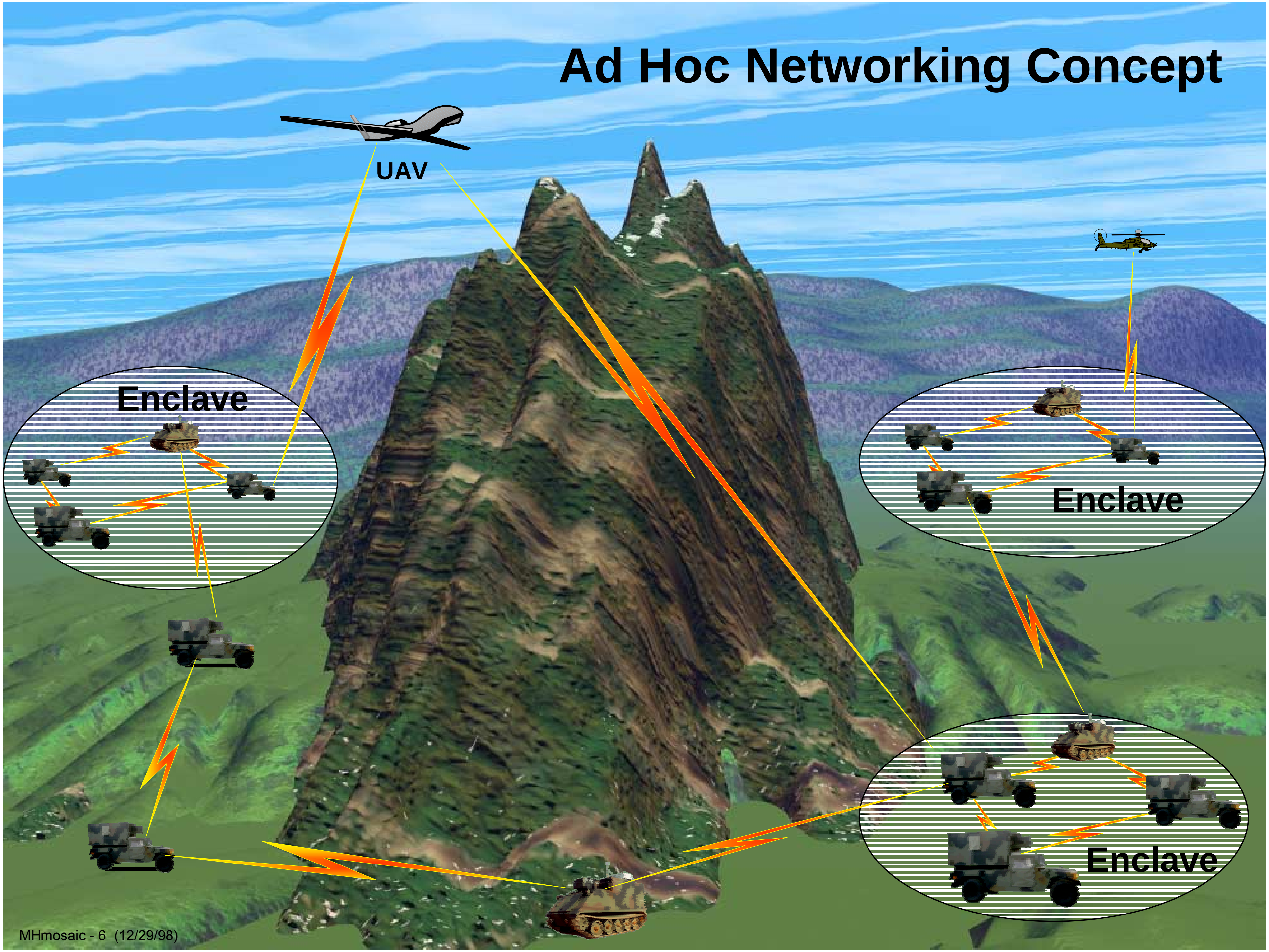
- Compare four routing protocols
  - Wireless
  - Ad-hoc
  - Multi-hop routing problem
- Provide realistic, quantitative analysis
  - Node Mobility
  - Characteristics of physical layer
  - Characteristics of air interface

Outline

- Background
- Simulation environment
- Ad-hoc protocols described
- Analysis methodology
- Simulation results
- Additional observations
- Conclusion

Ad-Hoc Networking

- Wireless mobile nodes
- “Infrastructure-less” networking
- Destination may not be in transmitter range
- Node is both host and router
- Each node involved in discovery of “Multi-hop” path through network



Ad Hoc Networking Concept
UAV
Enclave
Enclave
Enclave
MHmosaic - 6 (12/29/98)

Simulation Environment

- 50 wireless mobile nodes in a 1500m x 300m space
- ns-2 network simulator with modifications
  - Realistic physical layer (i.e. prop delay)
  - Node Mobility
  - Radio network interfaces (i.e. ant gain)
  - IEEE 802.11 Medium Access Control protocol

Simulation Environment

Physical Layer Model - Propagation

- Radio wave attenuation causes degraded receive signal at antenna
- Propagation models in free space attenuate receive power by $1/r^2$
- Models that consider reflection use $1/r^4$

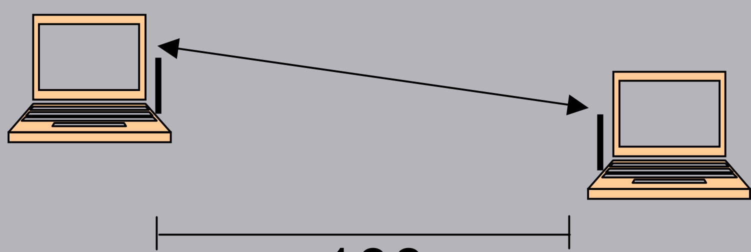
  r = distance between antennas
- This model uses both

Simulation Environment

Physical Layer Model - Propagation

Free Space Model

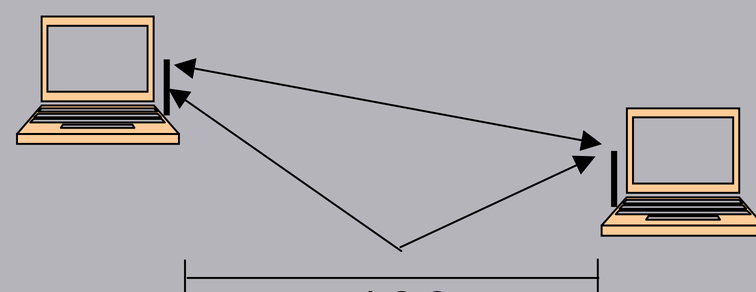
Receive Power~ $1/r^2$



r < 100 m

Two-Ray Model

Receive Power~ $1/r^4$



r > 100 m

Simulation Environment

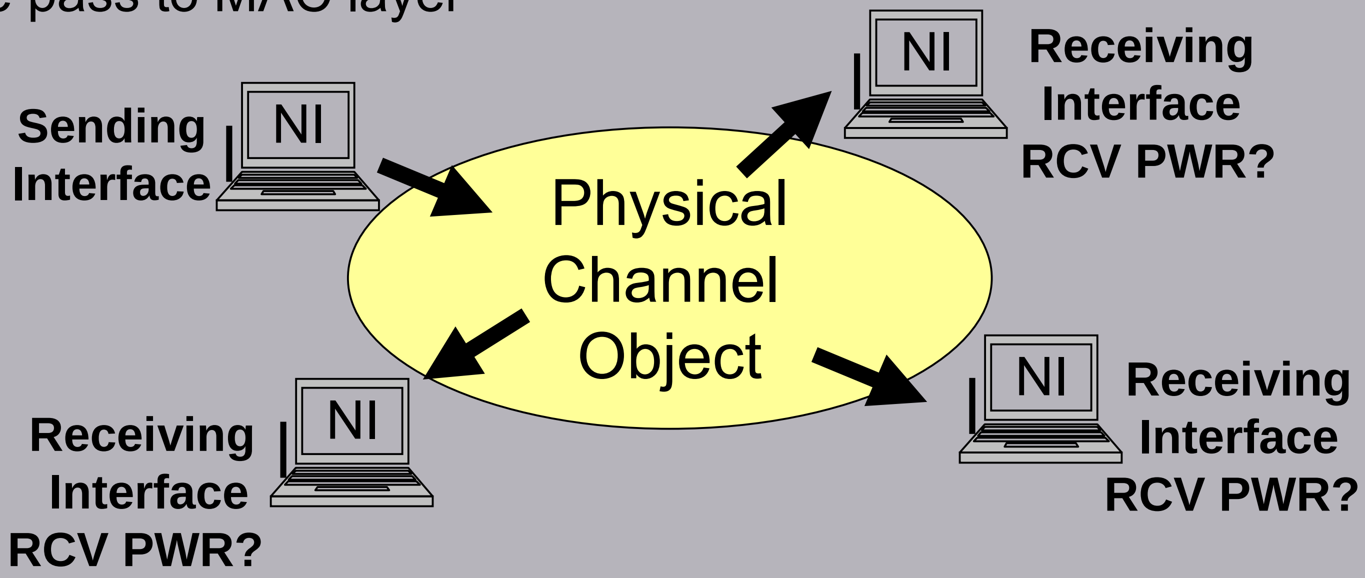
Physical Layer Model – Mobile Nodes & Network Interfaces

- Nodes have position and velocity in a topography (flat/digital elevation)
- Nodes have wireless network interfaces
  - Interfaces of the same type on all nodes are connected by a single physical channel
- Physical channel object calculates
  - Propagation delay to each interface on that channel
  - Power of received signal at interface
  - Schedules packet reception event

Simulation Environment

Physical Layer Model – Mobile Nodes & Network Interfaces

- Receiving interface compares power with carrier sense and receive power thresholds
  - RCV PWR < Carrier sense thresh then discard as noise
  - RCV PWR > Carrier sense thresh < RCV thresh then mark packet in error, pass to MAC layer
  - Else pass to MAC layer



Simulation Environment

Link Layer Model – MAC protocol

- MAC layer receives packet from net interface
  - If receiver not idle
    - If RCV PWR of packet in receiver ≥ 10dB higher than new packet then discard new
    - If RCV PWR < 10 dB higher – collision – discard both
  - If receiver idle
    - Compute transmission time
    - Schedules packet reception complete event
    - Address filtering and pass up protocol stack
- Link Layer uses 802.11 MAC Distributed Coordination Function - uses carrier sense mechanism to reduce collisions
  - Transmission preceded by RTS/CTS to reserve channel

Simulation Environment
Other Characteristics

- Address Resolution
  - An address resolution protocol (ARP) is used to resolve IP addresses to the link layer
  - ARP requests are broadcast
- Packet Buffering
  - Each node has a drop tail queue to hold up to 50 packets awaiting transmission by net interface
  - Additional 50 packet queues implemented in DSR and AODV
    - For packets awaiting discovery of a route

Simulation Environment

Ad-Hoc Network Routing Protocols

- Implemented according to specs and designer clarifications
- Modifications based on experimentation:
  - Period broadcasts and responses were jittered 0-10ms to prevent synchronization
  - Routing information queued ahead of ARP and data at network interface
  - Used link breakage detection feedback from 802.11 MAC except in DSDV

DSDV

Characteristics

- Hop-by-hop distance vector protocol
- Nodes broadcast periodic routing updates
- Guaranteed loop free
- Node routing table lists next hop for each destination
- Tags "route" in table with sequence number (SN)
  - Route to destination with higher SN is better
  - If SN equal then route with lower metric better
- Node advertises an increasing even SN for itself

DSDV

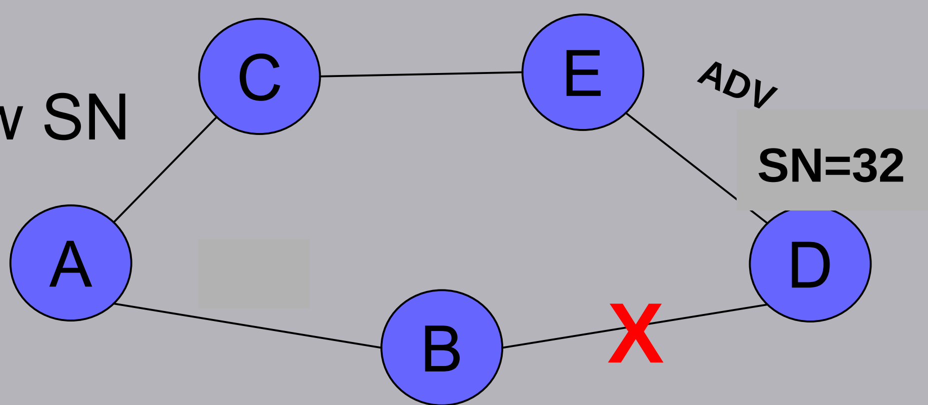
Basic Mechanisms

- When node B decides route to D is broken, B increases SN for that route by one (SN now odd) and advertises the route with an infinite metric
- Any node ‘A’ that routes through B adds the infinite metric to their route table
- ‘A’ keeps this metric until it hears a new route to D with a higher SN

DSDV

Basic Mechanisms

- D advertises even SN 30
- B senses its route to D has broken
- B labels route with infinite metric and increases SN to 31
- B adv infinite metric to A
- A changes metric
- D adv new SN
- Nodes propagate new SN



Dest	NH	SN	Met
D	B	30	∞
D	C	32	3

Dest	NH	SN	Met
D	-	31	∞
D	A	32	4

DSDV

Implementation Decisions

- No 802.11 MAC link layer breakage detection
  - Node B detects link to D is broken
  - Increases SN by 1 then broadcasts a triggered route update with infinite metric
  - All nodes propagate new SN and metric as oppose to only those routing traffic through B rendering node D unreachable
- Using DSDV-SQ vs DSDV
  - When should we send triggered update?
    - When node receives new SN or just new metric
    - Update with each new SN requires more overhead
  - Chose DSDV-SQ despite increased routing overhead because of better packet delivery ratio

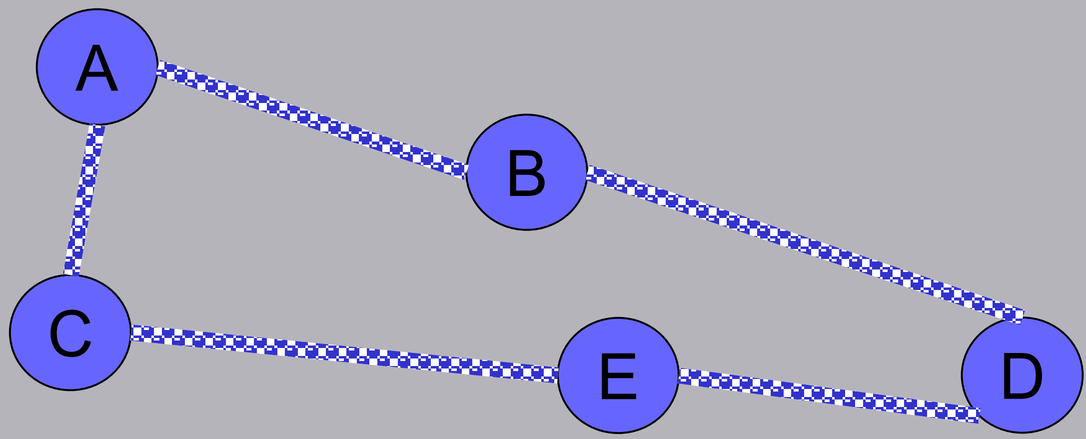
TORA
Characteristics

- On demand distributed routing protocol
  - Discover routes on demand
  - Provide multiple routes to destination
  - Establish routes quickly
  - Minimize routing overhead by localizing reaction to topological changes
  - Shortest path routing lower priority
    - Will use longer route to avoid overhead of discovering new ones
- "Link reversal" algorithm
  - Described as water flowing downhill toward destination

TORA

Basic Mechanisms – Link Reversal

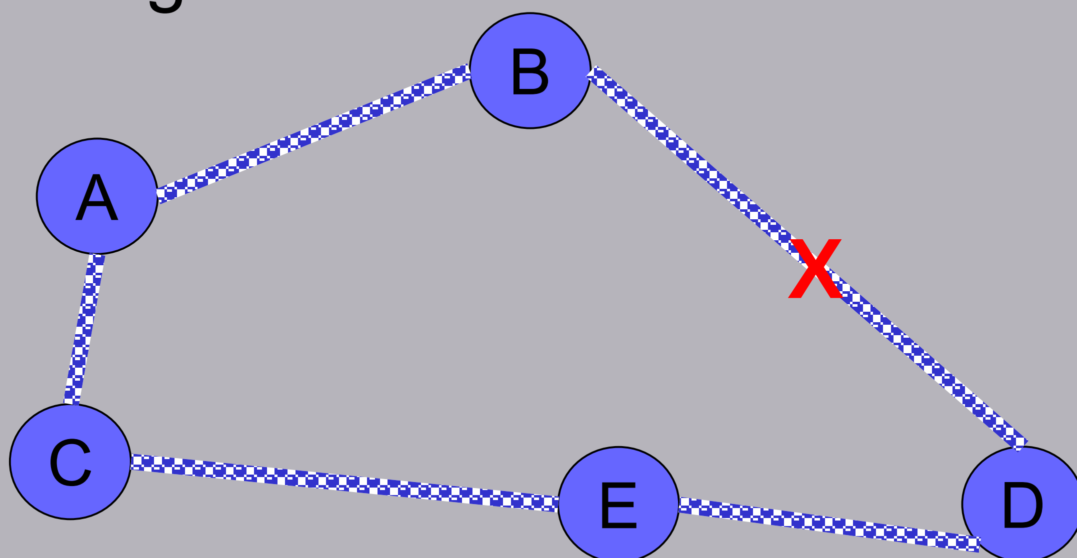
- Network of tubes model routing state of the real network
- Tubes represent links, intersections represent nodes
- Each node has height with respect to the destination
- Here Node A routes through B to destination D



TORA

Basic Mechanisms - Link Reversal

- If the tube between nodes B and D becomes blocked, B raises its height with respect to its remaining neighbors
- Water flows out of B towards A who had been routing through B



TORA

Basic Mechanisms – Route Discovery

- Each node has a logically separate copy of TORA for each destination D
- Broadcasts QUERY with address of D
- QUERY propagates through network until it reaches D or a node with route to D
- Node receiving QUERY broadcasts UPDATE with nodes height with respect to D
- All nodes that receive UPDATE set their height higher than neighbor from which it was received

TORA

Basic Mechanisms – Route Maintenance

- When a node discovers invalid route it
  - Adjusts height higher than its neighbors
  - Broadcasts UPDATE
- If all neighbors have infinite height then node broadcasts QUERY to discovery new route
- If network partition is found (isolated enclave) then node broadcasts CLEAR to reset state

TORA

Implementation Decisions

- TORA requires in-order delivery of routing control messages so it is layered with IMEP
- IMEP provides link sensing and a consistent picture of a node's neighbors to TORA
  - Transmit periodic beacon – each node answers with Hello
  - Queues control messages for aggregation into blocks reducing overhead (TORA excluded - limit long-lived loops)
  - Blocks carry SN and list of nodes not yet acknowledged
  - IMEP queues messages for 150-250ms - retransmits block with period 500ms with timeout at 1500ms
  - Upon timeout IMEP declares link down and notifies TORA

TORA

Implementation Decisions

- In-order delivery is enforced at receiver by:
  - Receive node B passes block from A up stack to TORA only if SN = expected SN
  - Blocks with lower SN are dropped
  - Blocks with higher SN are queued until missing blocks arrive or up to 1500ms
    - At 1500ms node A will have declared link to B down
  - Node B IMEP layer declares link down to maintain consistent picture with node A
- Improved IMEP link sensing – require beacons only when node is disconnected from all other nodes

DSR

Characteristics

- Source routing protocol
  - Each packet carries list of nodes in path in its header
  - Intermediate nodes do not maintain routing information
- No need for periodic route ads or neighbor detection

DSR

Basic Mechanisms

- Source node S uses Route Discovery to find route to destination D
  - S broadcasts ROUTE REQUEST – flooded in a controlled manner (initial hop limit set to zero, if no reply then propagate)
  - Answered by D or by a node with route to D with ROUTE REPLY
  - Each node maintains cache of source routes to limit frequency and propagation or ROUTE REQUESTs
- S uses Route Maintenance to detect topology changes that break a source route (i.e. node out of range)
  - Notifies S with ROUTE ERROR
  - S can use another cached route or invoke ROUTE REQUEST

DSR

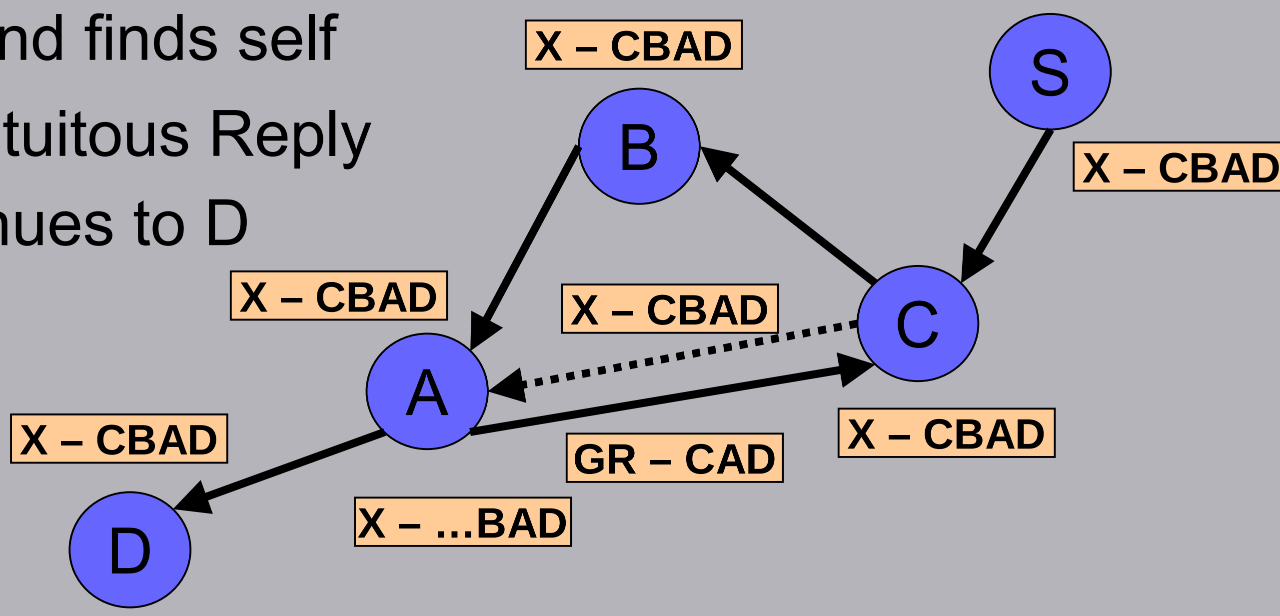
Implementation Decisions

- DSR supports unidirectional routes
  - However 802.11 requires RTS/CTS/Data/Ack exchange
  - Implementation requires ROUTE REPLY from destination via reverse of ROUTE REQUEST
  - Else S would not learn the unidirectional route
- Network Interfaces in *promiscuous mode*
  - Protocol receives all packets the interface hears
  - Learns information about source routes
- Route repair
  - If intermediate node senses broken link it will search cache for alternate route and repair source route

DSR

Implementation Mechanism – *Promiscuous Mode*

- S sends message X with source route C-B-A-D
- C forwards message to B
- A hears message on physical channel
- A reads header and finds self
- A broadcasts Gratuitous Reply
- Message X continues to D



AODV

Characteristics

- Combination of DSR and DSDV
- Uses on demand Route Discovery and Route Maintenance of DSR
- Hop-by-hop routing, SN and beacons from DSDV

AODV

Basic Mechanisms

- Route Discovery
  - Source node S broadcasts ROUTE REQUEST to include last known SN for destination D
  - Each node along path creates a reverse route back to S
  - ROUTE REPLY sent by D or by a node with route to D contains # hops to D and last seen SN
  - Each node in path of REPLY to S create the *forward route*
  - State created is hop-by-hop (node only remembers next hop)
- Route Maintenance
  - AODV uses Hello Messages to detect link breakage
  - Failure to receive three HELLOS indicates link down
  - Upstream nodes notified by UNSOLICITED ROUTE REPLY containing an infinite metric for that destination

AODV

Implementation Decisions

- Authors tested another version of AODV that relies only on Link Layer feedback from 802.11 as seen in DSR
  - Link breakage detection is on demand
  - Detected only when attempting to send packet
- Performance was improved in AODV-LL version
  - Saves overhead of HELLO messages
- Reduced the time before new ROUTE REQUEST is sent if no REPLY was received from 120s to 6s
  - Nodes hold reverse route information for only 3s
  - Without this route information a REPLY can't find source

Simulation Constants

Table II Constants used in the TORA simulation.

BEACON period	1 s
Time after which a link is declared down if no BEACON or HELLO packets were exchanged	3 s
Time after which an object block is retransmitted if no acknowledgment is received	500 ms
Time after which an object block is not retransmitted and the link to the destination is declared down	1500 ms
Min HELLO and ACK aggregation delay	150 ms
Max HELLO and ACK aggregation delay	250 ms

Table I Constants used in the DSDV-SQ simulation.

Periodic route update interval	15 s
Periodic updates missed before link declared broken	3
Initial triggered update weighted settling time	6 s
Weighted settling time weighting factor	7/8
Route advertisement aggregation time	1 s
Maximum packets buffered per node per destination	5

Table III Constants used in the DSR simulation.

Time between retransmitted ROUTE REQUESTs (exponentially backed off)	500 ms
Size of source route header carrying n addresses	$4n + 4$ bytes
Timeout for nonpropagating search	30 ms
Time to hold packets awaiting routes	30 s
Max rate for sending gratuitous REPLYs for a route	1/s

Table IV Constants used in the AODV-LL simulation.

Time for which a route is considered active	300 s
Lifetime on a ROUTE REPLY sent by destination node	600 s
Number of times a ROUTE REQUEST is retried	3
Time before a ROUTE REQUEST is retried	6 s
Time for which the broadcast id for a forwarded ROUTE REQUEST is kept	3 s
Time for which reverse route information for a ROUTE REPLY is kept	3 s
Time before broken link is deleted from routing table	3 s
MAC layer link breakage detection	yes

Analysis Methodology

- Goal – compare protocols - not determine the optimum performance in the scenarios
- Measure ability to react to changes and deliver packets successfully
- Given a variety of workloads, movement patterns and environmental conditions
- Compare using 210 scenarios each running for 900s
- Radio characteristics modeled after Lucent DSSS radio

Analysis Methodology
Movement Model

- Random waypoint model
  - Node begins simulation stationary for *pause time* s
  - Selects random destination and moves at a speed uniformly distributed from 0 and max
  - Node then pauses again for *pause time* s
  - Repeating for the duration of the 900s
- 7 *pause times* 0,30,60,120,300,600,900 s
  - 0s = constant motion   900s = stationary
- 70 movement patterns (10 per each *pause time*)
- Max speed = 20m/s Ave speed 10m/s
  - Comparison made with Max speed = 1m/s

Analysis Methodology

Communication Model

- Chose CBR sources to maintain exactness of scenario
- Fixed send rate at 4 packets/s
- Three different patterns with 10,20,30 sources
  - Protocols determine routes 40,80,120 times/s
- Packet size 64-bytes
  - 1024 byte packets caused congestion due to small simulation space (short RTT)
- Did not use TCP because congestion control mechanisms alters sending times making scenarios between protocols different

Analysis Methodology

Scenario Characteristics – Route Lengths

- Simulator measured the "ideal" lengths of the routes (in hops) in all 210 scenarios
- Average data packet traveled 2.6 hops

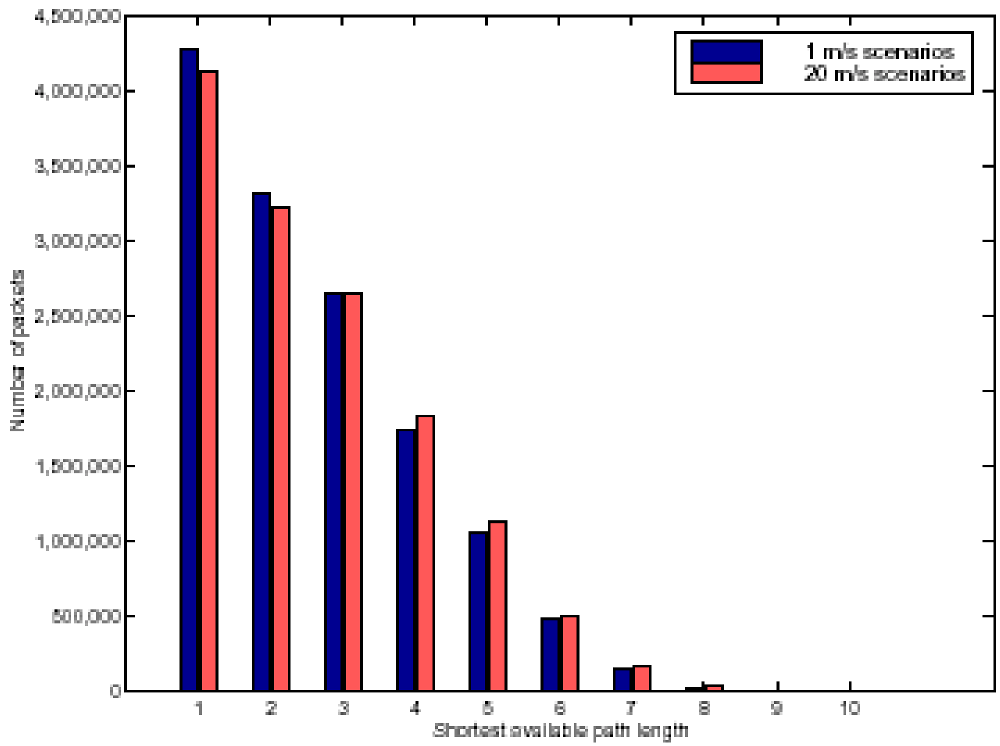


Figure 1 Distribution of the shortest path available to each application packet originated over all scenarios.

Analysis Methodology

Scenario Characteristics – Connectivity Changes

- Link connectivity changes whenever a node leaves radio contact with another node
- Jump in # of changes of 1m/s max speed at 30s pause time is an artifact of the scenario

Table V Average number of link connectivity changes during each 900-second simulation as a function of pause time.

Pause Time	# of Connectivity Changes	
	1 m/s	20 m/s
0	898	11857
30	908	8984
60	792	7738
120	732	5390
300	512	2428
600	245	1270
900	0	0

Analysis Methodology

Metrics

- Packet delivery ratio
  - Ratio of the # packets originated by CBR sources to the # received at CBR sink
  - Completeness and correctness: loss rate - throughput
- Routing overhead
  - Total # of routing packets transmitted during simulation (each hop is one transmission)
  - Scalability and efficiency in terms of battery power
- Path Optimality
  - The difference between the number of hops taken and the optimum path available
  - Efficiency of network resources

Simulation Results

Comparison Summary – Packet Delivery Ratio - 20 Sources

- Less mobility = better performance
- DSR & AODV-LL > 95%
- DSDV-SQ fails at *pause time* < 300s

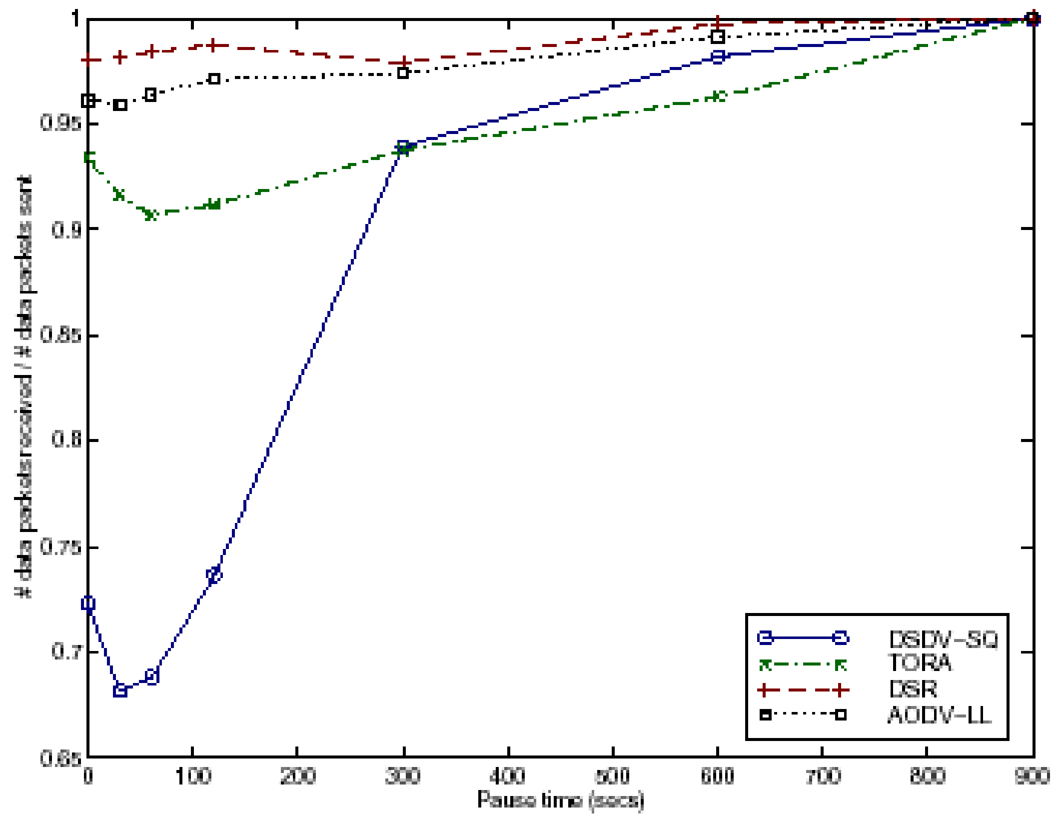


Figure 2 Comparison between the four protocols of the fraction of application data packets successfully delivered (packet delivery ratio) as a function of pause time. Pause time 0 represents constant mobility.

Simulation Results

Comparison Summary – Routing Overhead - 20 Sources

- TORA, DSR, AODV-LL are on-demand protocols Overhead drops with less mobility

- DSDV-SQ is a periodic protocol near constant overhead with respect to mobility rate

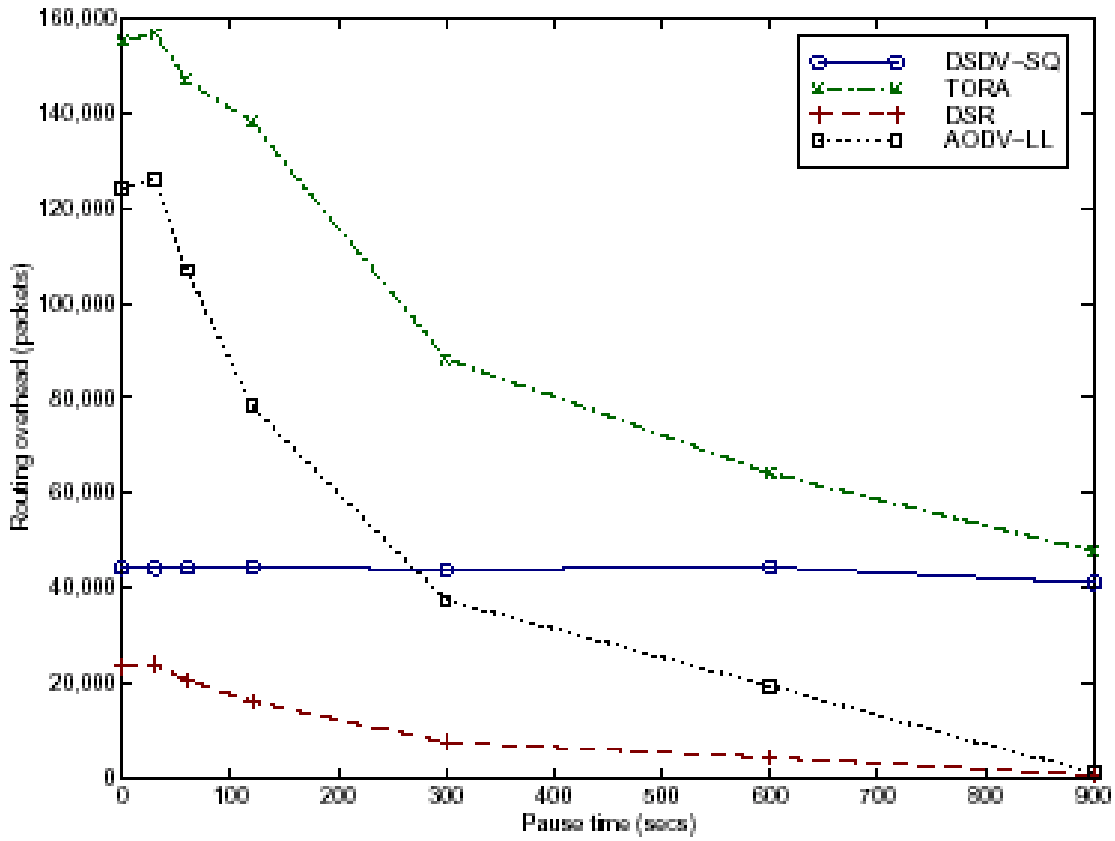


Figure 3 Comparison between the four protocols of the number of routing packets sent (routing overhead) as a function of pause time. Pause time 0 represents constant mobility.

Simulation Results

Details Packet Delivery Ratio – All Three Source Rates

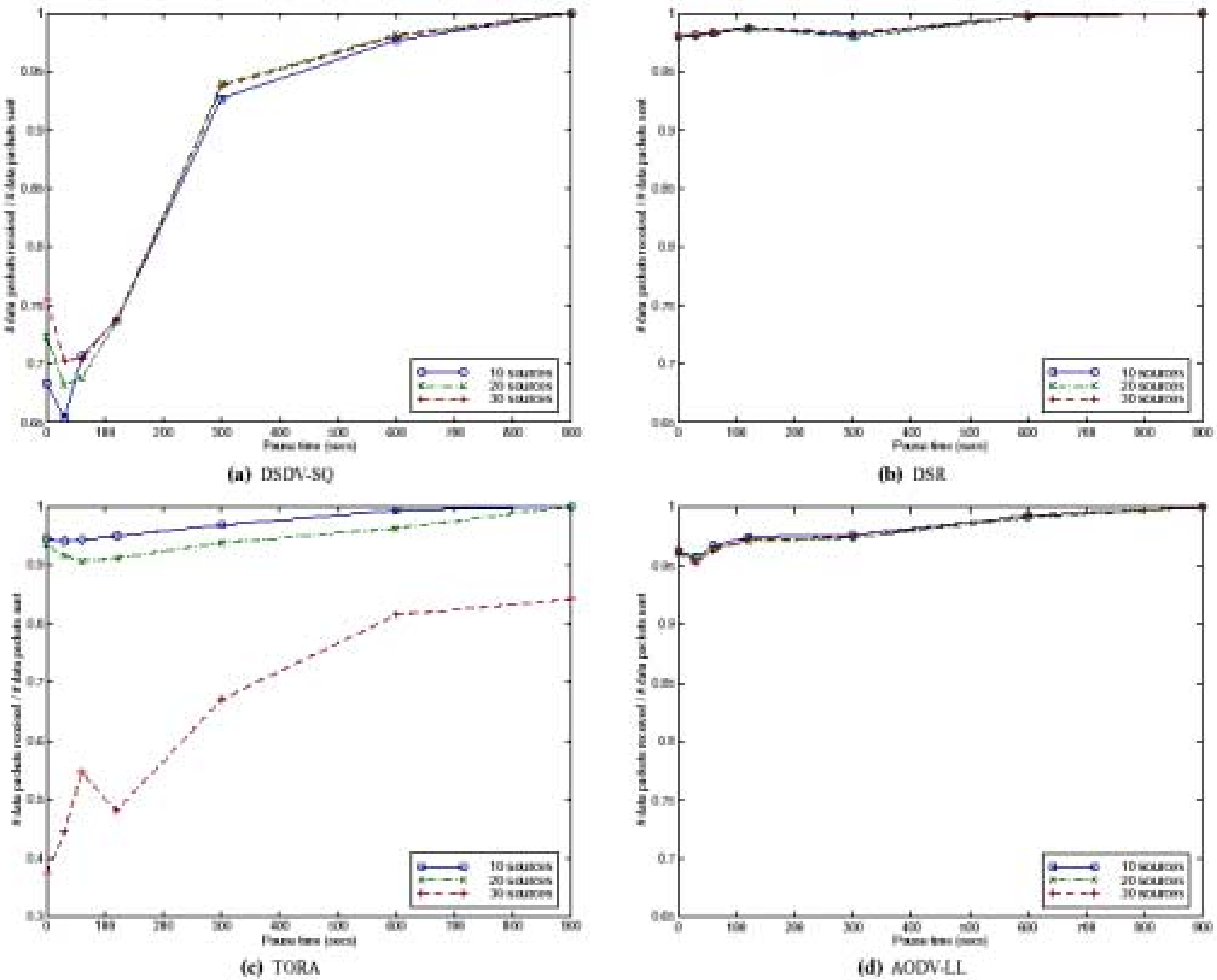
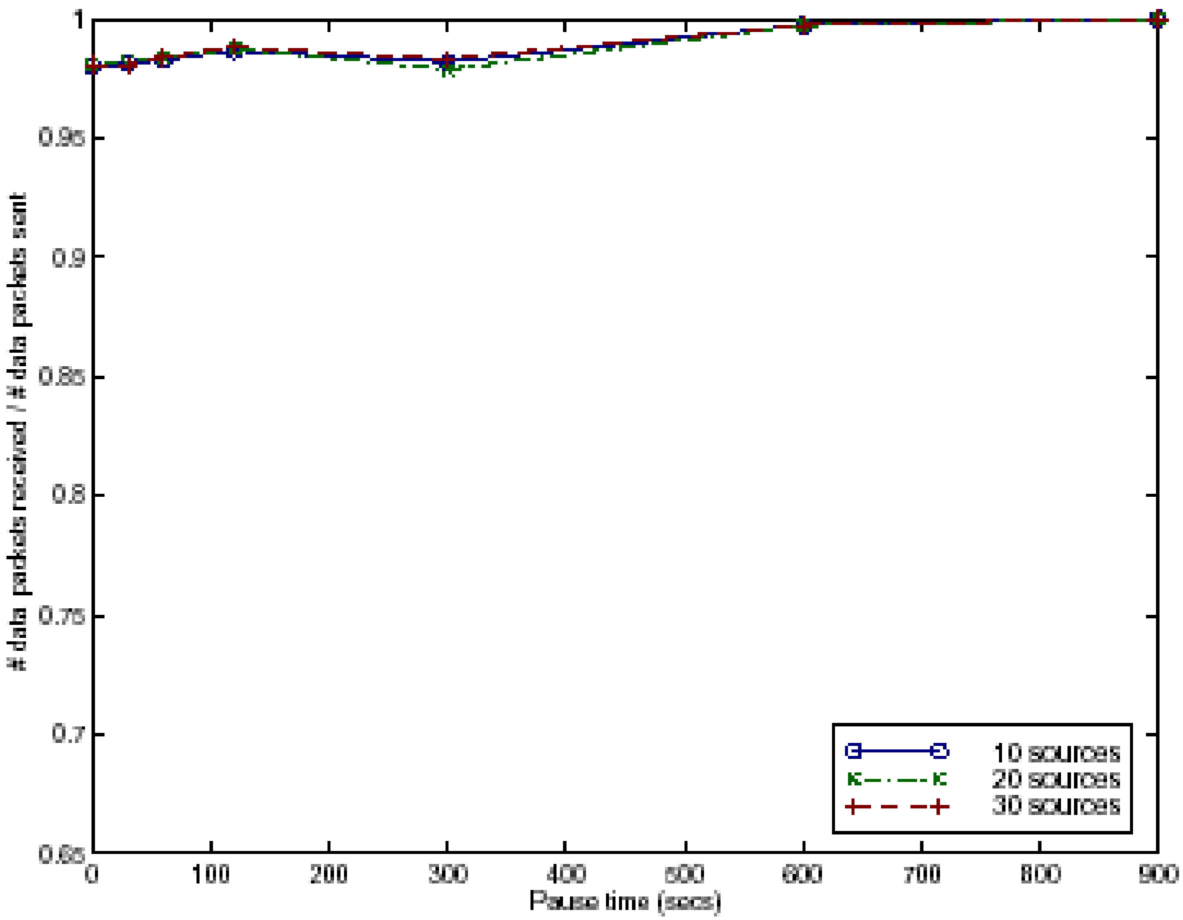


Figure 4 Packet delivery ratio as a function of pause time. TORA is shown on a different vertical scale for clarity (see Figure 2).

Simulation Results

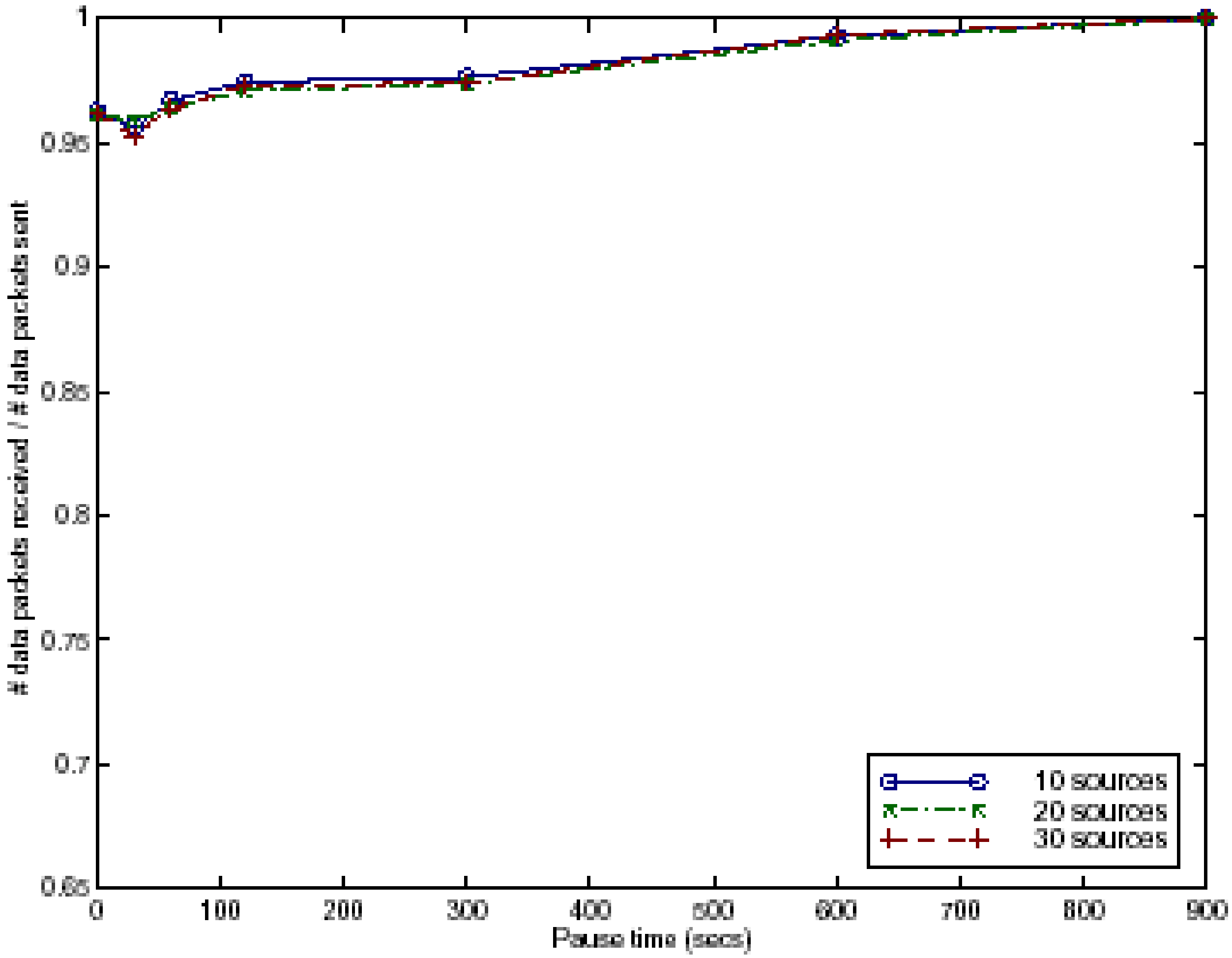
Packet Delivery Ratio – DSR



(b) DSR

Simulation Results

Packet Delivery Ratio – AODV-LL

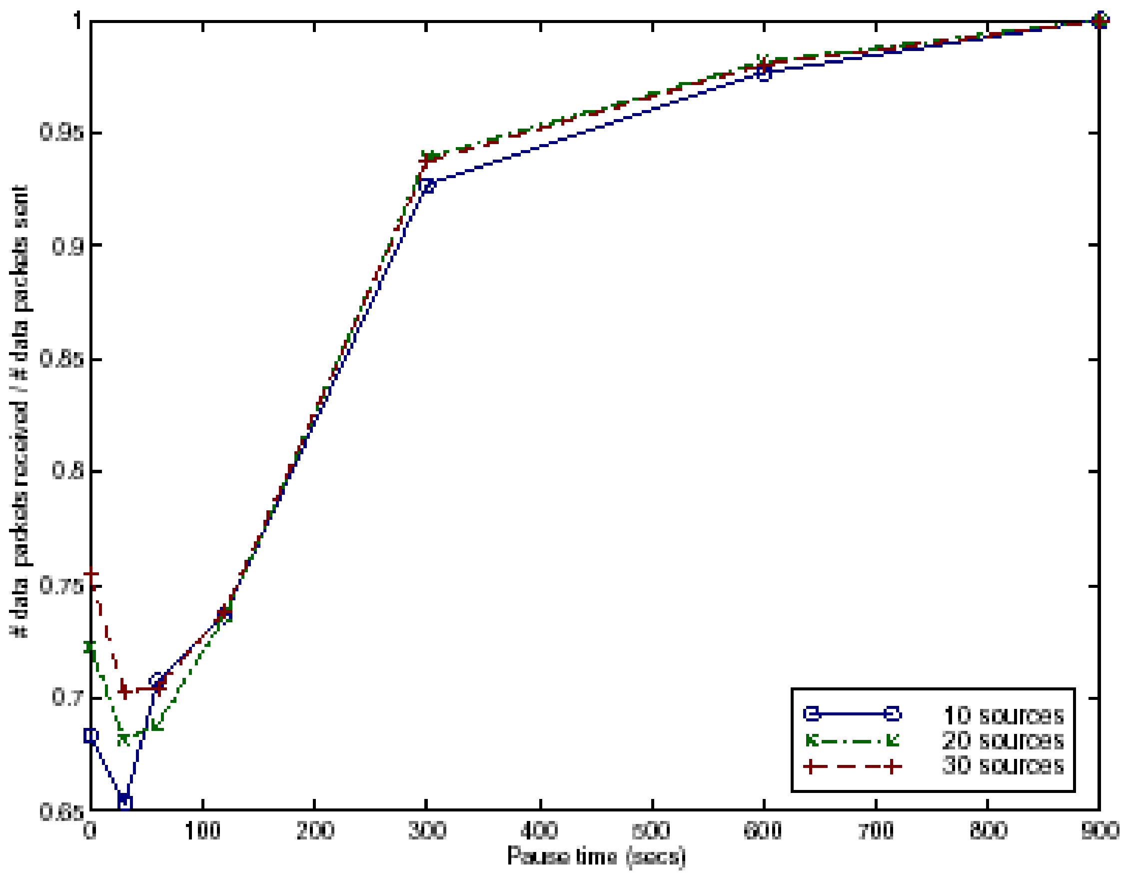


(d) AODV-LL

Simulation Results

Details Packet Delivery Ratio – DSDV-SQ

- DSDV-SQ fails at *pause time* < 300s for all # of sources
- Packets dropped because of stale routing table - forced packets over broken links
- DSDV-SQ maintains only one route per destination
- Packet is dropped if MAC layer is unable to deliver



(a) DSDV-SQ

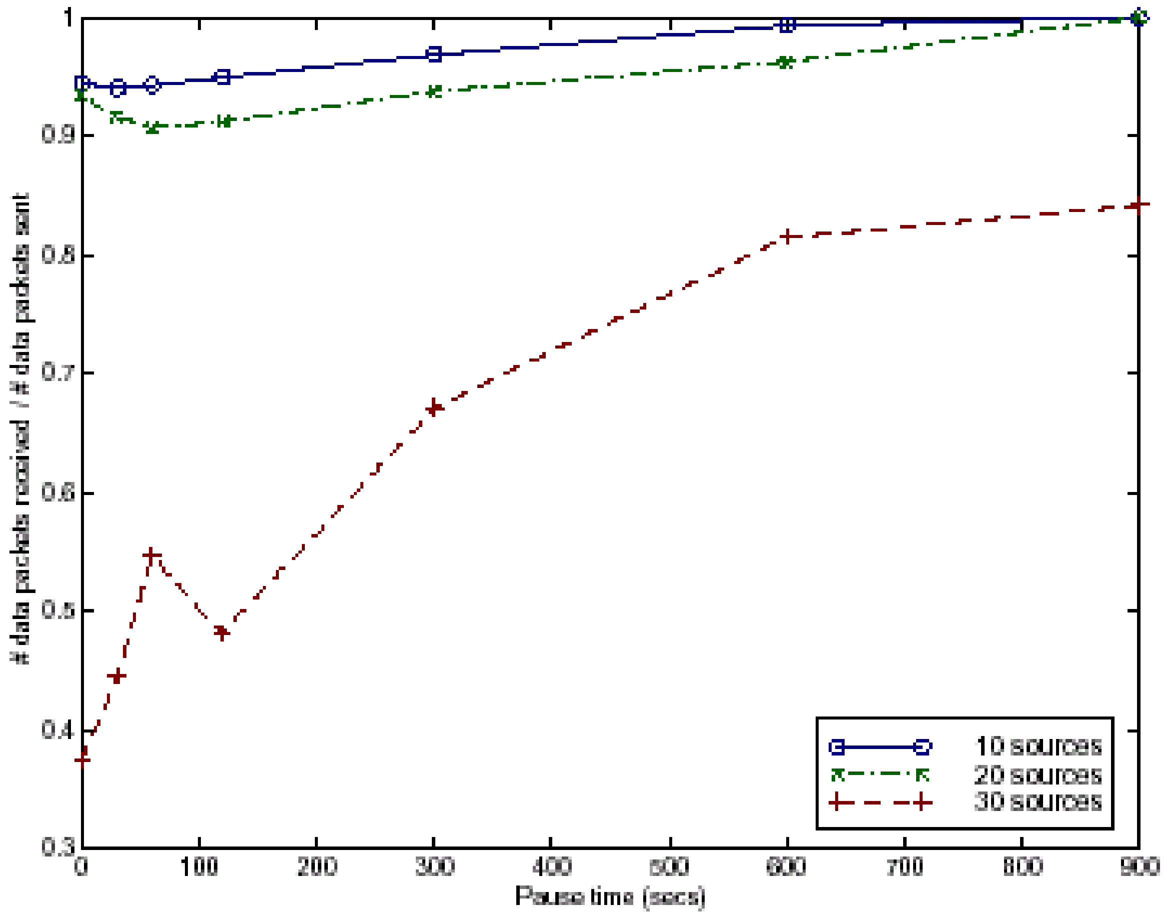
WPI

Simulation Results

Details Packet Delivery Ratio – TORA

- TORA > 90% for 10, 20 sources
- Packet drops from short-lived loops – due to link reversal

- Rate drops to 40% with 30 sources at full mobility
- Here TORA fails due to congestion collapse



(c) TORA

Simulation Results

Details Routing Overhead – Comparison for All Sources

- TORA, DSR, AODV-LL being on demand protocols show overhead increases as sources increase
- DSR and AODV-LL have same shape plots but AODV-LL has nearly 5 times the overhead
- DSDV-SQ has near constant overhead

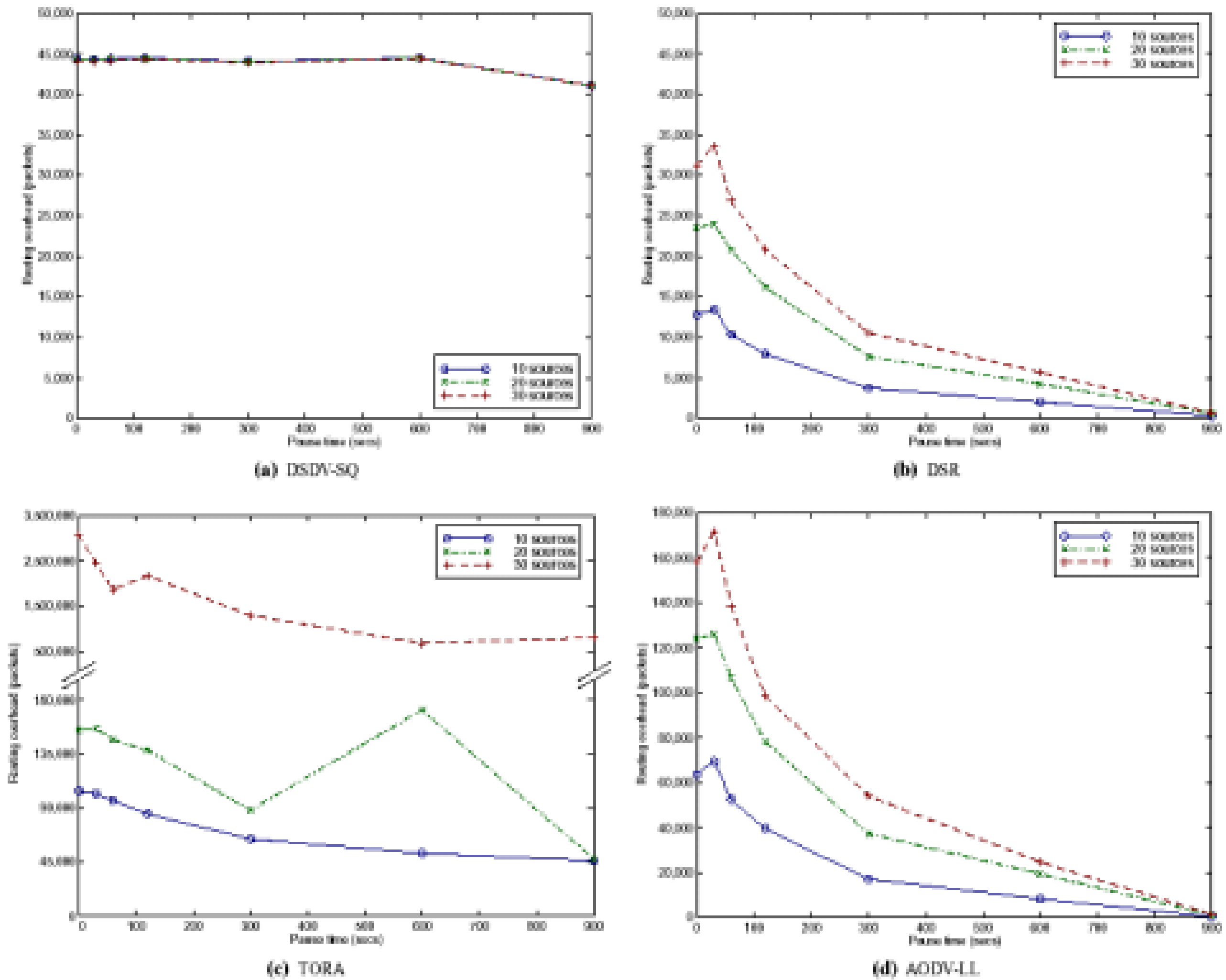


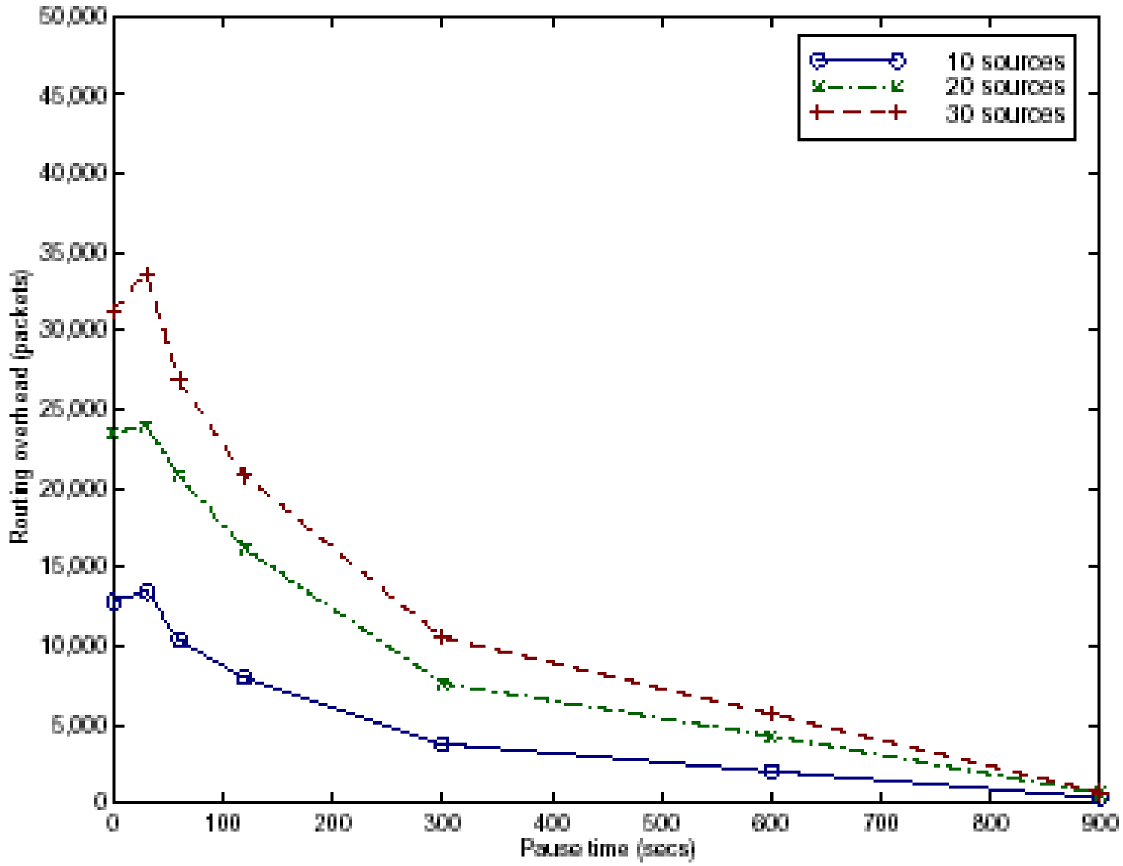
Figure 5 Routing overhead as a function of pause time. TORA and AODV-LL are shown on different vertical scales for clarity (see Figure 3).

WPI

Simulation Results

Details Routing Overhead – DSR

- With increase in sources incremental increase in overhead is proportionally less
- Info from one Route Discovery used to complete a new one
- DSR uses caching, promiscuous interface, and zero hop route requests to limit overhead

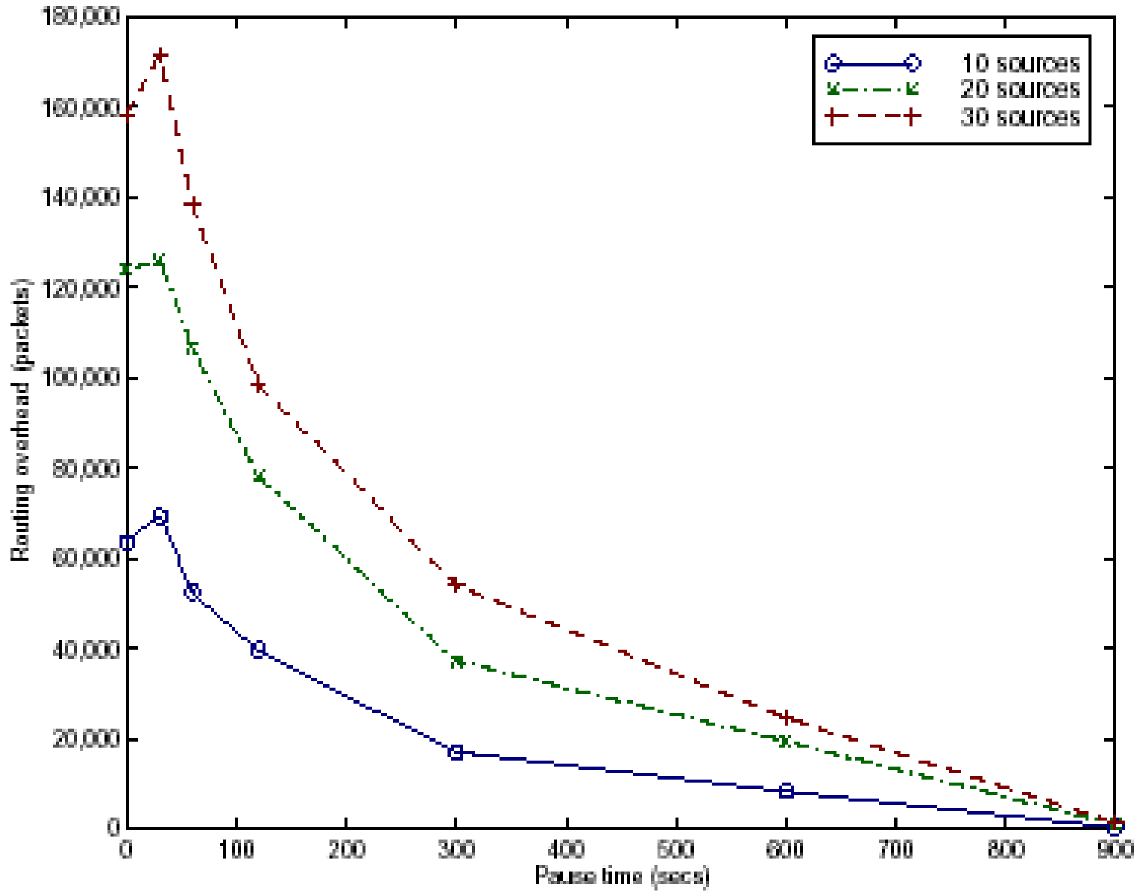


(b) DSR

Simulation Results

Details Routing Overhead – AODV-LL

- Same characteristic as DSR with increasing sources
- AODV-LL has up to 5 times the overhead of DSR
- Difference due to route discoveries going to every node and lack of caching

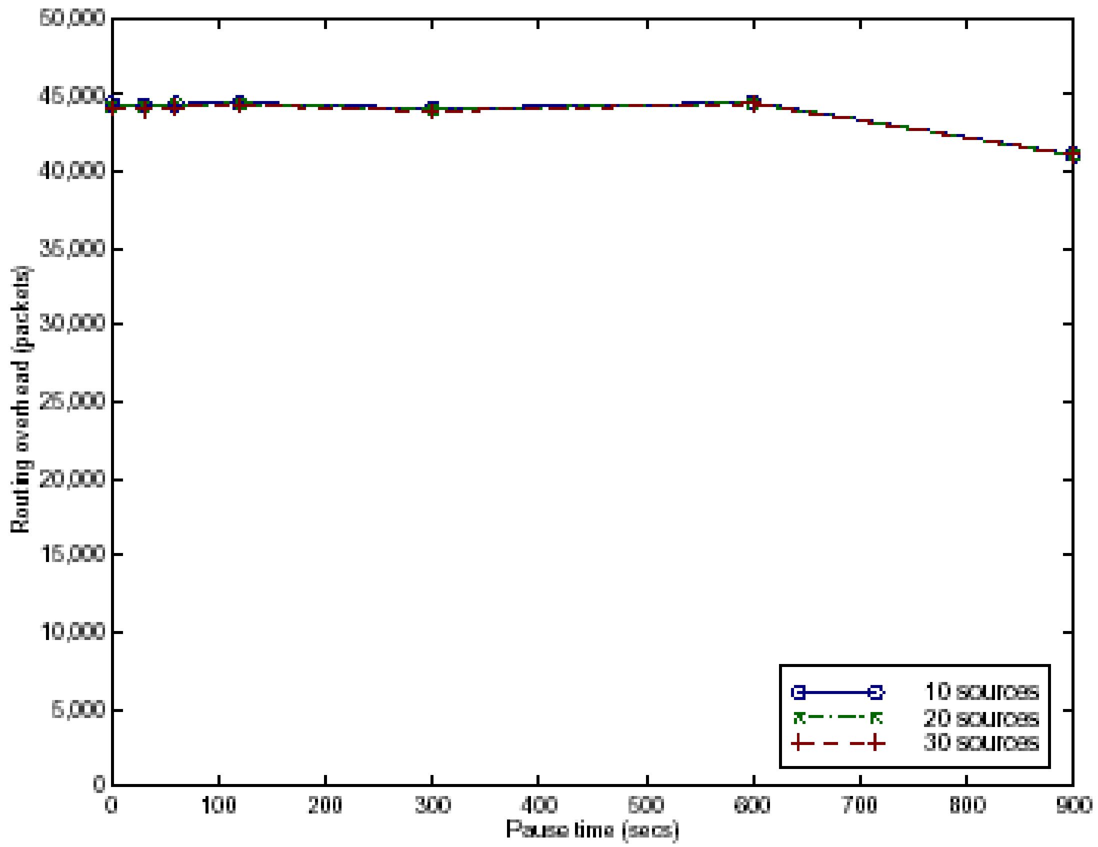


(d) AODV-LL

Simulation Results

Details Routing Overhead – DSDV-SQ

- DSDV-SQ has near constant overhead
- Destination updates SN each15s
- With 50 nodes a periodic update with new SN is being sent every second
- New SN generates triggered updates from each node receiving it
- Effective rate of triggered updates is one per node per second = 45,000 for 900s simulation

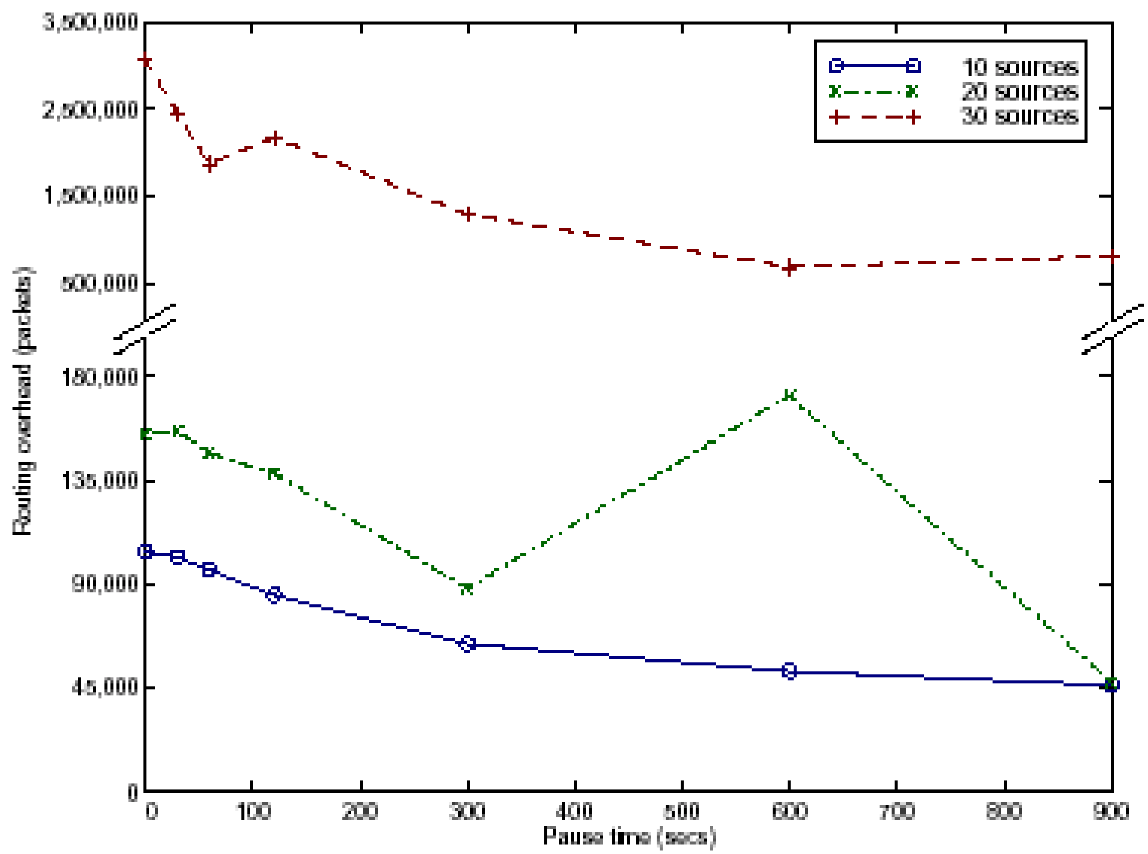


(a) DSDV-SQ

Simulation Results

Details Routing Overhead – TORA

- Constant and variable routing overhead
- Constant part due to IMEP Beacon/Hello messages for neighbor discovery
- Variable part from TORA route discovery and maintenance times IMEP control for in-order delivery
- Overhead causes collisions and data packet drops
- Perceptions of links breaking causes more UPDATES - collapse



(c) TORA

Simulation Results

Details Path Optimality

- DSDV-SQ and DSR used close to optimal routes – no change is noticed when broken out by pause time
- AODV-LL and TORA exceeded optimal as much as four hops – though TORA does not attempt to be optimal
- AODV-LL and TORA difference from optimal increases with mobility

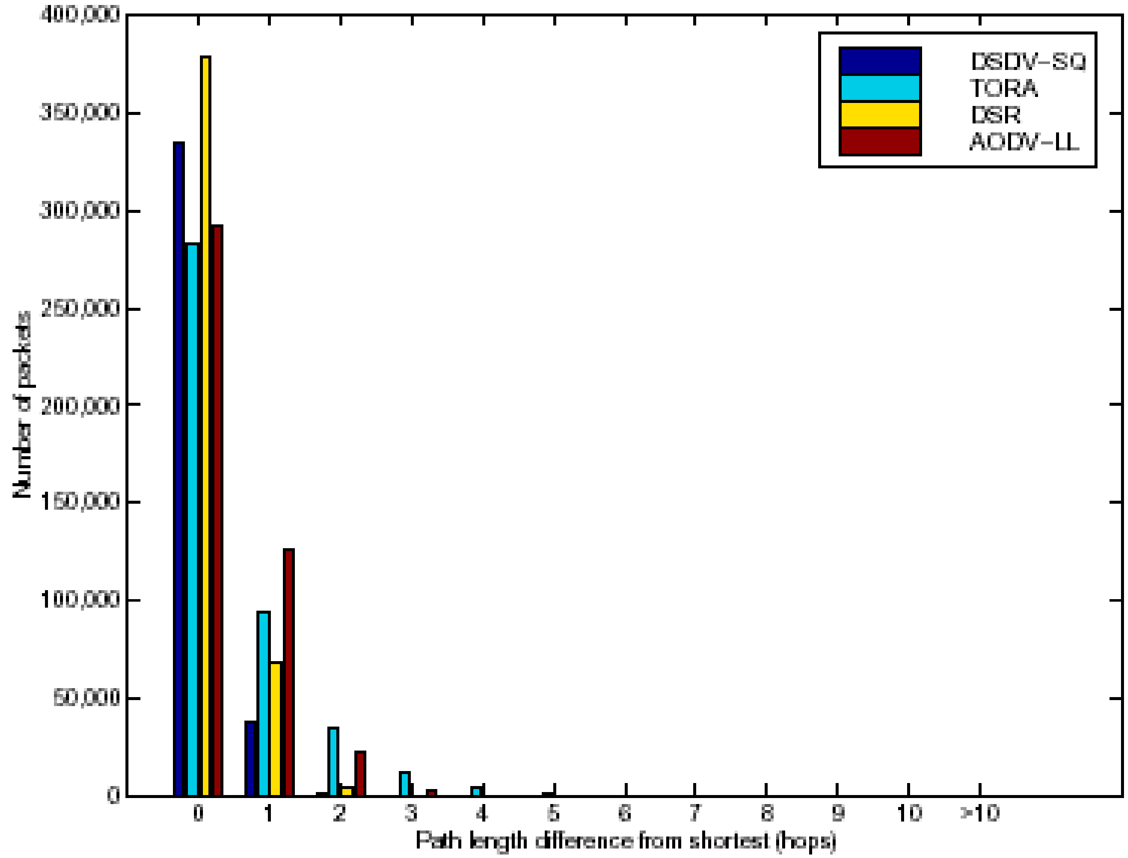


Figure 6 Difference between the number of hops each packet took to reach its destination and the optimal number of hops required. Data is for 20 sources.

Simulation Results

Lower Movement Speed – 1m/s

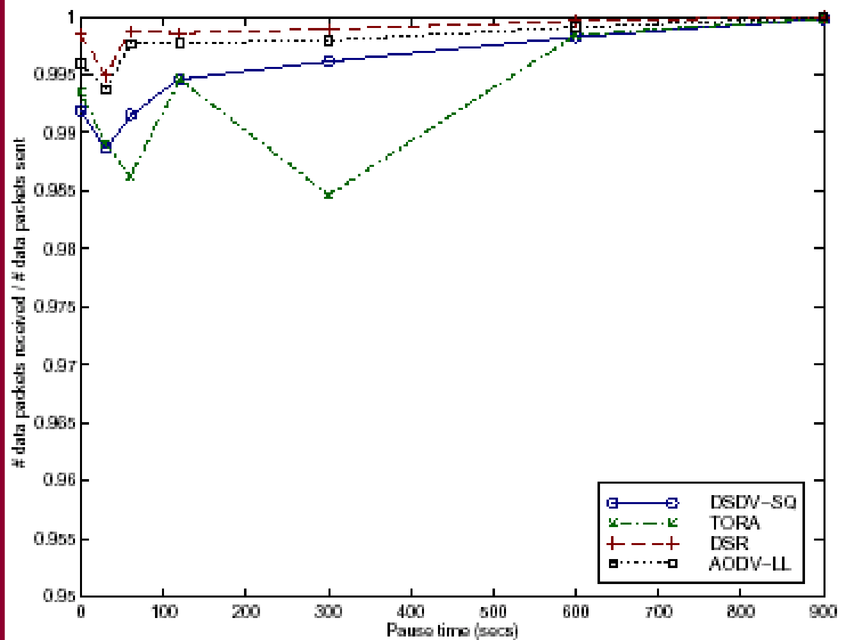


Figure 7 Comparison of the fraction of application data packets successfully delivered as a function of pause time. Speed is 1 m/s.

- DSDV-SQ periodicity continues to produce consistent overhead
- TORA still troubled by its link status/sensing mechanism IMEP

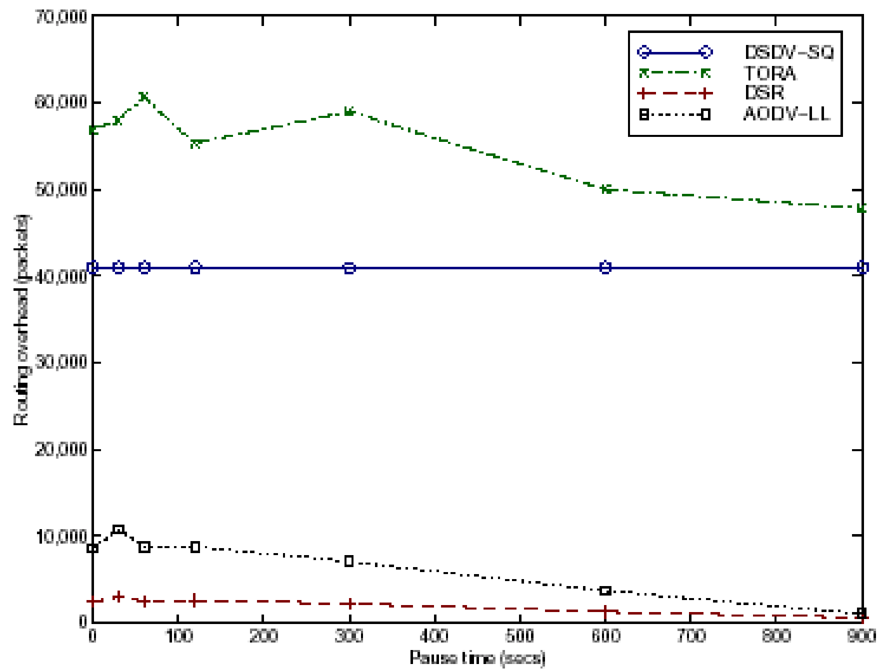


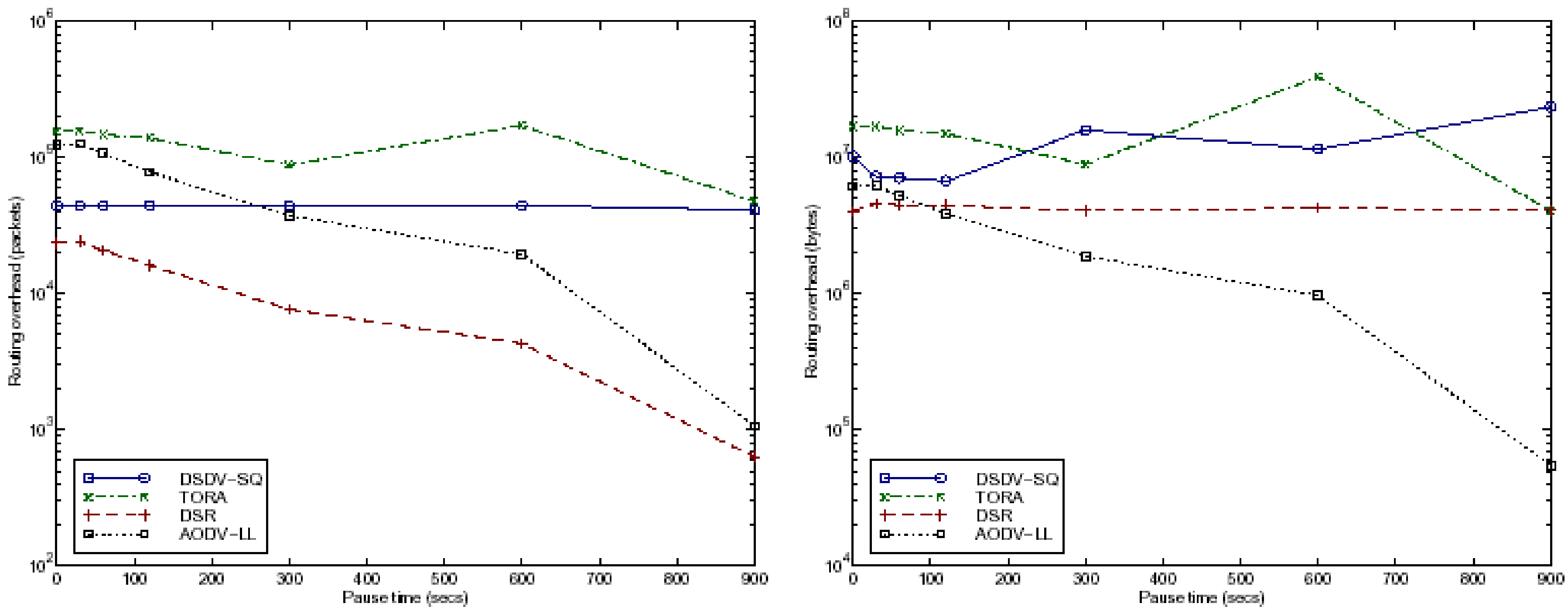
Figure 8 Comparison of the number of routing packets sent as a function of pause time. Speed is 1 m/s.

- All protocols deliver more than 98.5% of packets

Additional Observations

Source Routing Overhead - Bytes vs Packets

- When overhead measured in bytes AODV-LL outperforms DSR – AODV keeps a hop by hop state count vs. the source routing info in the DSR packet header



(a) Routing overhead in packets.

(b) Routing overhead in bytes.

Figure 9 Contrasting routing overhead in packets and in bytes. Both graphs use semi-log axes.

Additional Observations

DSDV-SQ vs. DSDV

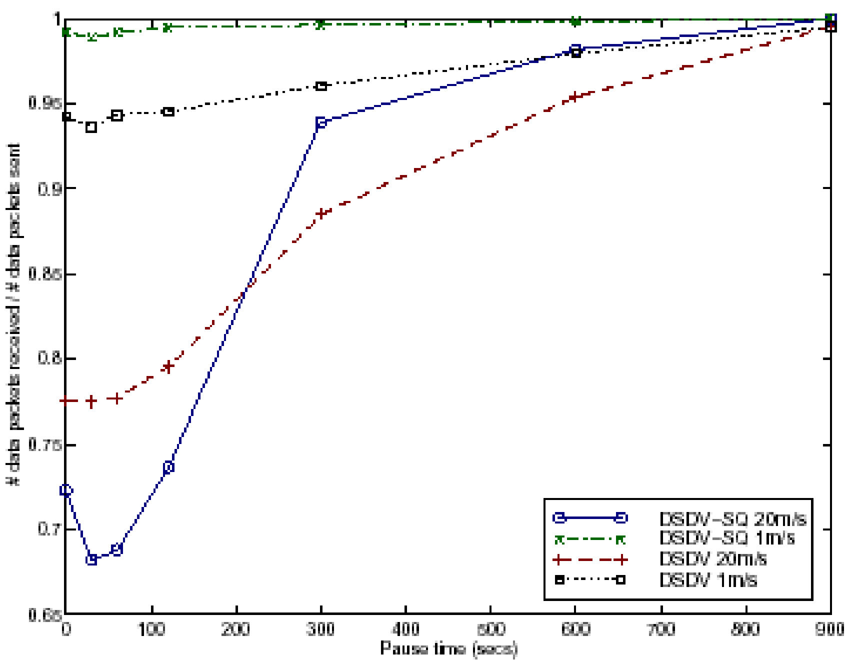


Figure 10 Fraction of originated data packets successfully delivered by DSDV-SQ and DSDV.

DSDV overhead is nearly a factor of four less than DSDV-SQ

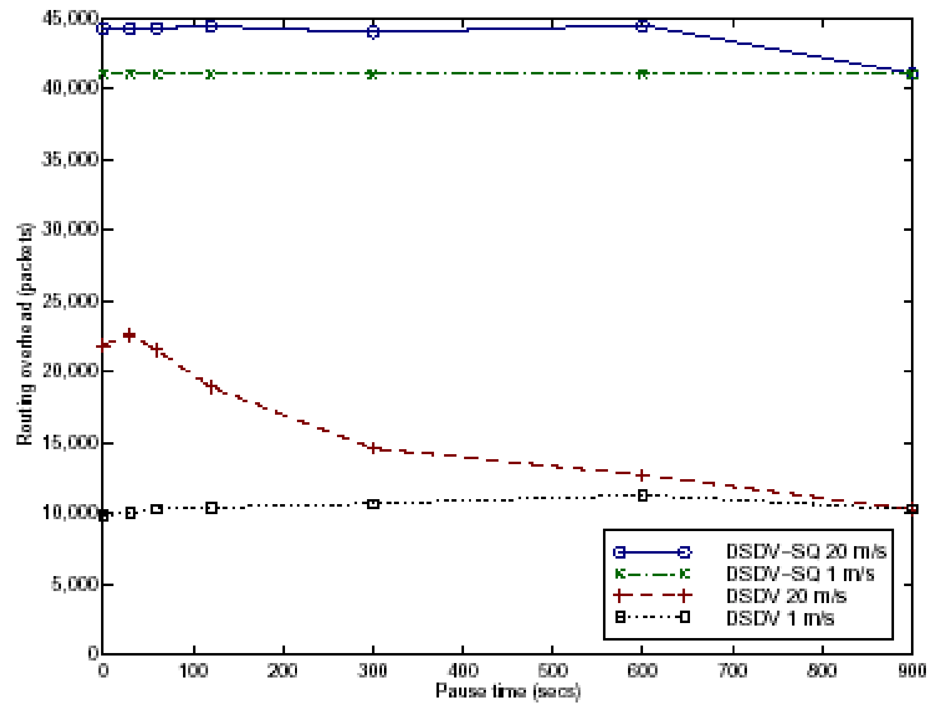


Figure 11 Routing overhead as a function of pause time for DSDV-SQ and DSDV.

Triggered updates with every new SN vs. updates only with new metric

Additional Observations

Reliability of Broadcast Packets

- Broadcast packets can not reserve wireless channel before transmitting
- Therefore they are less reliable than unicast packets
- Sampling of scenarios found that 99.8% unicast packets were successfully received vs. 92.6% of broadcast packets
- The difference due to collisions

Summary

- First paper to perform realistic quantitative analysis comparing performance of ad hoc networking protocols
- Modification of *ns-2* network simulator provides an accurate simulation of MAC and physical layer of 802.11 standard
- Simulated protocols cover a range of design choices

Conclusion

- DSDV performs well at low mobility and low speed with consistent overhead
- TORA is worst in overhead but delivers over 90% at 10,20 sources – doesn’t scale
- DSR performs well at all rates, speeds and sources with low packet overhead – source routing causes high byte overhead
- AODV performs near as well as DSR eliminating source routing overhead - # of overhead packets is high which can be more “expensive”at high mobility

WPI

BACKUP SLIDES

DSDV-SQ

Implementation Mechanisms - Sim Constants

Table I Constants used in the DSDV-SQ simulation.

Periodic route update interval	15 s
Periodic updates missed before link declared broken	3
Initial triggered update weighted settling time	6 s
Weighted settling time weighting factor	7/8
Route advertisement aggregation time	1 s
Maximum packets buffered per node per destination	5

TORA

Implementation Mechanisms - Sim Constants

Table II Constants used in the TORA simulation.

BEACON period	1 s
Time after which a link is declared down if no BEACON or HELLO packets were exchanged	3 s
Time after which an object block is retransmitted if no acknowledgment is received	500 ms
Time after which an object block is not retransmitted and the link to the destination is declared down	1500 ms
Min HELLO and ACK aggregation delay	150 ms
Max HELLO and ACK aggregation delay	250 ms

DSR

Implementation Mechanisms - Sim Constants

Table III Constants used in the DSR simulation.

Time between retransmitted ROUTE REQUESTs (exponentially backed off)	500 ms
Size of source route header carrying *n* addresses	$4n + 4$ bytes
Timeout for nonpropagating search	30 ms
Time to hold packets awaiting routes	30 s
Max rate for sending gratuitous REPLYs for a route	1/s

AODV-LL

Implementation Mechanisms - Sim Constants

Table IV Constants used in the AODV-LL simulation.

Time for which a route is considered active	300 s
Lifetime on a ROUTE REPLY sent by destination node	600 s
Number of times a ROUTE REQUEST is retried	3
Time before a ROUTE REQUEST is retried	6 s
Time for which the broadcast id for a forwarded ROUTE REQUEST is kept	3 s
Time for which reverse route information for a ROUTE REPLY is kept	3 s
Time before broken link is deleted from routing table	3 s
MAC layer link breakage detection	yes