Analysis and Design of Link Metrics for Quality Routing in Wireless Multi-hop Networks

PhD Thesis Defense by
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Outline

- Performance Evaluation of Routing Protocols
  - Mobility/Speed Analysis
  - Scalability Analysis
  - Traffic Analysis
- Modeling Routing Overhead of Reactive Protocols
- Design Requirements for Routing Link Metrics
- Min Hop-count
- ETX-based Metrics
  - Expected Transmission Count (ETX)
  - Expected Link Performance (ELP)
  - Expected Throughput (ETP)
- New Link Metric IBETX

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Routing Protocols for Wireless Networks

- Reactive protocols
  - Reactive protocols perform RD and RM
  - Take an action when request arrives
  - More suitable for mobile scenarios
  - AODV, DSR, DYMO

- Proactive protocols
  - Periodically exchange information
  - More scalable
  - More suitable for less dynamic networks
  - DSDV, FSR, OLSR

Reactive Protocols Mobility/Speed/Scalability/Traffic Analyses

Protocol	Performance	Reasons
AODV	+++	•Provides multiple timely routes in RT •Time association •LLR quickly repairs link
DSR	++	•Multiple routes in RC •Promiscuous listening mode. •Highest speed and highest mobility, low convergence
DYMO	+	•Not suitable for highly dynamic scenarios •Absence of grat. RREPs •Absence of supplementary maintenance strategies

Proactive Protocols Mobility/Speed Analysis

Protocol	Performance	Reasons
DSDV	+++	•Delay advertisement for route stabilization (Periodic, Nghbr) •Keep data for route settling time •Periodic and triggers updates
OLSR	++	•More suitable for static or less dynamic networks •MPR-redundancy provides convergence in high mobility •Periodic updates
FSR	+	•Suitable for mobile scenarios as compared to static scenarios •Graded-frequency mechanism

Proactive Protocols Scalability Analysis

Protocol	Performance	Reasons
OLSR	+++	•More density, more optimization through MPRs •Absence of trigger updates •Retransmission reduction through MPRs
FSR	++	•Exchange link state messages by GF (<MPR) •Absence of trigger updates •Broadcasting messages only to neighbors; no flooding
DSDV	+	•Transmission of trigger updates utilize more bandwidth

Proactive Protocols
Traffic Analysis

Protocol	Performance	Reasons
FSR	+++	•Exchange link state messages by GF •Absence of trigger updates •no flooding
OLSR	++	•Absence of trigger updates •Retransmission reduction by MPRs (better in dense)
DSDV	+	•Transmission of trigger updates utilize more bandwidth

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Modeling Routing Overhead-Motivation

- [Park06] define cost for routing overhead for reactive protocols;

$$C_{total}^{(rp)} = C_E^{(rp)} \times C_T^{(rp)}$$

- No evaluation for C_E and C_T,

- We define Energy Consumed per packet,

$$C_E^{(rp)} = C_{E-RD}^{(rp)} + C_{E-RM}^{(rp)}$$

- We define Time Consumed per packet,

$$C_T^{(rp)} = C_{T-RD}^{(rp)} + C_{T-RM}^{(rp)}$$

Modeling Routing Overhead-Motivation

- [sal10] considered:
  - only RREQ;
  - modeled only RD
  - evaluated energy-cost

- We consider:
  - both RREQ, RREP and RERR overheads
  - both RD and RM
  - evaluate both energy and time-cost of RD and RM

Flooding

- Flooding exchanges topological information in a network
  - Plain flooding
    - Each received packet is (re)transmitted
  - Super flooding
    - A packet is (re)transmitted, if it has a shorter path
  - MPRs flooding
    - Only MPR nodes flood
  - Blind flooding
    - Each packet is (re)transmitted for first time

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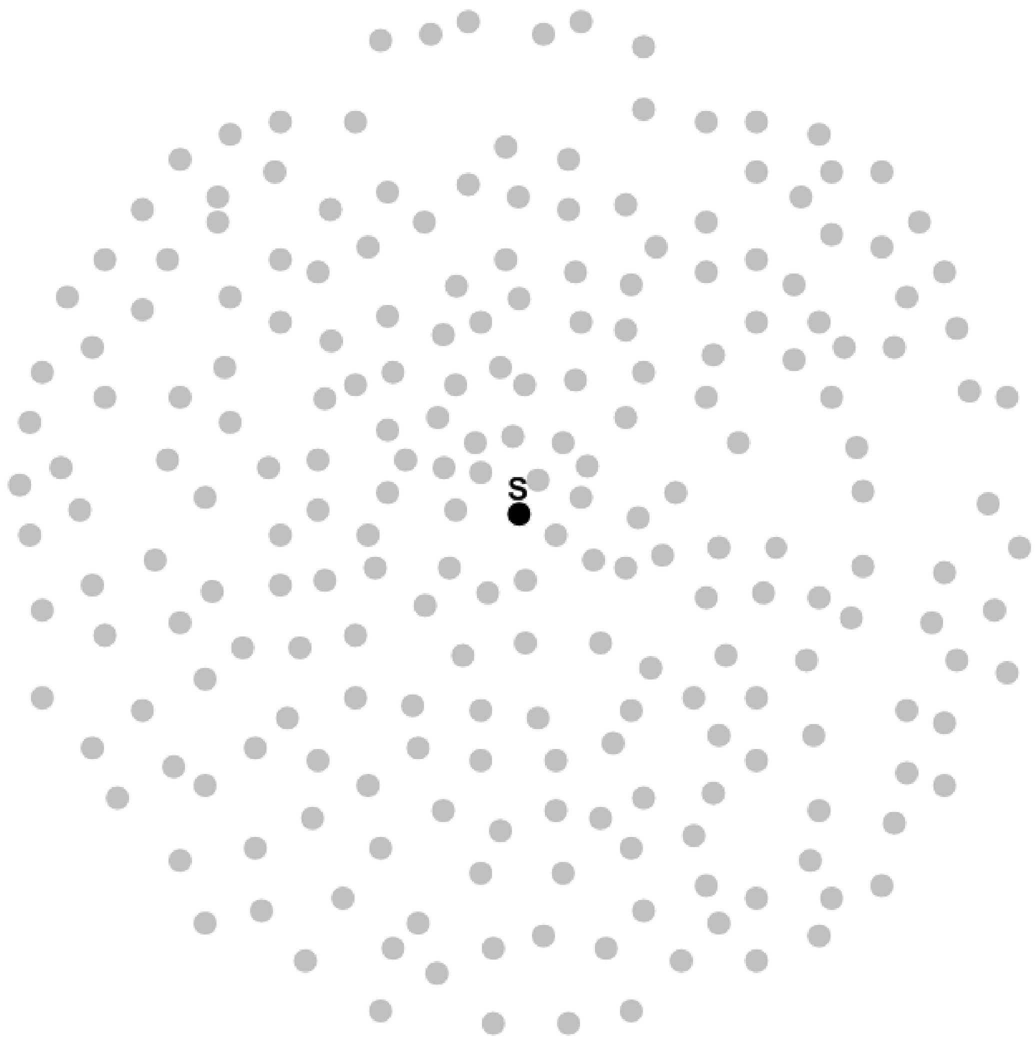

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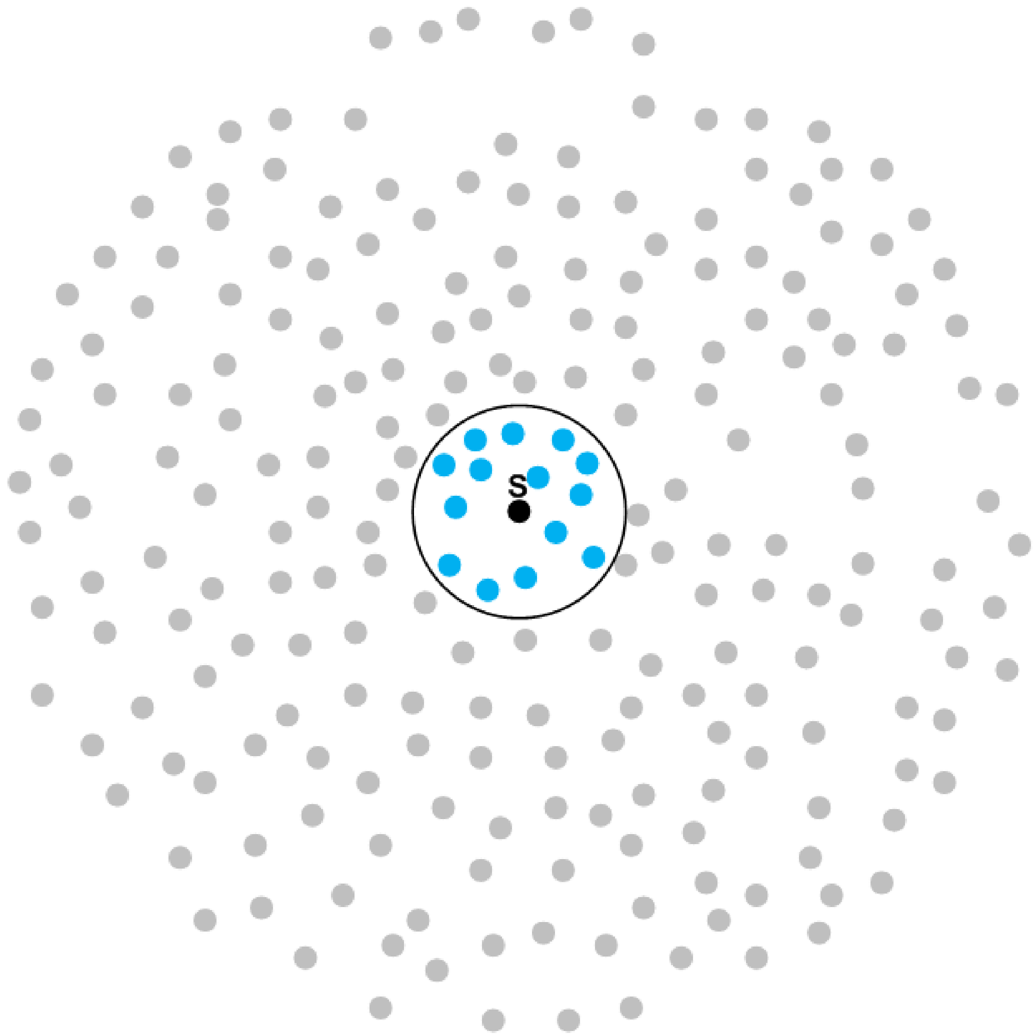

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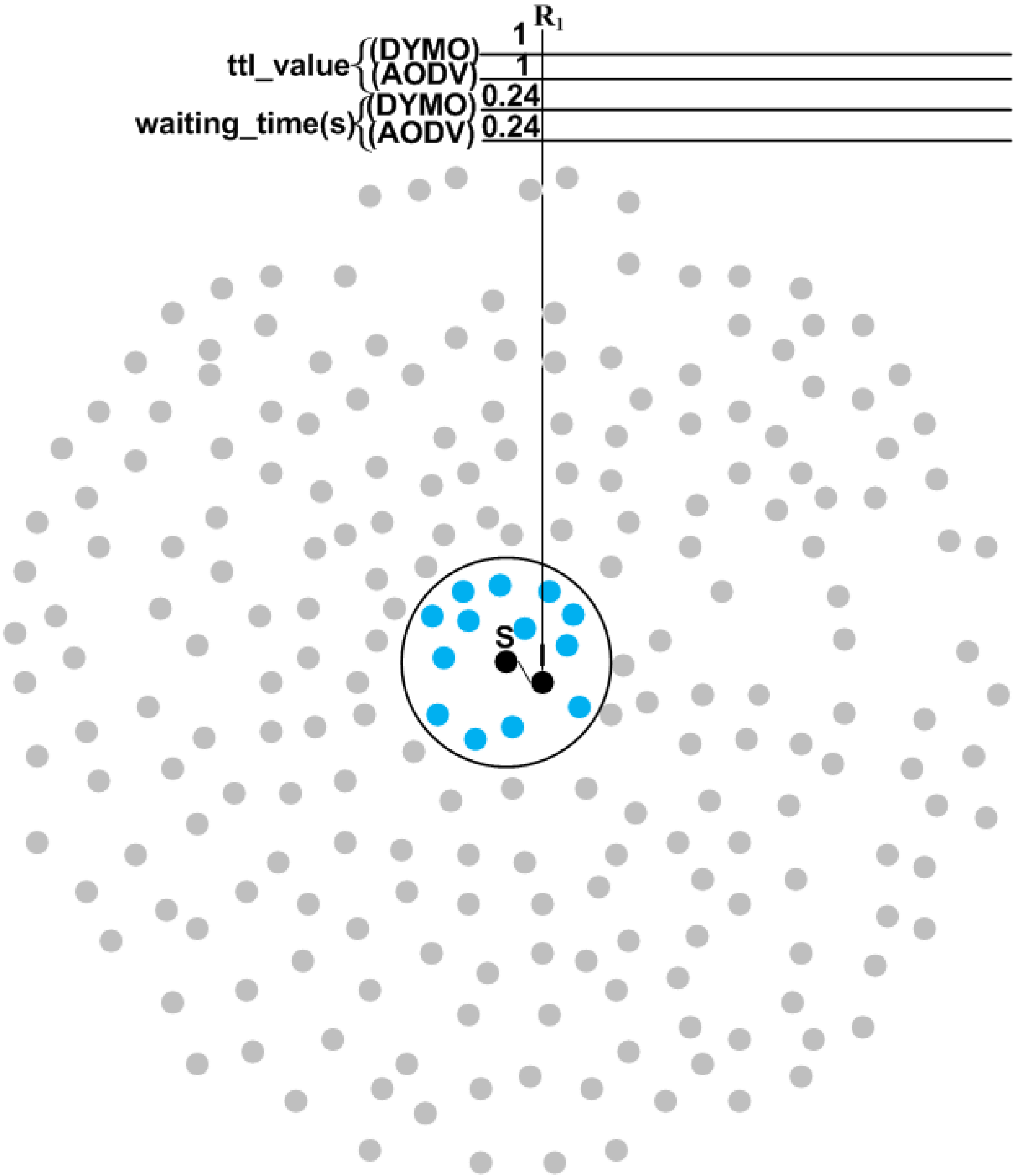

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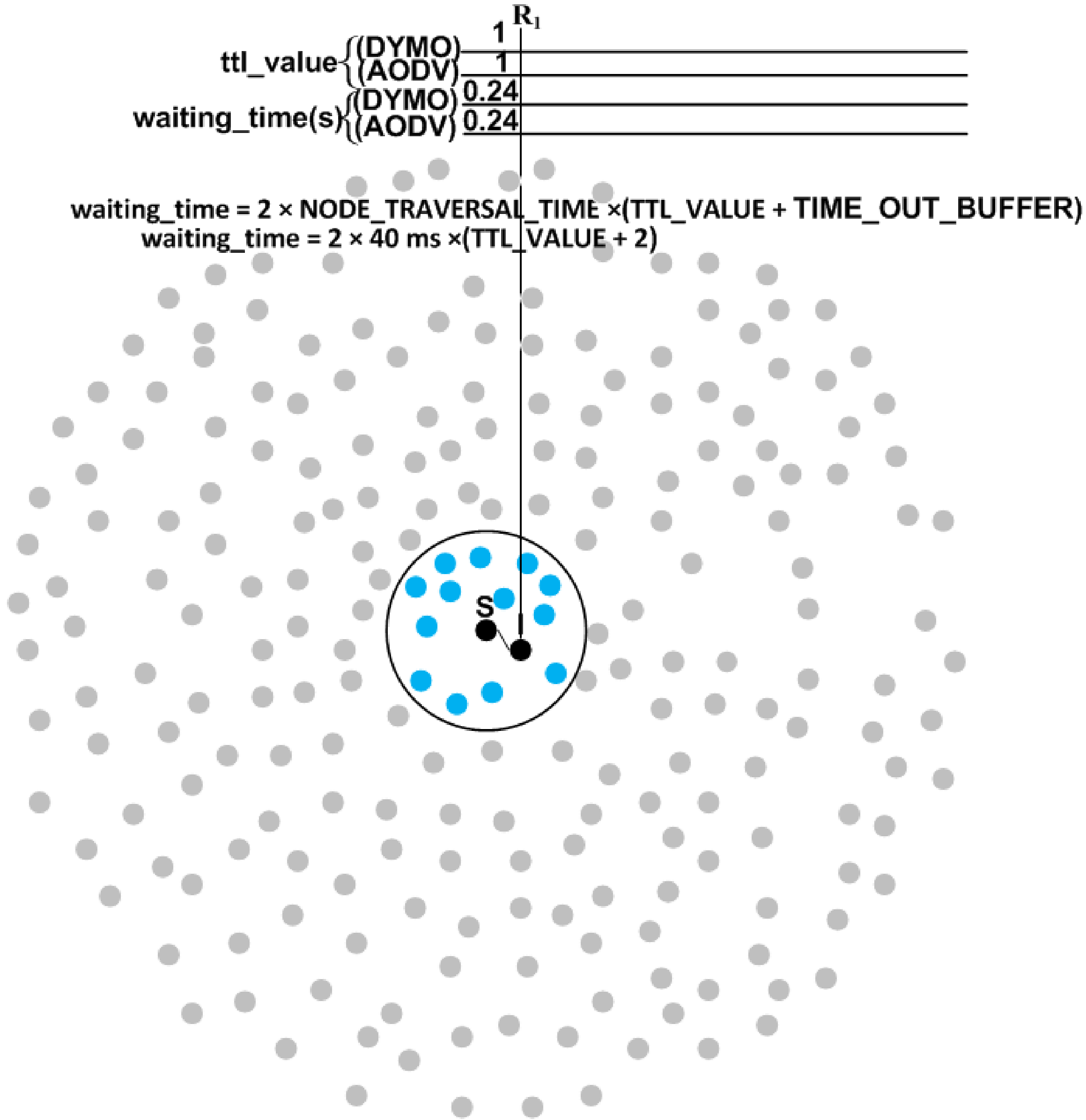
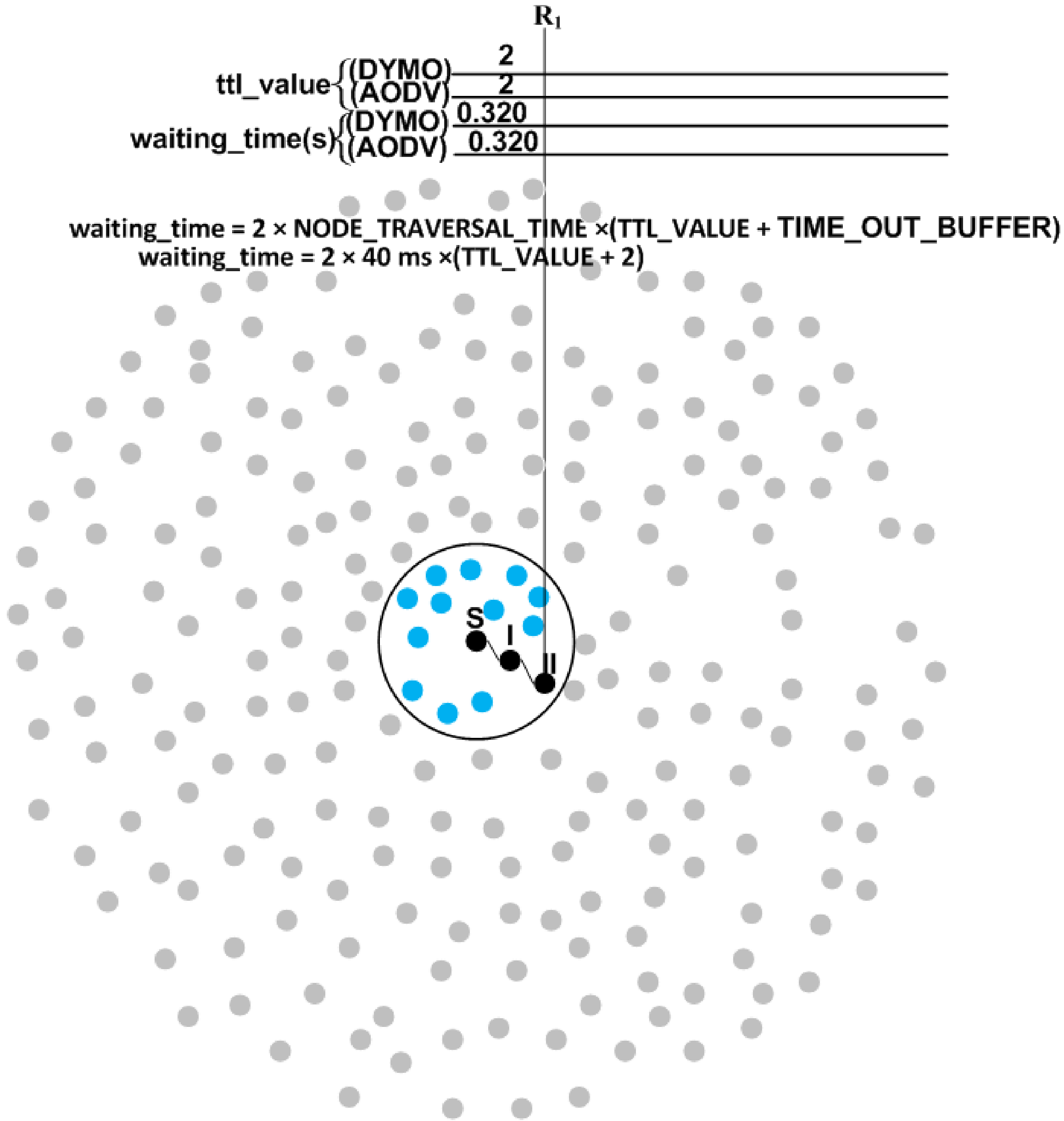
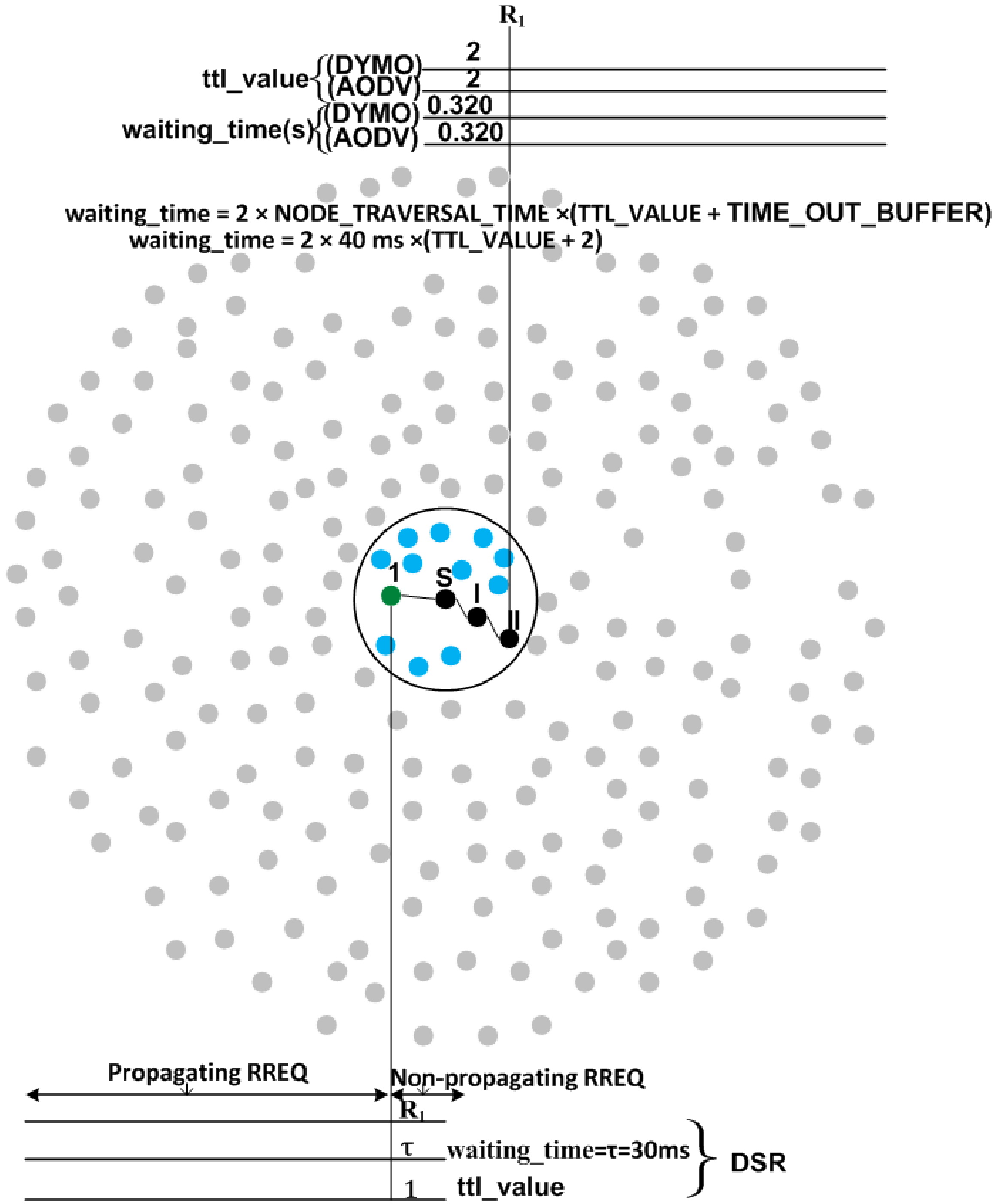

R1
ttl_value (DYMO) 1
(AODV) 1
waiting_time(s) (DYMO) 0.24
(AODV) 0.24
waiting_time = 2 × NODE_TRAVERSAL_TIME ×(TTL_VALUE + TIME_OUT_BUFFER)
waiting_time = 2 × 40 ms ×(TTL_VALUE + 2)
S
I

ERS



R1
ttl_value
(DYMO) 2
(AODV) 2
waiting_time(s)
(DYMO) 0.320
(AODV) 0.320
waiting_time = 2 × NODE_TRAVERSAL_TIME ×(TTL_VALUE + TIME_OUT_BUFFER)
waiting_time = 2 × 40 ms ×(TTL_VALUE + 2)
S
I
II

ERS



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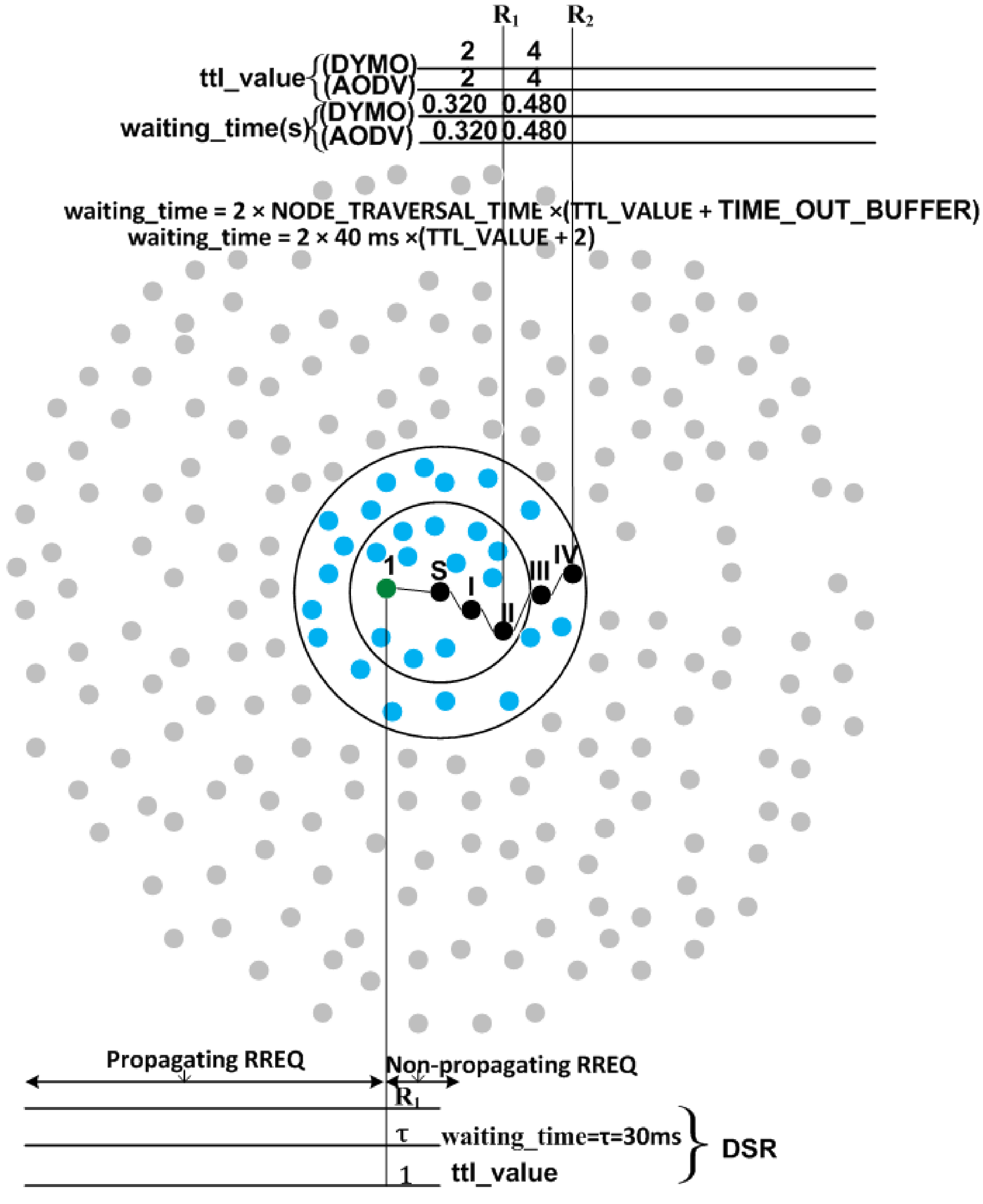

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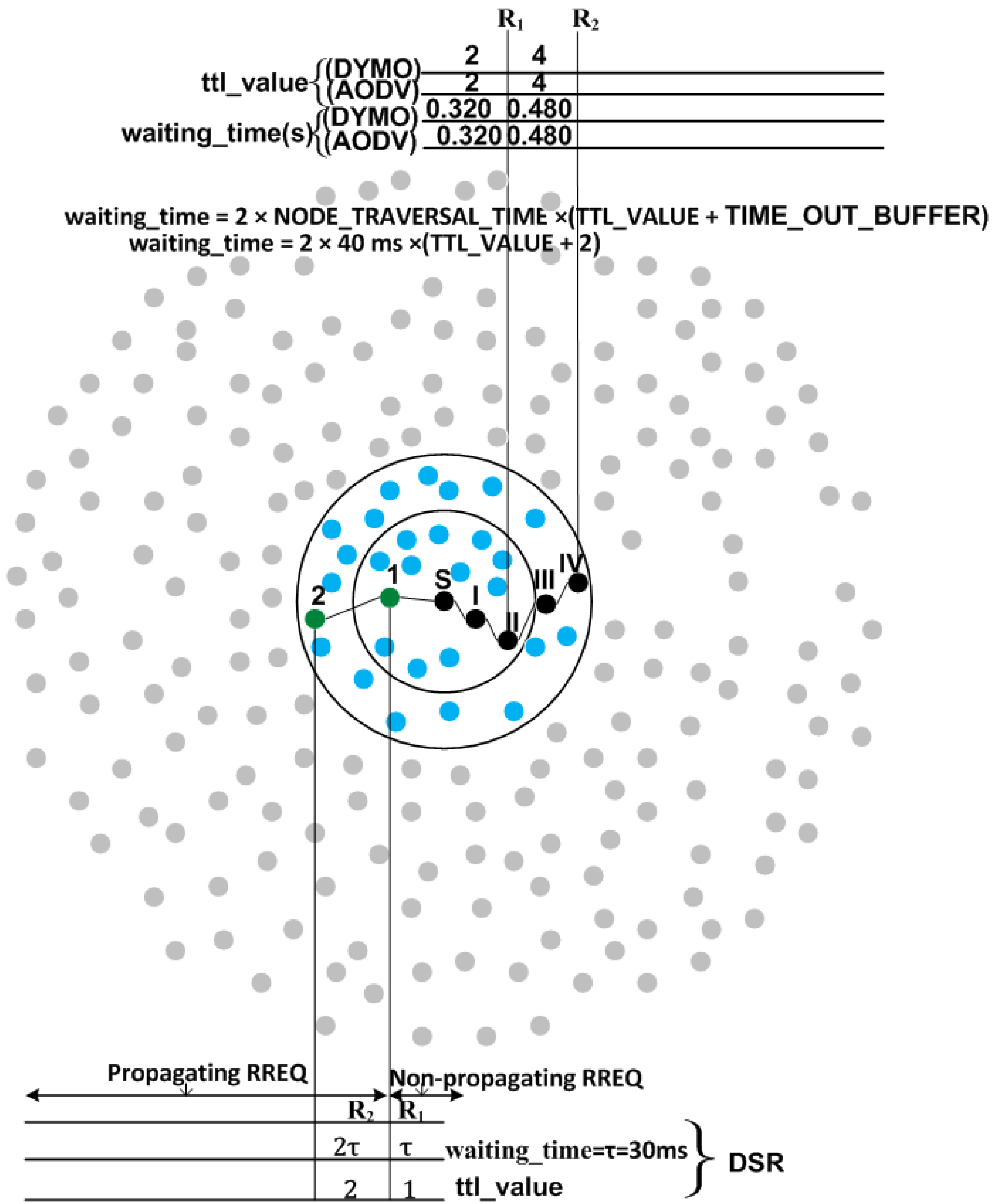

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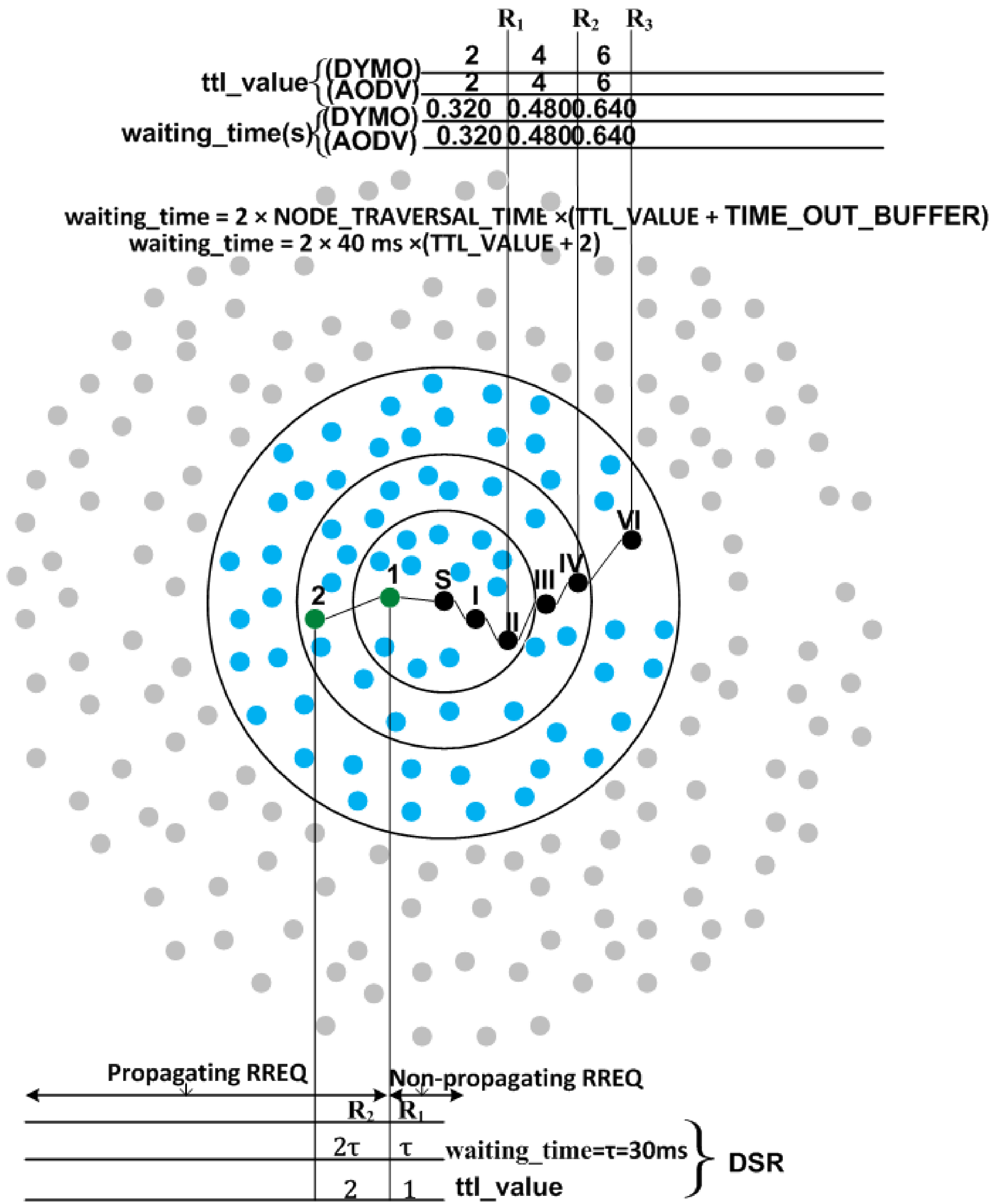
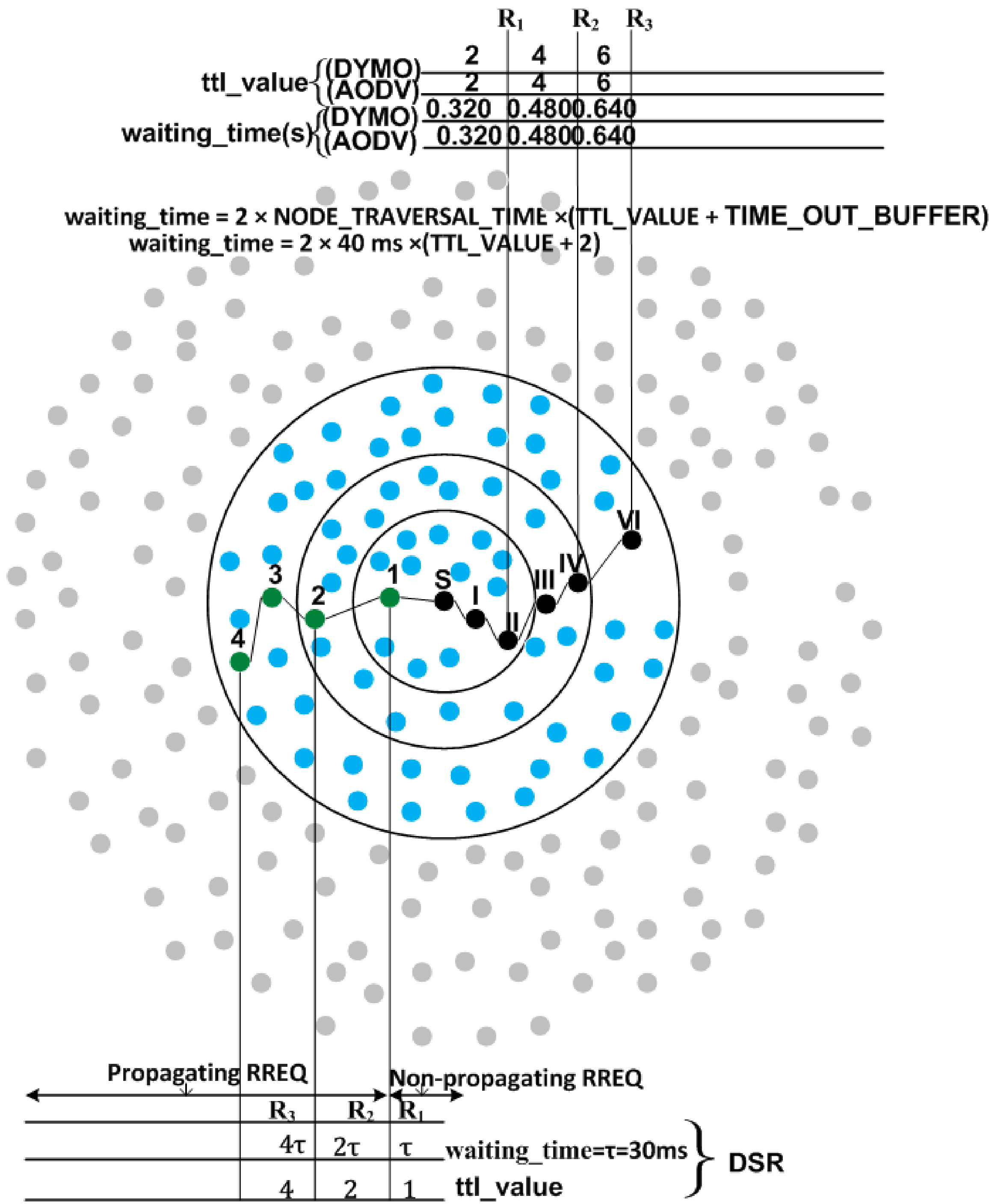
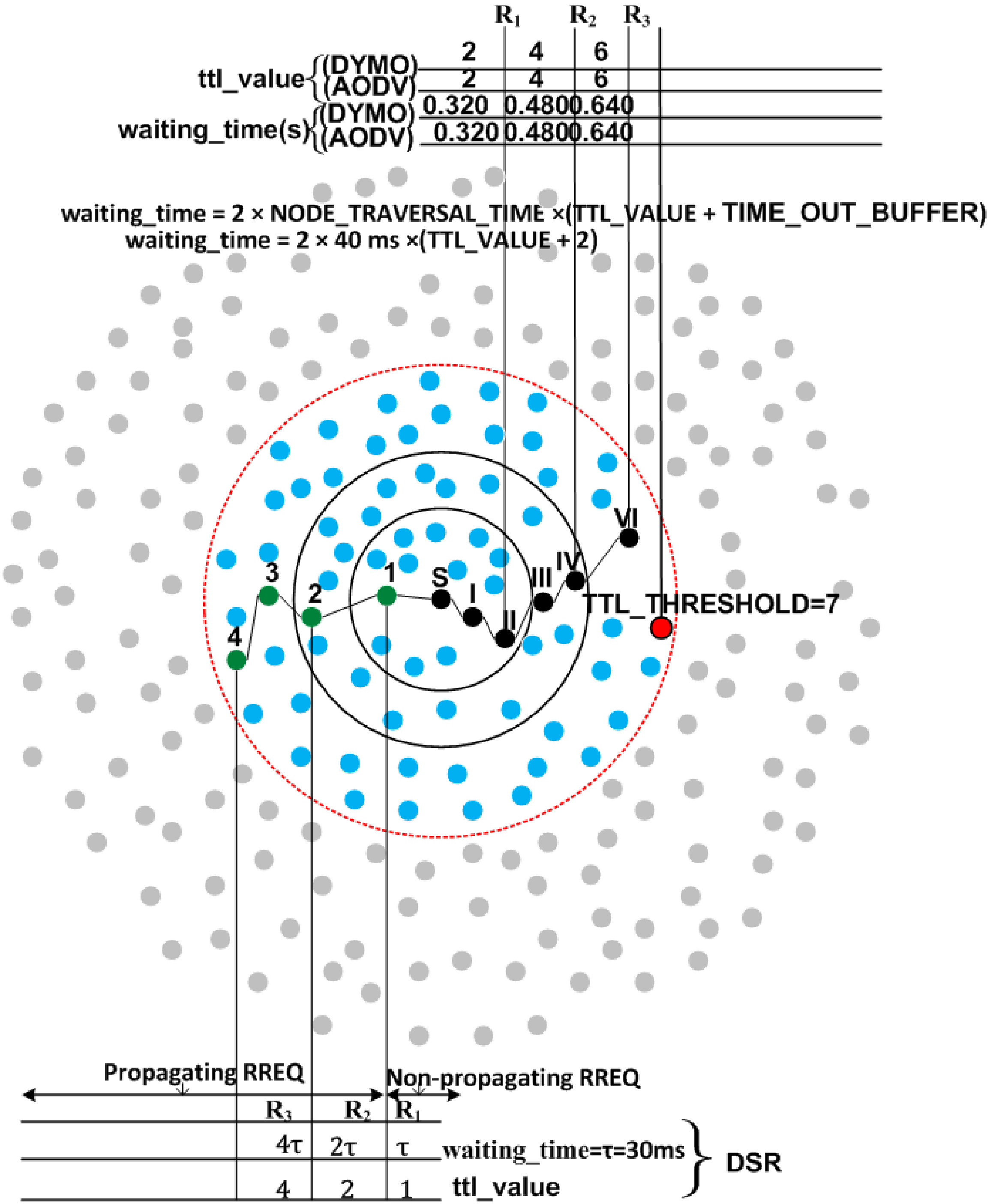

R1 R2 R3
ttl_value (DYMO) 2 4 6
(AODV) 2 4 6
waiting_time(s) (DYMO) 0.320 0.480 0.640
(AODV) 0.320 0.480 0.640
waiting_time = 2 × NODE_TRAVERSAL_TIME ×(TTL_VALUE + TIME_OUT_BUFFER)
waiting_time = 2 × 40 ms ×(TTL_VALUE + 2)
VI
IV
III
II
I
S
1
2
Propagating RREQ
Non-propagating RREQ
R2 R1
2τ τ waiting_time=τ=30ms
2 1 ttl_value
DSR

ERS



R1 R2 R3
ttl_value (DYMO) 2 4 6
(AODV) 2 4 6
waiting_time(s) (DYMO) 0.320 0.480 0.640
(AODV) 0.320 0.480 0.640
waiting_time = 2 × NODE_TRAVERSAL_TIME ×(TTL_VALUE + TIME_OUT_BUFFER)
waiting_time = 2 × 40 ms ×(TTL_VALUE + 2)
S
I
II
III
IV
VI
1
2
3
4
Propagating RREQ
Non-propagating RREQ
R3 R2 R1
4τ 2τ τ waiting_time=τ=30ms
4 2 1 ttl_value
DSR

ERS



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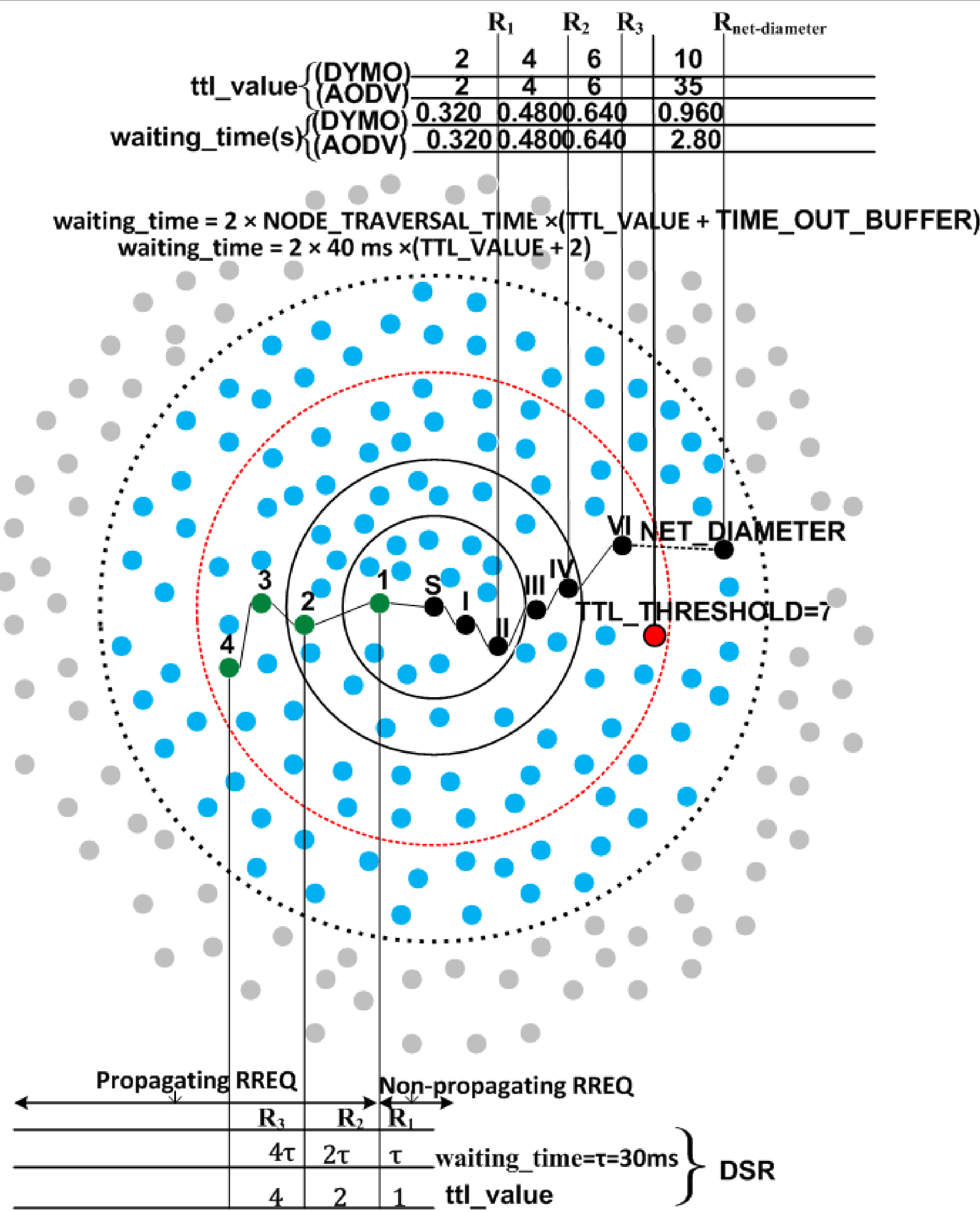
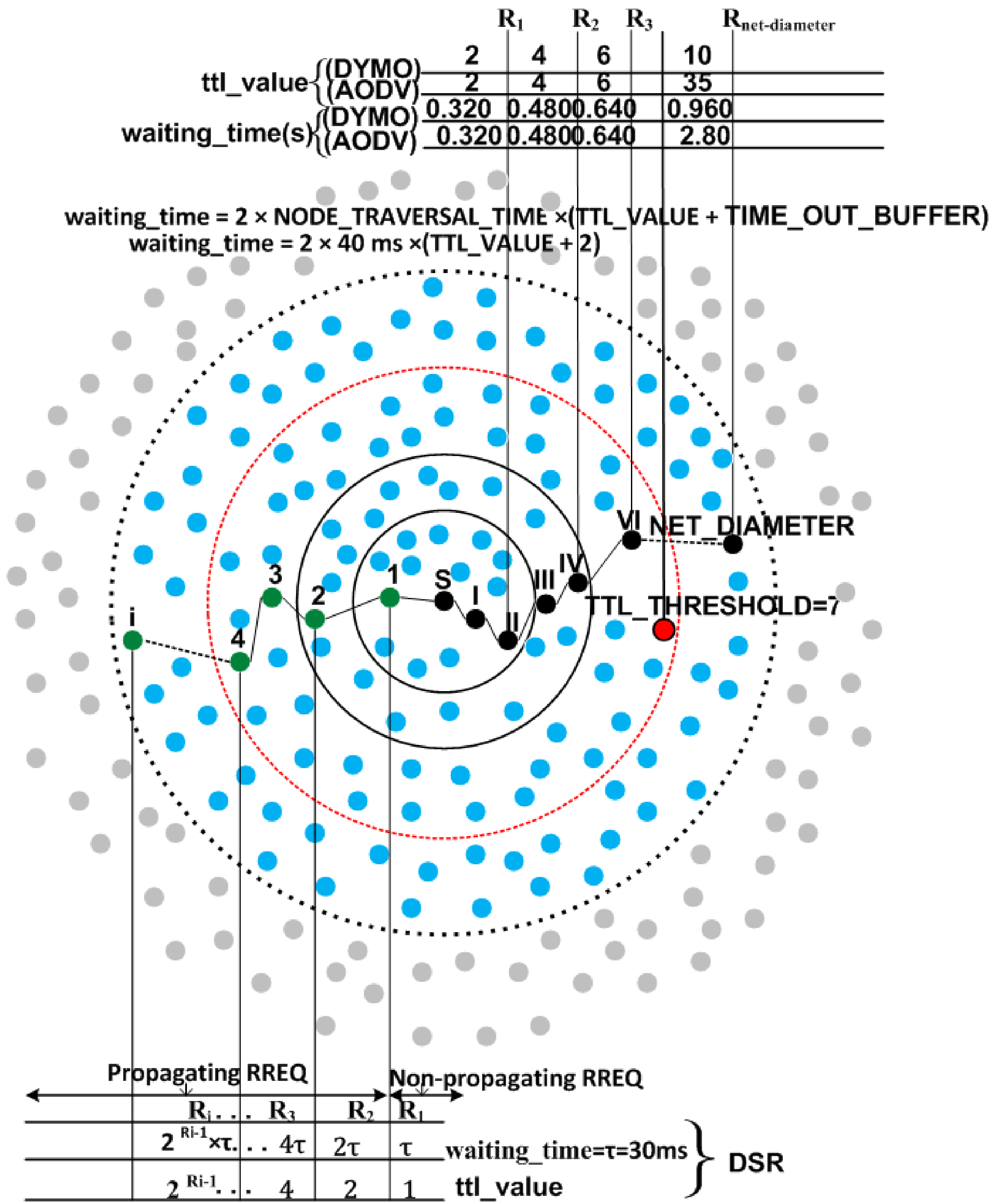


R1 R2 R3 Rnet-diameter
ttl_value (DYMO) 2 4 6 10
(AODV) 2 4 6 35
waiting_time(s) (DYMO) 0.320 0.480 0.640 0.960
(AODV) 0.320 0.480 0.640 2.80
waiting_time = 2 × NODE_TRAVERSAL_TIME ×(TTL_VALUE + TIME_OUT_BUFFER)
waiting_time = 2 × 40 ms ×(TTL_VALUE + 2)
VI NET_DIAMETER
S
I
II
III
IV
TTL_THRESHOLD=7
1
2
3
4
Propagating RREQ
Non-propagating RREQ
R3 R2 R1
4τ 2τ τ waiting_time=τ=30ms
4 2 1 ttl_value
DSR

ERS



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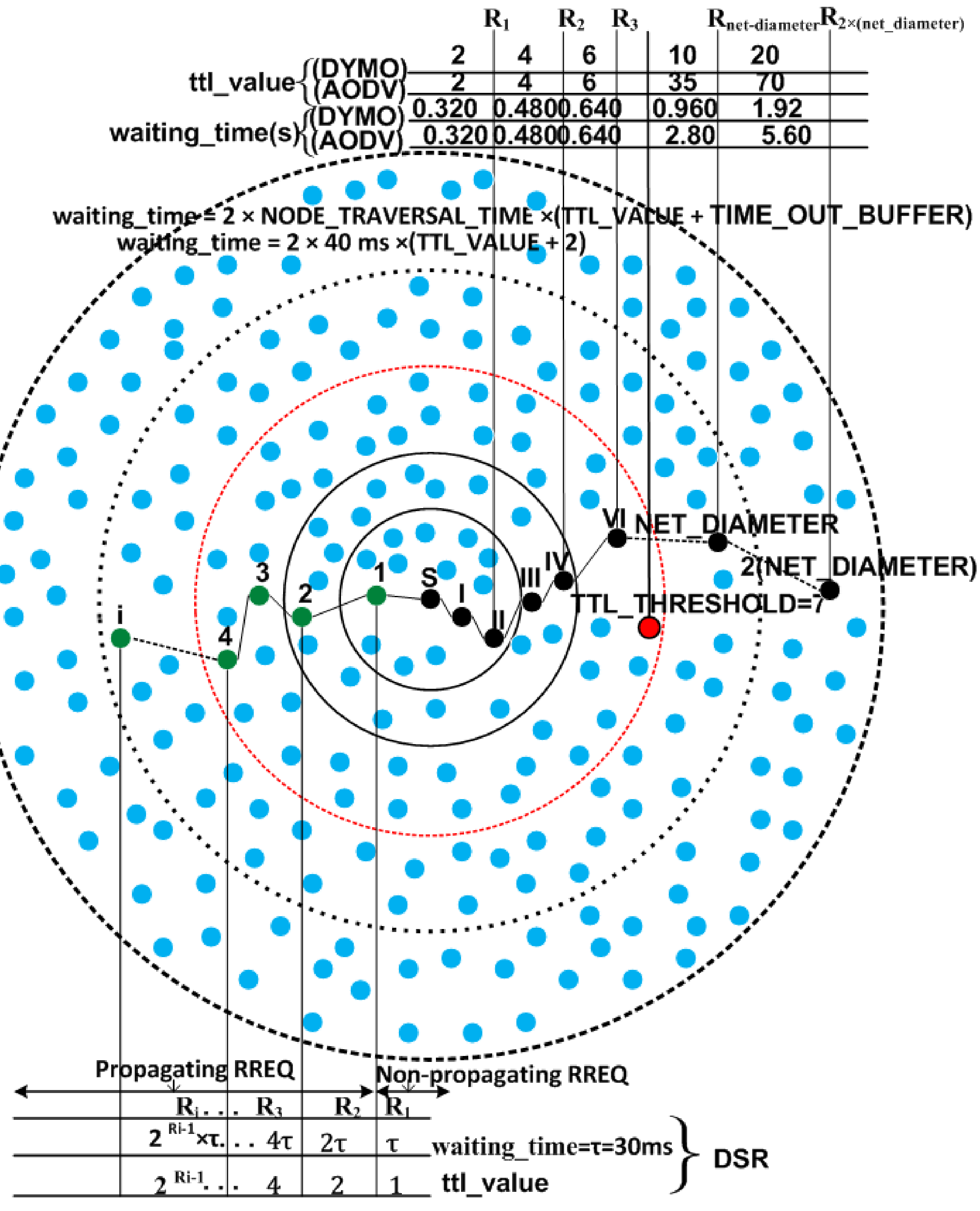

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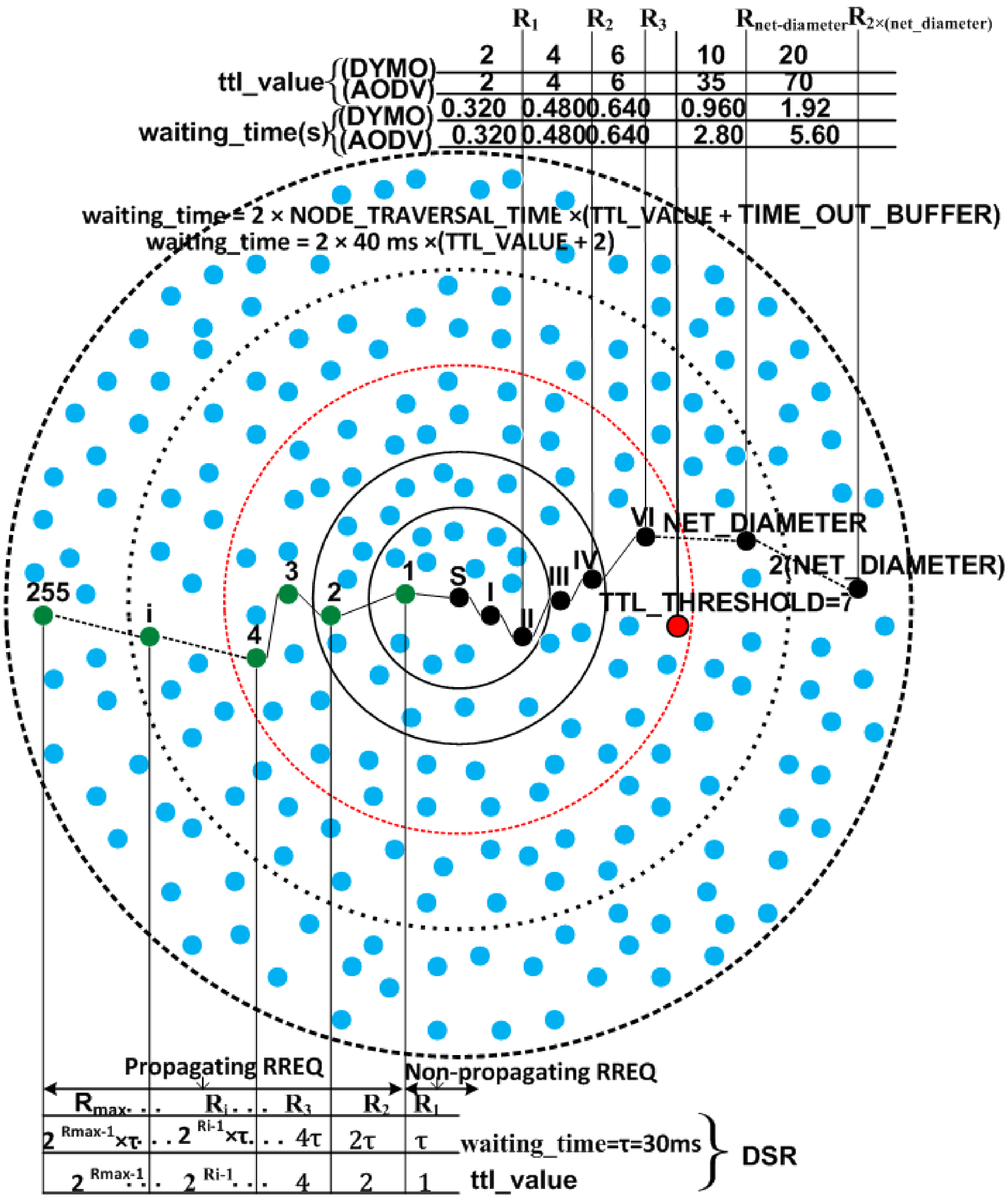

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Energy-cost for RD

- Energy-cost for a single ring,

$$C_{E-R_i} = \begin{cases} P_r \times d_{avg} & if\, TTL(R_i) = 1 \\ \{P_r d_{avg} + d_{avg} \sum_{TTL=1}^{TTL(R_i)-1} (P_r)^{TTL+1} \prod_{j=1}^{TTL} d_f[j]\} & otherwise \\ \quad \{R_i \backslash R_i \in R_i \rightarrow R_{rrep} \vee R_i \in R_i \rightarrow R_{max\_limit}\} & \end{cases}$$

- We consider routing overhead for ERS,
- Energy-cost for RD ,

$$C^{(rp)}_{E-RD} = \begin{cases} \sum_{R_i=1}^{R_{max\_limit}} (C_{E-R_i})_{R_i} & if\, no\, RREP\, received \\ C_{E-R_{rrep}} + \sum_{n=1}^{n_{rrep}} (RREP)_n & if\, TTL(R_{rrep}) = 1 \\ \sum_{R_i=1}^{R_{rrep}} (C_{E-R_i})_{R_i} + \sum_{n=1}^{n_{rrep}} (RREP)_n & otherwise \\ \quad \{R_{rrep} = 1, 2, 3, ..., max\_limit\} & \end{cases}$$

Time-cost for RD

o AODV and DYMO

waiting_time = 2 × NODE_TRAVERSAL_TIME ×(TTL_VALUE + TIME_OUT_BUFFER)

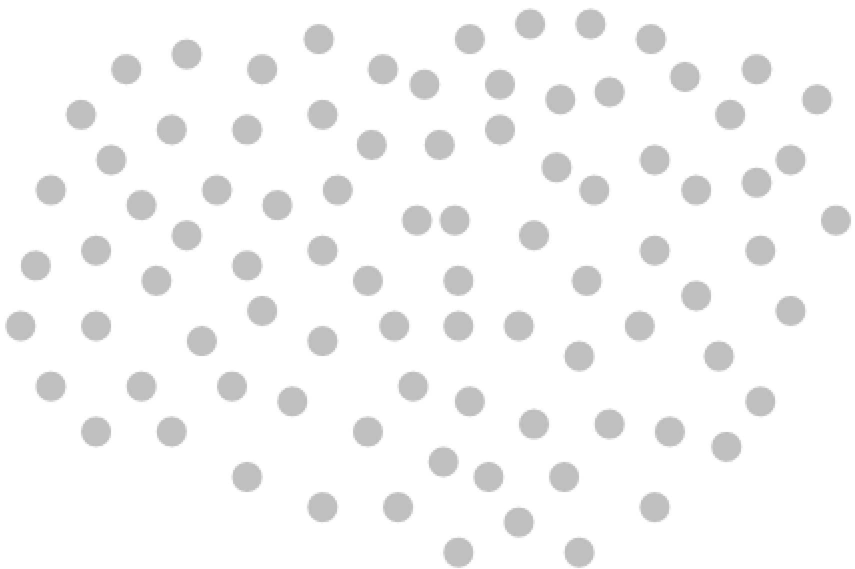
$$C_{T-RD}^{(AODV, DYMO)} = \begin{cases} \sum_{R_i=1}^{R_{max\_limit}} \tau_1(TTL(R_i) + \tau_2) & if\, no\, RREP\, received \\ \sum_{R_i=1}^{R_{rrep}} \tau_1(TTL(R_i) + \tau_2) & otherwise \end{cases}$$

o For DSR

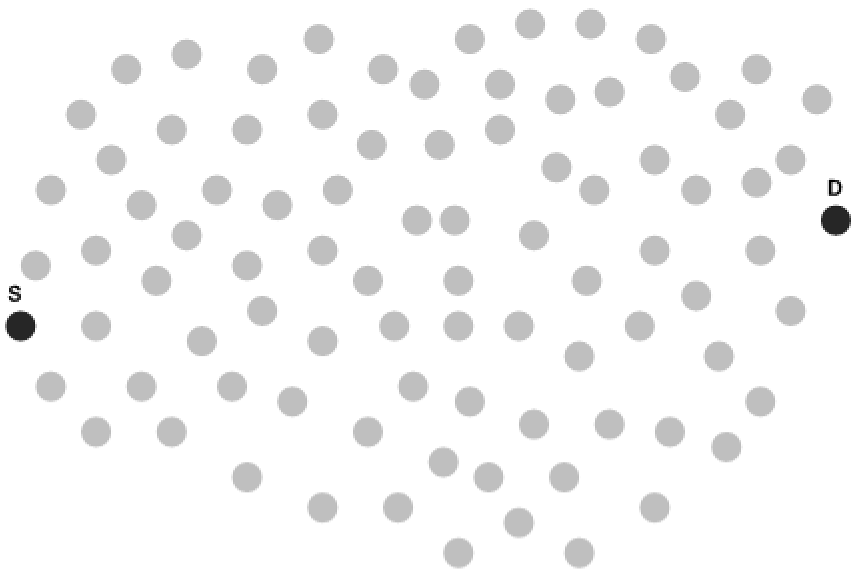
- τ = 30ms
- For TTL=TTL x 2, $\tau = \tau$ x 2

$$C_{T-RD}^{(DSR)} = \begin{cases} \tau & if\, R_{rrep} = 1 \\ \sum_{R_i=1}^{R_{max\_limit}} 2^{R_i - 1} \times \tau & if\, no\, RREP\, received \\ \sum_{R_i=1}^{R_{rrep}} 2^{R_i - 1} \times \tau & otherwise \end{cases}$$

Route maintenance

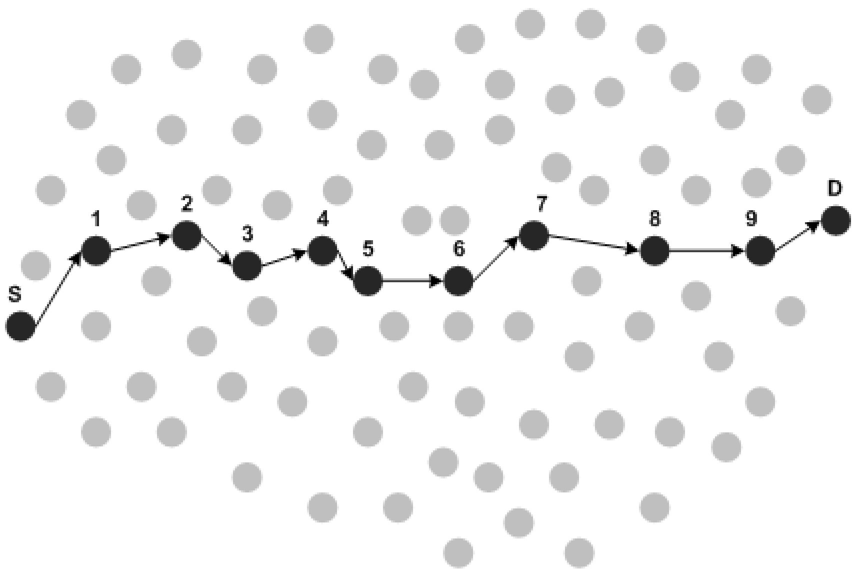


Route maintenance

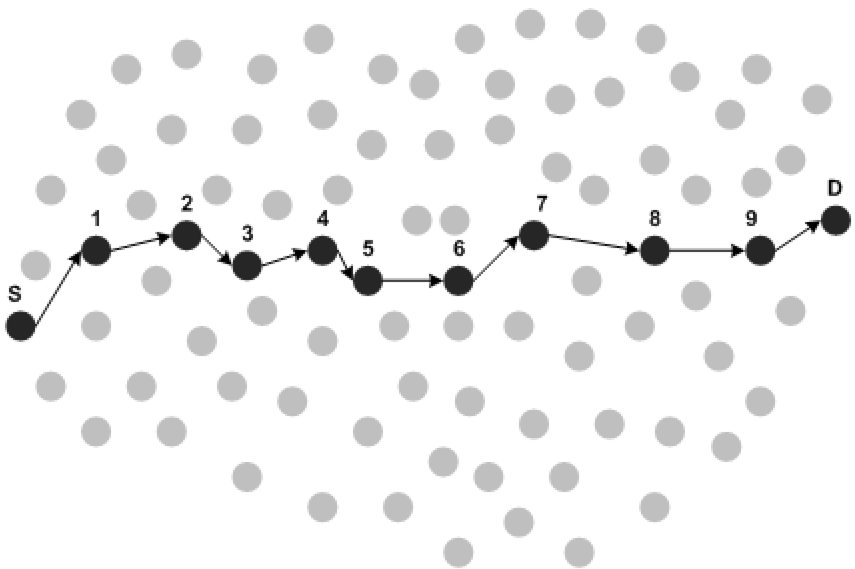


Route maintenance

- S establishes path to D

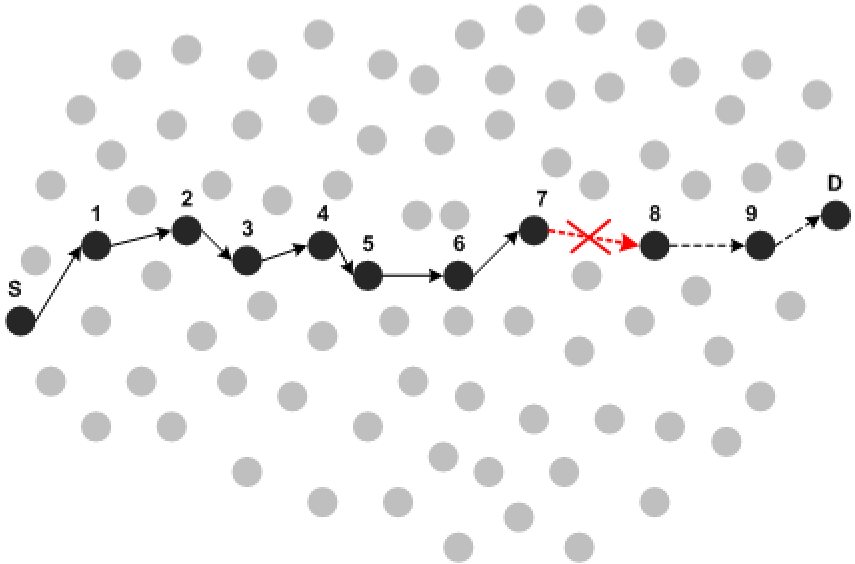


Route maintenance



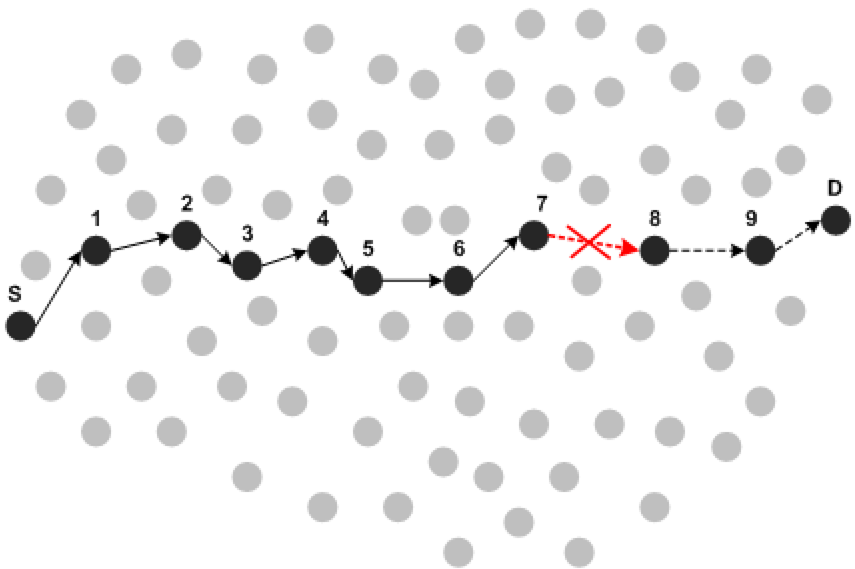
- S establishes path to D
- AODV and DYMO use HELLO messages to check connectivity
- DSR uses link level feed-back

Route maintenance



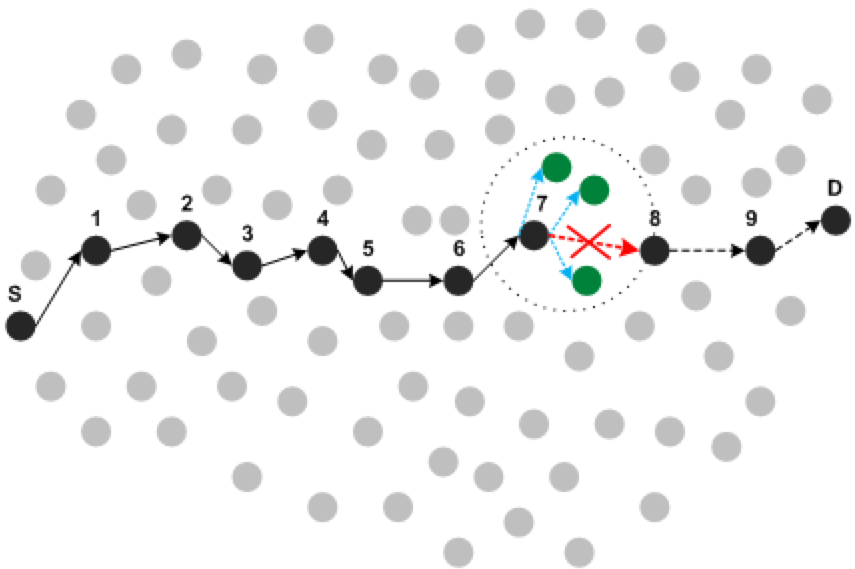
- S establishes path to D
- AODV and DYMO use HELLO messages to check connectivity
- DSR uses link level feed-back
- Node 7 detects link break

Route maintenance



- S establishes path to D
- AODV and DYMO use HELLO messages to check connectivity
- DSR uses link level feed-back
- Node 7 detects link break
- AODV starts LLR
- LLR repairs the broken links
- Reduces chance of route re-discovery
- More suitable in large networks

Local Link Repair



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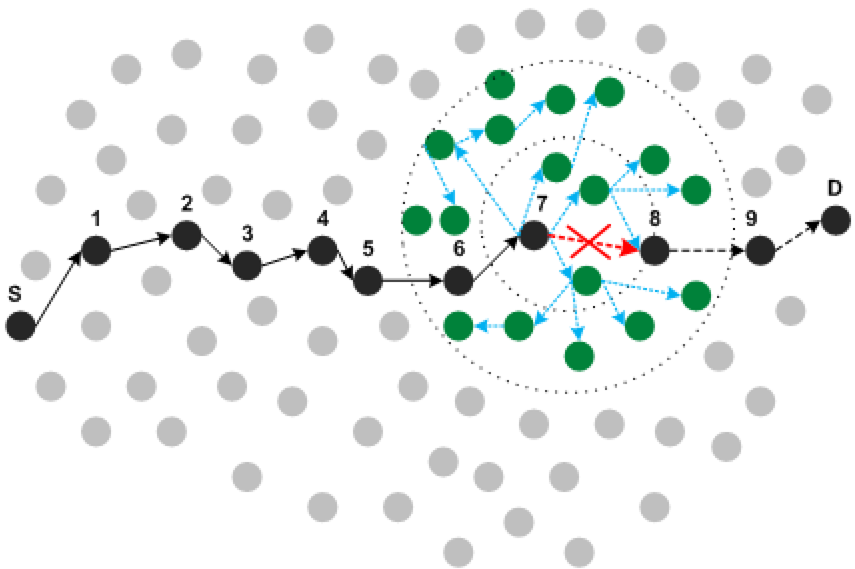

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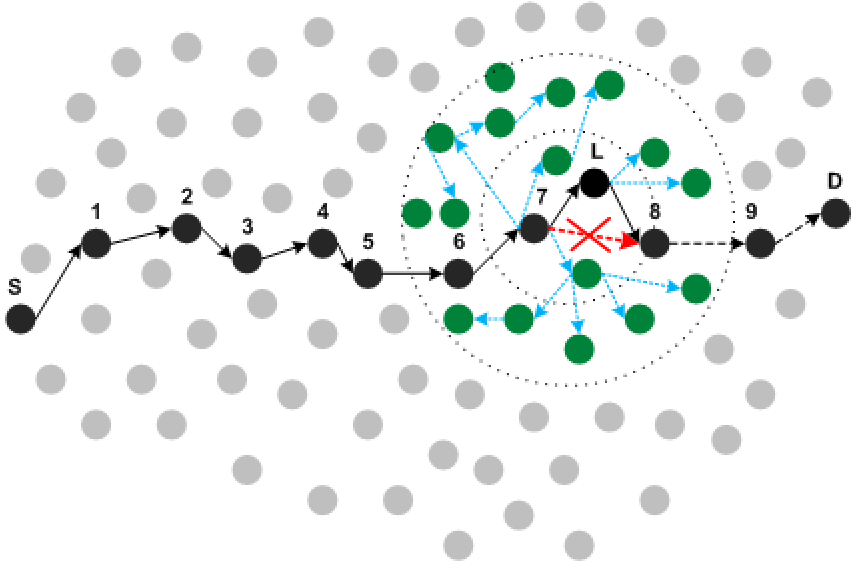

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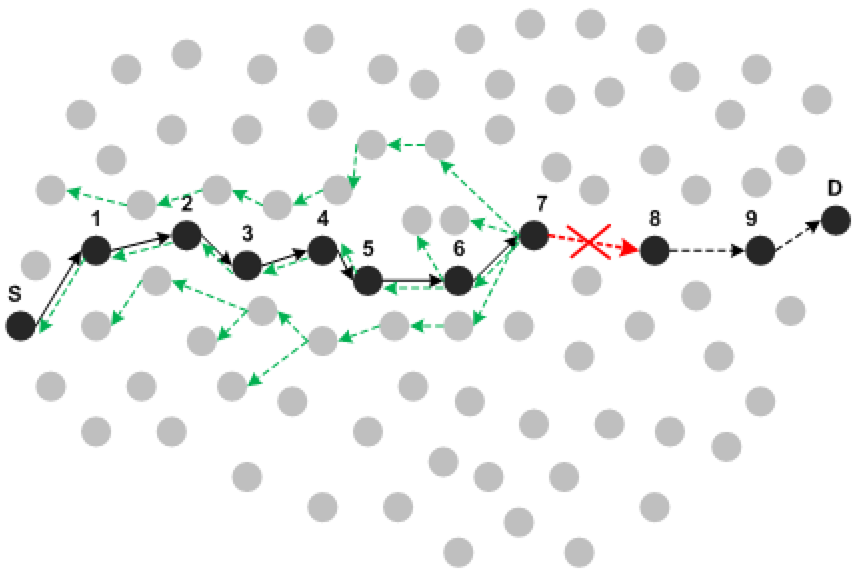
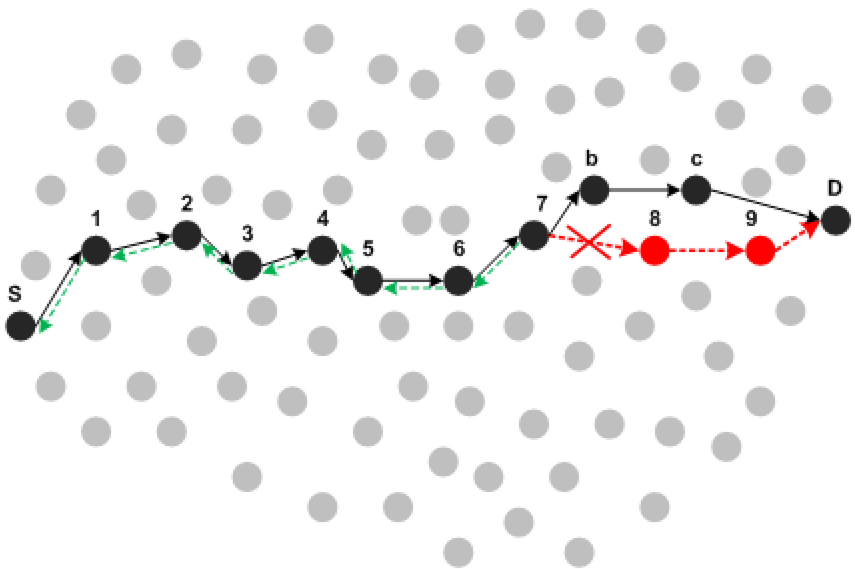
RERR in reactive protocols



AODV

- If LLR fails then send RERR messages to neighbors
- A RERR message is *broadcasted* (if there are many precursors)
- Or *unicasted* (if there is only 1 precursor)
- a node send upto RERR_RATELIMIT (=10) RERR messages per second

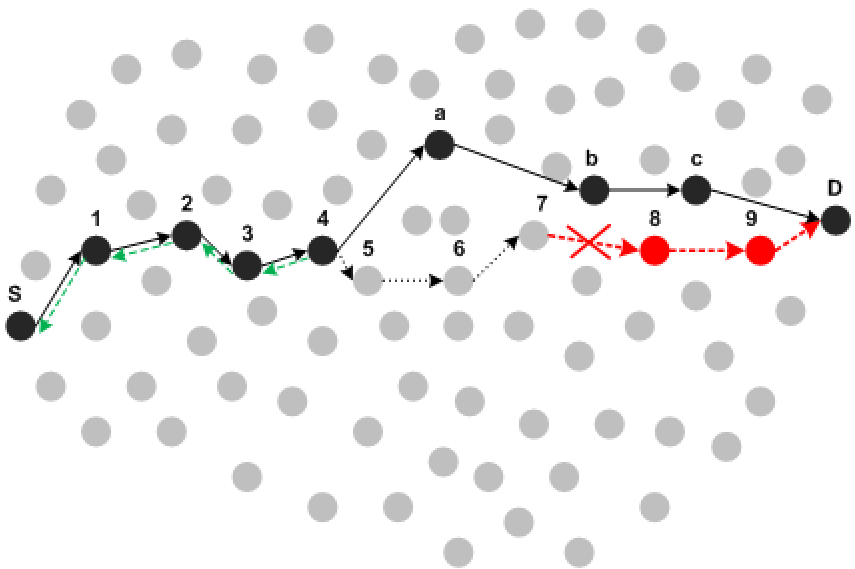
RERR in reactive protocols



DSR

- Success of PS
- Node returns a RERR to sender of packet
- Then salvages packet
- Node 7 is the originating node for RERR

RERR in reactive protocols



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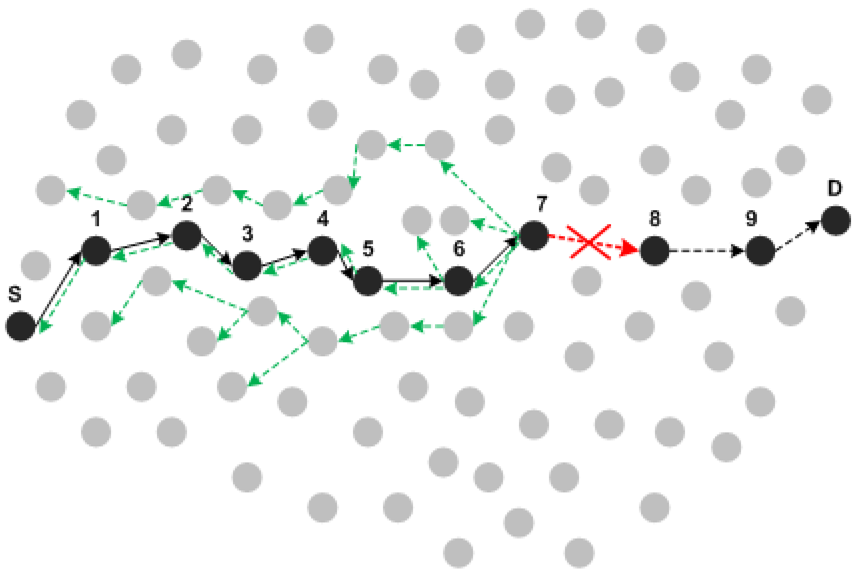
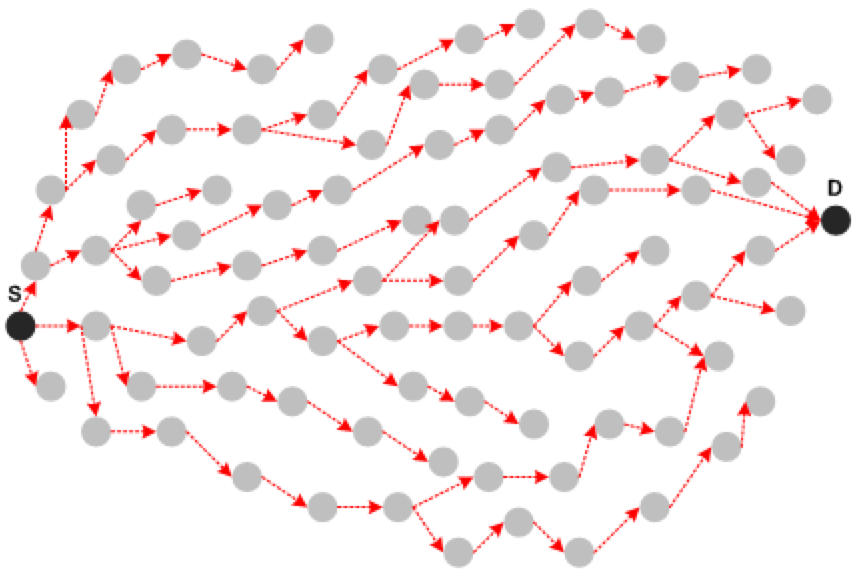
RERR in reactive protocols



DYMO

- Broadcast RERR messages at link failure
- MsgHdr.HopLimit is to NET_DIAMETER (=10)
- MsgHdr.HopCnt is set to one

Re-RD in reactive protocols



AODV (LLR)

- RREQ_RETRIES = 2 to start new RD

DSR (PS)

- Source piggy-backs RERR with new RREQ
- Initiating RREQ based on MaxMainRexmt=2

DYMO

- Decision based on RREQ_TRIES =3 in DYMO to start new RD

Energy-cost of RM

AODV

$$C_{E-RM}^{(AODV)} = \frac{\tau_{link-in-use}}{\tau_{HELLO\_INTERVAL}} \times N_{hops-in-route} + P_r d_{avg} + d_{avg} \sum_{TTL=1}^{TTL(R_{LLR})-1} (P_r)^{TTL+1} \prod_{j=1}^{TTL} d_f[j] + \sum_{z=0}^{n} (RERR)_z$$

DSR

$$C_{E-RM}^{(DSR)} = \sum_{k=n_{BLB}}^{n_{PS}} (RREQ)_k + \sum_{z=0}^{n} (RERR)_z$$

DYMO

$$C_{E-RM}^{(DYMO)} = \frac{\tau_{link-in-use}}{\tau_{HELLO\_INTERVAL}} \times N_{hops-in-route} + \sum_{z=0}^{n} (RERR)_z$$

Time cost for RM

AODV

$$C_{T-RM}^{(AODV)} = \begin{cases} \sum_{R_i=1}^{R_{LLR}} \tau_1(TTL(R_i) + \tau_2) & if\, LLR\, is\, successful \\ \sum_{R_i=1}^{R_{LLR}} \tau_1(TTL(R_i) + \tau_2) + \tau_{recv-RERR} & if\, LLR\, fails,\, RREQ\_RETRIES\, exp \\ \sum_{R_i=1}^{R_{LLR}} \tau_1(TTL(R_i) + \tau_2) + \tau_{recv-RERR} + C_{T-re-RD} & otherwise \end{cases}$$

DSR

$$C_{T-RM}^{(DSR)} = \begin{cases} \sum_{k=n_{BLB}}^{n_{PS}} \tau_k(PS) & if\, PS\, is\, successful \\ \sum_{k=n_{BLB}}^{n_{originator}} \tau_k(PS) + C_{T-re-RD} & otherwise \end{cases}$$

DYMO

$$C_{T-RM}^{(DYMO)} = \begin{cases} \tau_{recv-RERR} & if\, RREQ\_TRIES\, expires \\ \tau_{recv-RERR} + C_{T-re-RD} + & otherwise \end{cases}$$

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Routing Link Metric

- To have appreciable performance from a wireless network, a routing protocol (RP) plays an important role
- Key component of a RP is link metric (LM)
- LM helps a RP first to find all possible end-to-end paths and then selects the fastest path

Routing Link Metric

- Minimum Hop-count (Min-HC) is the most popular and IETF standard metric and is appropriately used by wireless RP's
- Min-HC rapidly finds new paths; where quality paths could not be found in due time due to higher rates of node mobility
- Min-HC is the simplest to calculate, as it avoids any computational burden on RP

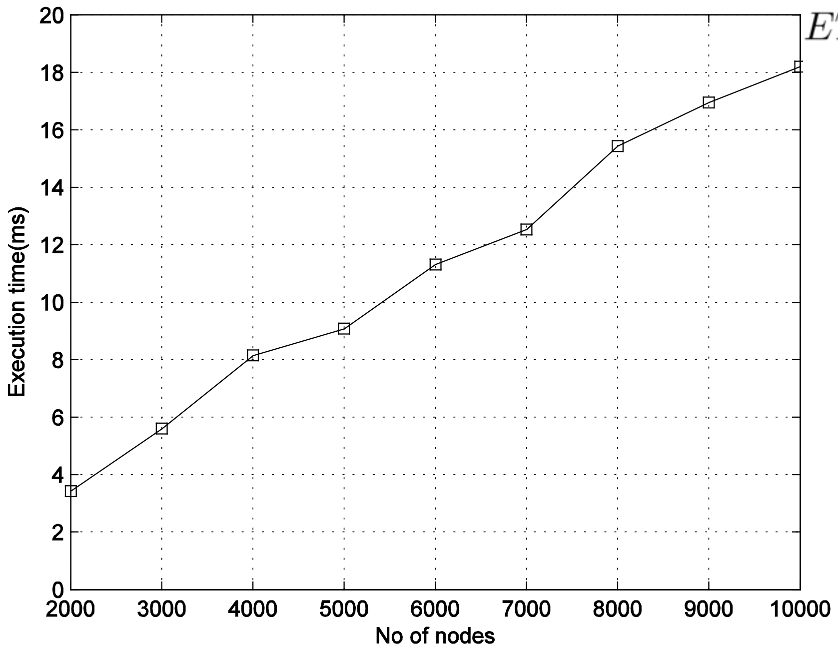
Designing a routing metric

- Minimum-hop path
- Balancing traffic load
- Minimizing delay
- Maximizing data delivery/aggregating bandwidth
- Minimizing energy consumptions
- Minimizing channel/interface switching

Designing a routing metric

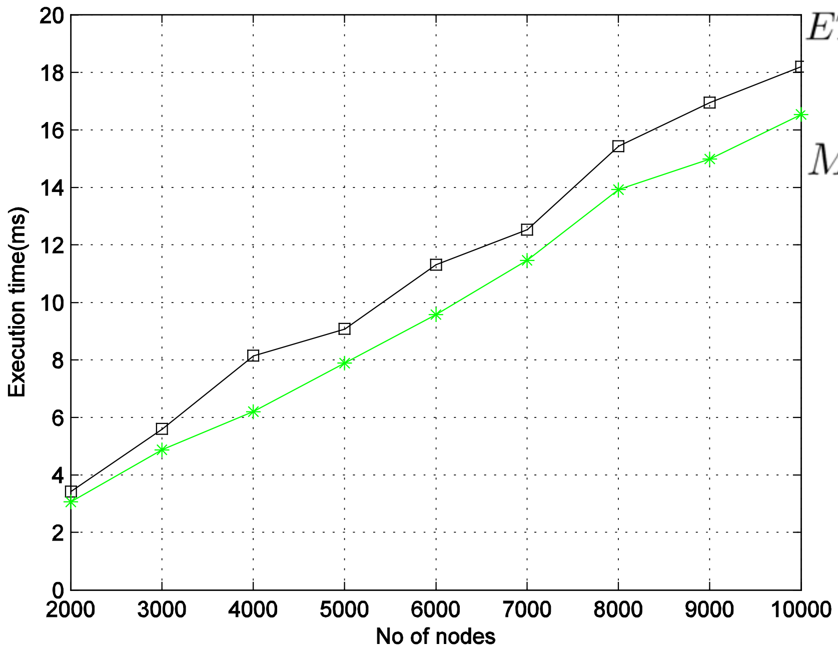
- Minimizing interference
- Maximizing route stability
- Maximizing fault tolerance/minimizing route sensitivity
- Avoiding short and long lived loops
- **Considering performance trade-offs**
- **Minimizing the Computational overhead**

Computational Overhead



$$ETX_{P_{e2e}} = \sum_{l \in P_{e2e}} \frac{1}{(d_f^{(l)} \times d_r^{(l)})}$$

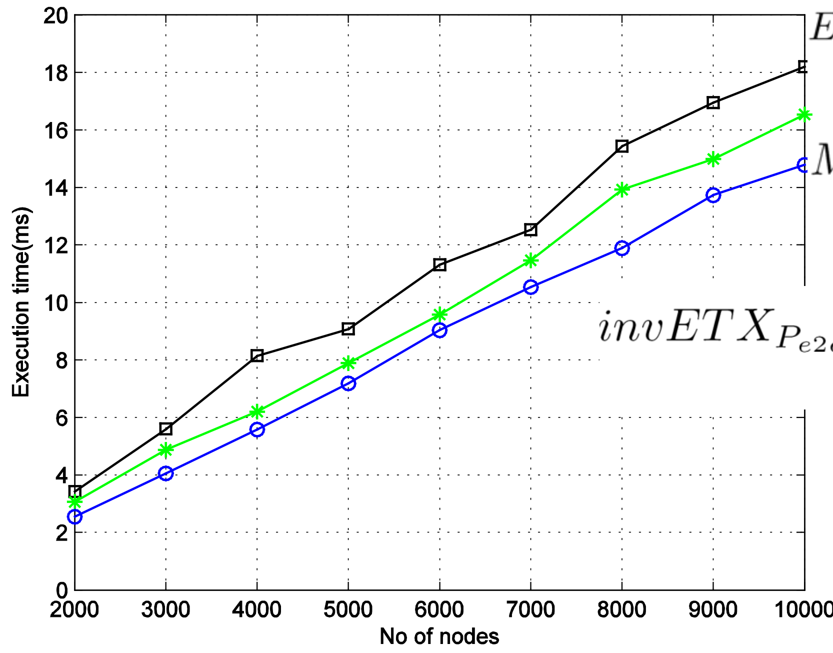
Computational Overhead



$$ETX_{P_{e2e}} = \sum_{l \in P_{e2e}} \frac{1}{(d_f^{(l)} \times d_r^{(l)})}$$

$$ML_{P_{e2e}} = \prod_{l \in P_{e2e}} (d_f^{(l)} \times d_r^{(l)})$$

Computational Overhead

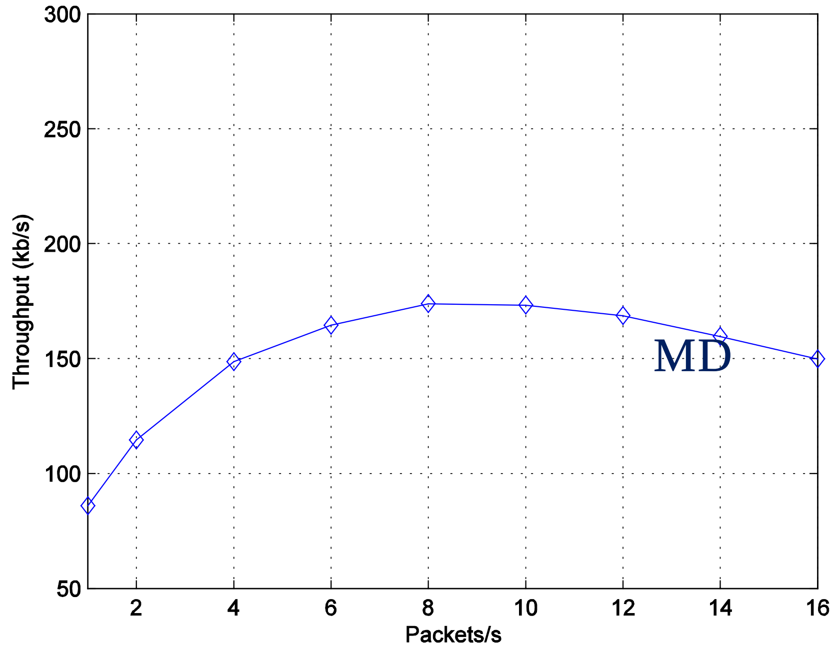


$$ETX_{P_{e2e}} = \sum_{l \in P_{e2e}} \frac{1}{(d_f^{(l)} \times d_r^{(l)})}$$

$$ML_{P_{e2e}} = \prod_{l \in P_{e2e}} (d_f^{(l)} \times d_r^{(l)})$$

$$invETX_{P_{e2e}} = \sum_{l \in P_{e2e}} (d_f^{(l)} \times d_r^{(l)})$$

Throughput



300
250
200
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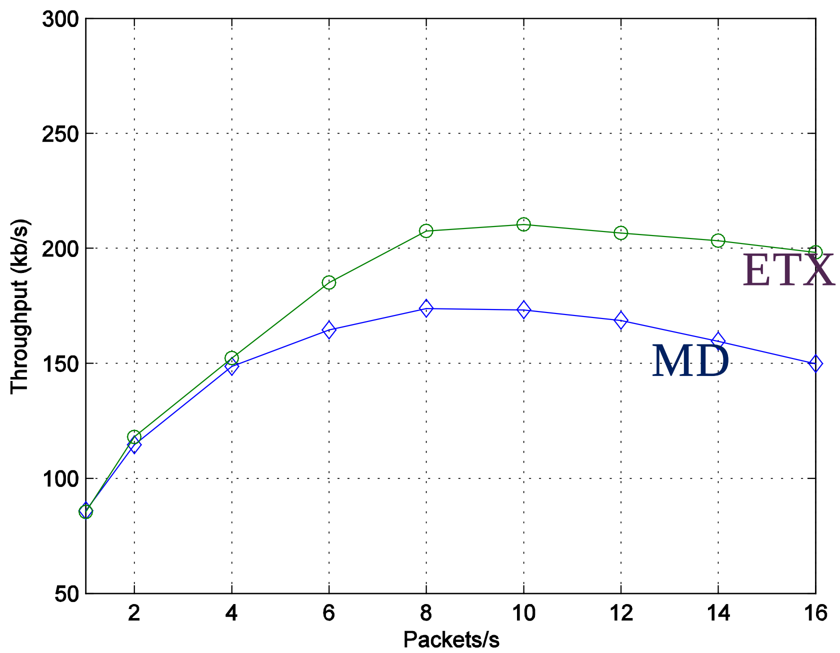
100
50
Throughput (kb/s)
2
4
6
8
10
12
14
16
Packets/s
MD

Throughput



Throughput (kb/s)
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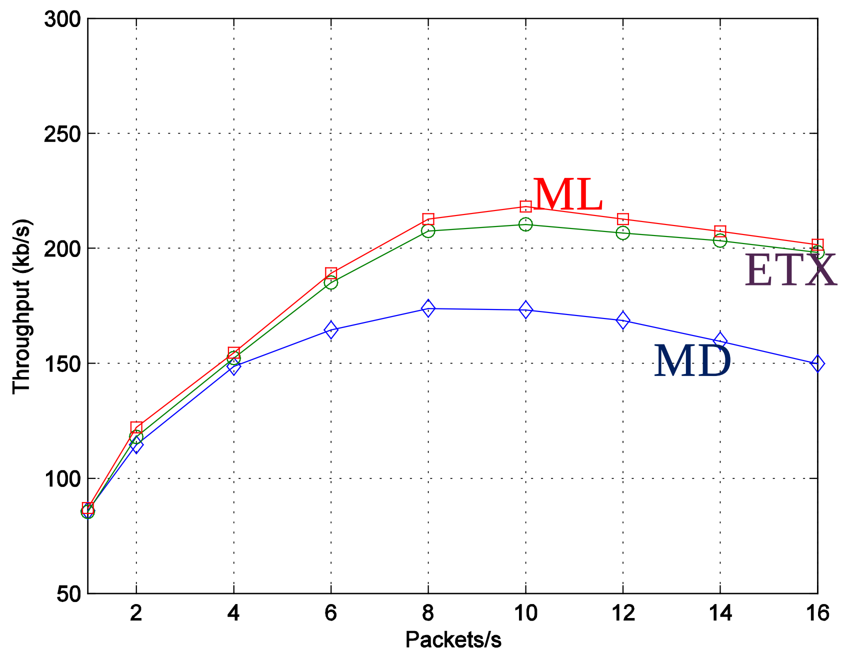
Packets/s
ETX
MD

Throughput



300
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Throughput (kb/s)
2
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10
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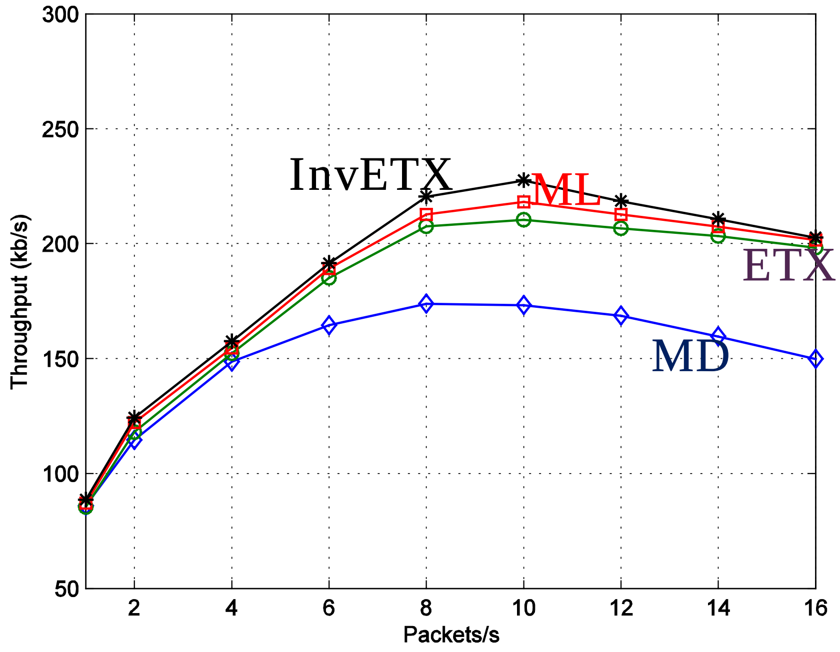
Packets/s
ML
ETX
MD

Throughput



300
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Throughput (kb/s)
2
4
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8
10
12
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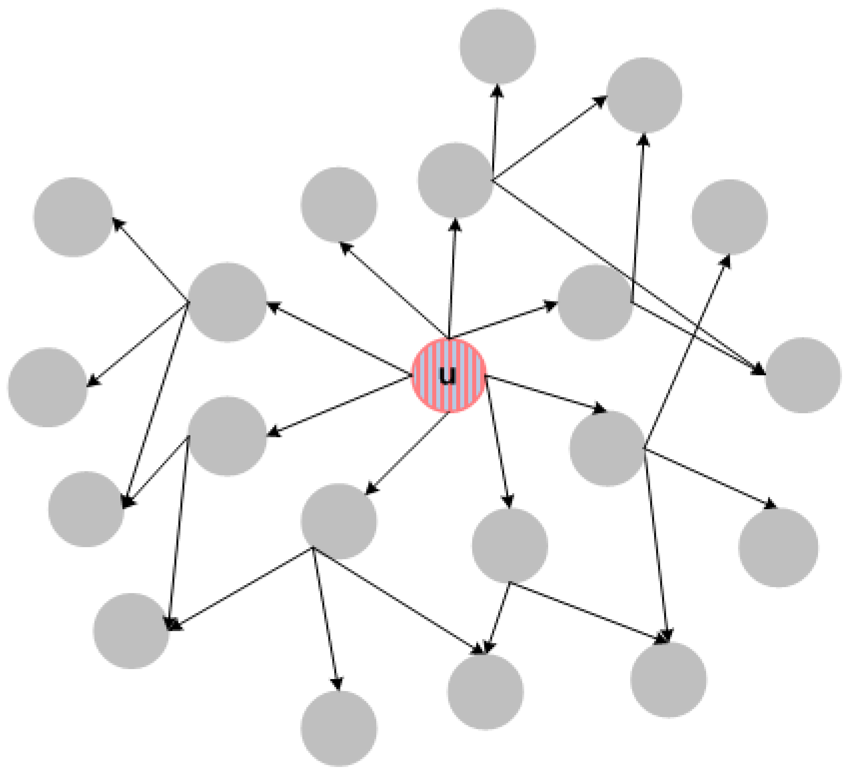
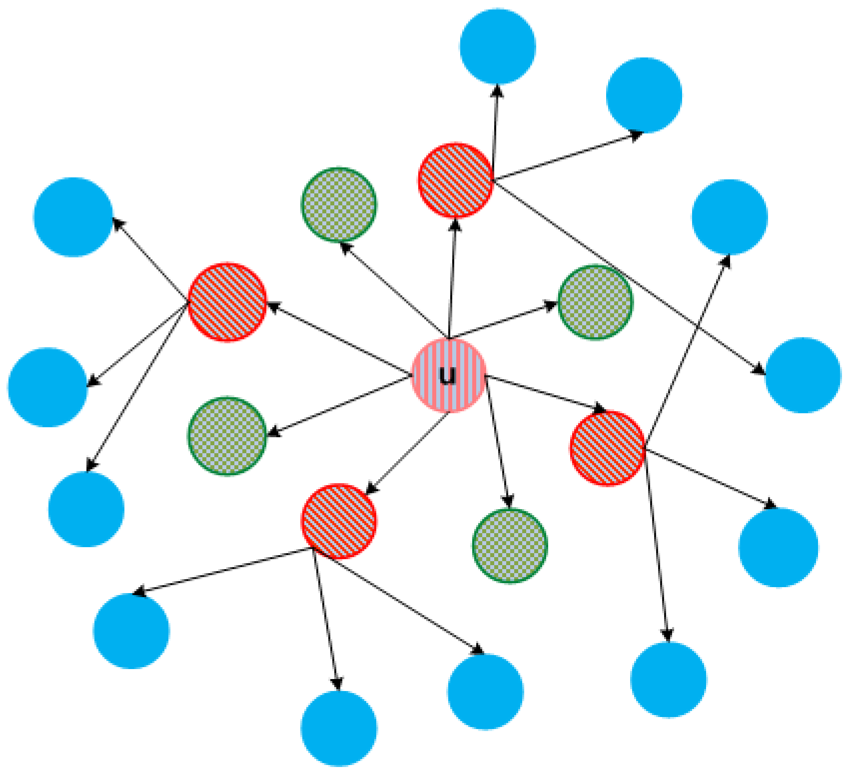
16
Packets/s
InvETX
ML
ETX
MD

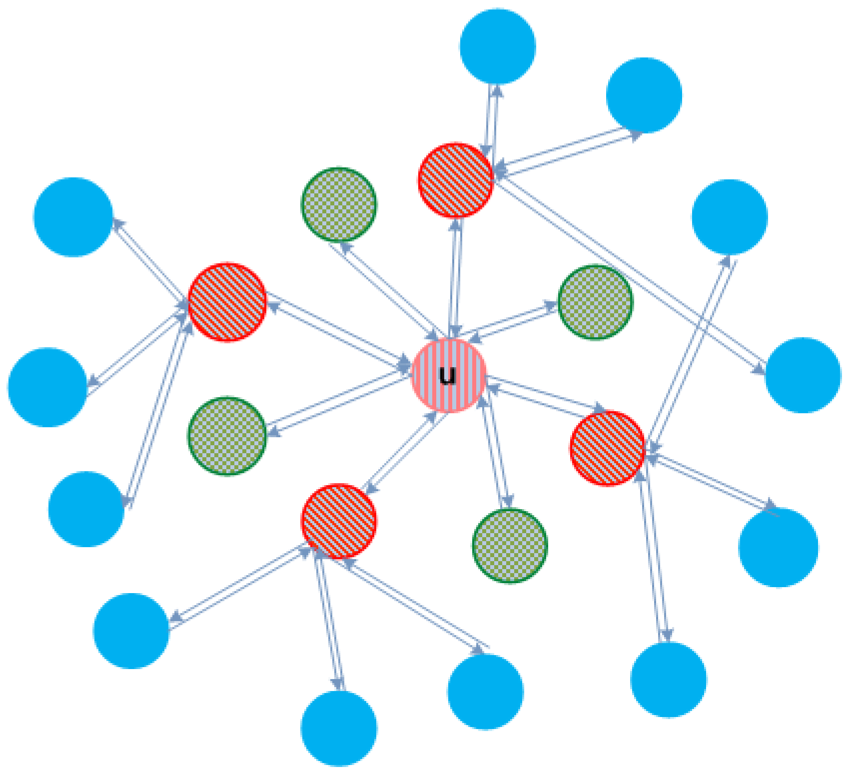
Plane Flooding



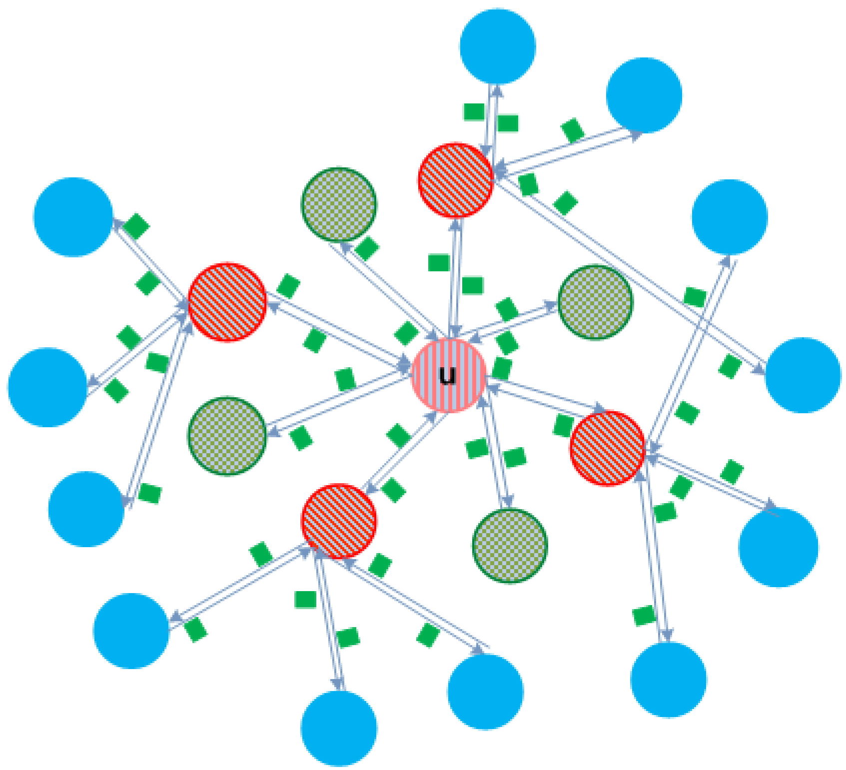
MPR Flooding



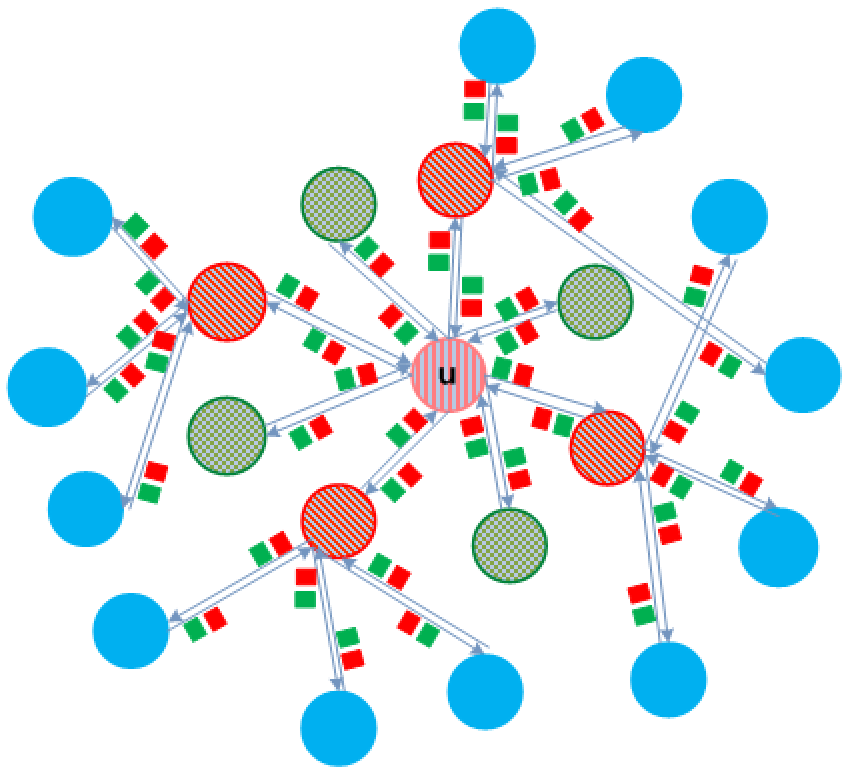
OLSR-ETX / InvETX / ML



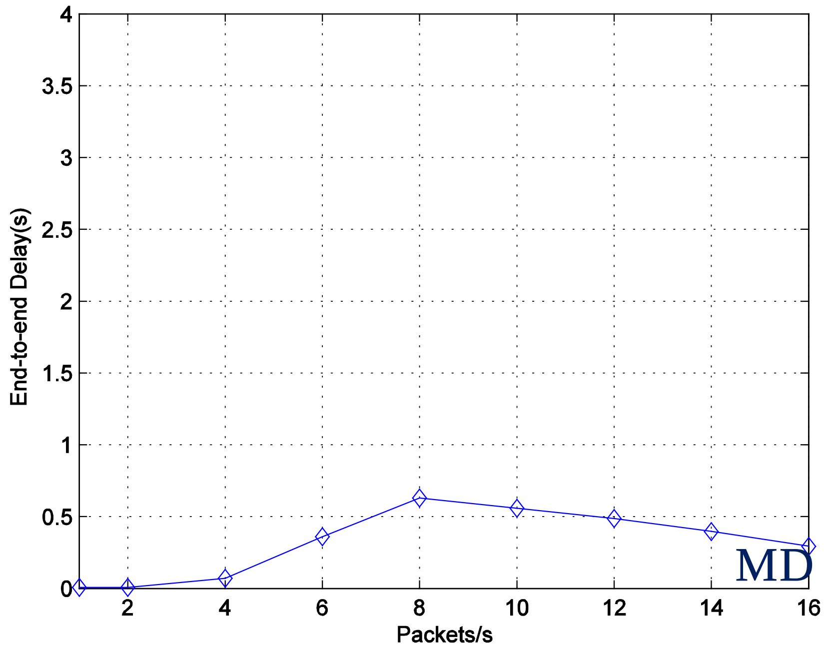
OLSR-ETX / InvETX / ML



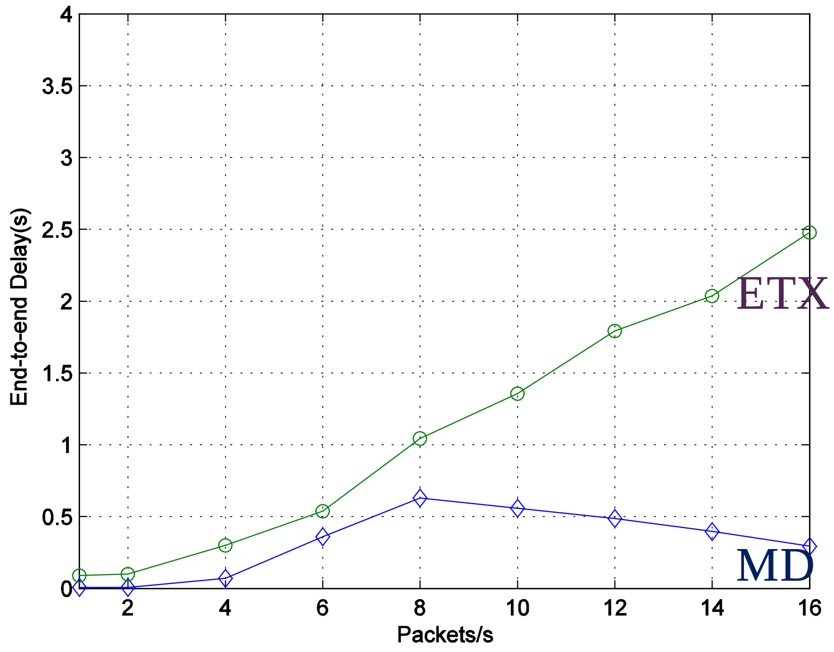
OLSR-MD



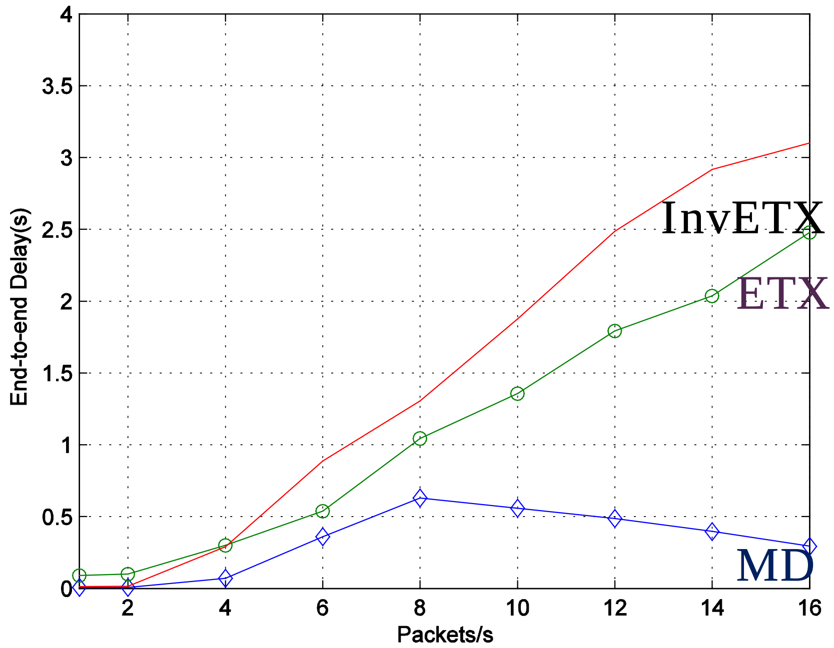
End-to-end Delay



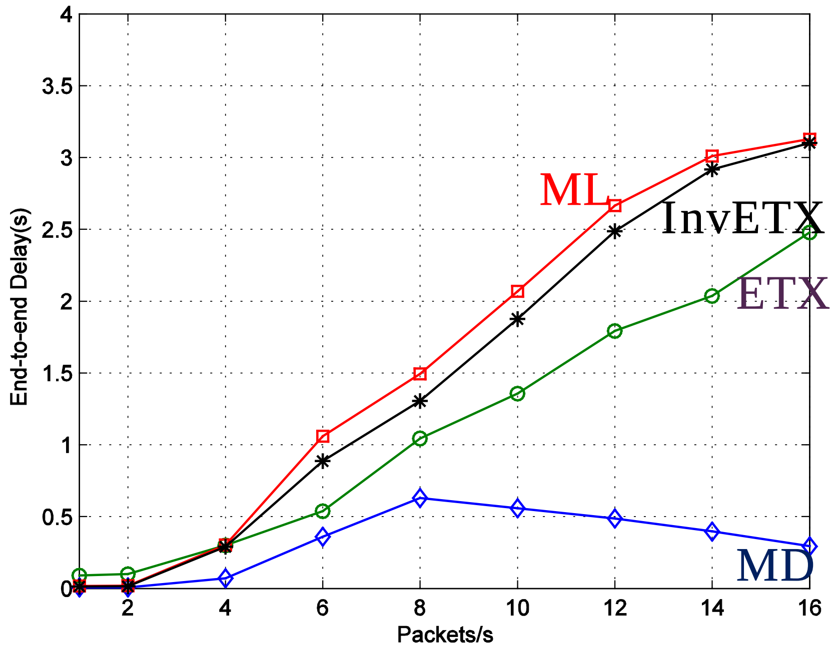
End-to-end Delay



End-to-end Delay



End-to-end Delay



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Outline

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  - Mobility/Speed Analysis
  - Scalability Analysis
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- Design Requirements for Routing Link Metrics
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  - Expected Link Performance (ELP)
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- New Link Metric IBETX

ETX-based Metrics

Issues	Solution
Links have different characteristics	**Link asymmetry**
Low bit-rate links effect faster links	**Bandwidth**
Congestion and Collisions	**Interference**

ETX-based Metrics

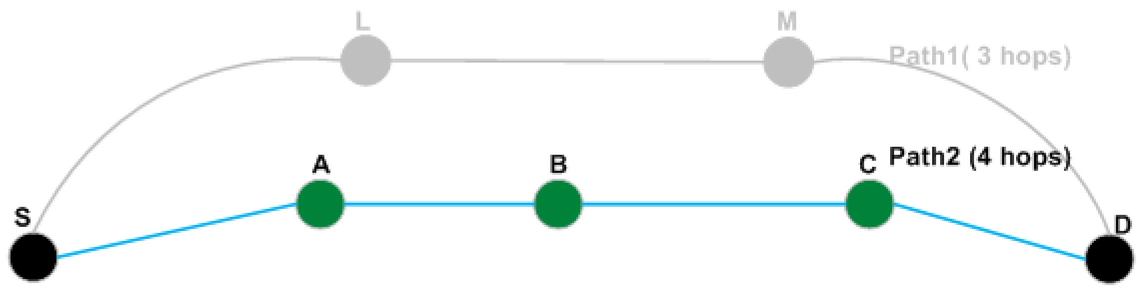
Issue(s) not considered	Link metric
Interference	ETT, DBETX, EETT, EstdTT, MCR, METX, **ETP**
Bandwidth	**ELP**, WCETT, MIC, iAWARE, EDR, ETX Dist
Link asymmetry	MTM
Bandwidth and Interference	**ETX,** mETX and ENT
Link asymmetry + Bandwidth + Interference	No Metric yet

Min Hop-count

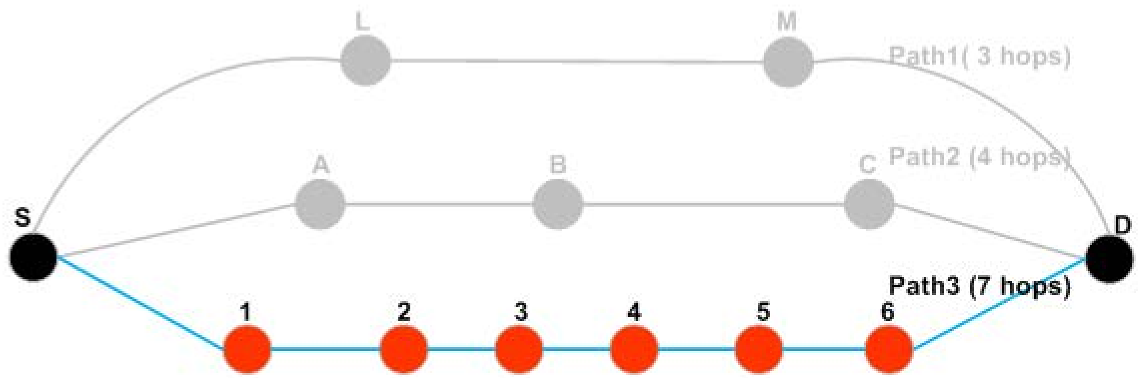
Min Hop-count

Min Hop-count

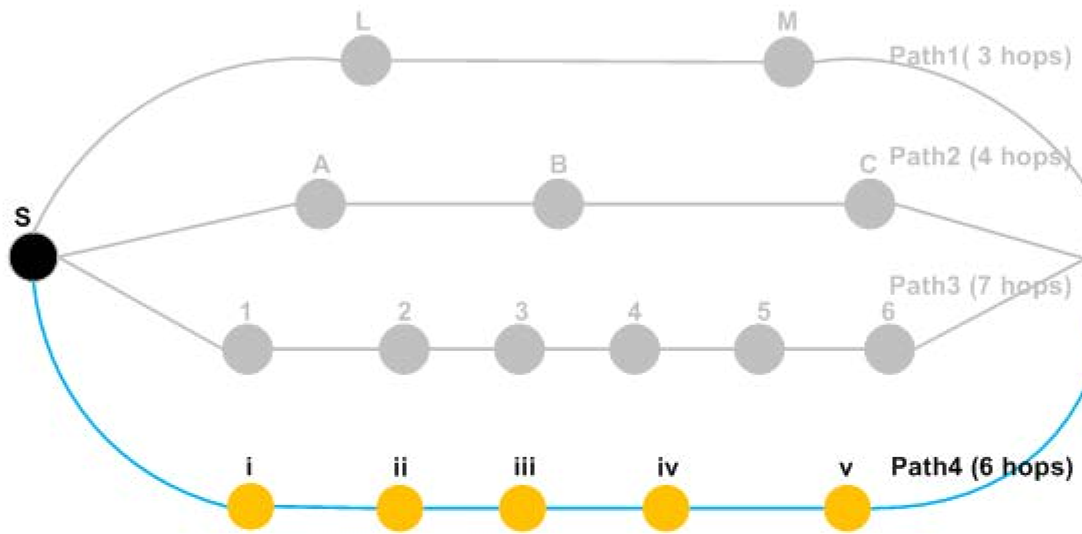
Min Hop-count



Min Hop-count



Min Hop-count



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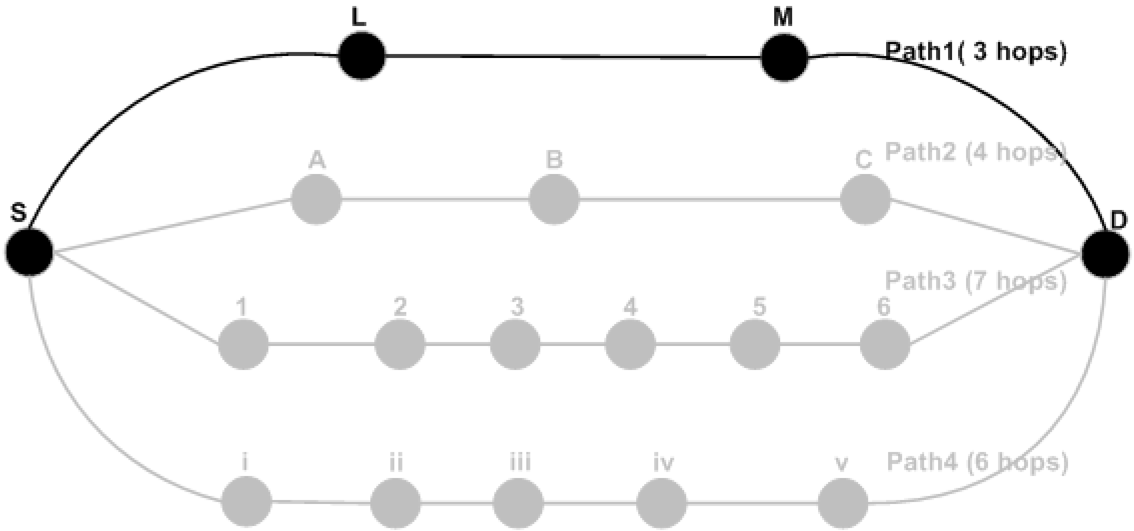
Min Hop-count



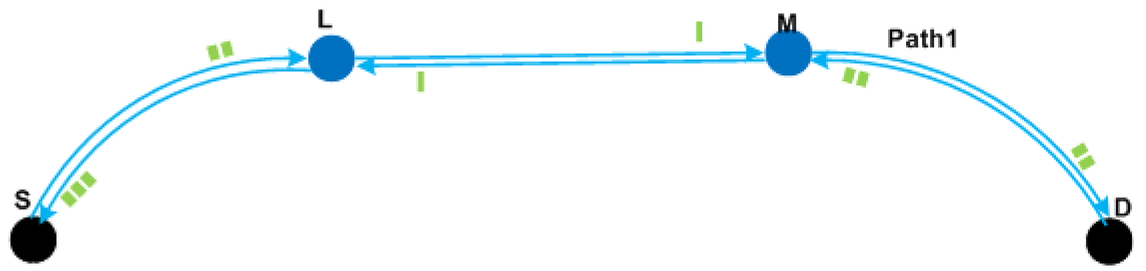
ETX

ETX

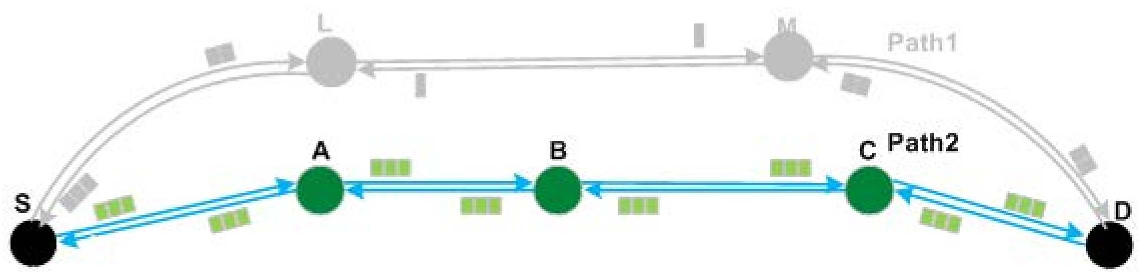
ETX

ETX

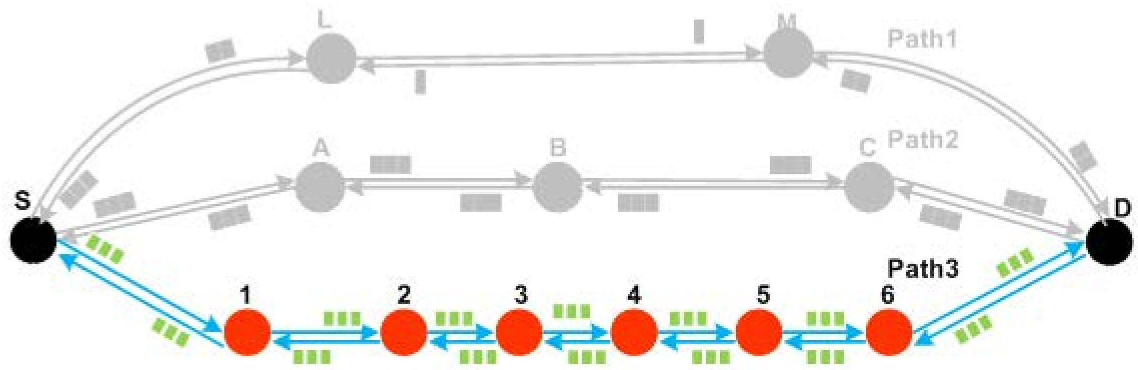
ETX



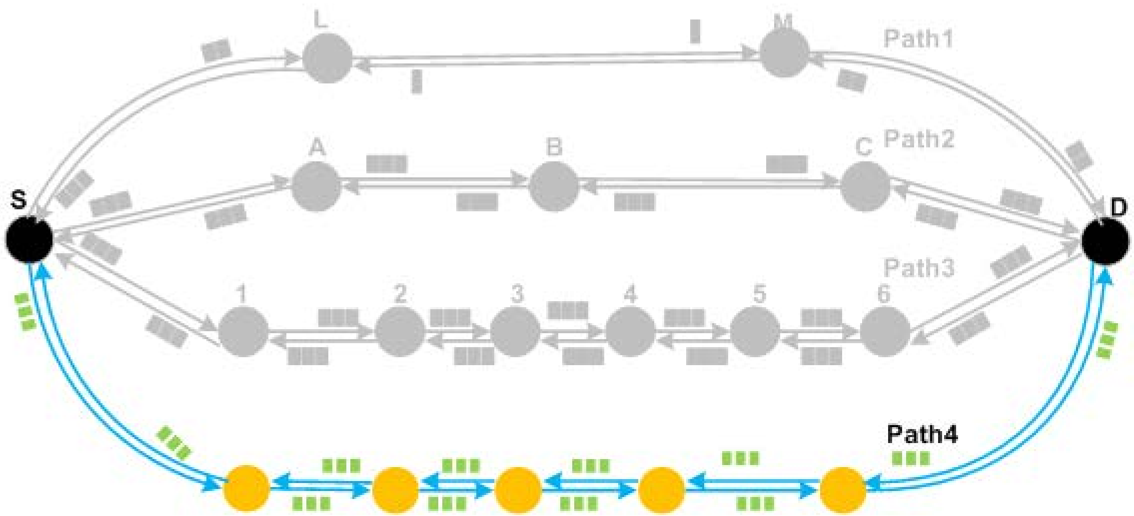
ETX



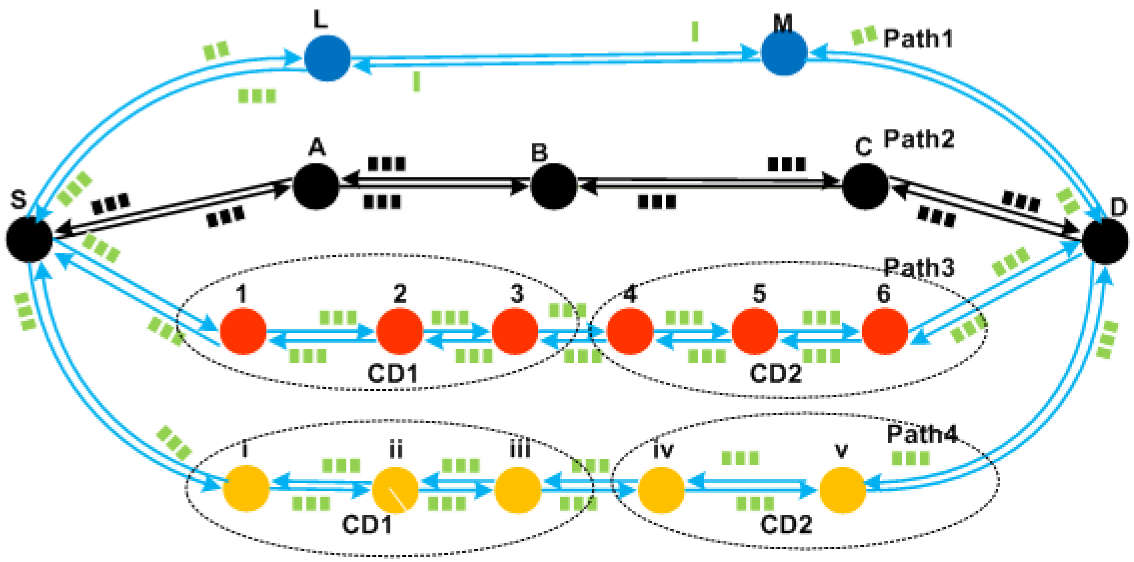
ETX



ETX



ETX


L
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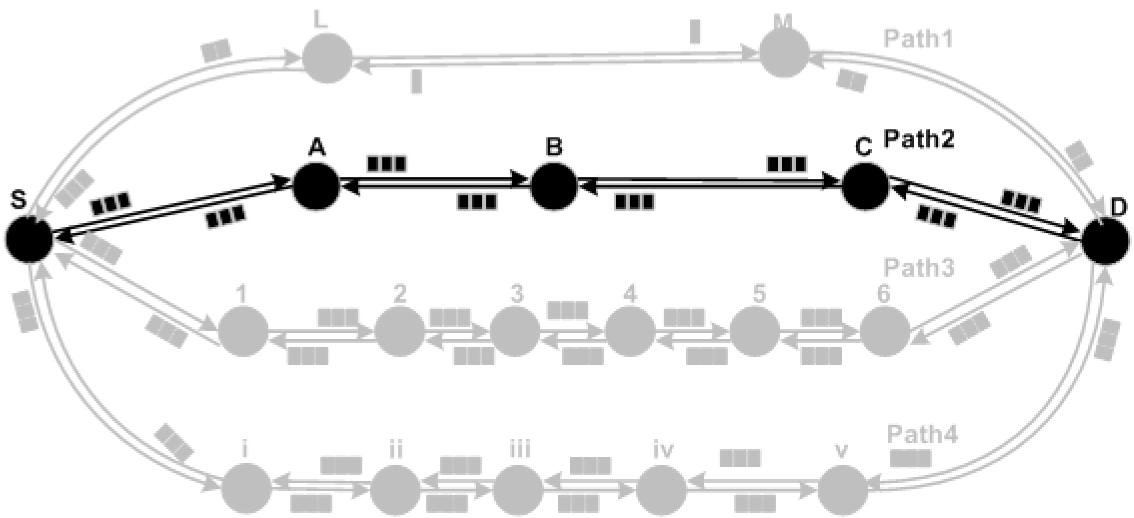
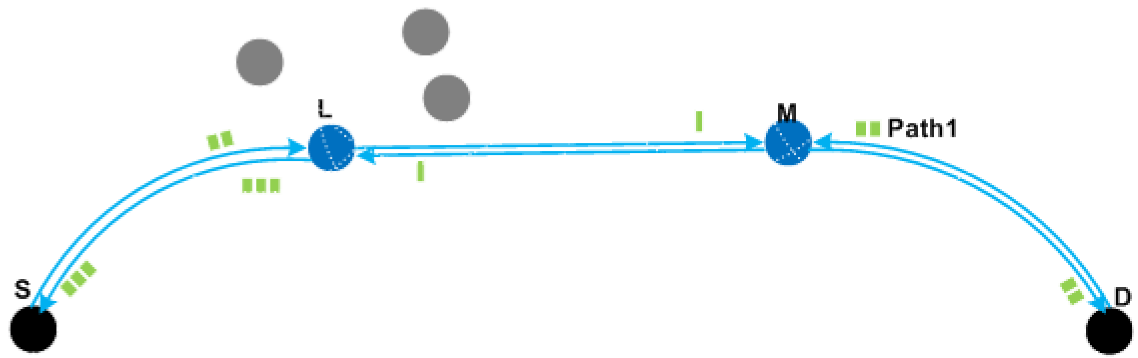
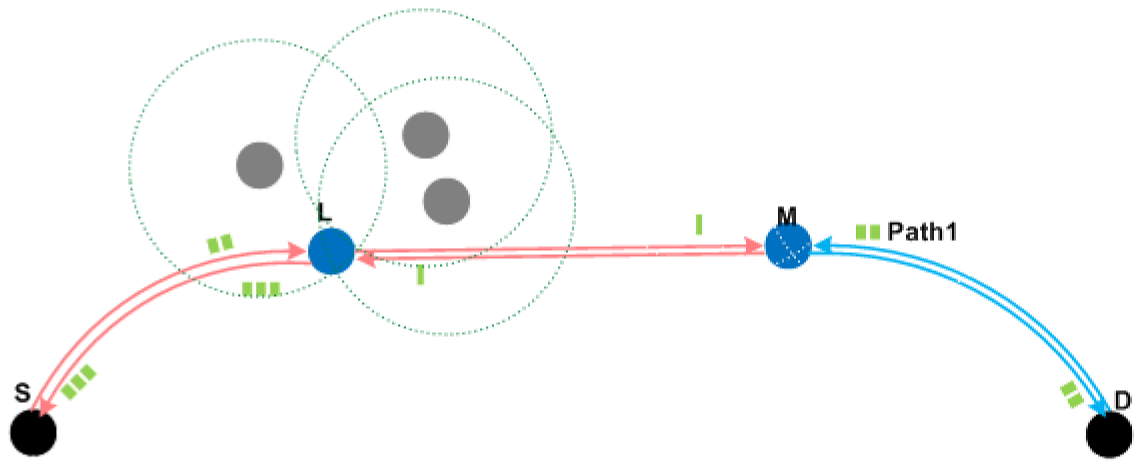
ETX



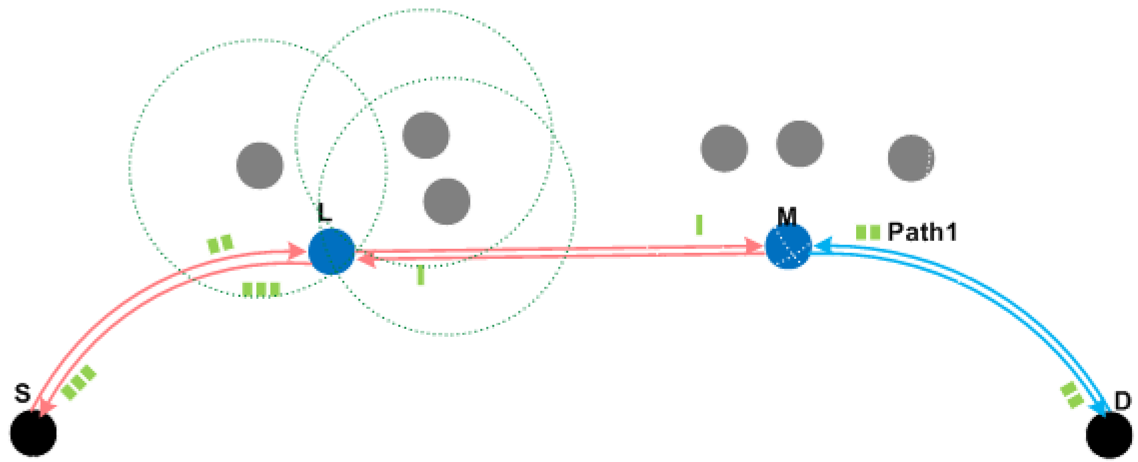
ETX-based Metrics - ELP



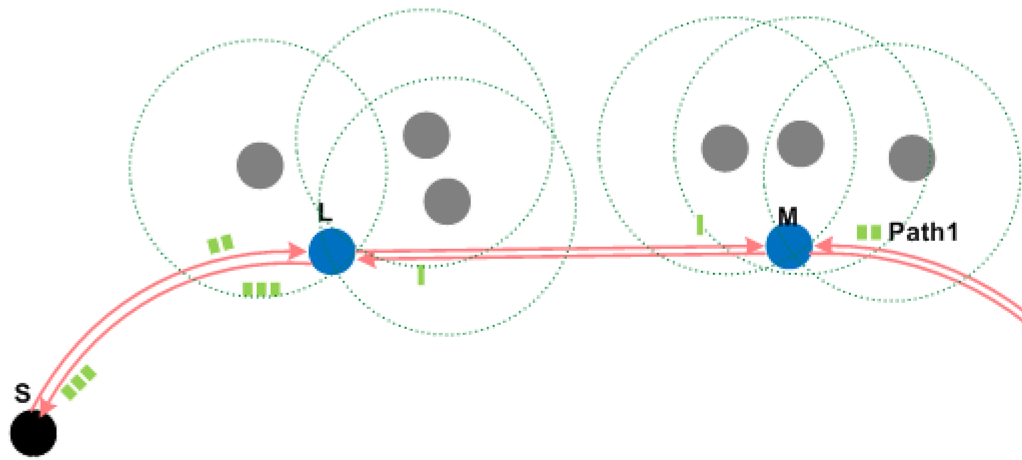
ETX-based Metrics - ELP



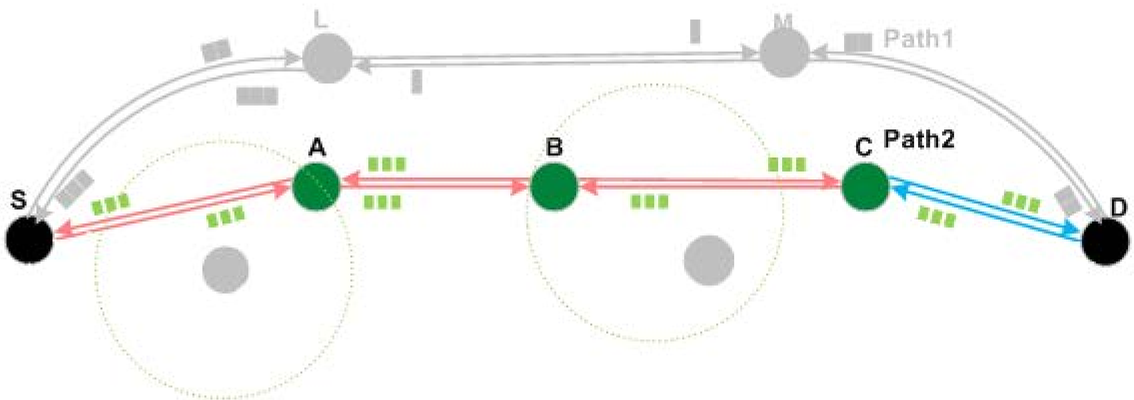
ETX-based Metrics - ELP



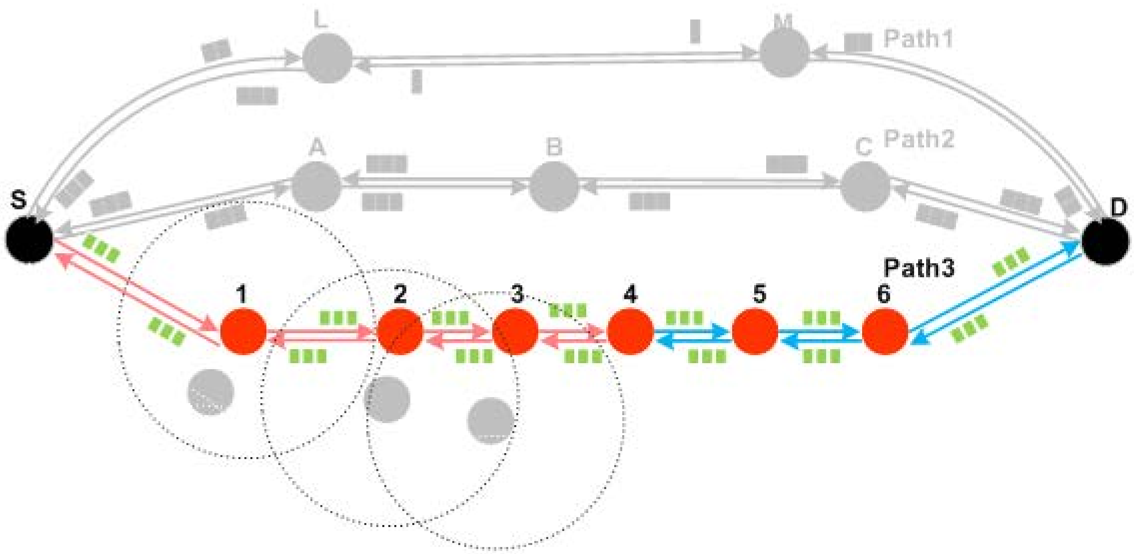
ETX-based Metrics - ELP



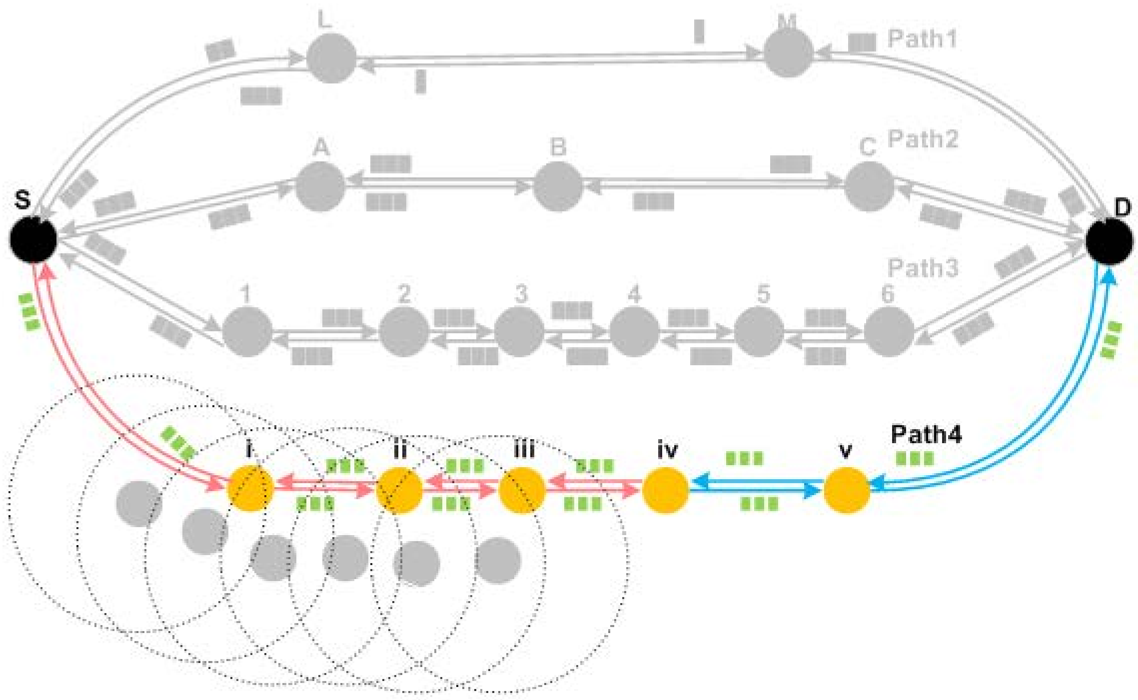
ETX-based Metrics - ELP



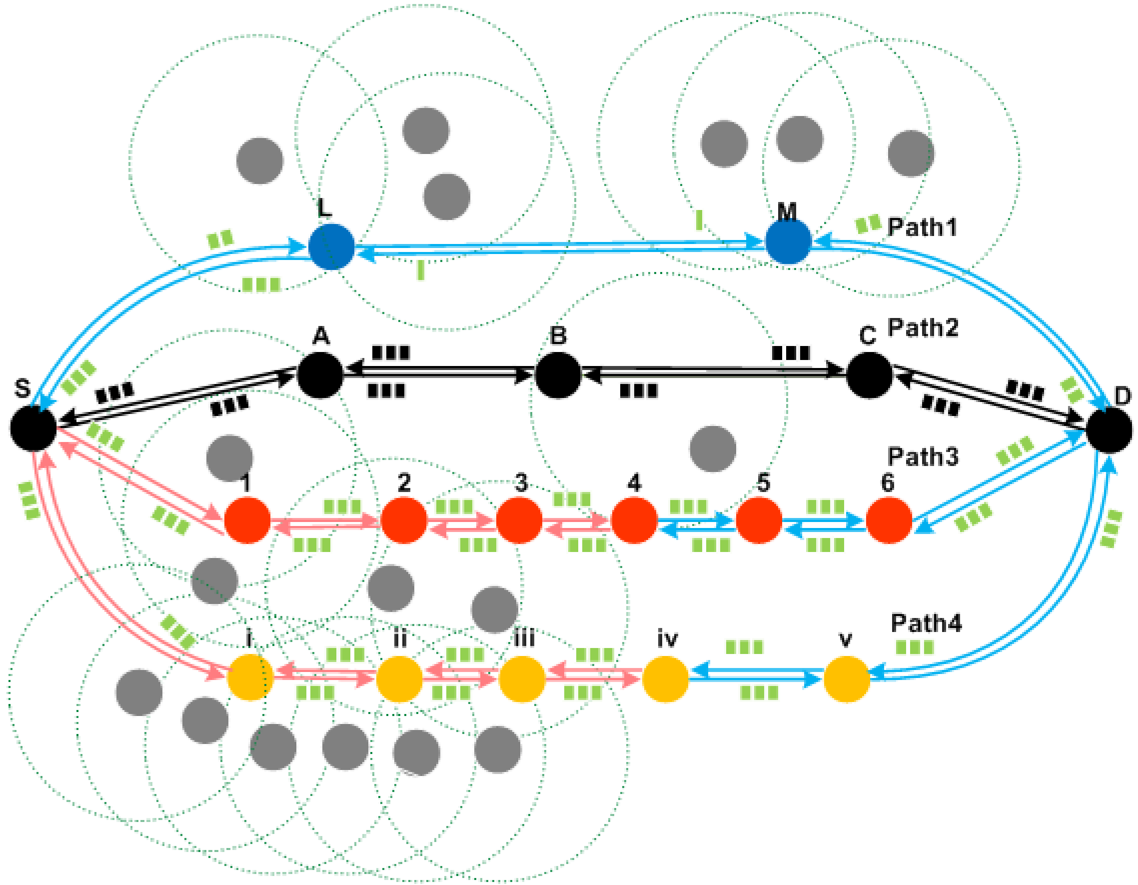
ETX-based Metrics - ELP



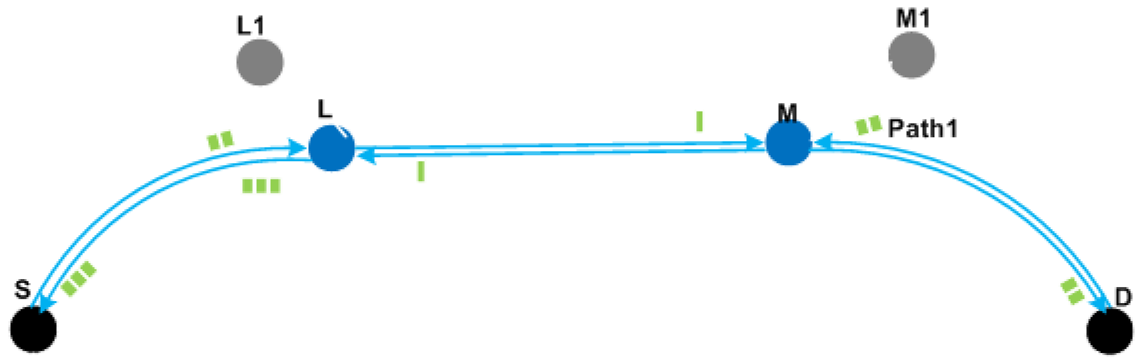
ETX-based Metrics - ELP



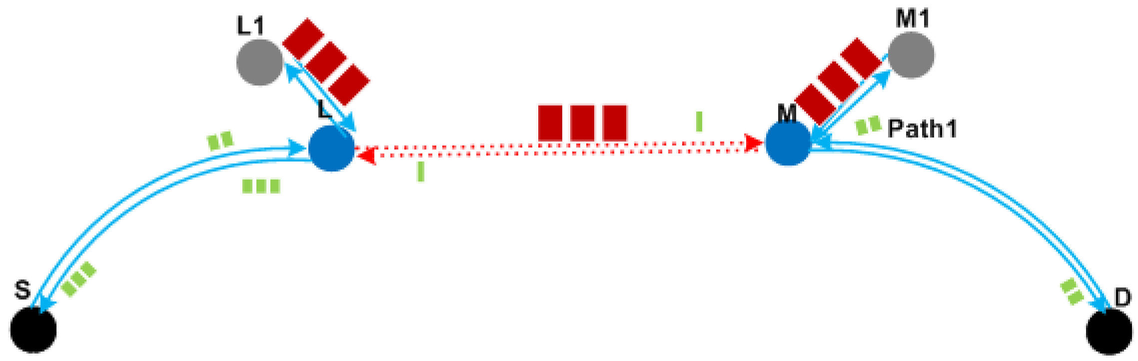
ETX-based Metrics - ELP



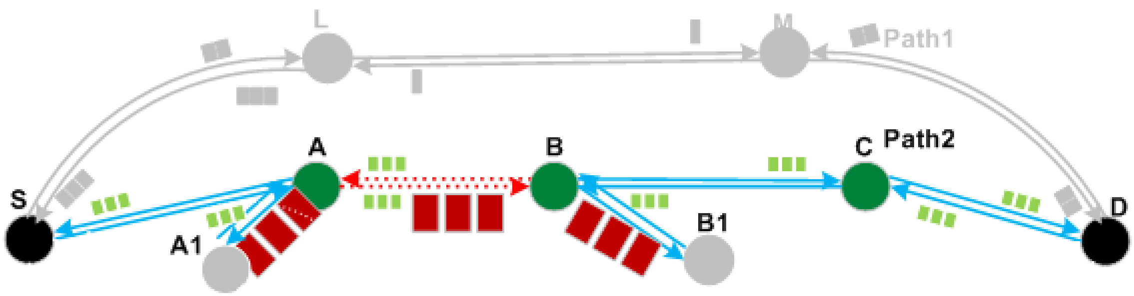
ETX-based Metrics - ETP



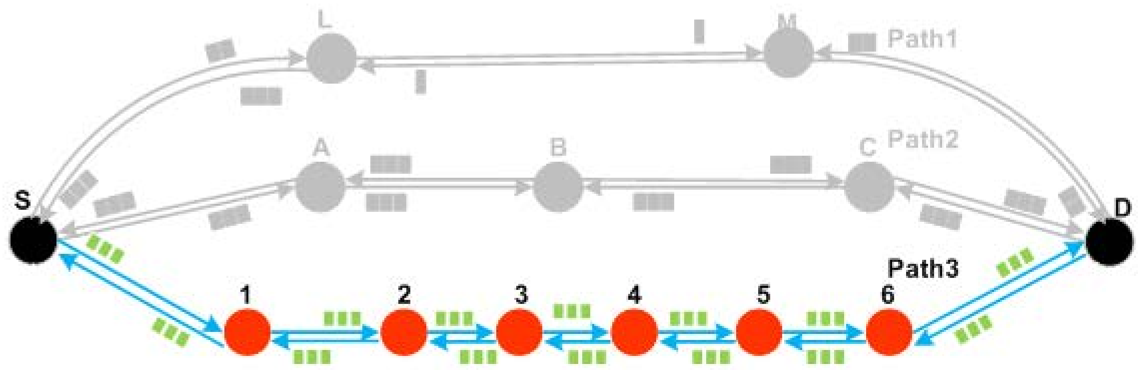
ETX-based Metrics - ETP



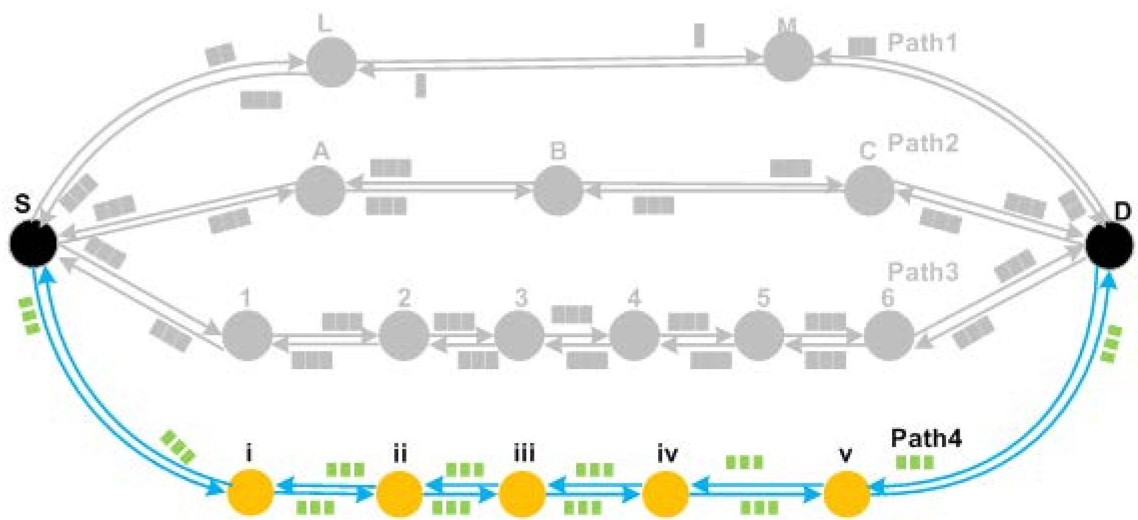
ETX-based Metrics - ETP



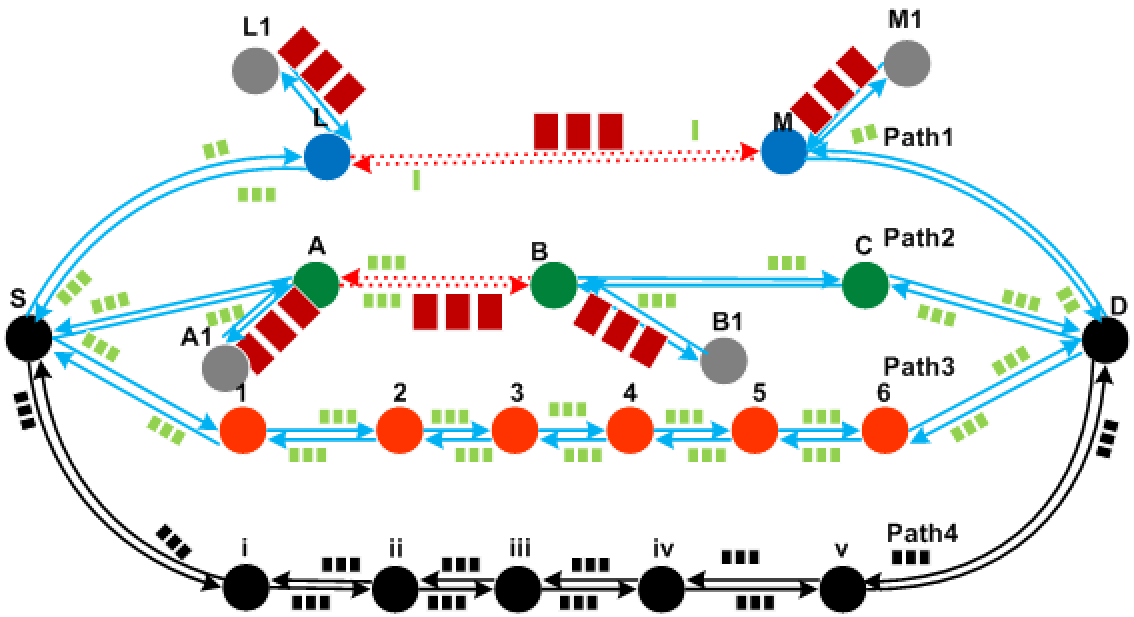
ETX-based Metrics - ETP



ETX-based Metrics - ETP



ETX-based Metrics - ETP



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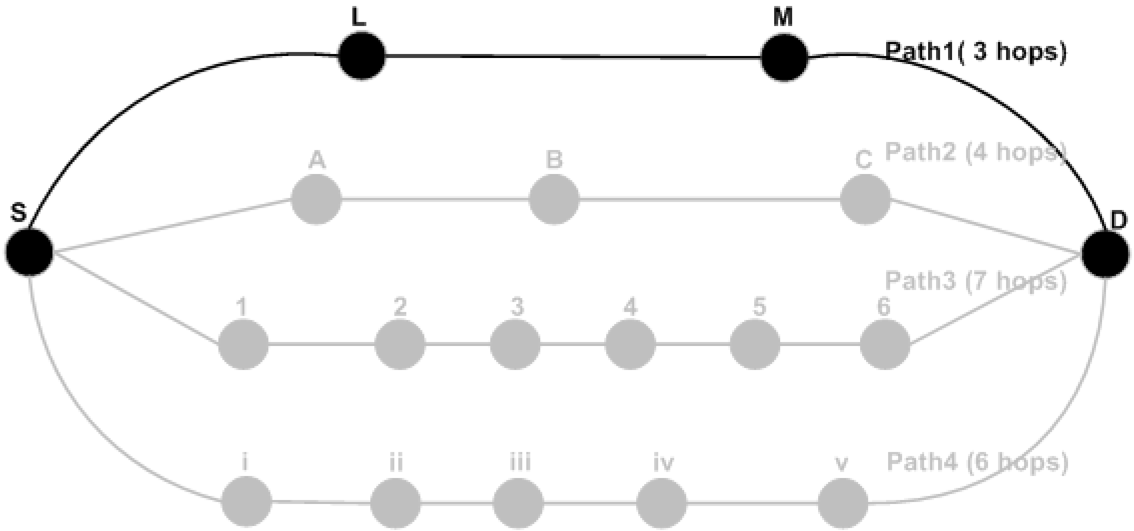
IBETX - Motivation

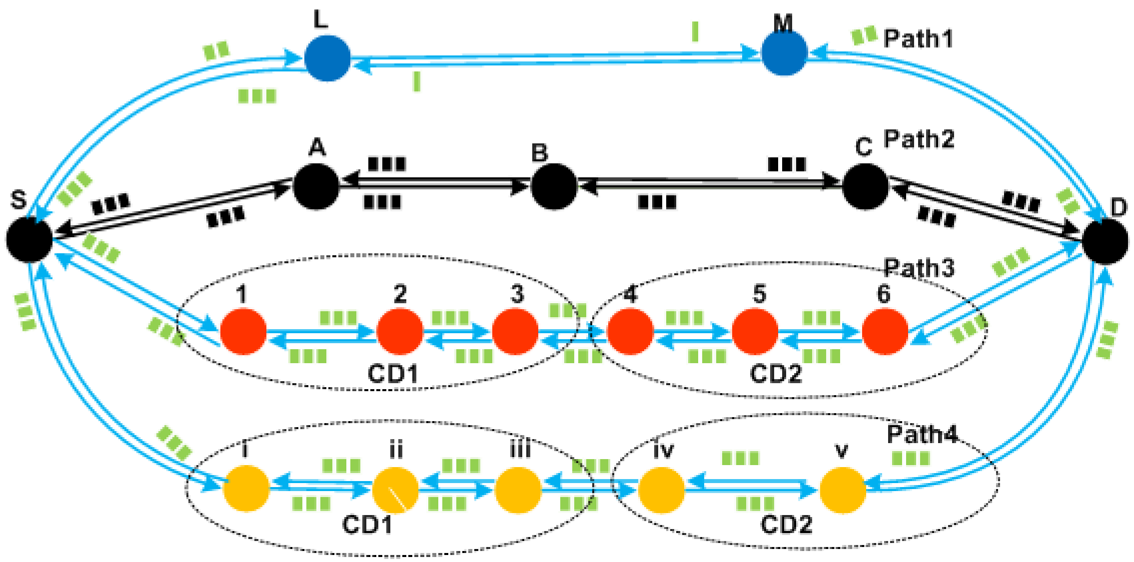
- In a WMN-backbone, either stationary or minimally mobile nodes are interconnected
- Thus, WMNs demand **low end-to-end delay** and **high throughput** paths from its operating RP
- So, RP must choose a **Quality LM** to select the quality links

IBETX - Motivation



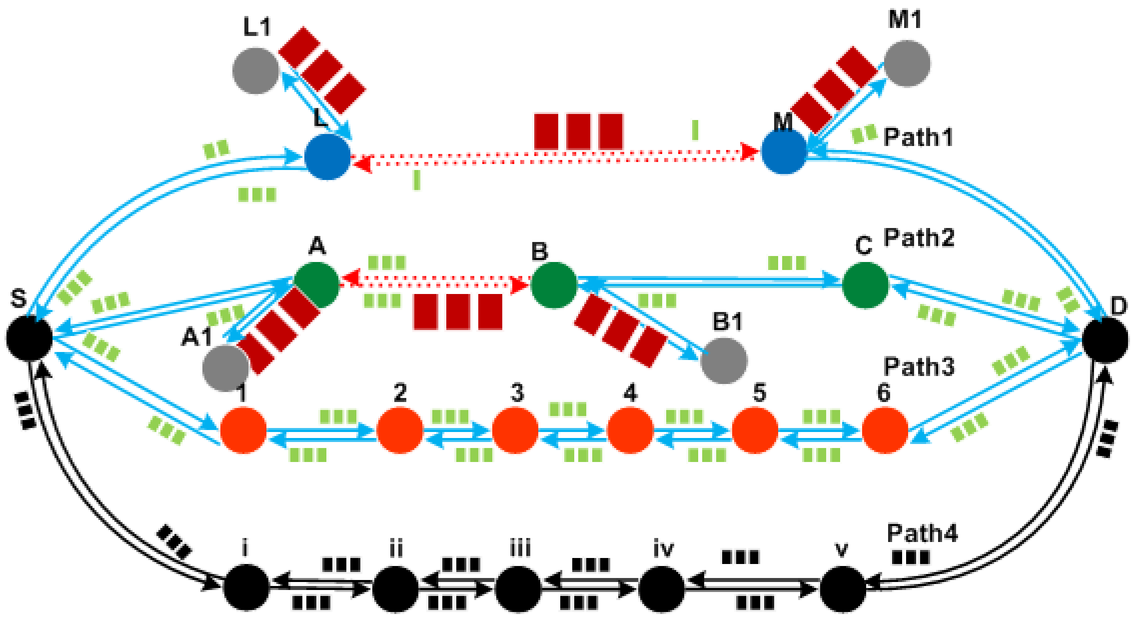
$$Min\ Hopcount_{SD} = \sum_{l=1}^{n} l$$

IBETX - Motivation



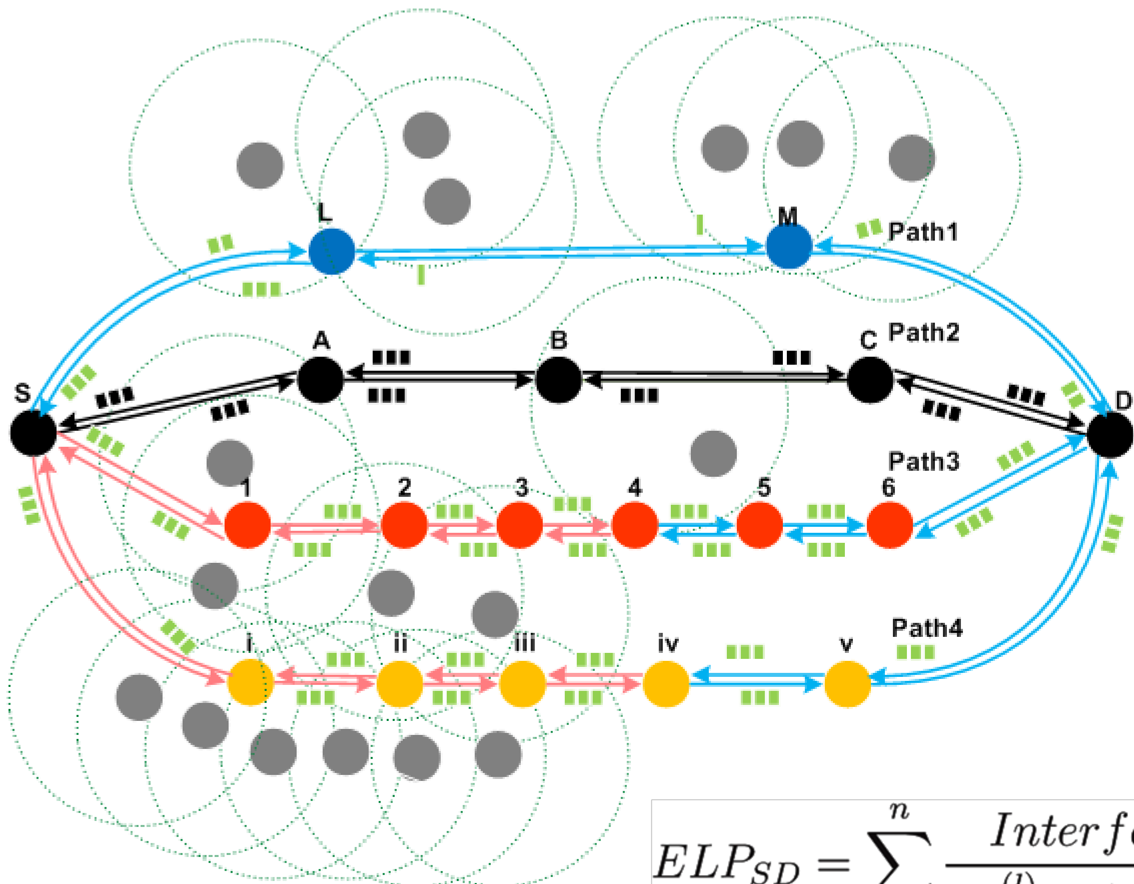
$$ETX_{SD} = \sum_{l=1}^{n} \frac{1}{d_f^{(l)} \times d_r^{(l)}}$$

IBETX - Motivation



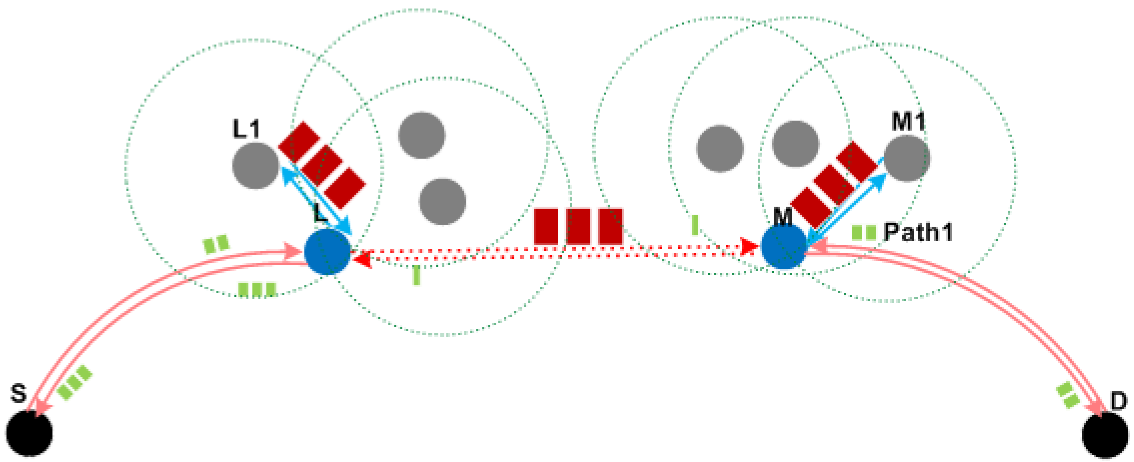
$$ETP_{SD} = \sum_{l=1}^{n} \frac{d_f^{(l)} \times d_r^{(l)}}{\sum_{i \epsilon P \cap NP} \frac{1}{r_i(l)}}$$

IBETX - Motivation

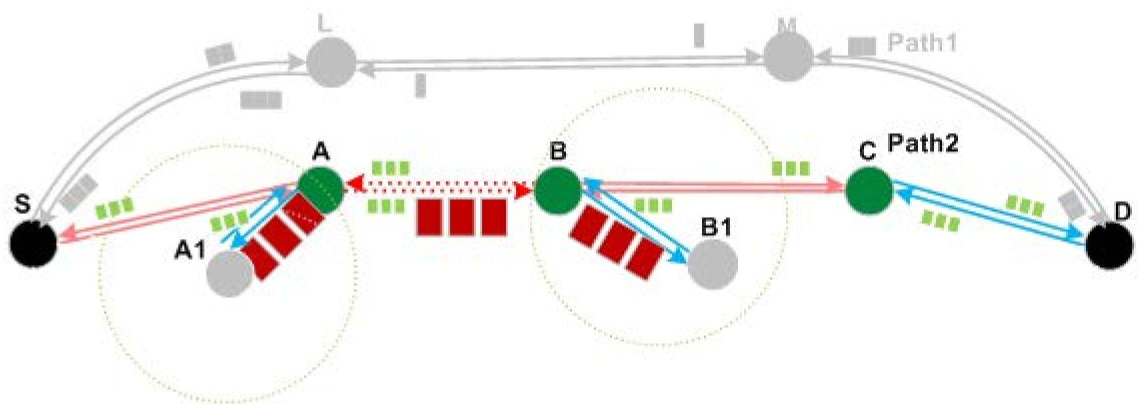


$$ELP_{SD} = \sum_{l=1}^{n} \frac{Interference}{\alpha d_f^{(l)} + (1-\alpha) d_r^{(l)}}$$

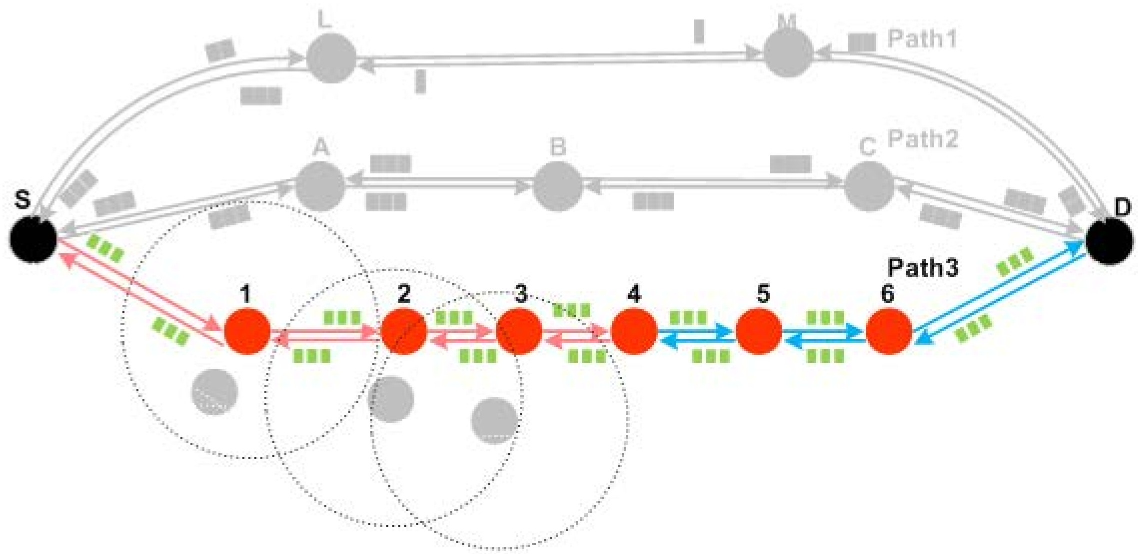
IBETX



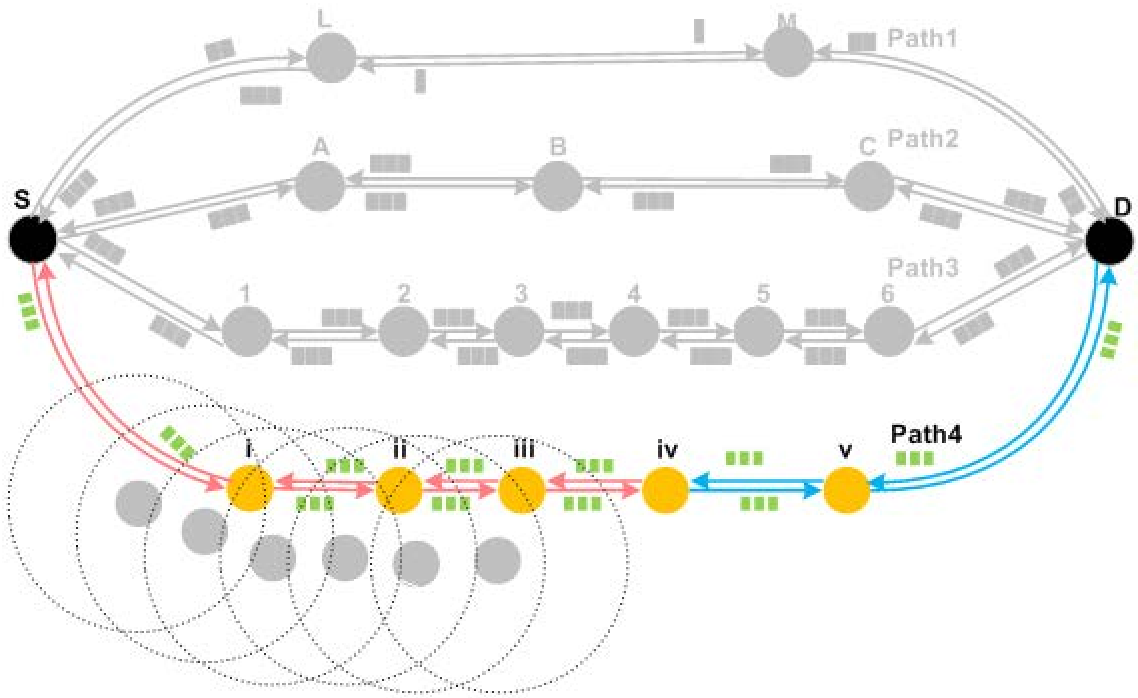
IBETX



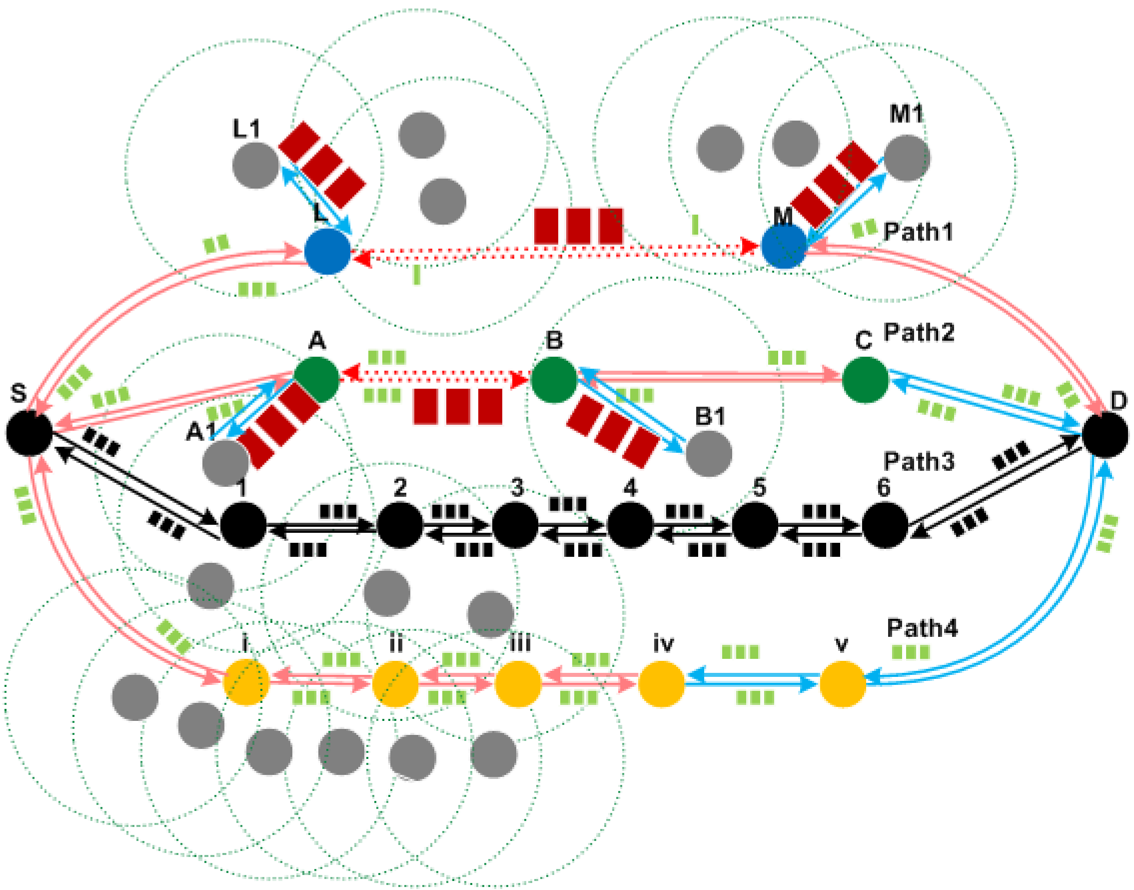
IBETX



IBETX



IBETX



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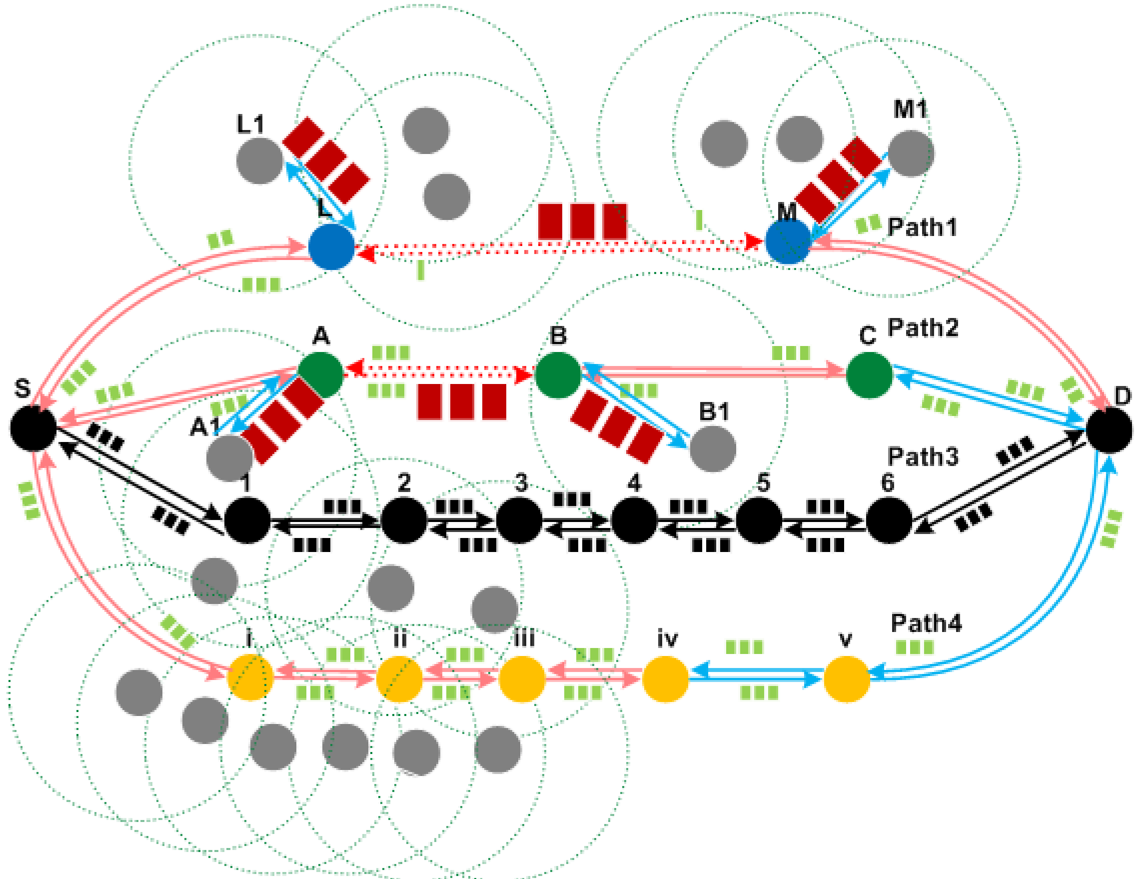
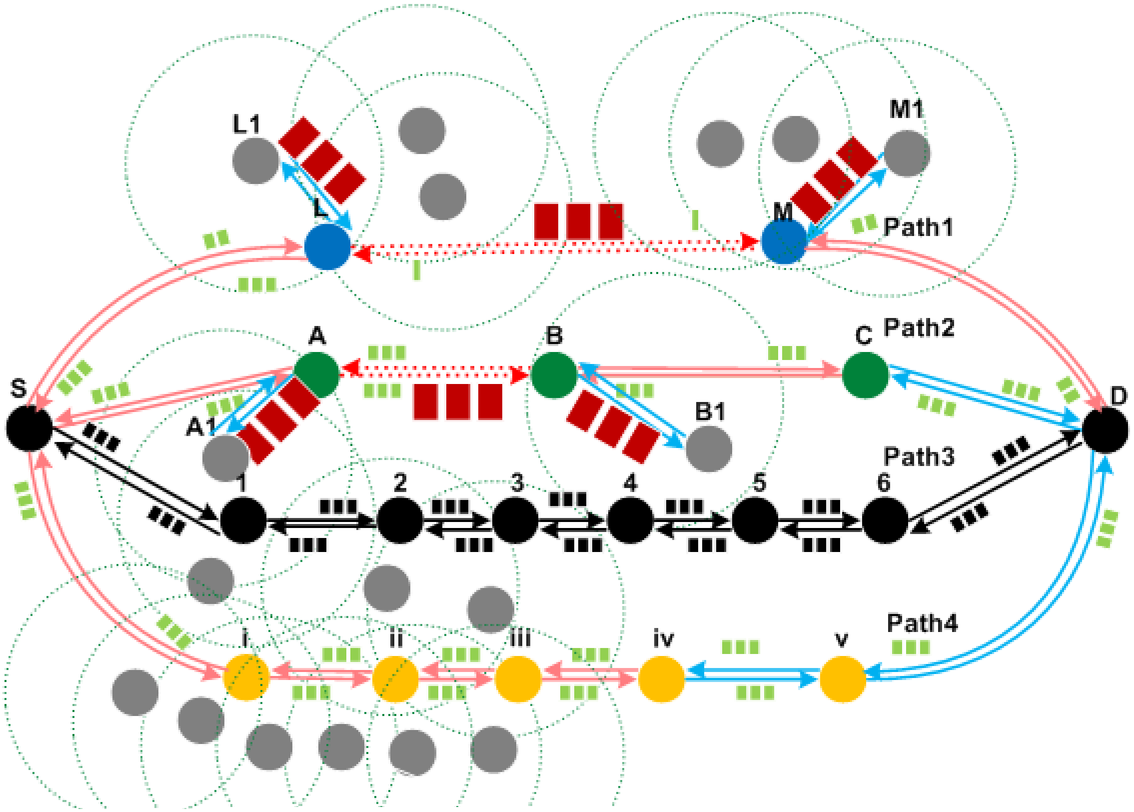
Path4

IBETX



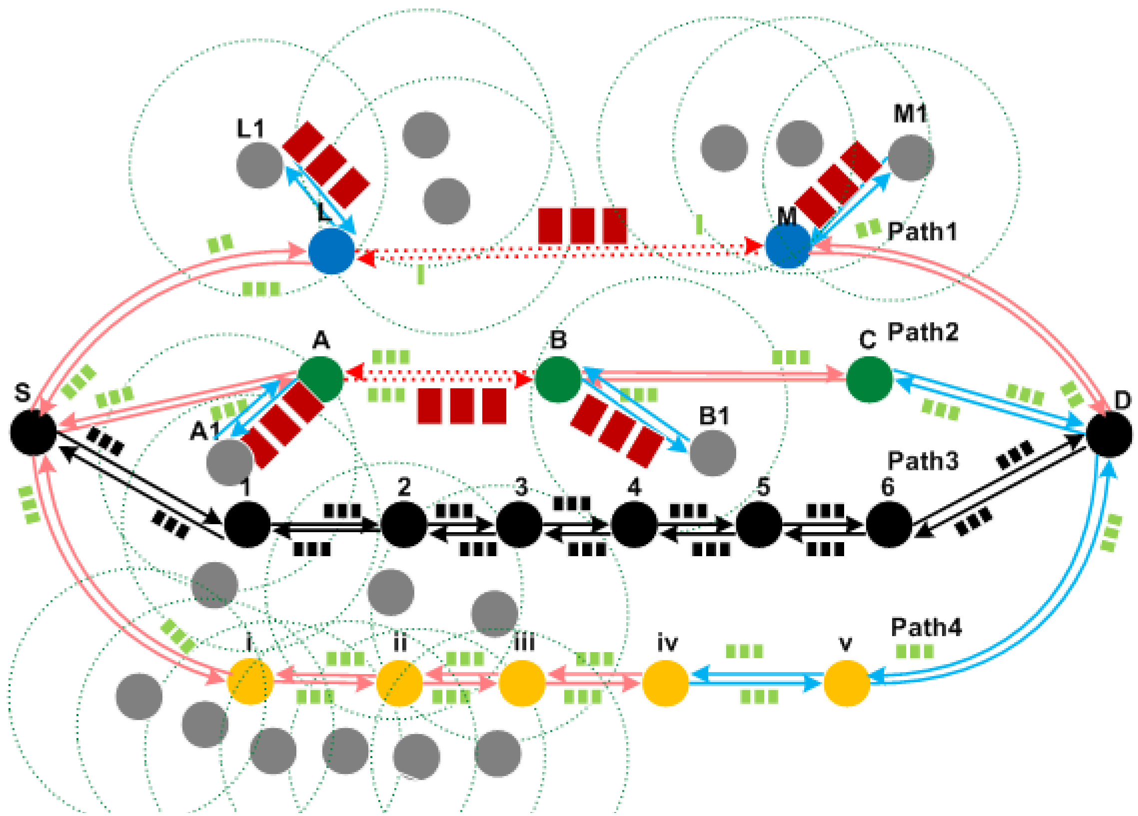
$$IBETX_l = d_f^{(l)} \times d_r^{(l)}$$

IBETX



$$IBETX_l = \frac{d_f^{(l)} \times d_r^{(l)}}{\frac{1}{\sum_{i \epsilon P \cap NP} \frac{1}{r_i}}}$$

IBETX

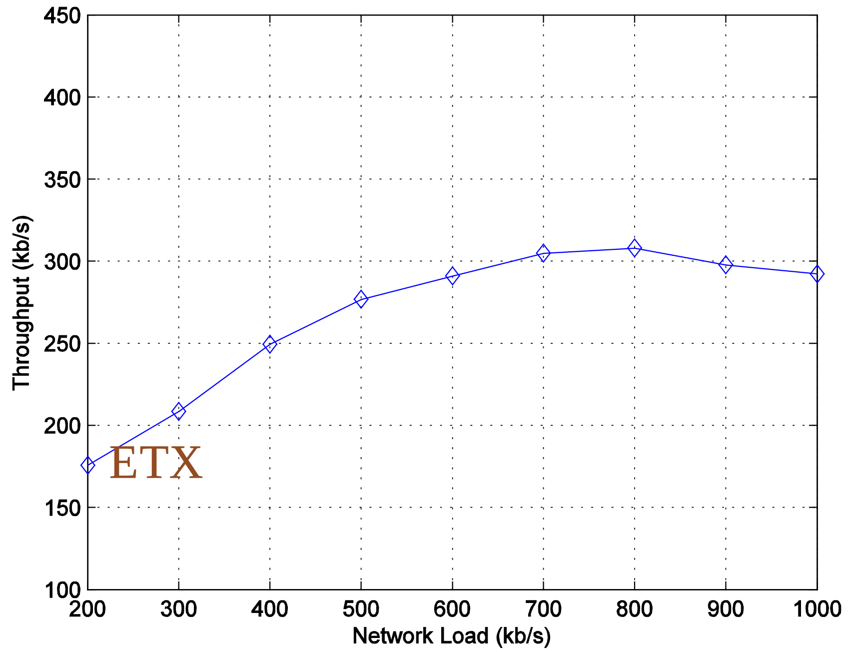


$$IBETX_l = \frac{d_f^{(l)} \times d_r^{(l)}}{\frac{1}{\sum\limits_{i\epsilon P\cap NP} \frac{1}{r_i}}} \times \frac{max[(\frac{\tau_{R_x}+\tau_{RTS}+\tau_{CTS}}{\tau_t}),(\frac{\tau_{R_x}+\tau_{T_x}+\tau_{RTS}+\tau_{CTS}}{\tau_t})]}{1+max[(\frac{\tau_{R_x}+\tau_{RTS}+\tau_{CTS}}{\tau_t}),(\frac{\tau_{R_x}+\tau_{T_x}+\tau_{RTS}+\tau_{CTS}}{\tau_t})]}$$

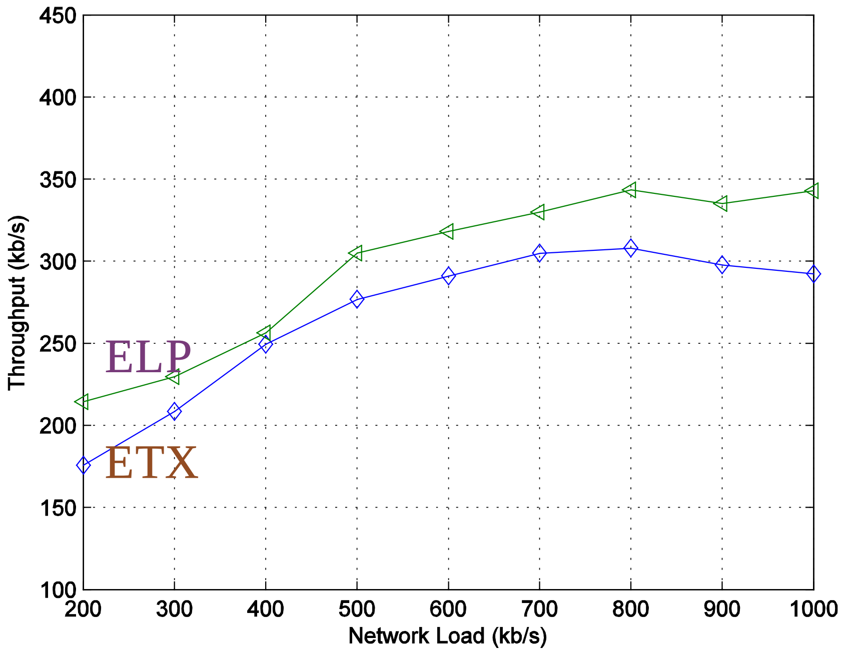
Simulation parameters

Parameters	Values
NS version	NS 2.34
Protocol	DSDV
Link metrics	ETX, ELP, ETP, IBETX
Network area	1000m x 1000m
Number of nodes	50
Source-destination pairs	20
CBR packet size	640Bytes
Data traffic rates	2pack/s to 10pack/s
Topologies	Mean of 5 random topologies is used
Total simulation time	900s

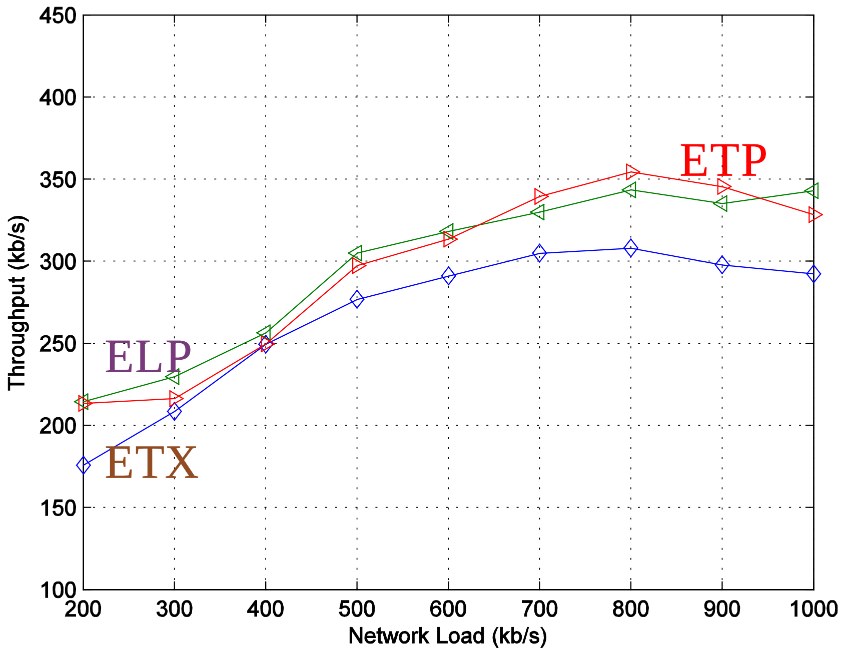
Simulations-Throughput



Simulations-Throughput



Simulations-Throughput



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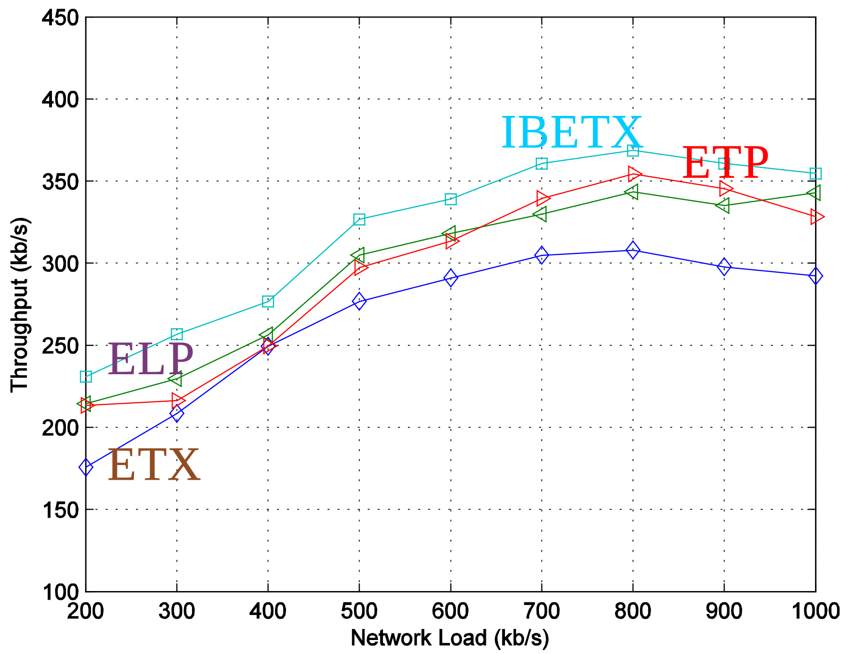
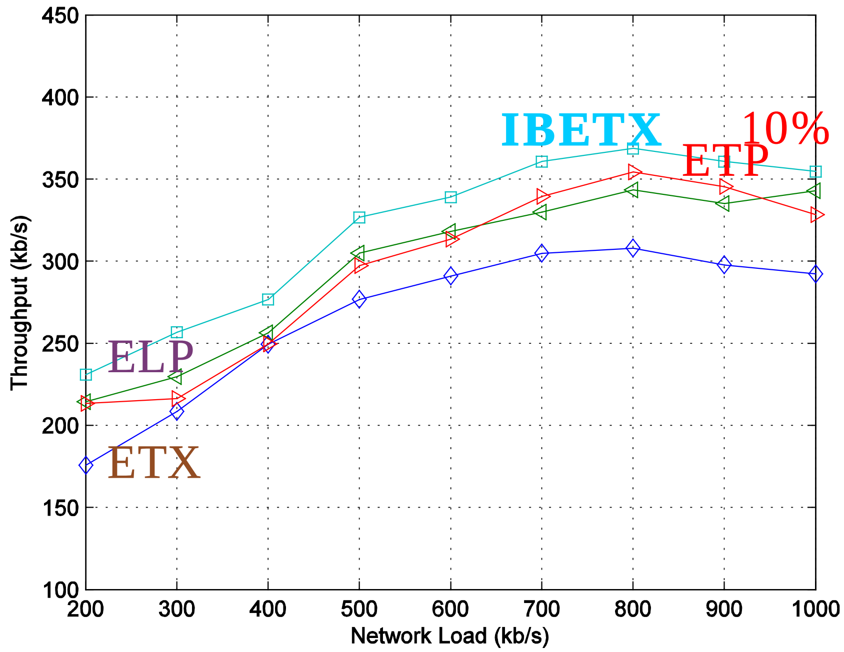
Simulations-Throughput



Simulations-Throughput



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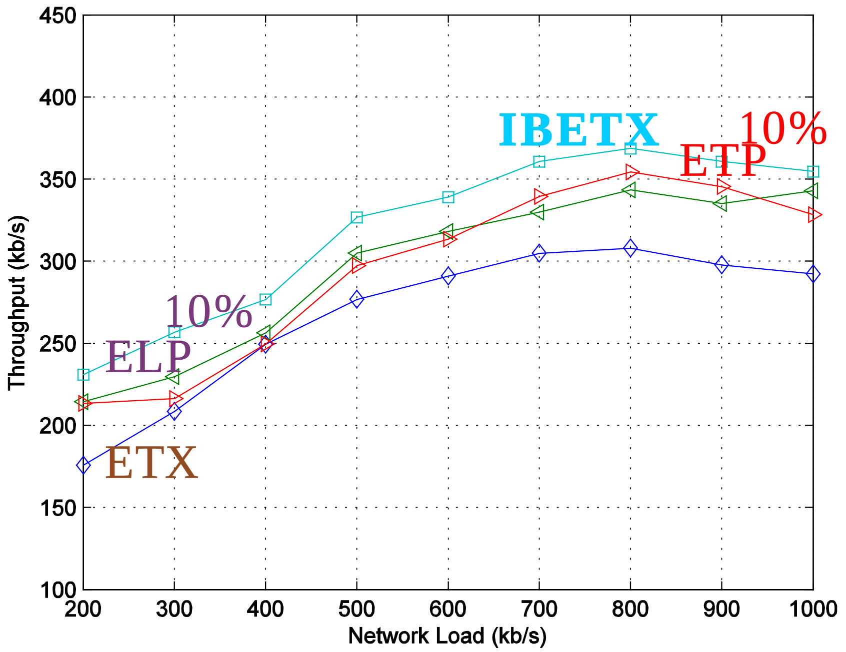
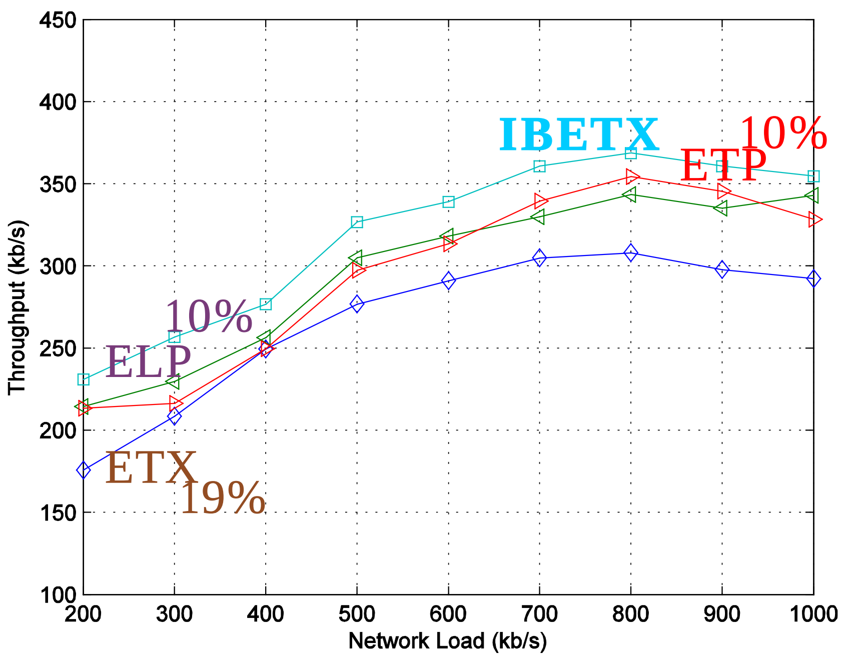
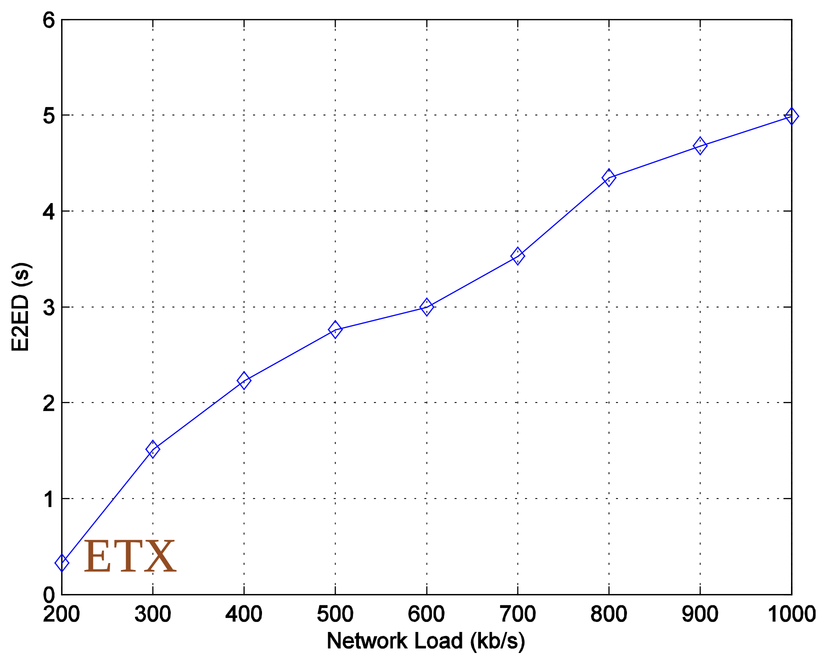
Simulations-Throughput



Simulations-Throughput



Simulations-End-to-end Delay



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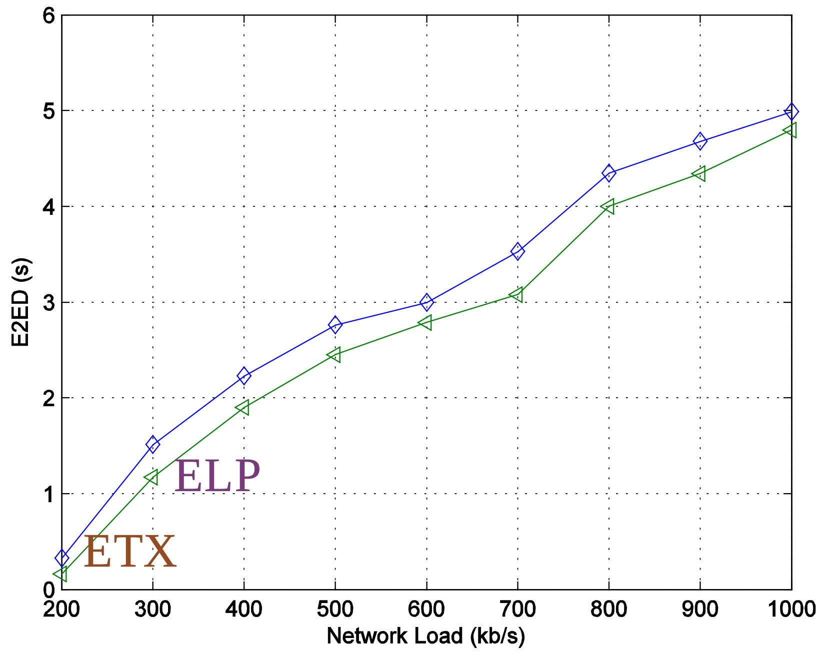
Simulations-End-to-end Delay



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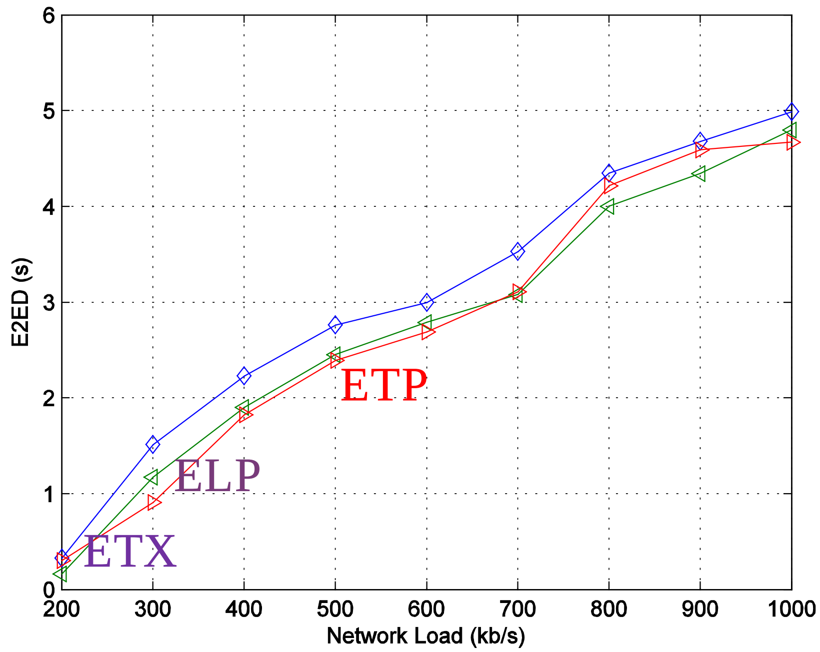

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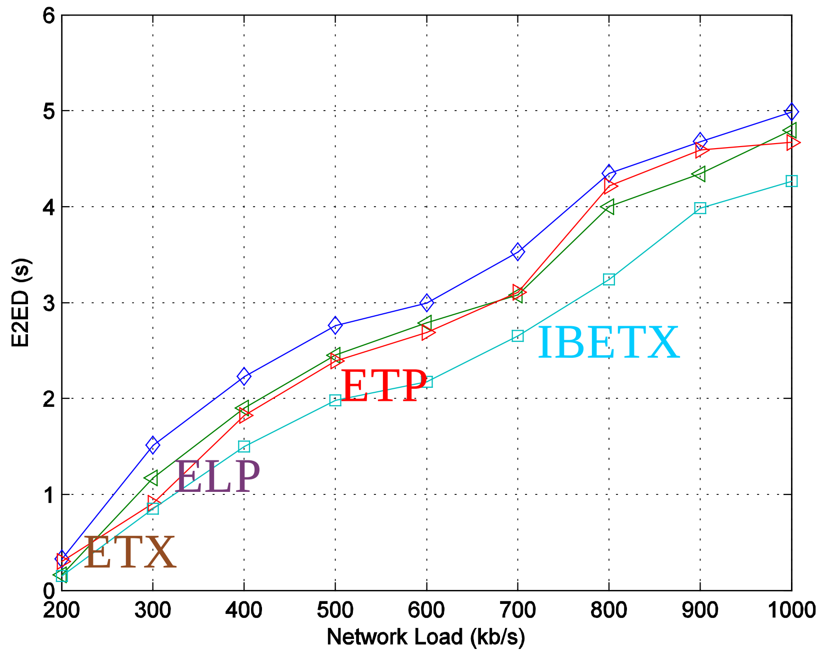

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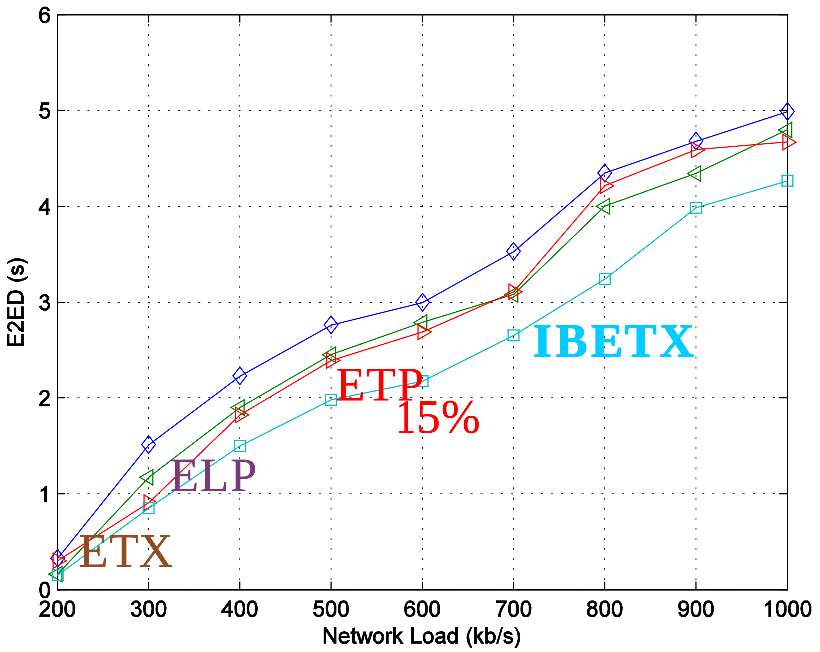

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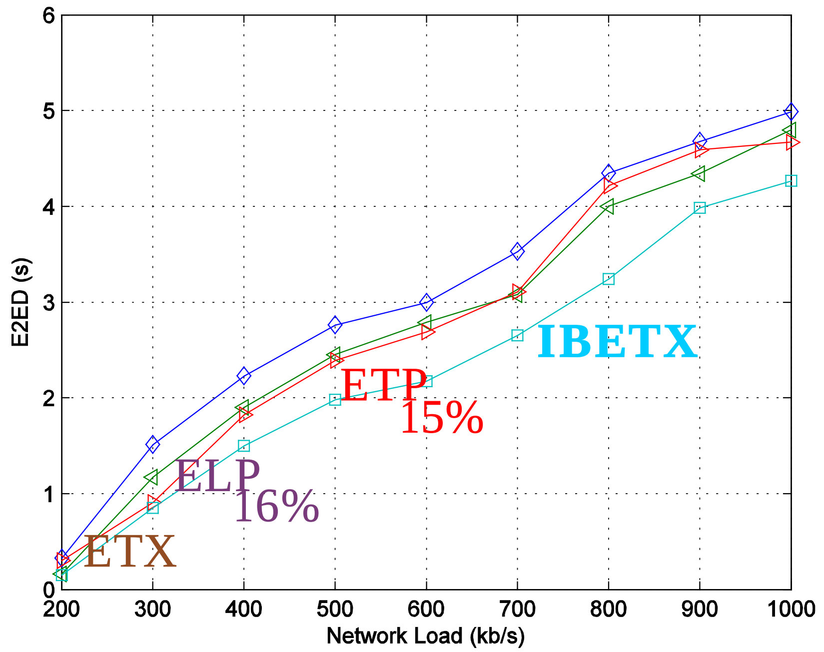

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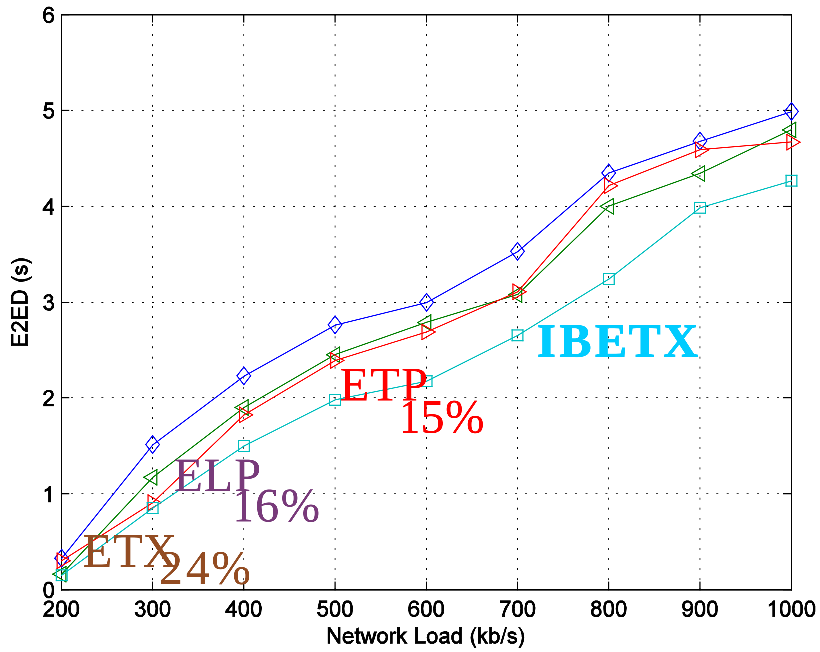

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Conclusion

- Performance Evaluation and Comparison of:
  - 3 reactive protocols
  - 3 proactive protocols

- Modeling cost paid by reactive routing protocols for RD and RM in the form of time-spent and energy-consumed

- Performance study of ETX-based metrics

- Designing a Quality Link Metric and InvETX

- IBETX: Proposal and validation