TECHNISCHE UNIVERSITÄT DRESDEN

ComNets Deutsche Telekom Chair of Communication Networks

Sobe, Marek
Deutsche Telekom Chair for Communication Networks
TU Dresden

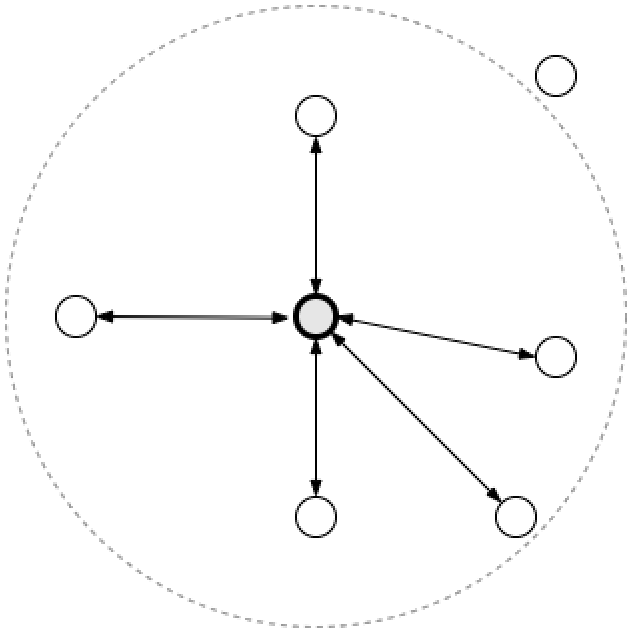
Optimizing Broadcast Delivery in Dynamic Wireless Mesh Networks

Diploma Thesis

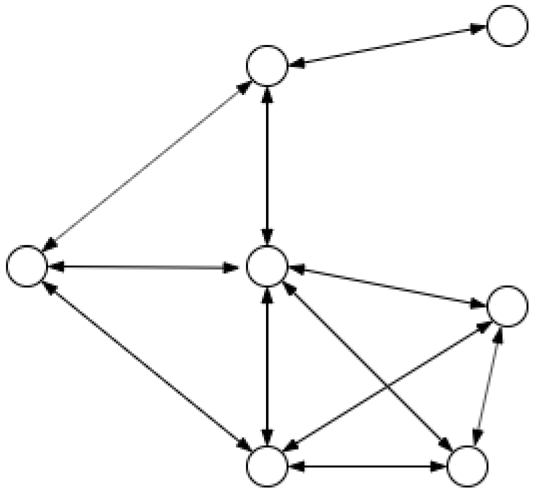
13.11.2019

Motivation – Wireless Mesh Networks (WMNs)

- Exploitation of broadcast nature of the wireless medium
- Coordination and management tasks distributed in the network
- Routing challenge



Cellular topology



Mesh topology

Motivation – Broadcast in WMN

- Broadcast as basic requirement for general operability
  - Network protocols (ARP, DHCP)
  - Wireless solution for industrial ethernet (motion & automation control)
- Increased demand for future use
  - Media delivery (video streaming)

Motivation

- State of the art: Flooding, B.A.T.M.A.N., OLSR:
  - Fixed rate schemes
  - No link quality awareness

- Related work on multi-rate protocols, difficult dependencies:
  - Up-to-date, complete network knowledge
  - Central entity for coordination

Motivation

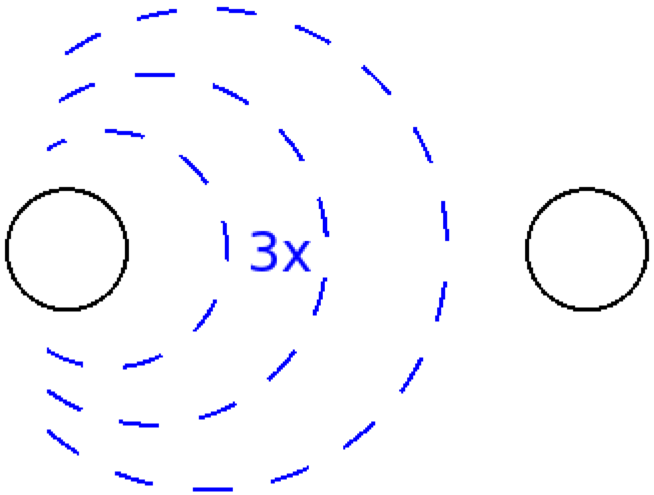
- State of the art: Flooding, B.A.T.M.A.N., OLSR:
  - Fixed rate schemes
  - No link quality awareness

- Related work on multi-rate protocols, difficult dependencies:
  - Up-to-date, complete network knowledge
  - Central entity for coordination

➡ Still missing: Multi-rate broadcast, generally applicable to all scenarios

State of the Art - Protocols

- Basic flooding still used
- B.A.T.M.A.N.
  - „Triple flooding“ – simple approach to tackle lossy links
  - Fixed transmission rate
  - Simple avoidance mechanism for unnecessary broadcasts

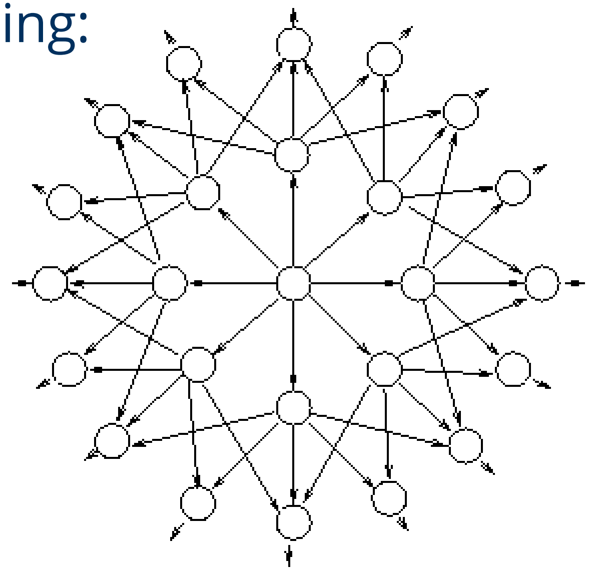


https://www.open-mesh.org/projects/batman-adv/wiki/Broadcast

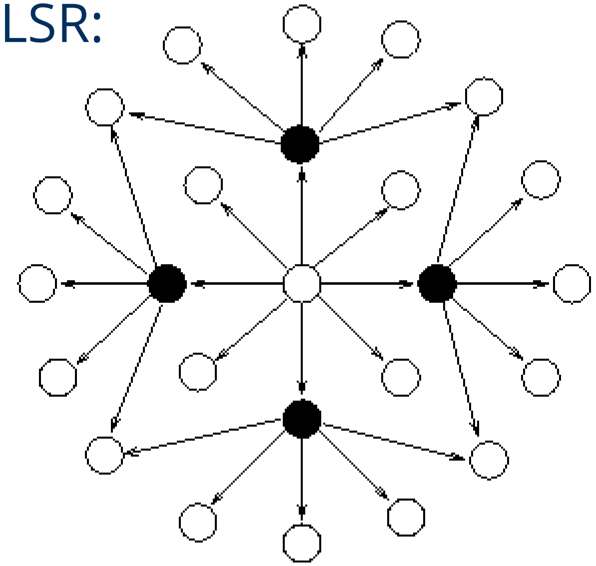
State of the Art - Protocols

- Optimized Link State Routing (OLSR)
  - Implements broadcast reduction strategy of Multipoint Relaying (MPR)
  - Fixed transmission rate

Flooding:



OLSR:



http://www.olsr.org/docs/report_html/node28.html

Challenge – Protocol Requirements

- High reliability, low airtime
- Primarily designed for low traffic volume use cases (network protocols, industrial applications)
- Dynamic multi-rate capability, usage of multiple Modulation and Coding Schemes (MCS)
- Link quality awareness
- 2-hop neighborhood discovery to provide network knowledge

Contribution – Problem Formulation

Key protocol challenges:

1. Targets – Which nodes should be considered as recipients for my own broadcast?
2. Rate – What rate is optimal to reach all desired recipients?
3. Forwarders – Which recipients should participate in forwarding?

Contribution – Problem Formulation

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3. Forwarders – Which recipients should participate in forwarding?

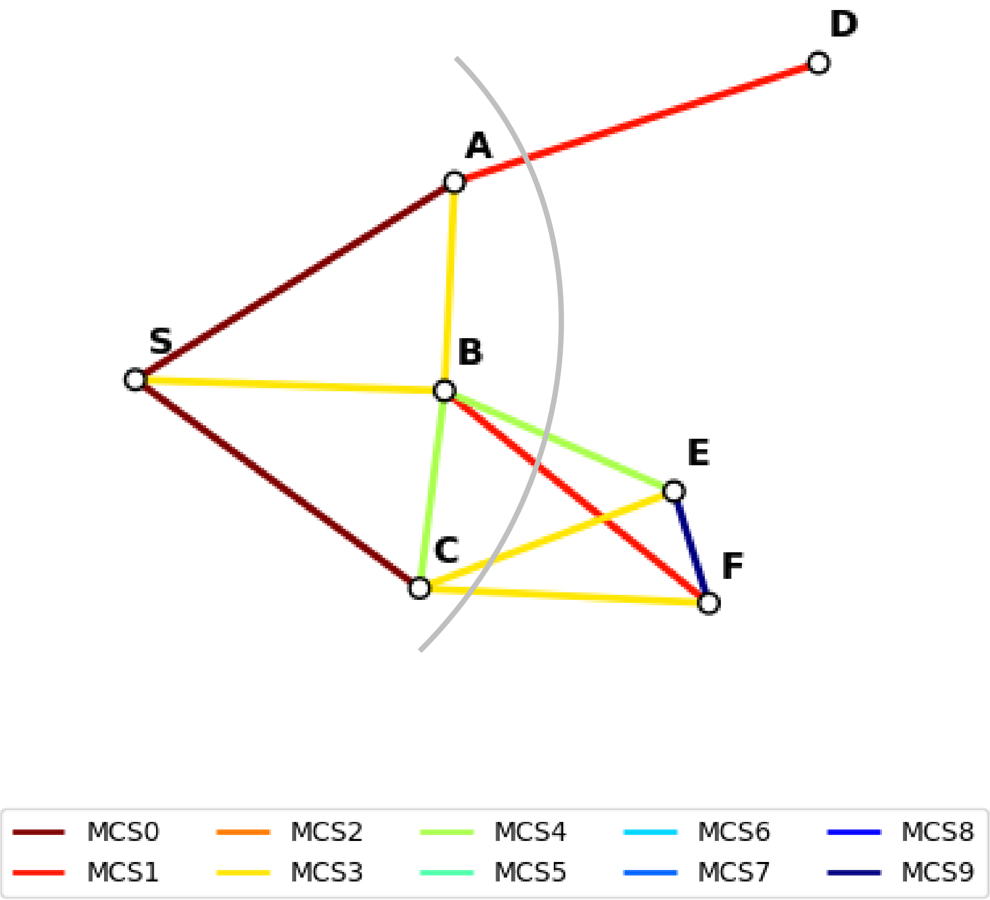
Solution:

Rate **A**ware **I**nformation **D**issemination with **E**xtra **R**eliability (RAIDER)

Contribution – RAIDER Description

1. Targets
   - One hop neighbors
   - Exclude direct neighbors from previous transmission sender

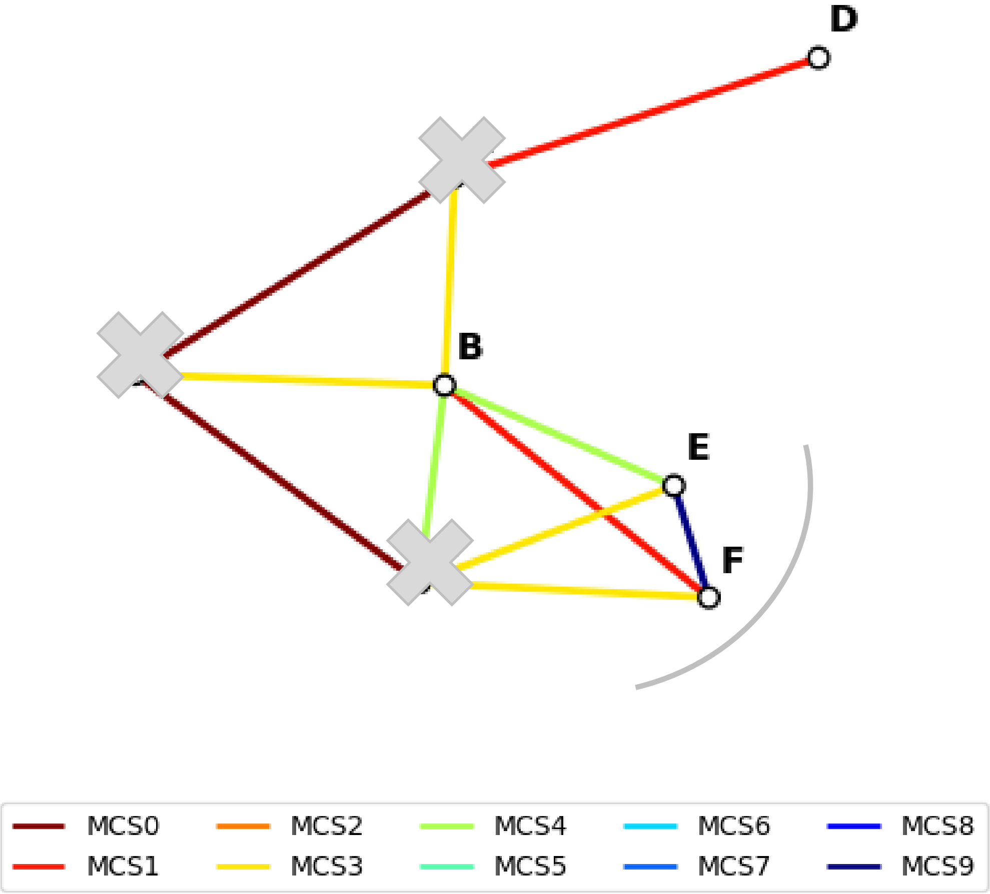
   - Example sender: **S**
     - Targets: A, B, C



Contribution – RAIDER Description

1. Targets
   - One hop neighbors
   - Exclude direct neighbors from previous transmission sender

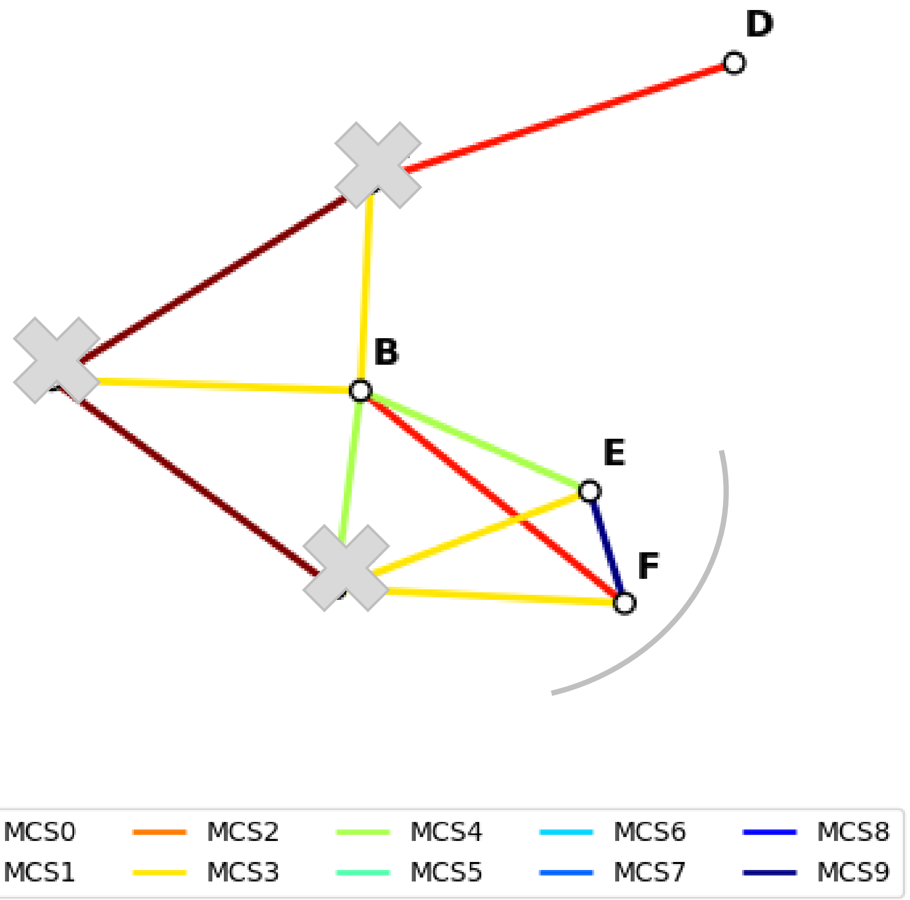
   - Example sender: **B**
     – Targets: S, A, C, E, F



Contribution – RAIDER Description

1. Targets
   - One hop neighbors
   - Exclude direct neighbors from previous transmission sender
   - Assigned targets by the previous transmission sender

   - Example sender: **B**
     - Targets: S, A, C, E, F

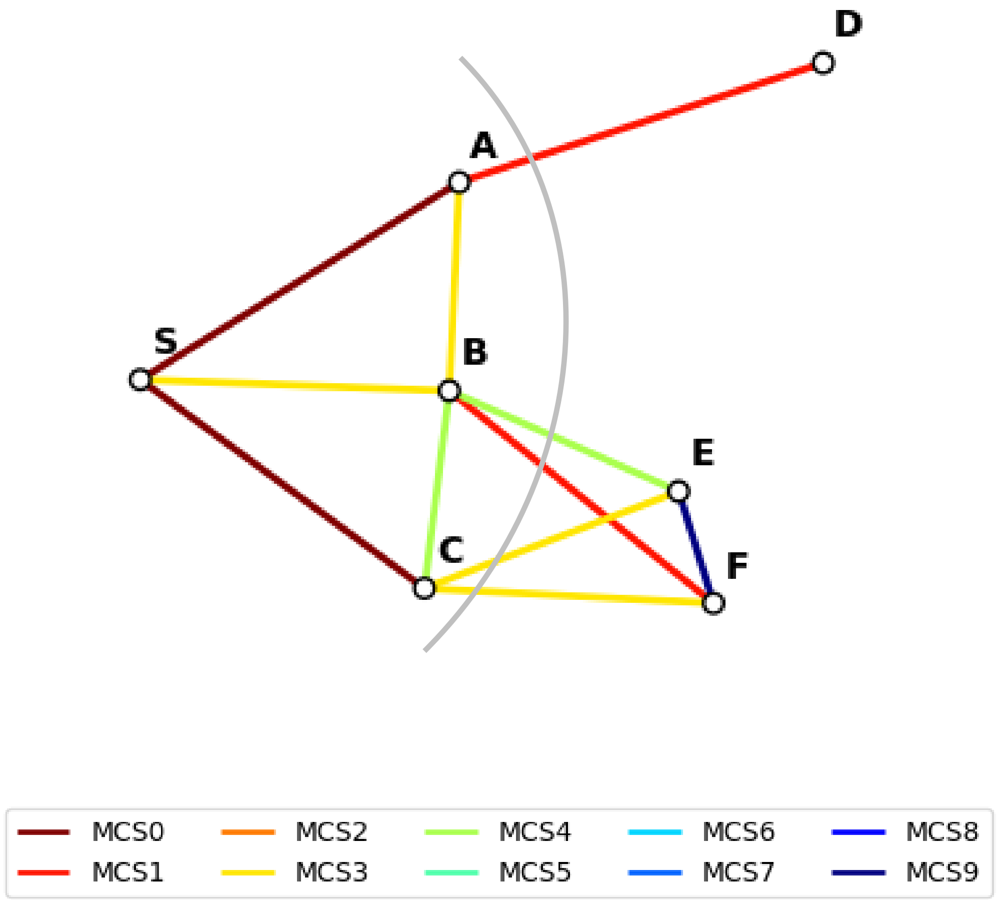


Contribution – RAIDER Description

2. Rate

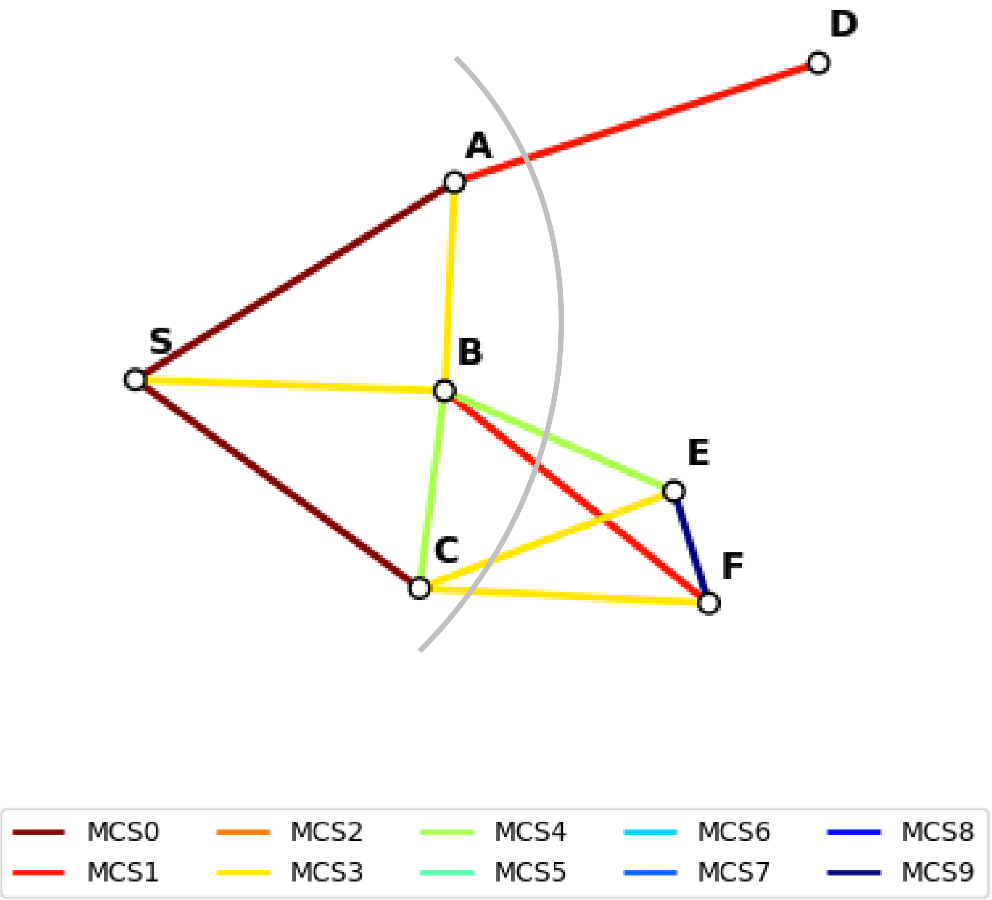
The sender should only lower the rate, when there is no faster path to a recipient via nearby nodes.

- Highest rate (highest MCS) that reaches all targets



Contribution – RAIDER Description

2. Rate
   - Minimize expected transmission time towards each target with Dijkstra

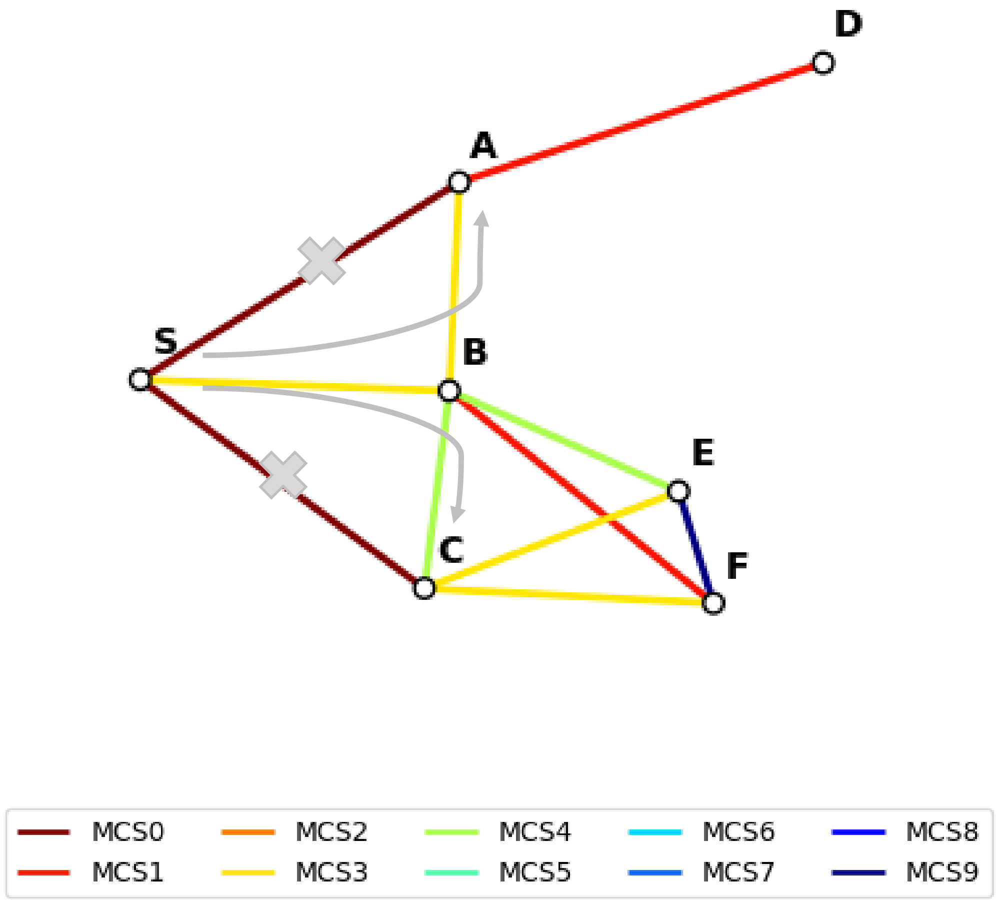


Contribution – RAIDER Description

2. Rate
    - Minimize expected transmission time towards each target with Dijkstra
    - Create forwarding assignments

- S to A via B $$\frac{N\ Bit}{8\ MBit/s} > 2 \cdot \frac{N\ Bit}{33\ MBit/s}$$

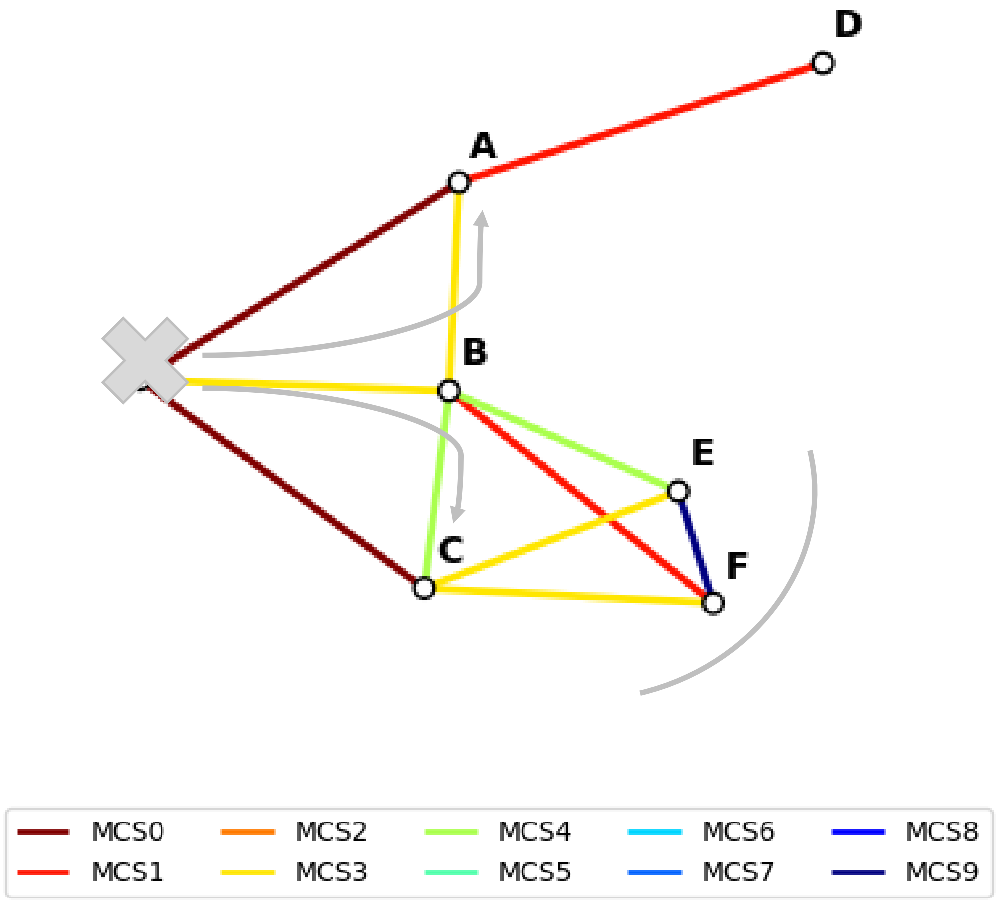
- S to C via B



Contribution – RAIDER Description

1. Targets
   - One hop neighbors
   - Exclude direct neighbors from previous transmission sender
   - Assigned targets by the previous transmission sender

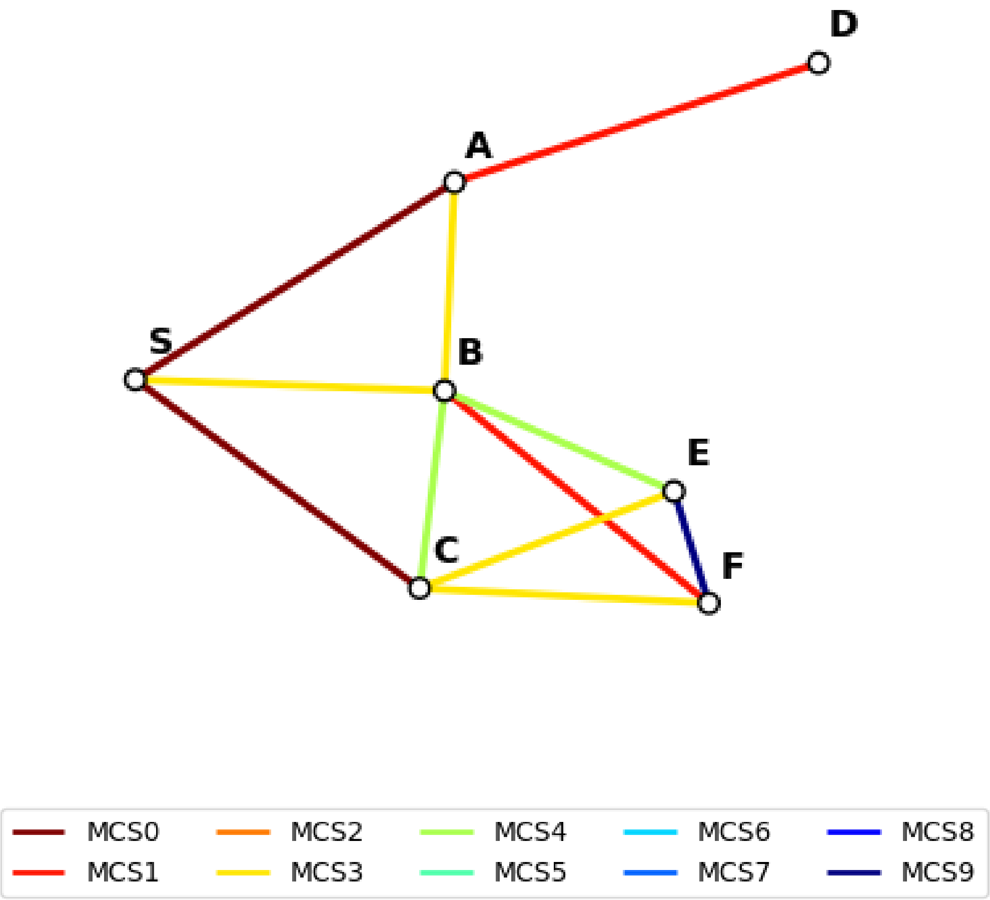
   - Example sender: **B**
     - Targets: S, A, C, E, F



Contribution – RAIDER Description

2. Rate
   - Minimize expected transmission time towards each target with Dijkstra
   - Create forwarding assignments

   - Optimizations:
     - Minimum link quality threshold p_{tr} for considered paths
     - Retransmissions on MCS0

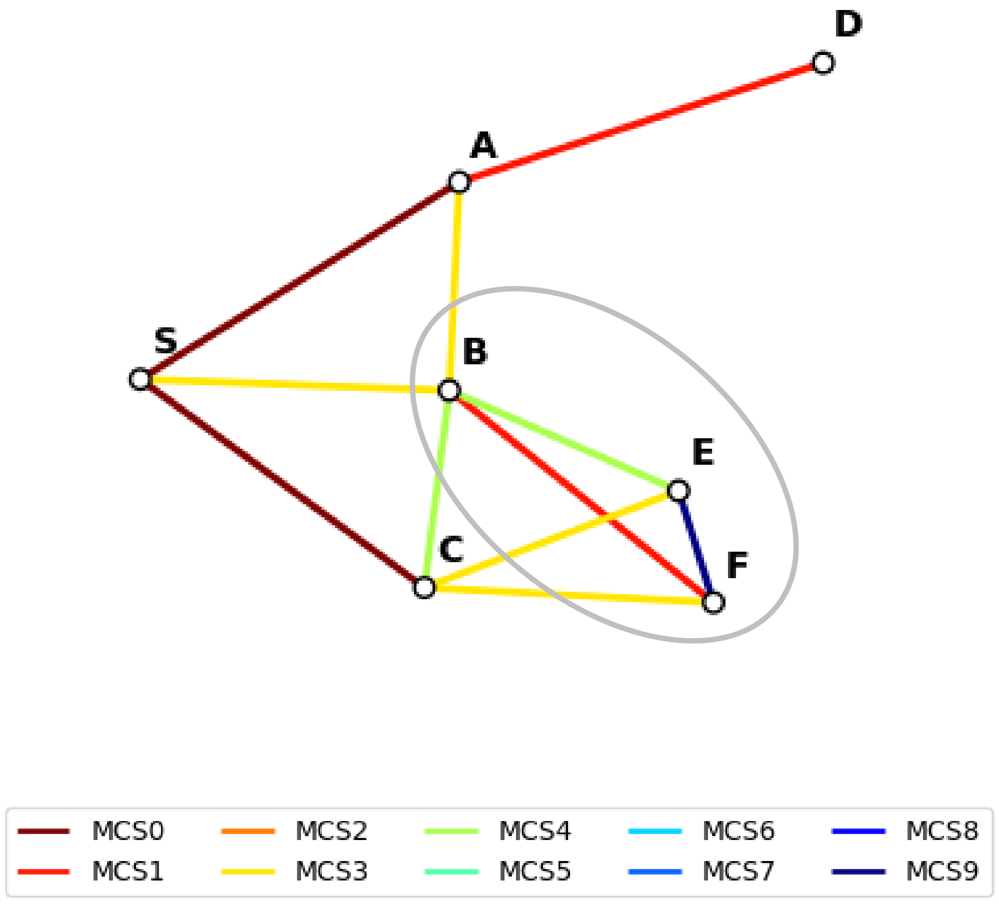


Contribution – RAIDER Description

3. Forwarders
   - Cover complete 2-hop neighborhood

   - Adopt forwarding assignments
   - Assign more forwarders as necessary to cover 2-hop neighborhood

   - B as forwarder (according to assignment from S)

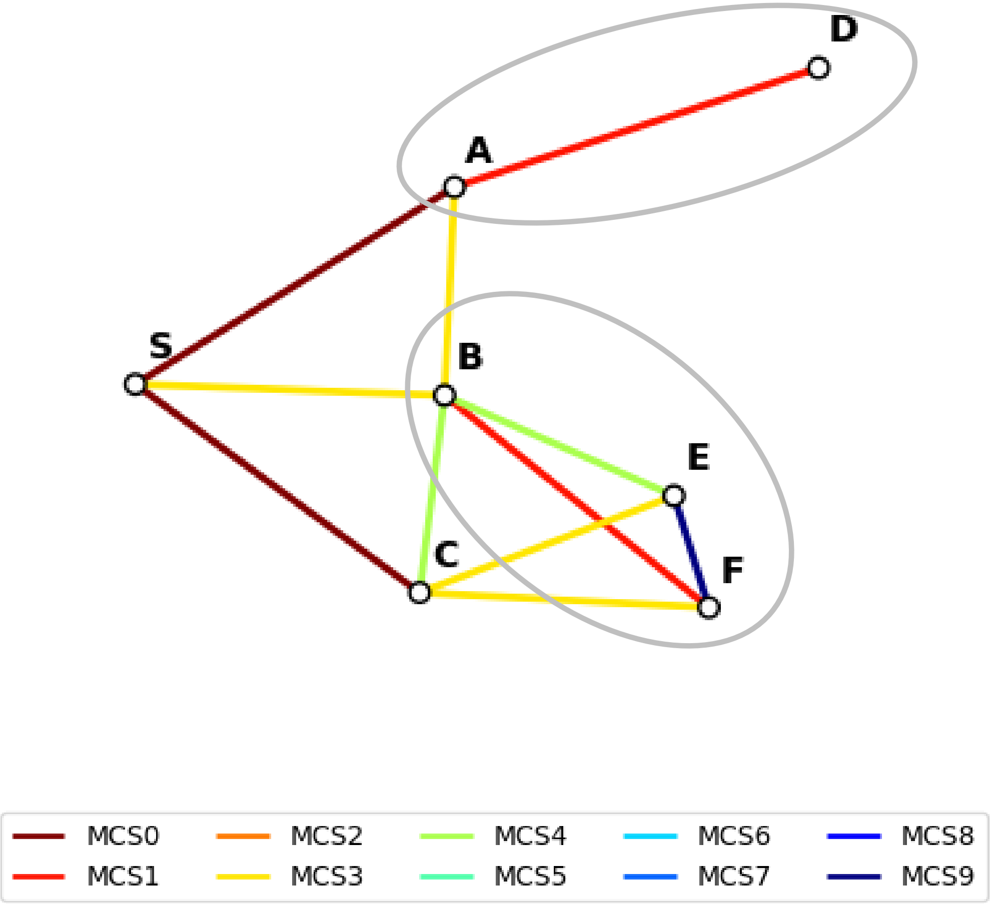


Contribution – RAIDER Description

3. Forwarders
   - Cover complete 2-hop neighborhood

   - Adopt forwarding assignments
   - Assign more forwarders as necessary to cover 2-hop neighborhood

   - B as forwarder (according to assignment from S)
   - A as forwarder

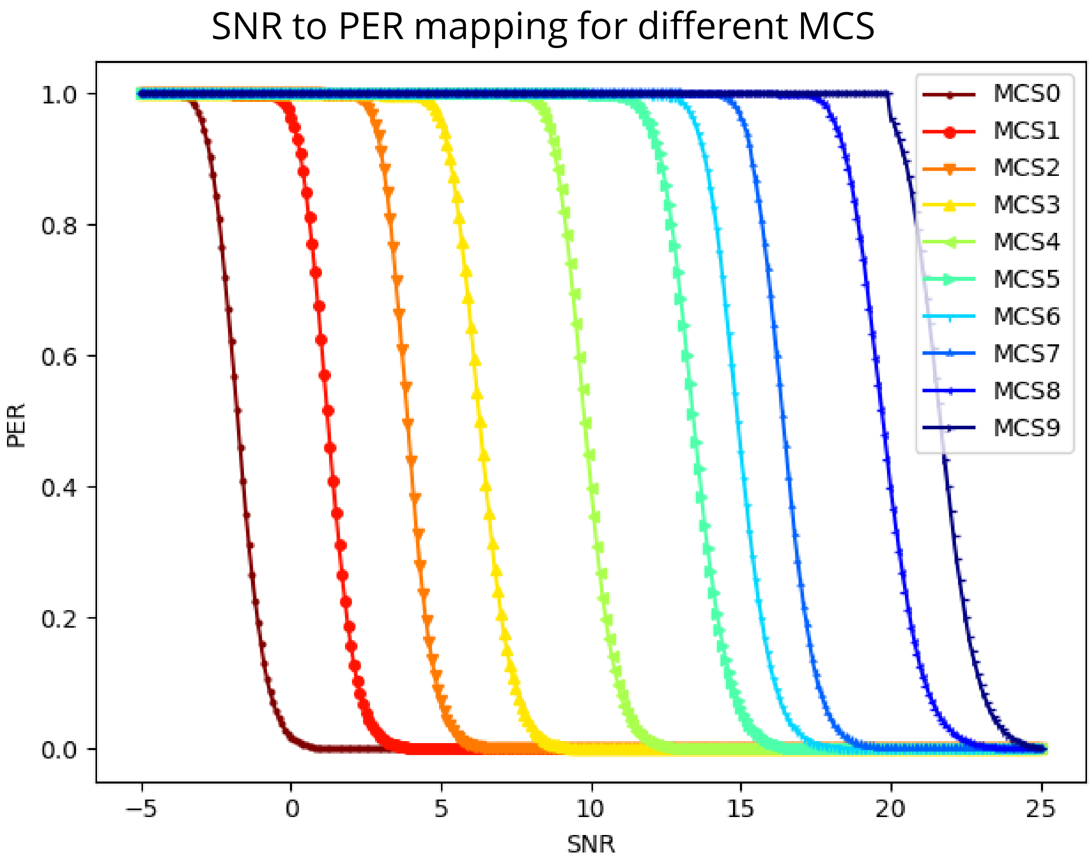


Contribution – Broadcast Simulator

- Python-based
- n randomly placed nodes
- Variable area $l \cdot l$

  (default $n = 15$, $l = 200$ m)

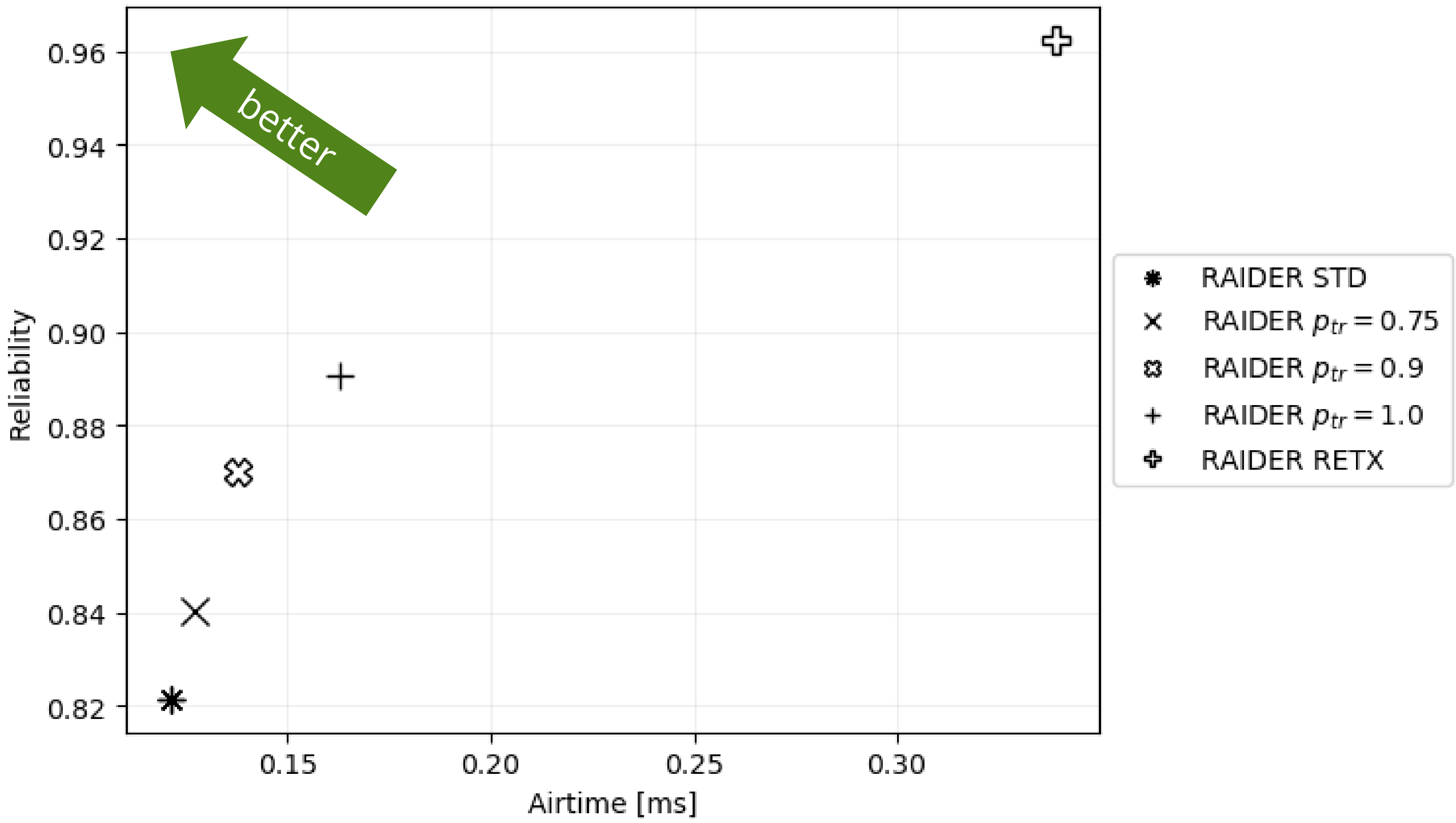
- IEEE TGn Channel Model D
- SNR to PER lookup table
- 10 different Modulation and Coding Schemes (MCS) → 10 different data rates



Evaluation – RAIDER

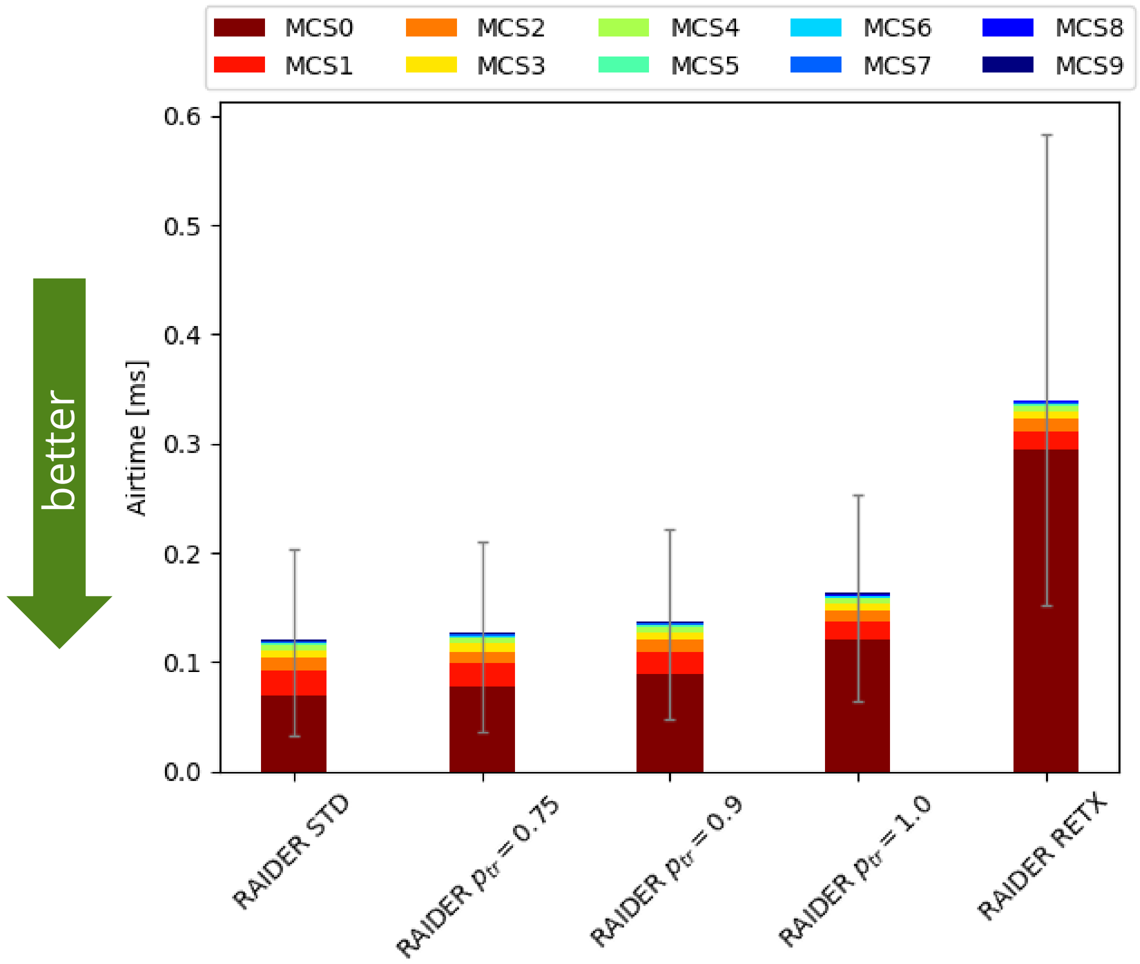
250 random networks,

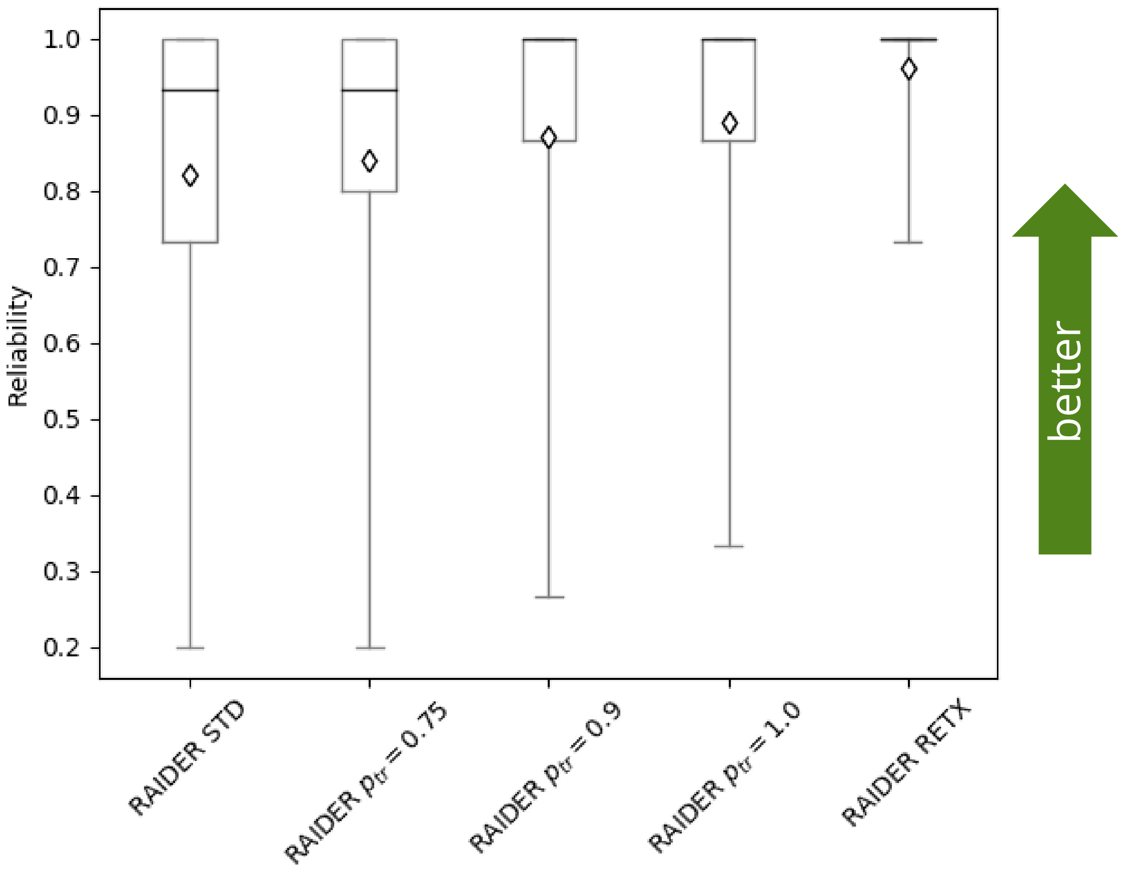
$l = 300$ m
$n = 15$



Performance overview for all RAIDER versions for $l = 300$ m

Evaluation – RAIDER





Airtime and reliability details for all RAIDER versions for $l = 300$ m

Evaluation – Performance Comparison

- Evaluate RAIDER against lower & upper performance bound

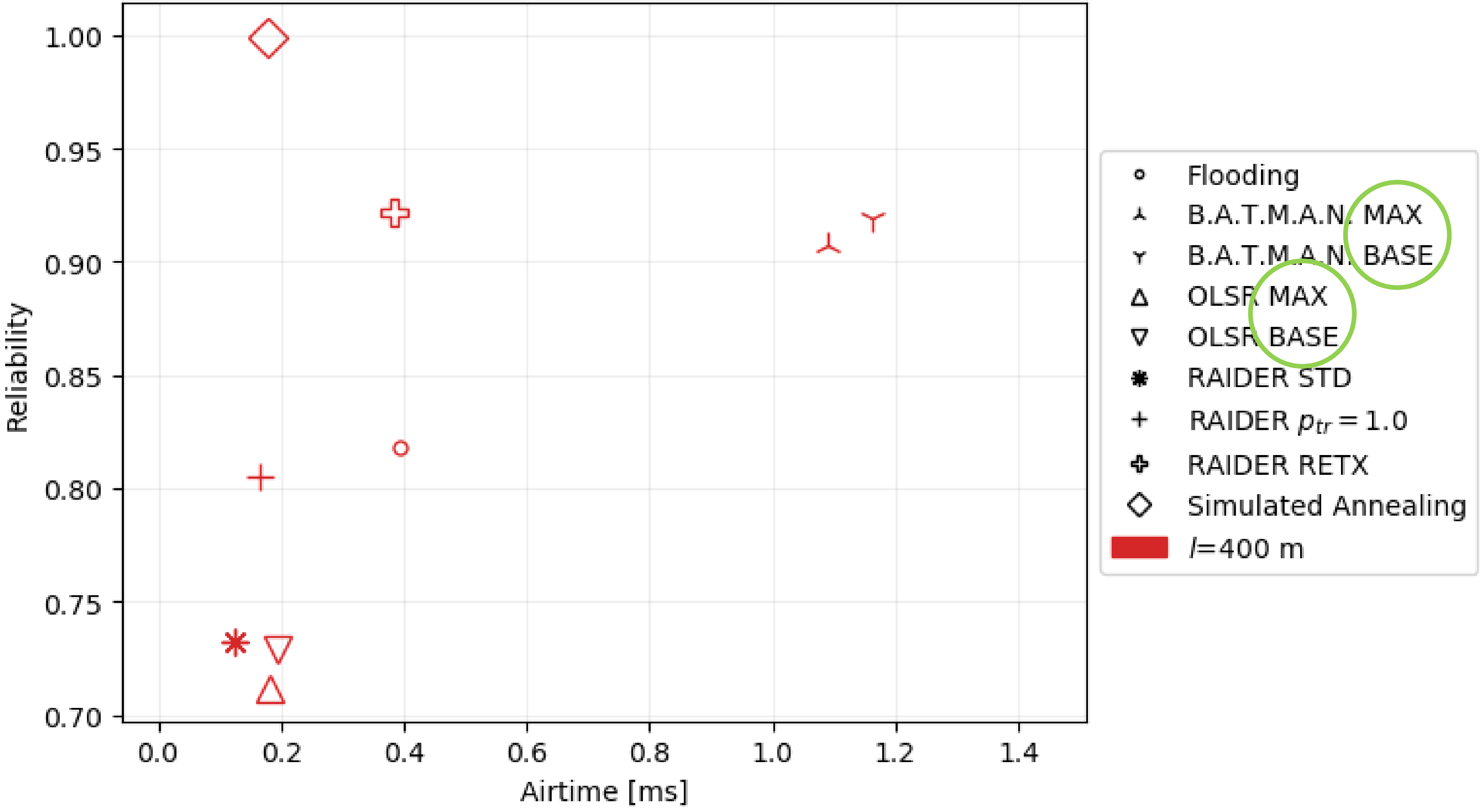
- All state of the art protocols considered as lower bound

- Upper performance bound:
  - NP-hard optimization problem
  - Simulated Annealing as optimization method to estimate solution

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 400$ m
$n = 15$

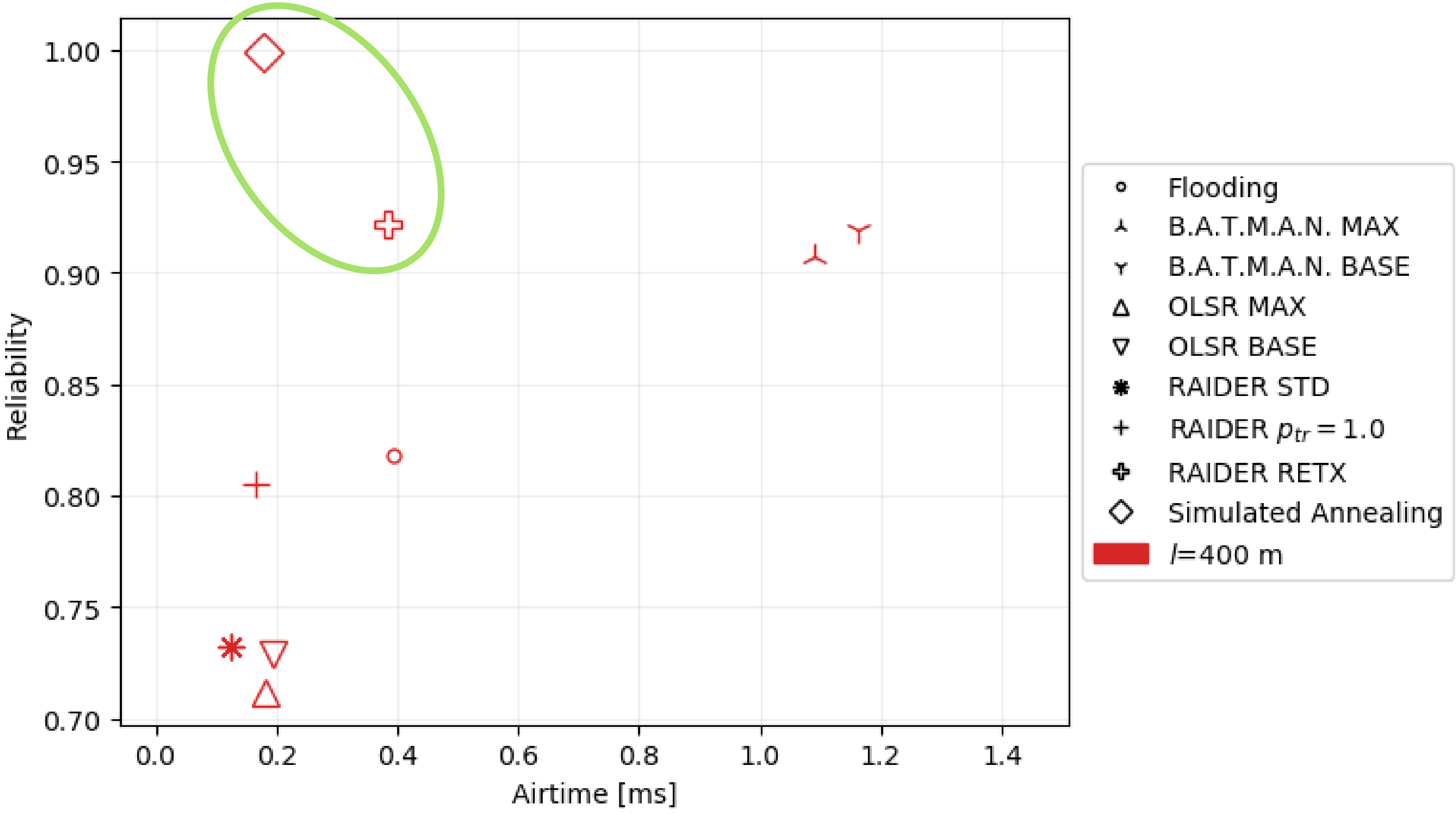


Performance overview for all protocols for $l = 400$ m

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 400$ m
$n = 15$

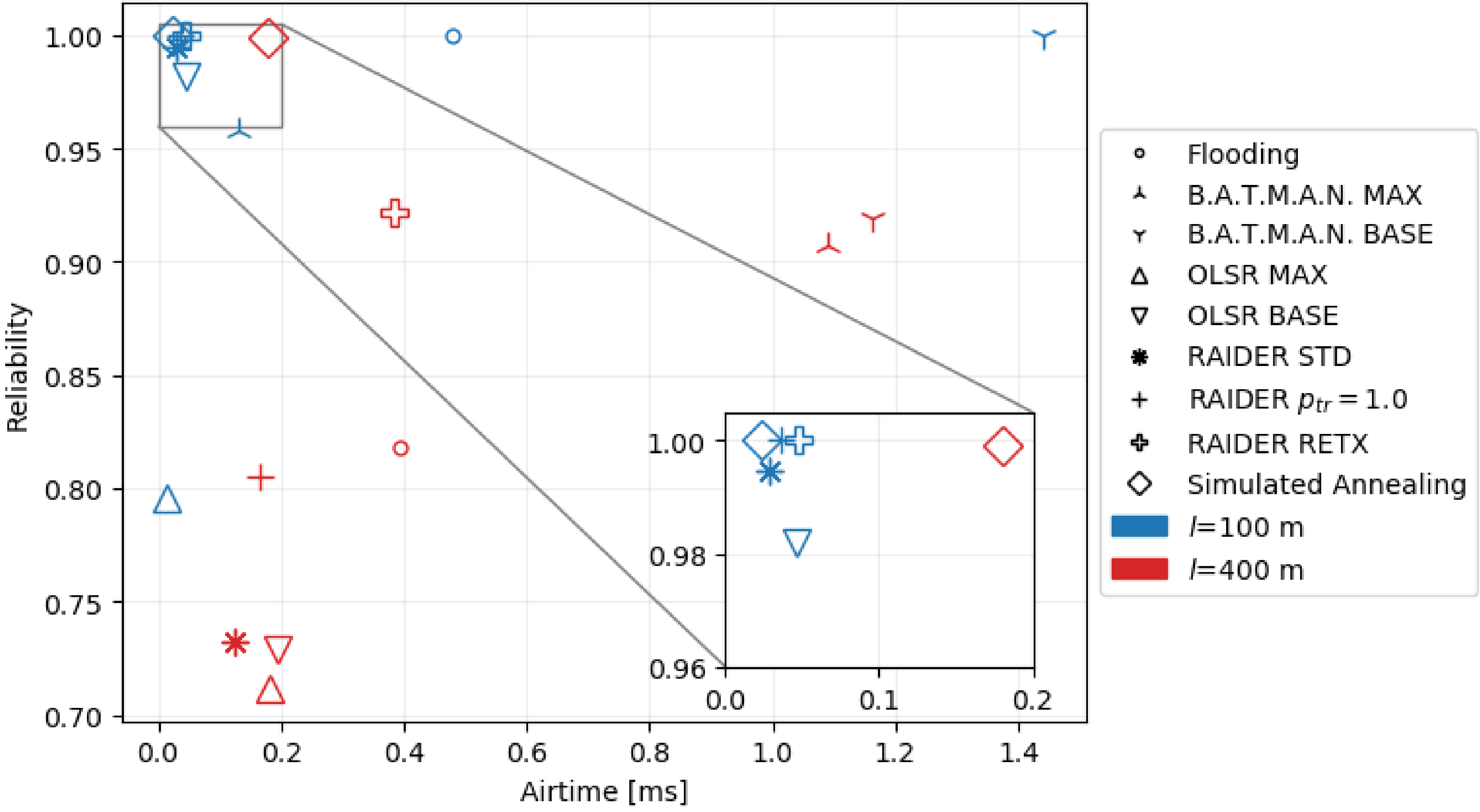


Performance overview for all protocols for $l = 400$ m

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 100, 400$ m
$n = 15$

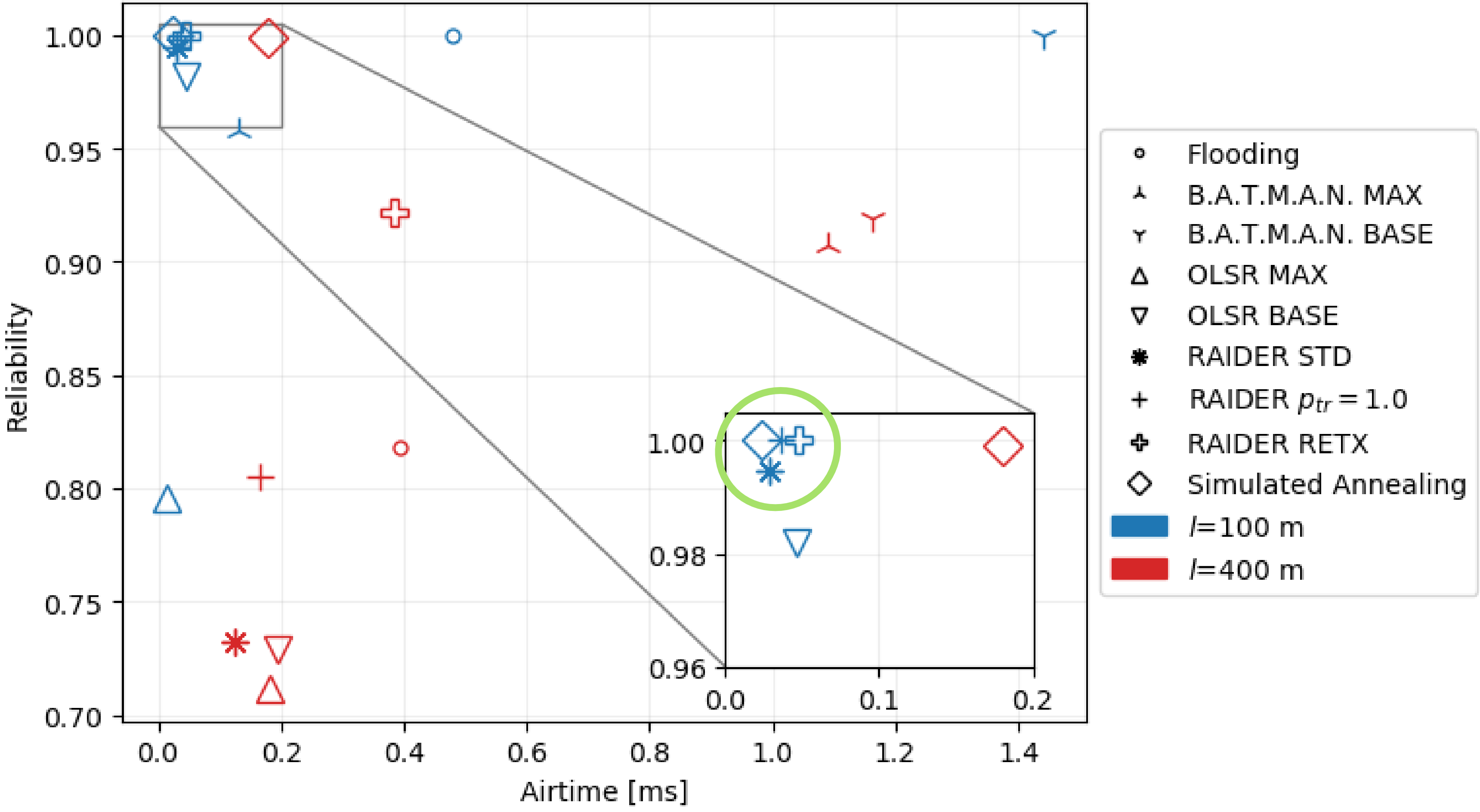


Performance overview for all protocols for $l = 100, 400$ m

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 100, 400$ m
$n = 15$

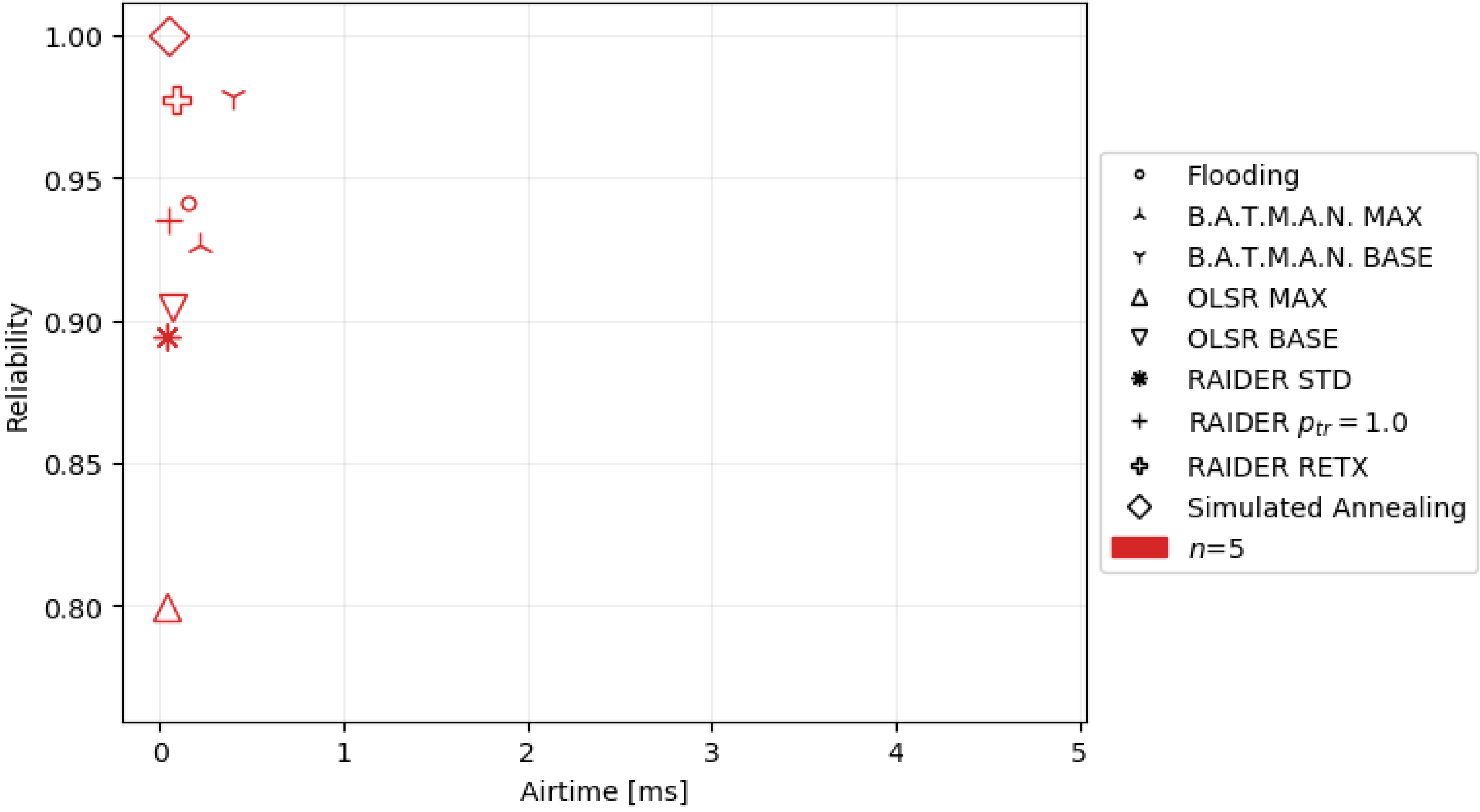


Performance overview for all protocols for $l = 100, 400$ m

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5$

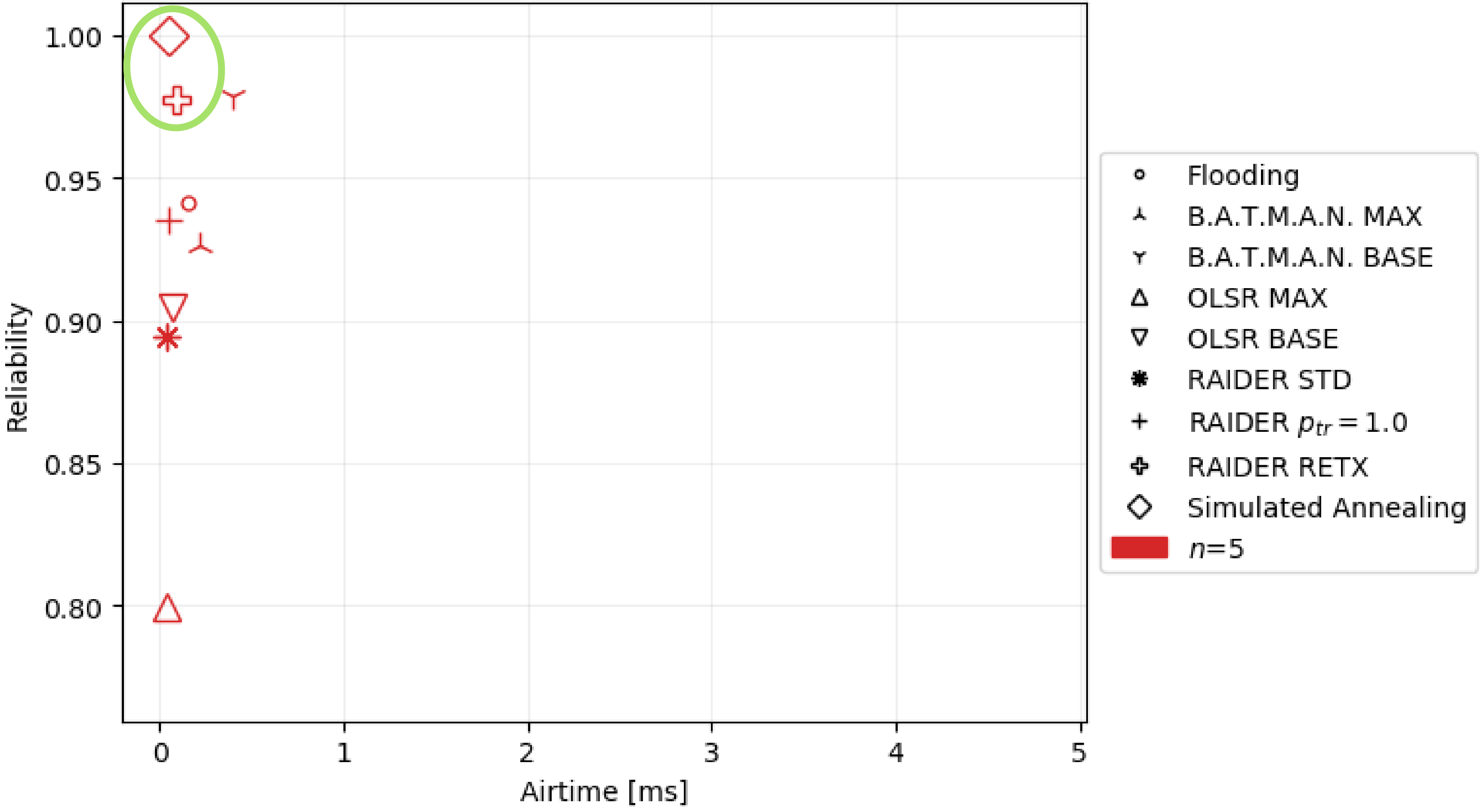


Performance overview for all protocols for $n = 5$

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5$

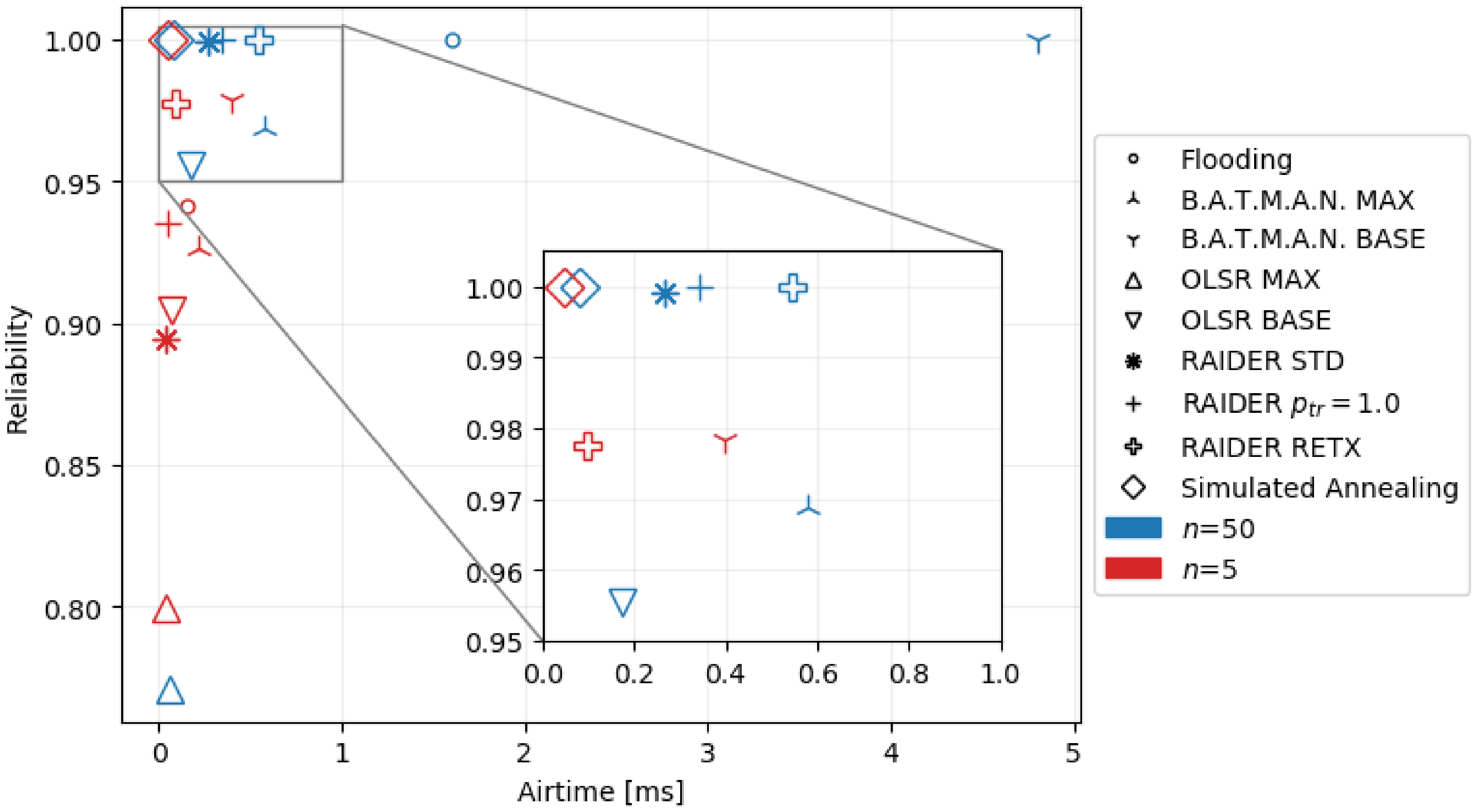


Performance overview for all protocols for $n = 5$

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5, 50$

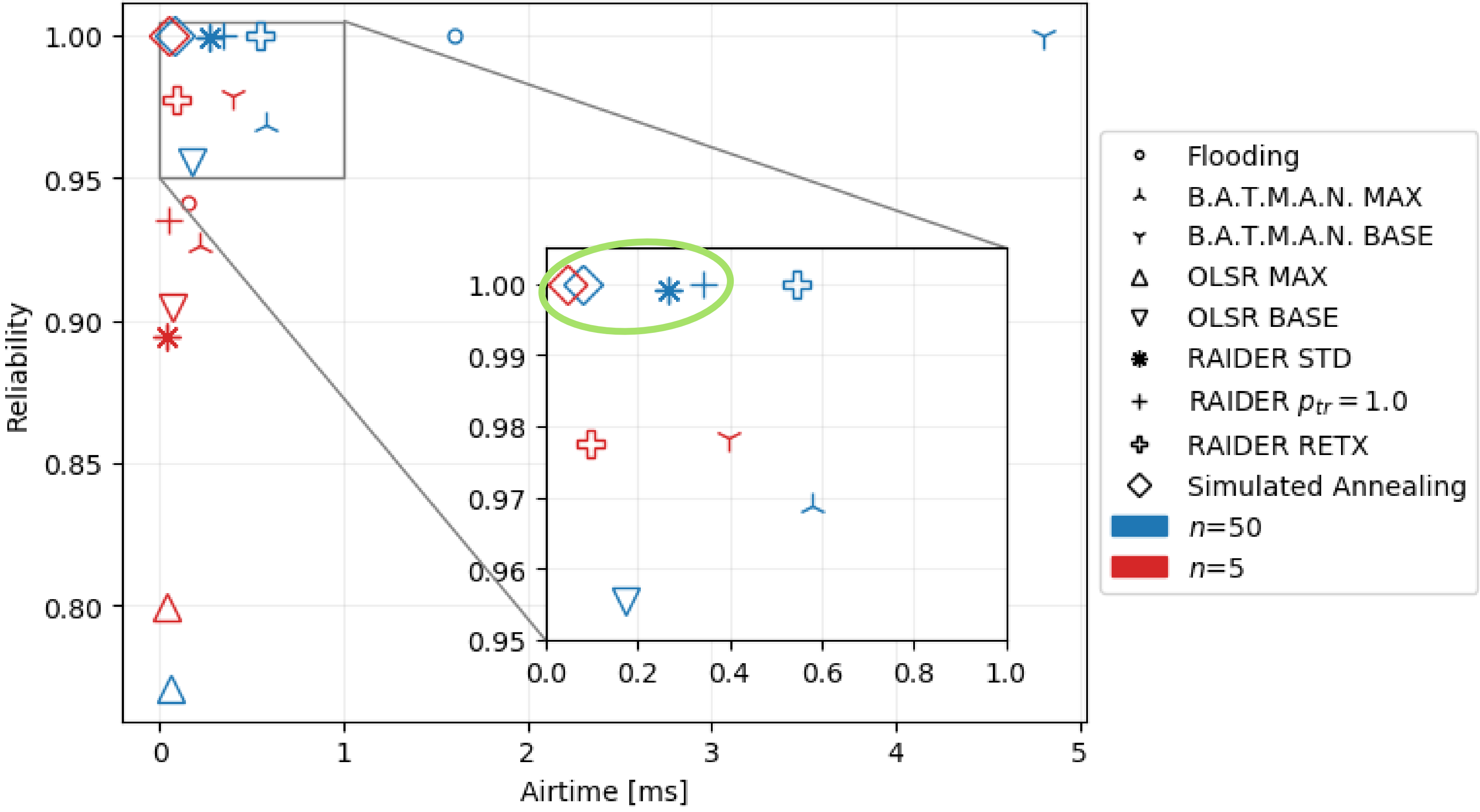


Performance overview for all protocols for $n = 5, 50$

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5, 50$



Performance overview for all protocols for $n = 5, 50$

Summary

Contribution

- First approach to incorporate multi-rate capabilities into general broadcast in WMN

- WMN broadcast protocol simulator
- Development of **RAIDER**, an improved broadcast protocol for WMN
- Higher reliability, improved by up to **19%** compared to the state of the art
- Lower airtime, reduced by up to **80%** compared to the state of the art

- Reduced gap between current solutions and optimal performance

Outlook

- Improve Resilience
- Integration into Meshmerize
- Hardware deployment, field test

Thank you for your attention

Motivation – Broadcast in WMN

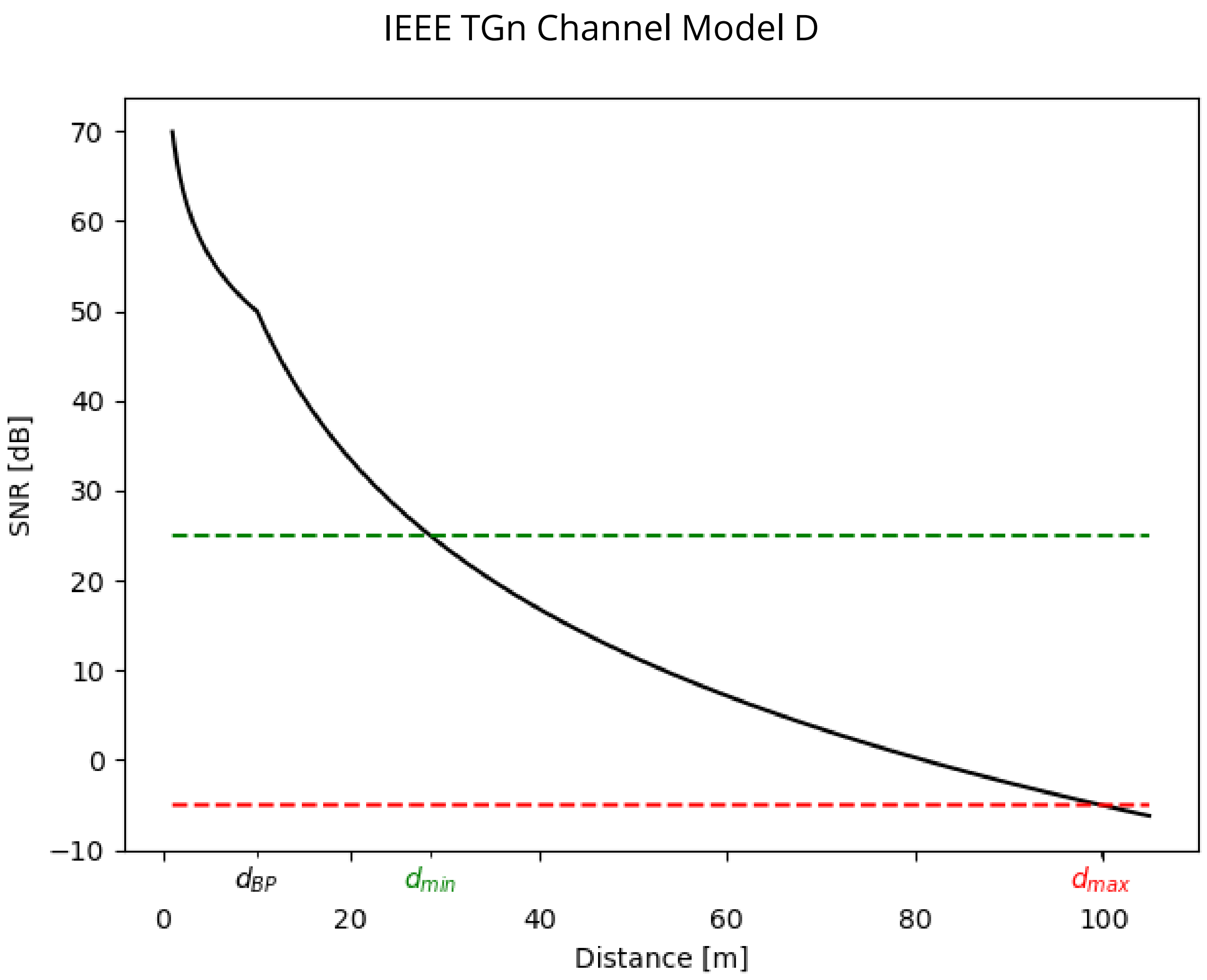
- Broadcast as basic requirement for general operability
- Increased demand for future use

Broadcast application	Packet size	Traffic volume	Traffic requirements
Network operability (ARP, DHCP)	28 – several 100 bytes	Low, infrequent	High reliability
Industrial ethernet (Motion & Automation control)	40-250 bytes	Low to medium, frequent	High reliability, low resource consumption
Media delivery (Video streaming)	>1000 bytes	High, continuous	Support for large amount of data

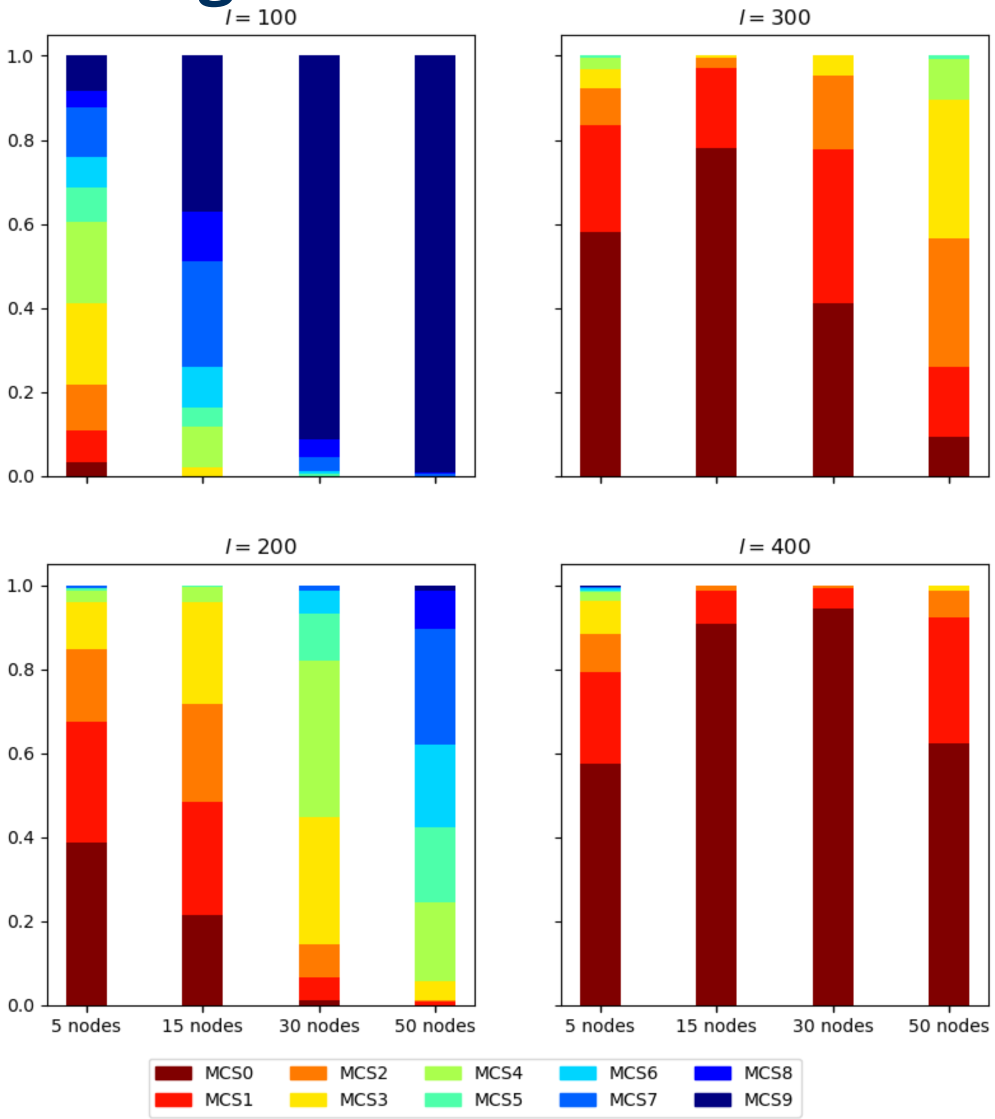
State of the Art – Multi-rate Approaches

- UFlood
  - Usage of Coding
  - Requires full network knowledge, feedback
- Distributed Rate First Algorithm
  - Optimal broadcast, only in subtrees
  - Requires full network knowledge
- Weighted Connected Dominating Set (WCDS)
  - Low latency optimization
  - Requires central network scheduler

Contribution – Broadcast Simulator



Contribution – Connecting MCS



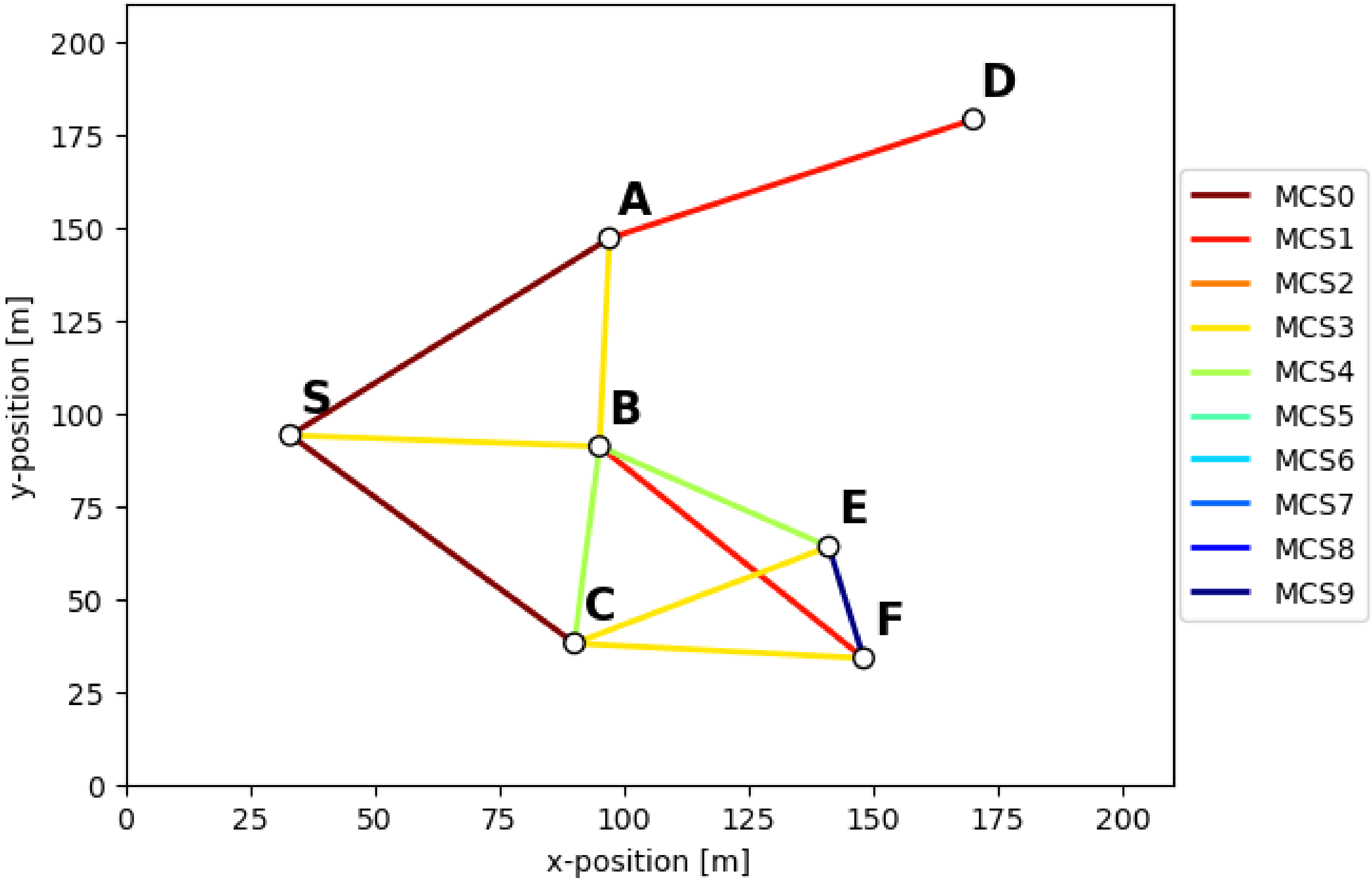
Connecting MCS for different network configurations

Contribution – State of the Art Analysis

- No link quality awareness

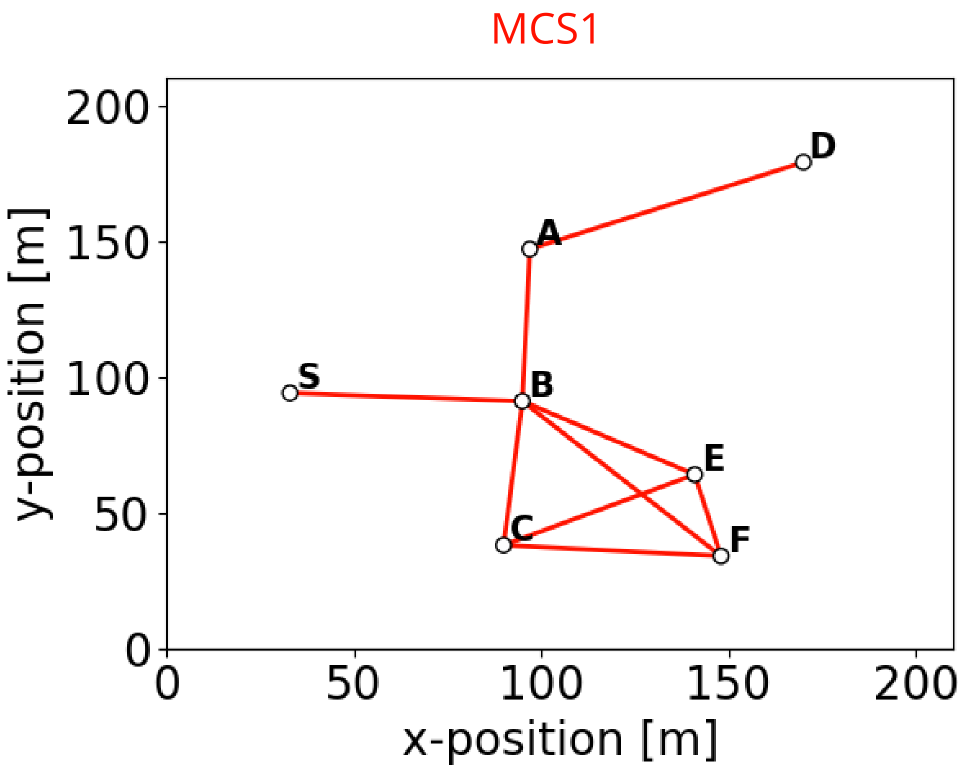
Link (A – D):

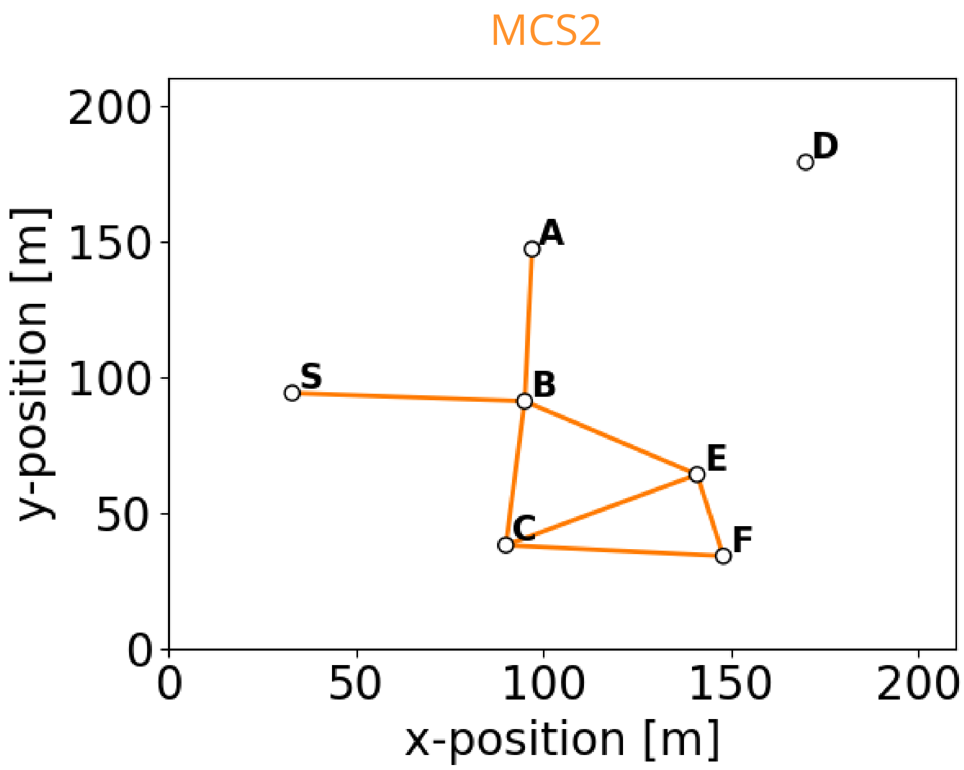
- Packet Error Rate MCS0 – 0.00
- Packet Error Rate MCS1 – 0.88



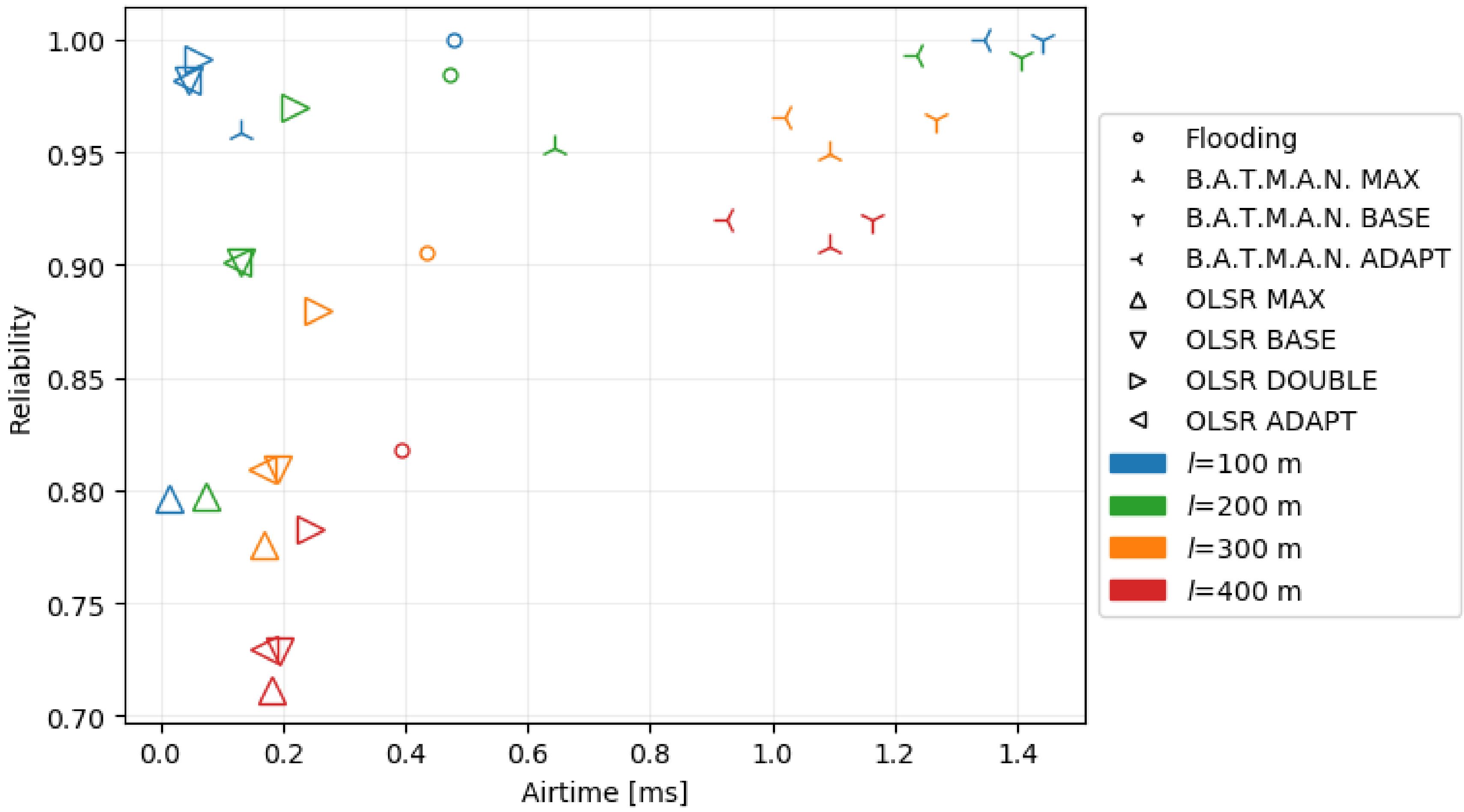
Contribution – State of the Art Analysis

- Dependent on lowest MCS to provide network-wide connectivity





Contribution – State of the Art Analysis



Overview for performance of state of the art protocols and variations for different l

Upper Performance Bound

Performance Evaluation:

$$performance = reliability^{\alpha} \cdot {}^{1}/_{airtime}$$

Simulated Annealing:

- Errors expected: $\alpha = 5$
- No errors: $\alpha = \infty$

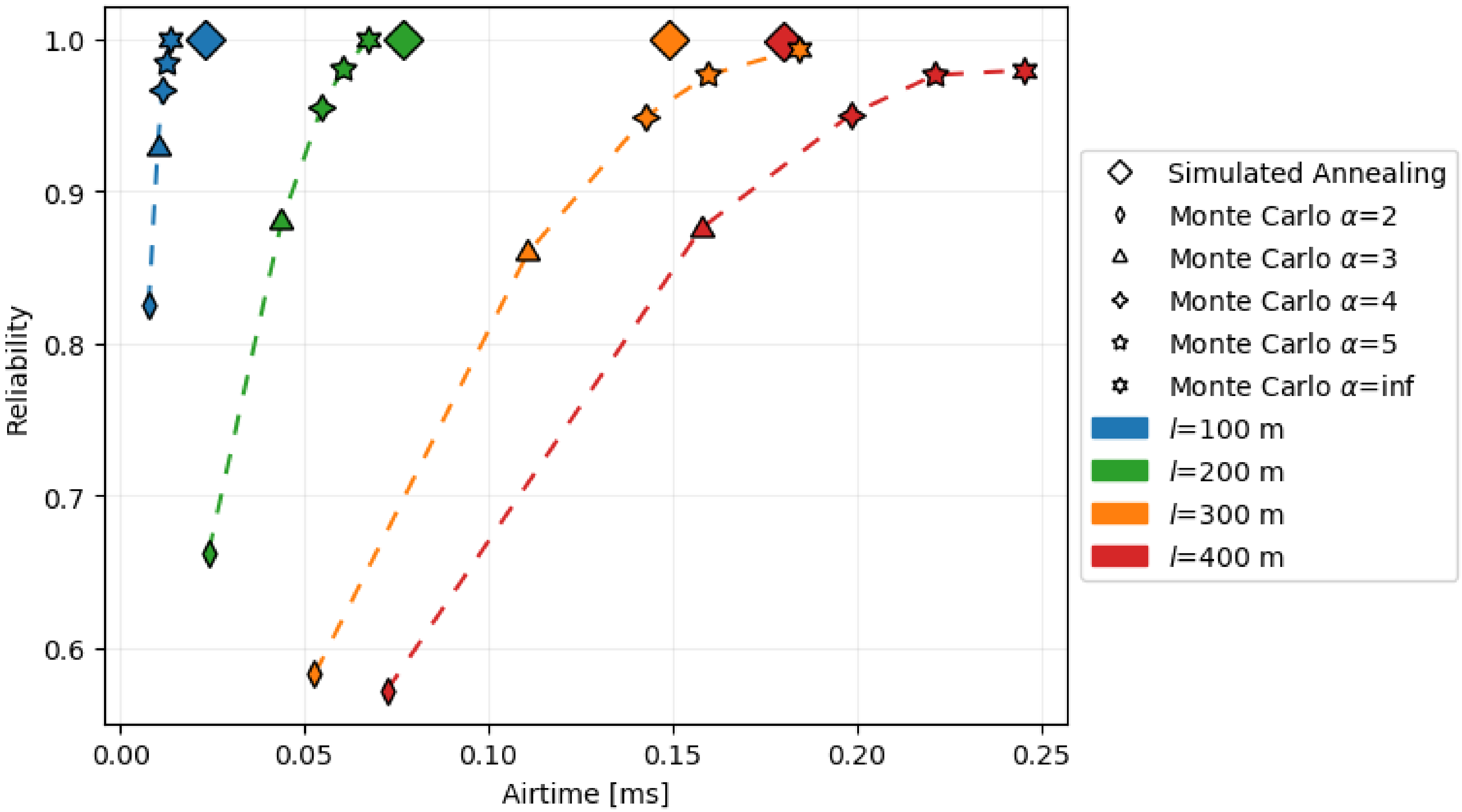
Upper Performance Bound

Simulated Annealing:

- State s ∈ S, neighbor state s‘, cost function c(s), temperature T, cooling schedule T(t)

- If c(s‘) <= c(s), set s = s‘
- If c(s‘) > c(s), set s = s‘ with $\exp\left(\frac{-(c(s')-c(s))}{T(t)}\right)$

Upper Performance Bound



Simulated Annealing vs Monte Carlo Simulation for different l

Evaluation – Performance Comparison

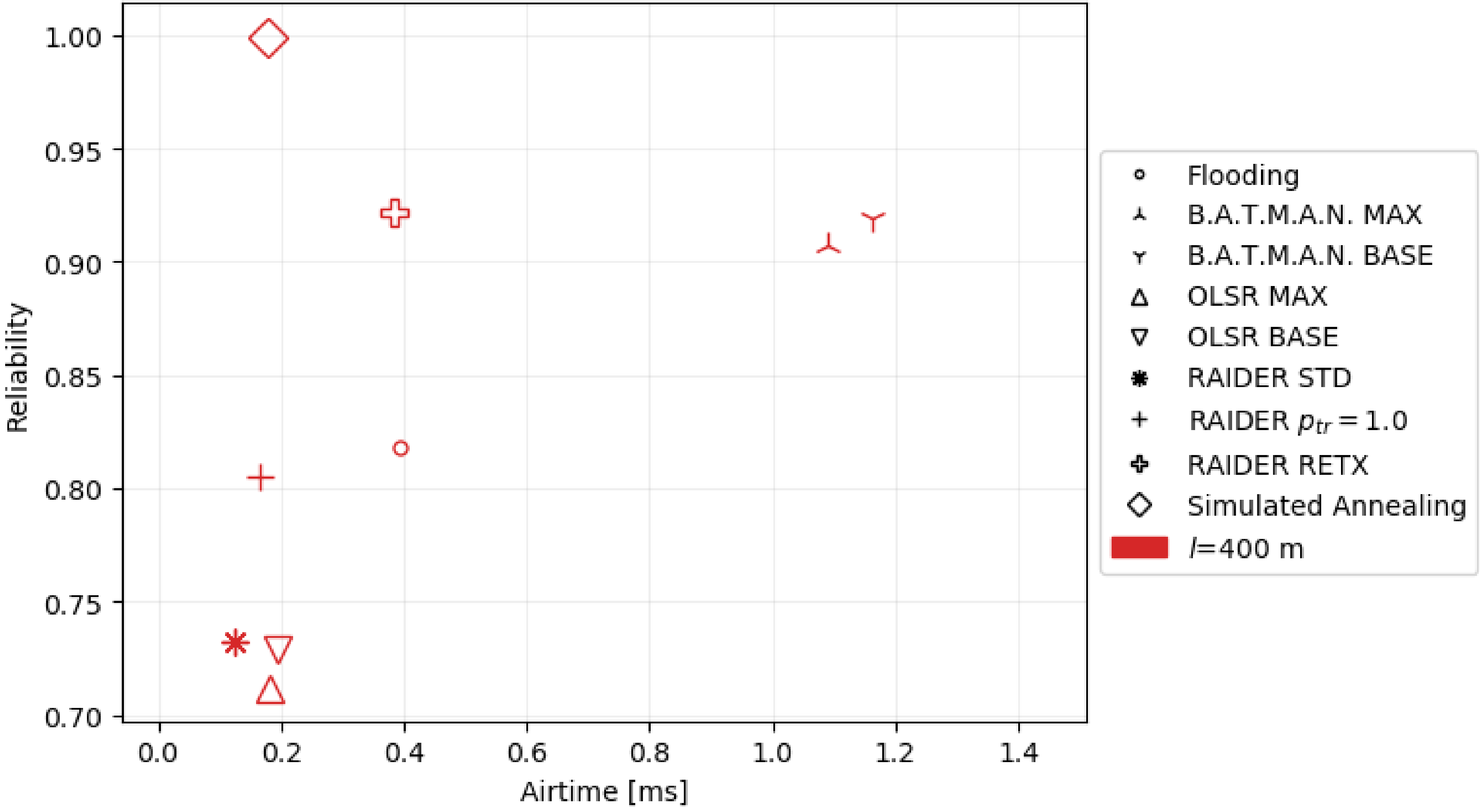
- Upper performance bound:
  - NP-hard optimization problem
  - Simulated Annealing to estimate solution

Protocol Name	Implementation Details	
Flooding	Base rate	○
B.A.T.M.A.N. BASE/MAX	B.A.T.M.A.N. with fixed rate (lowest possible/highest possible)	Y ⅄
OLSR BASE/MAX	OLSR with fixed rate (lowest possible/highest possible)	▽ △
Simulated Annealing	Reliable data rates only	◇
RAIDER STD	Standard implementation, $p_{tr} = 0$	✳
RAIDER $p_{tr} = 1$	Link quality threshold $p_{tr} = 1$	+
RAIDER RETX	Link quality threshold $p_{tr} = 1$, retransmissions enabled	✙

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 400$ m
$n = 15$

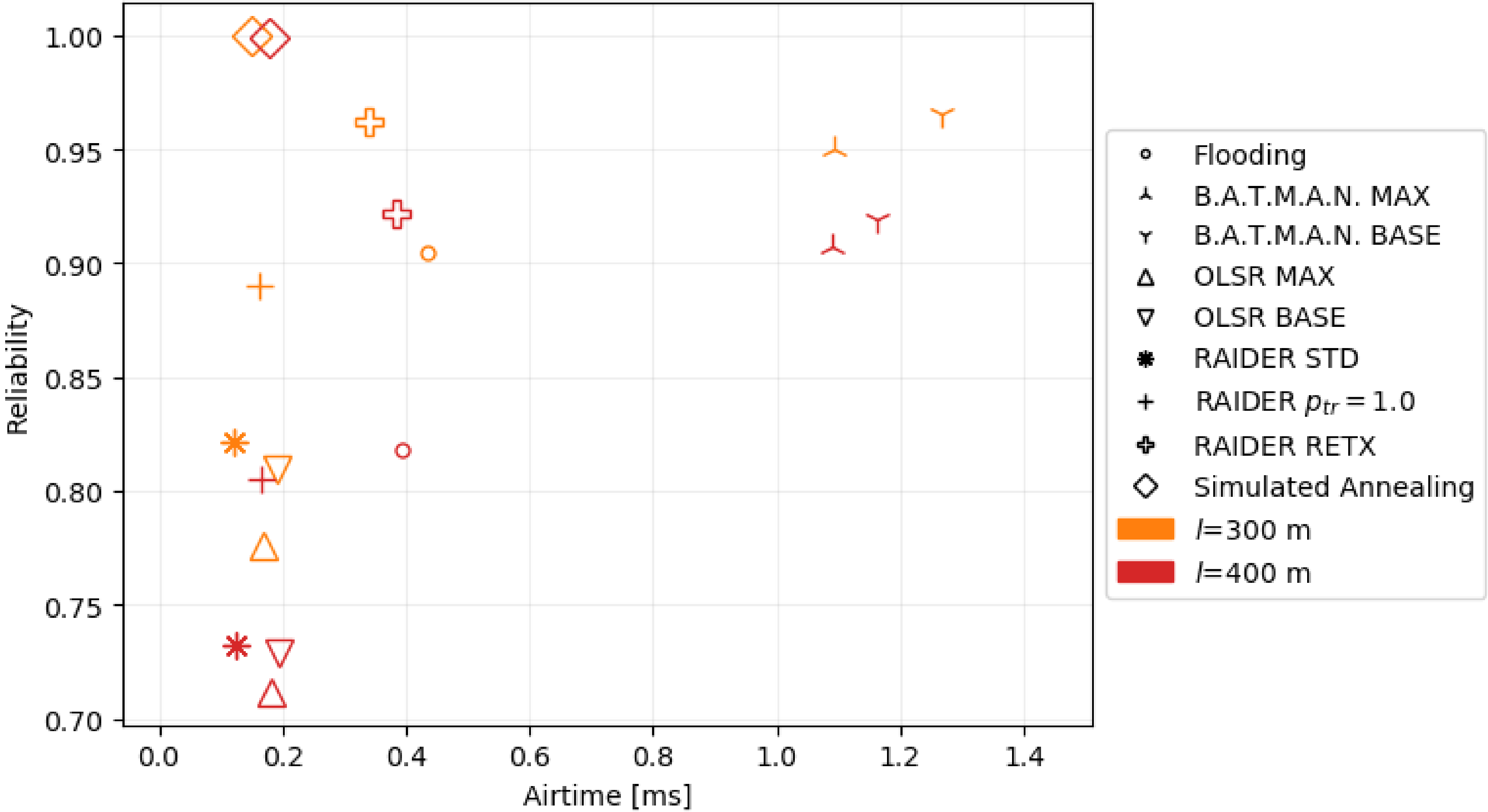


Performance overview for all protocols for $l = 400$ m

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 300, 400$ m
$n = 15$

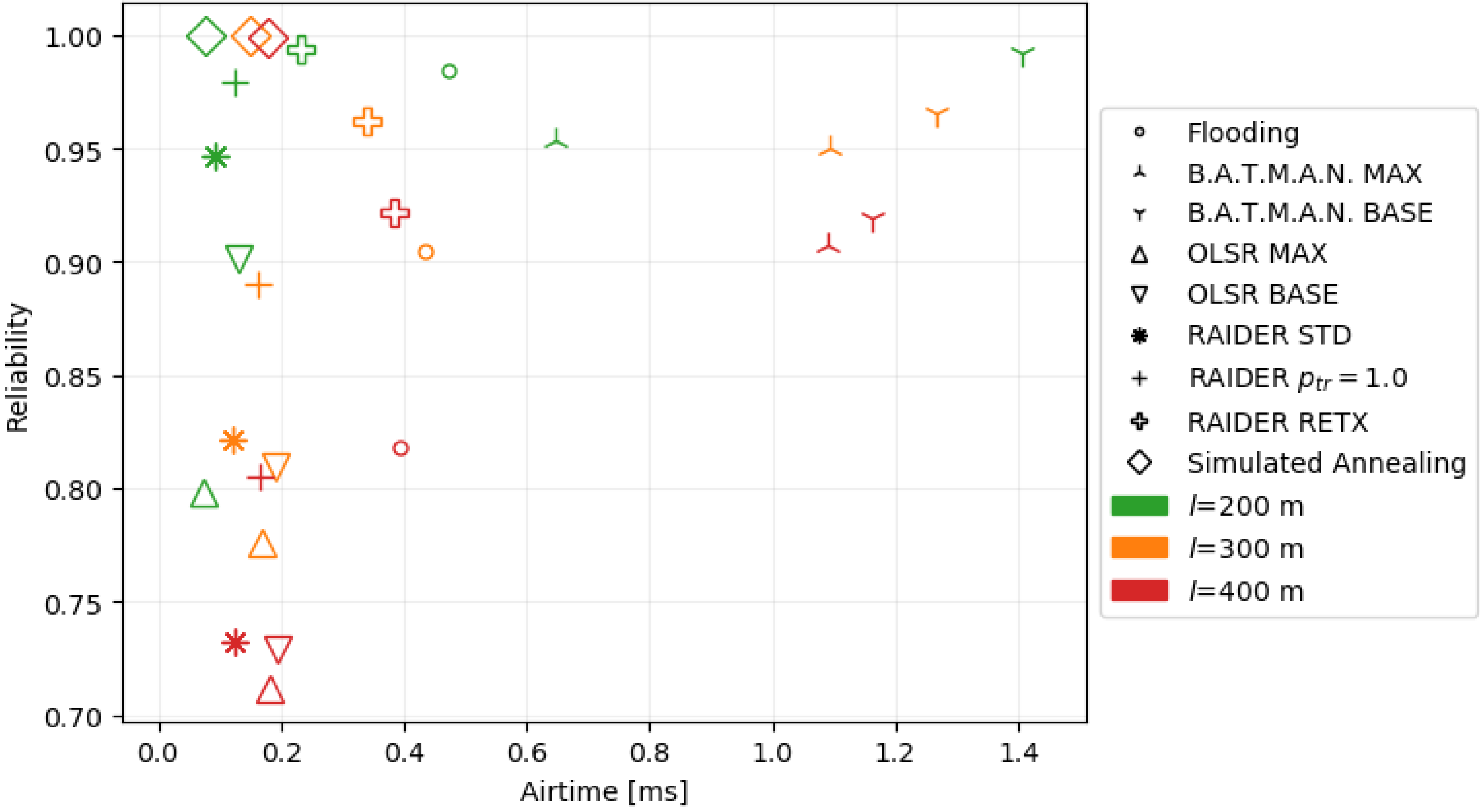


Performance overview for all protocols for different l

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 200 \ldots 400$ m
$n = 15$

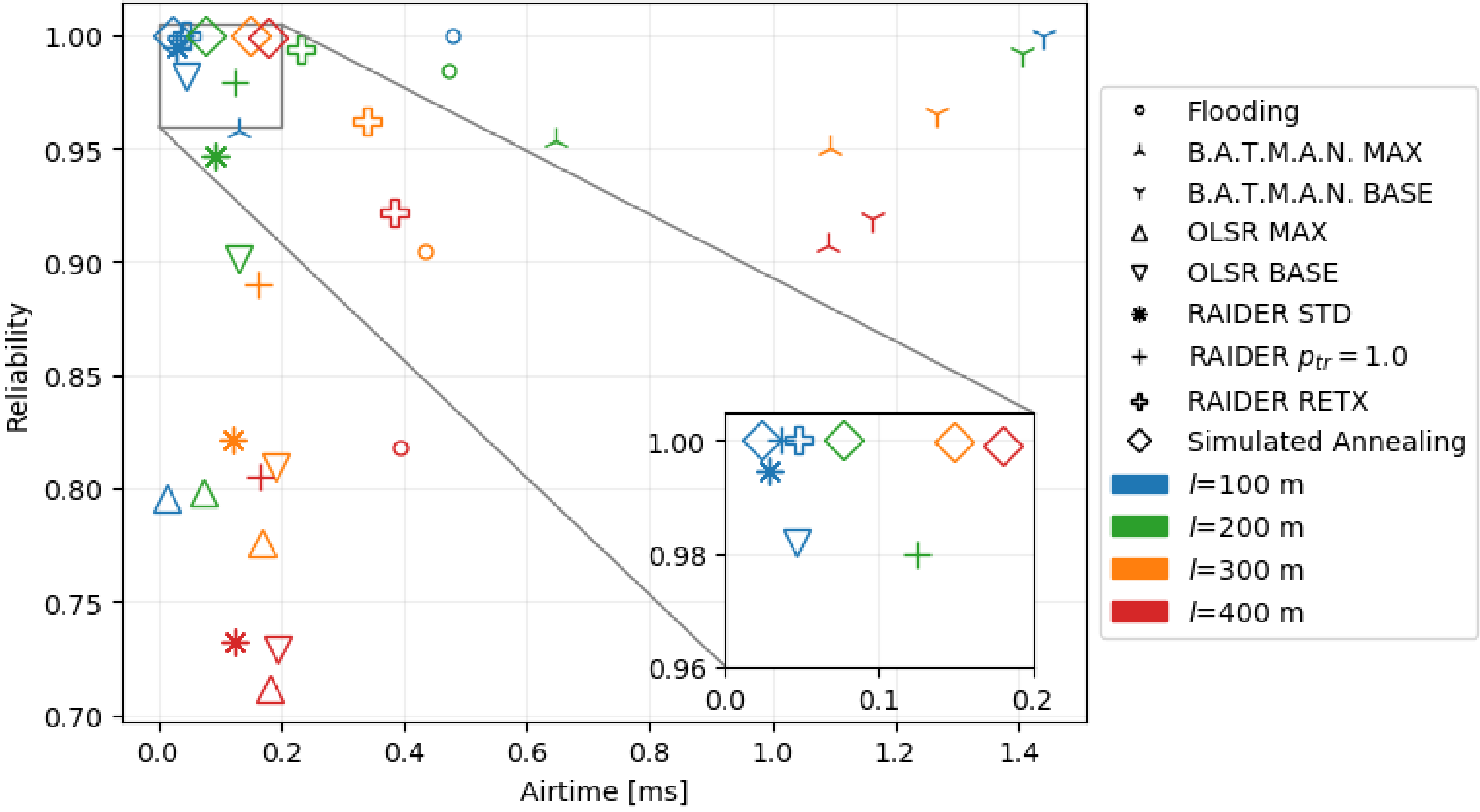


Performance overview for all protocols for different l

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 100 \dots 400$ m
$n = 15$

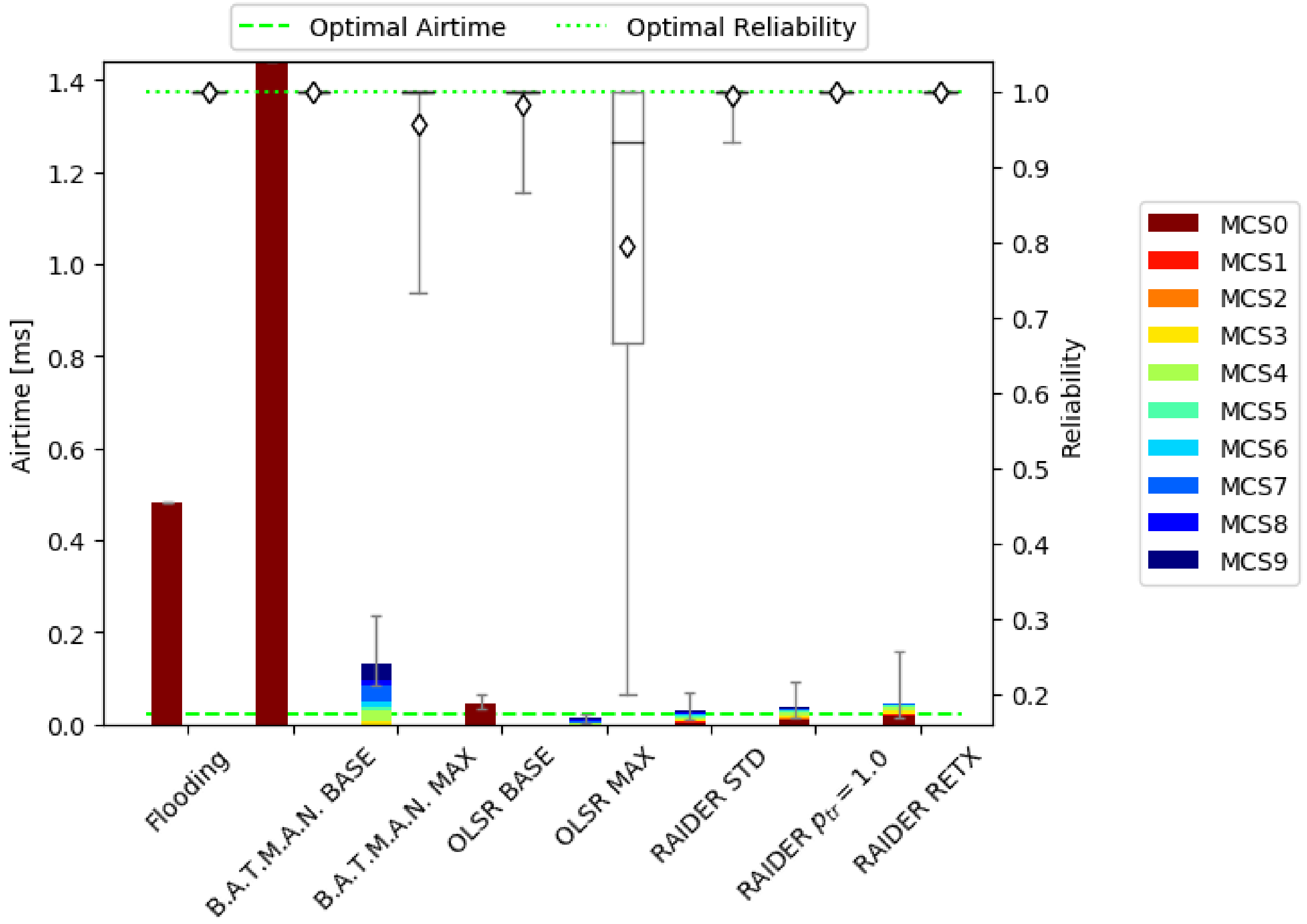


Performance overview for all protocols for different l

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 100$ m
$n = 15$

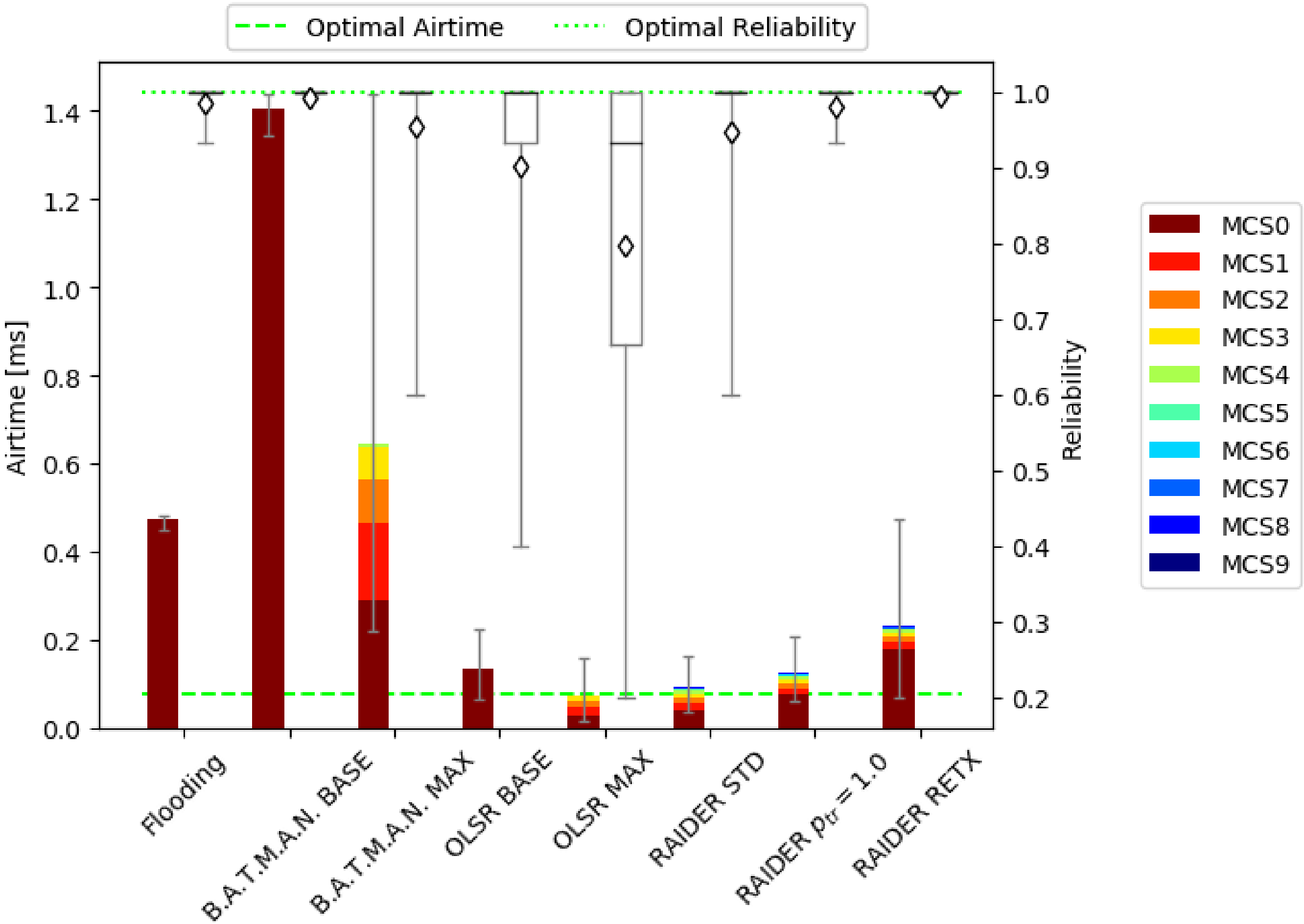


Performance overview for all protocols for $l = 100$ m

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 200$ m
$n = 15$

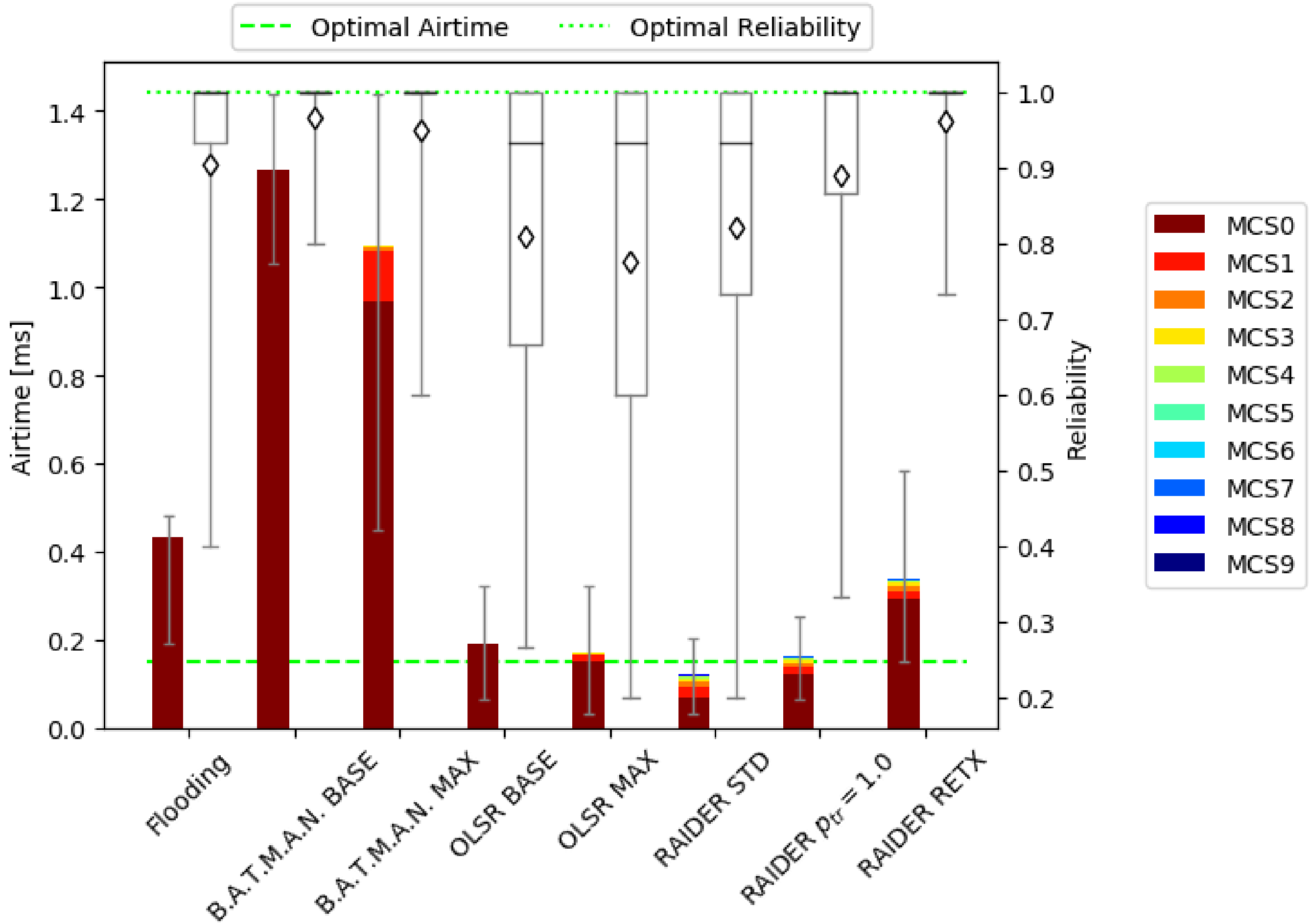


Performance overview for all protocols for $l = 200$ m

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 300$ m
$n = 15$

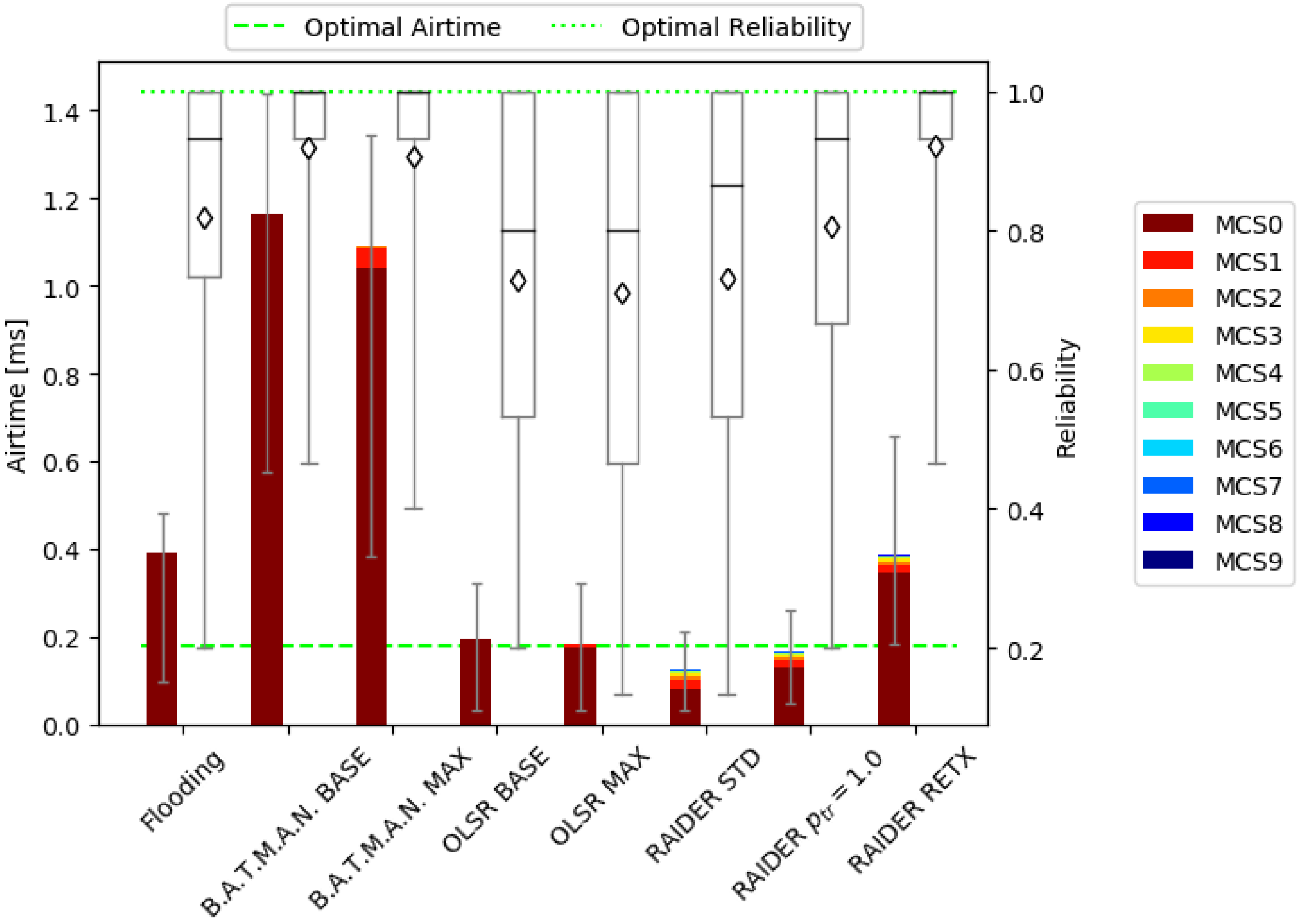


Performance overview for all protocols for $l = 300$ m

Evaluation Scenario 1 – Average Link Quality

250 random networks,

$l = 400$ m
$n = 15$

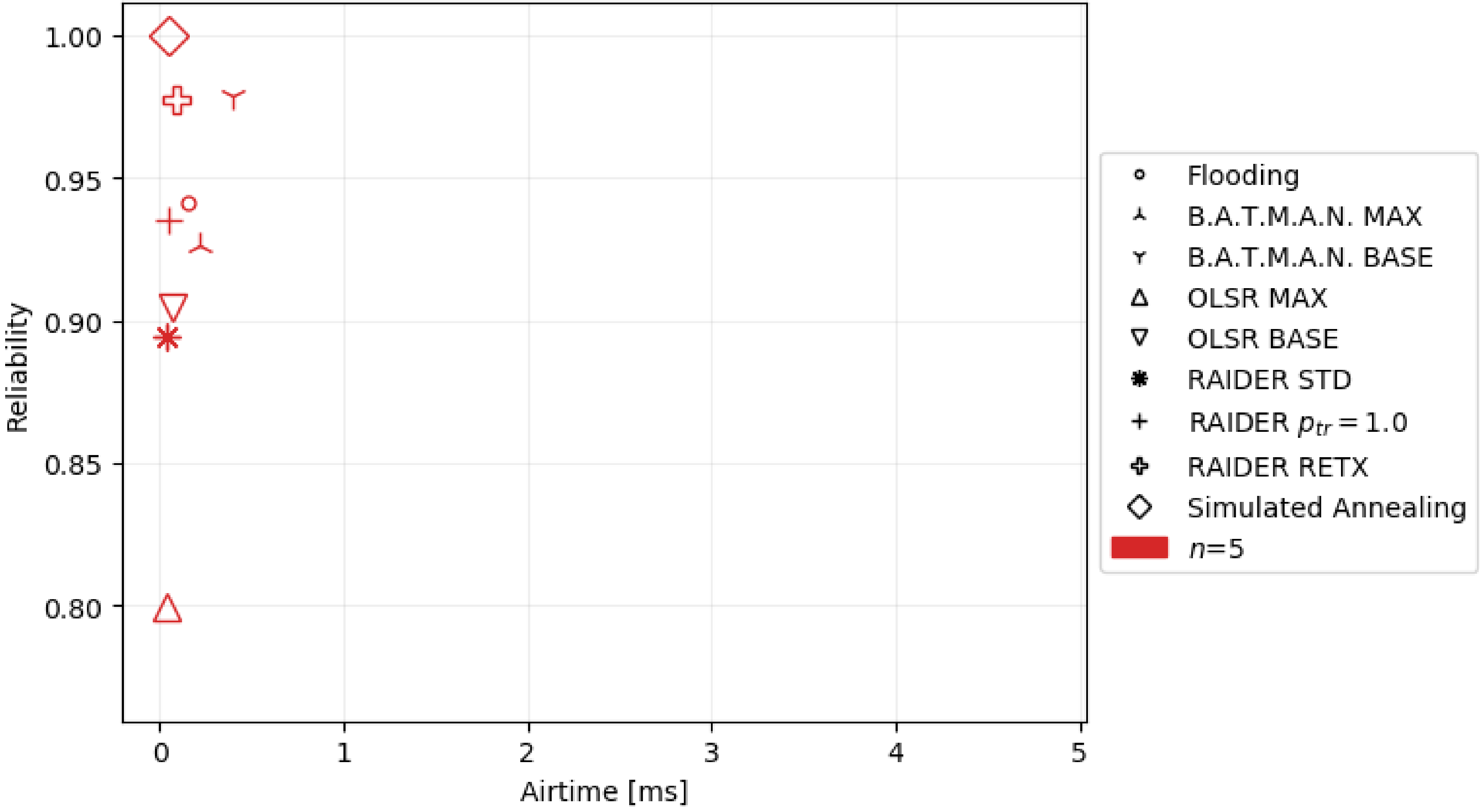


Performance overview for all protocols for $l = 400$ m

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5$

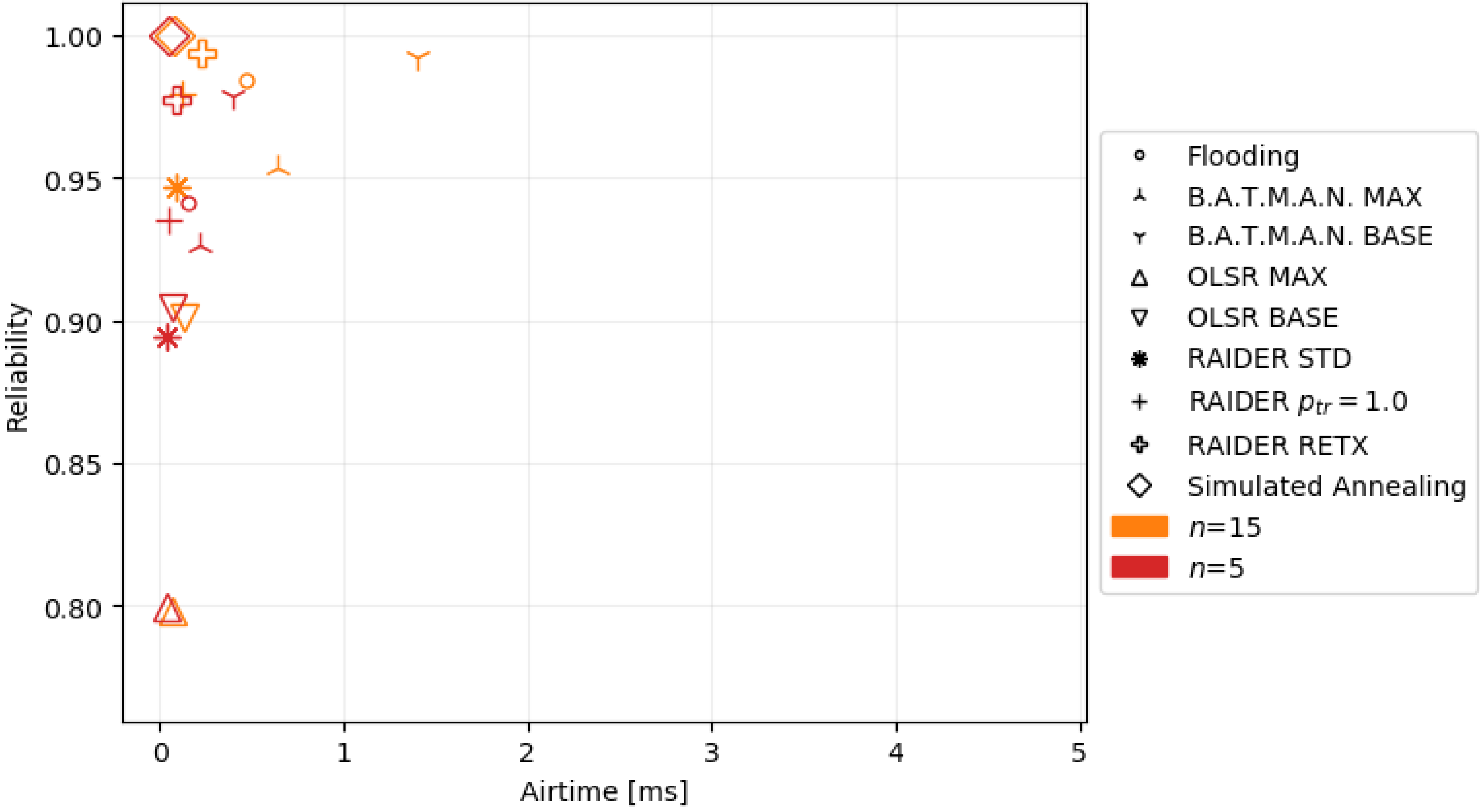


Performance overview for all protocols for $n = 5$

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5, 15$

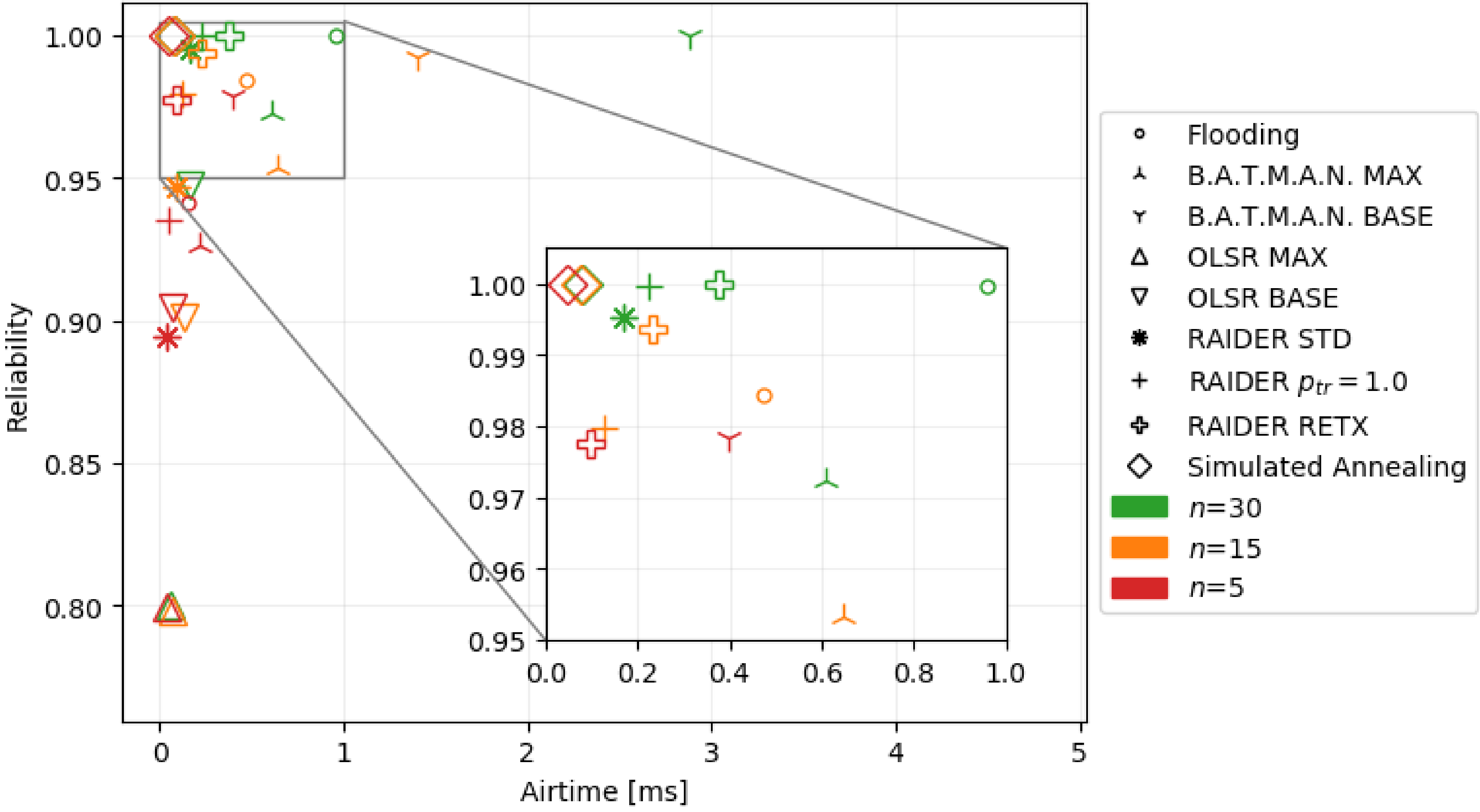


Performance overview for all protocols for different n

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5 \dots 30$

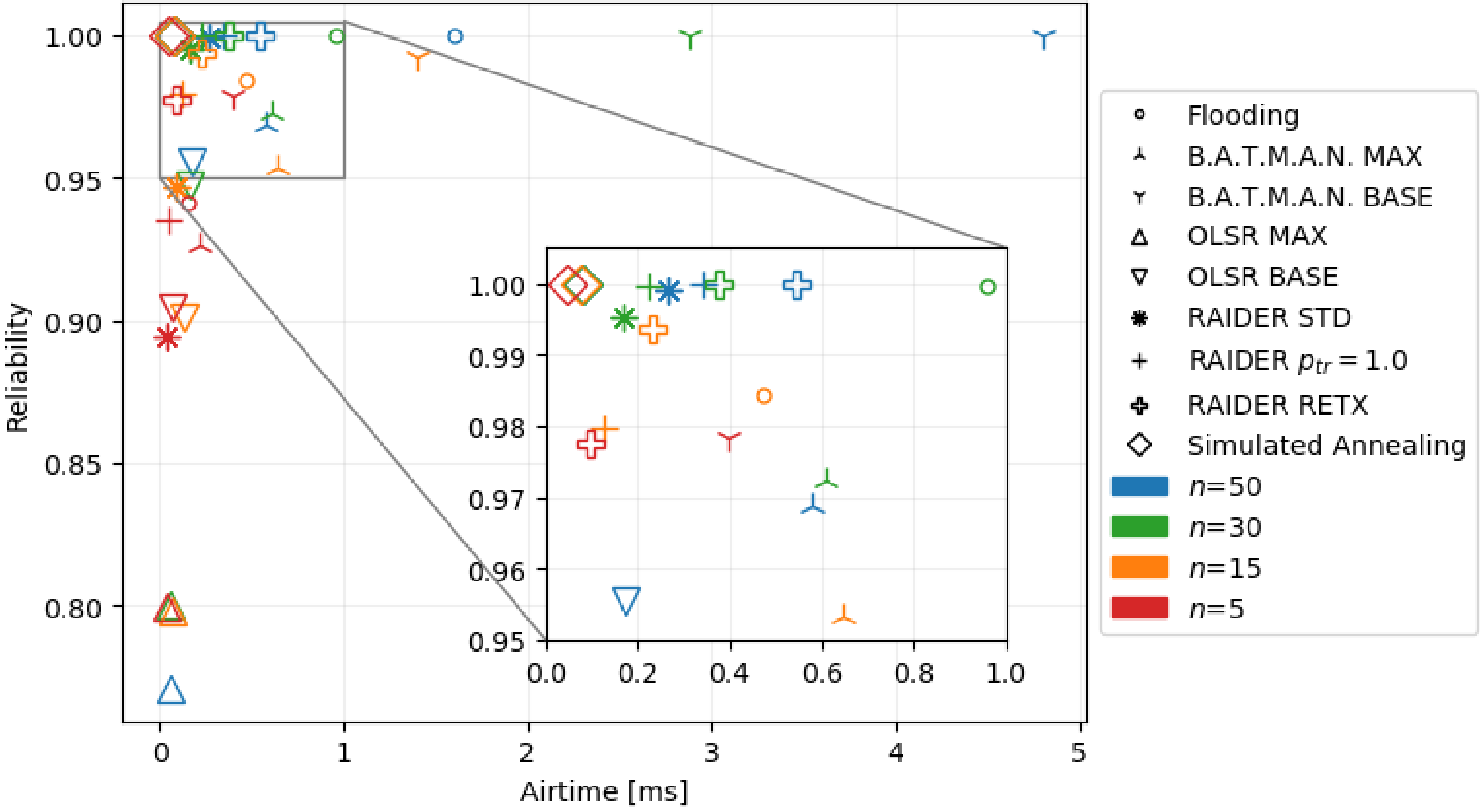


Performance overview for all protocols for different n

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5 \dots 50$

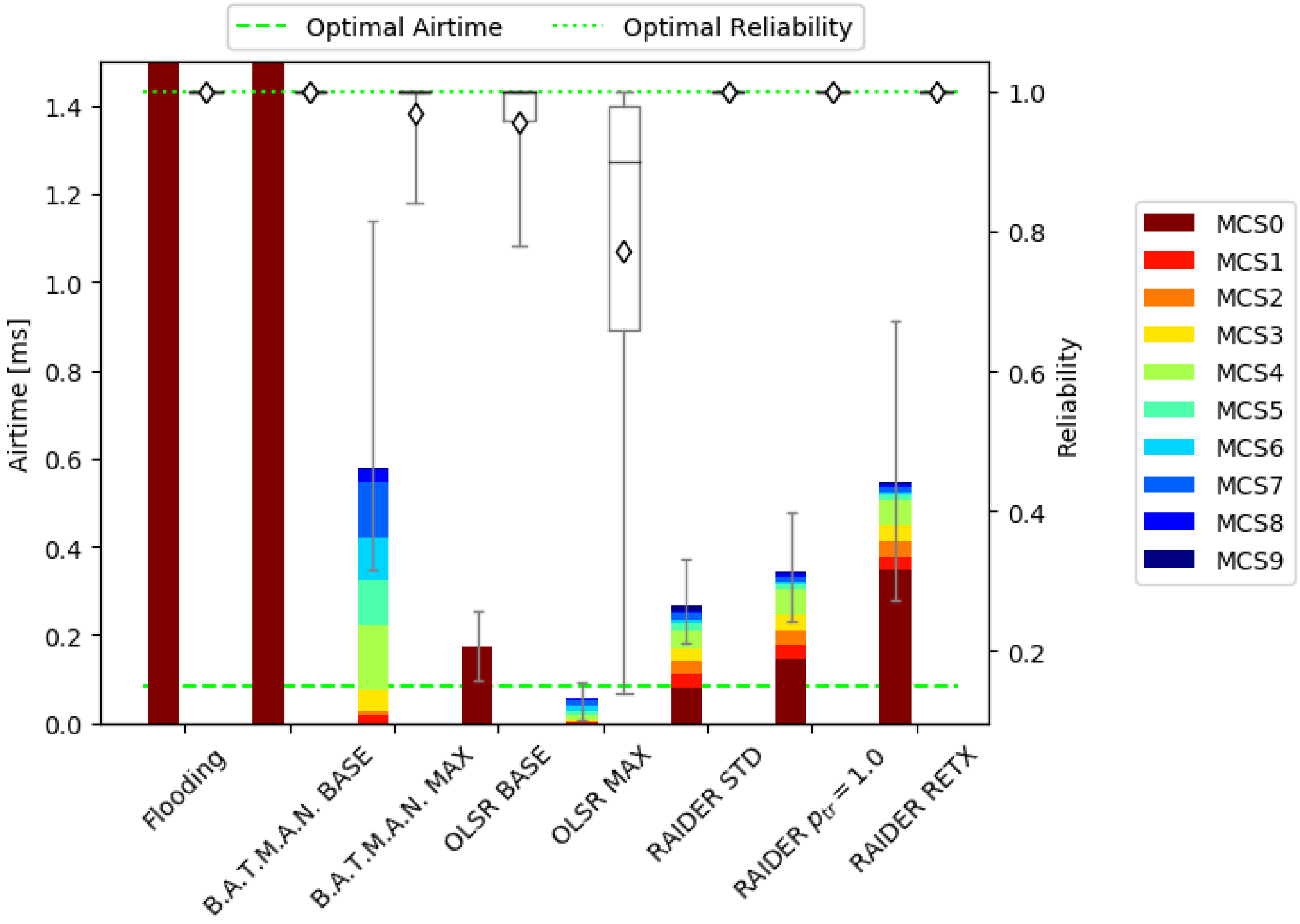


Performance overview for all protocols for different n

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 50$

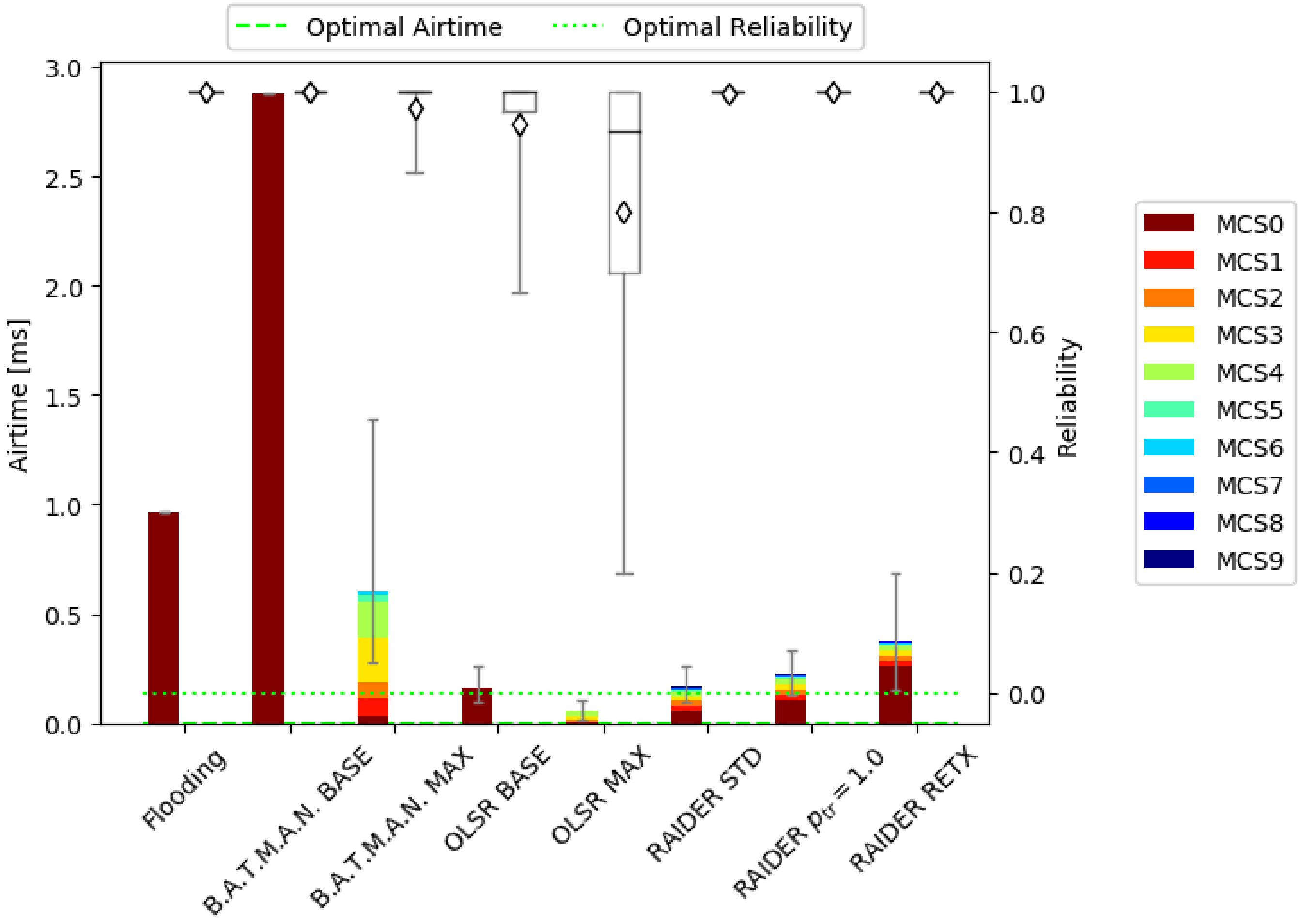


Performance overview for all protocols for $n = 50$

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 30$

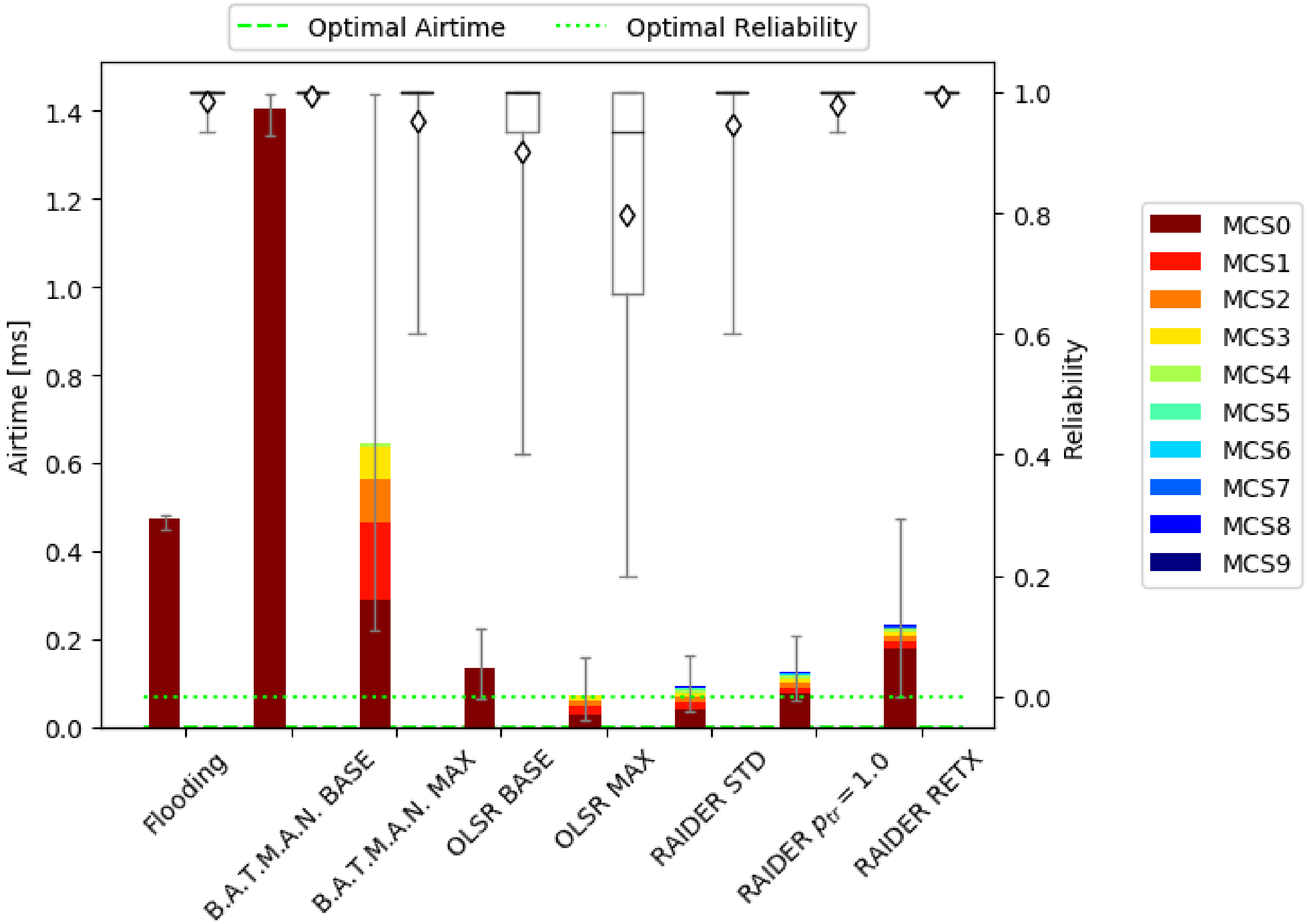


Performance overview for all protocols for $n = 30$

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 15$

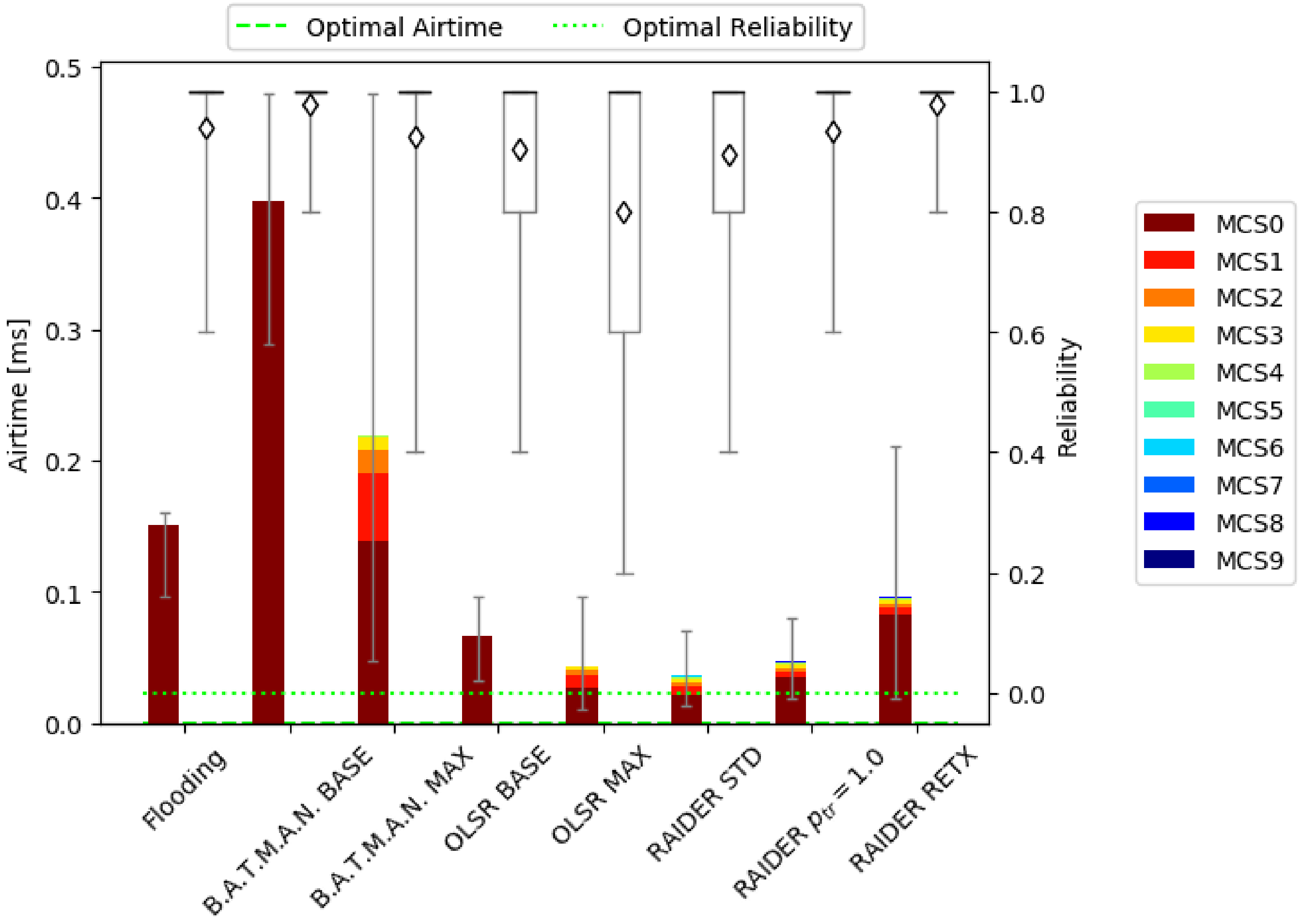


Performance overview for all protocols for $n = 15$

Evaluation Scenario 2 – Scalability

250 random networks,

$l = 200$ m
$n = 5$



Performance overview for all protocols for $n = 5$

Summary

Contribution

Protocol	Reliability	Airtime	Reliability	Airtime
Flooding	5 %	47 %	0 %	76 %
B.A.T.M.A.N.	1 %	80 %	0 %	87 %
OLSR	19 %	-59 %	14 %	-60 %
Optimal performance	-3 %	-90 %	-2 %	-165 %

Gains for Scenario 1 – Average Link Quality

Gains for Scenario 2 - Scalability

Summary

Contribution

Protocol	Performance	Performance
Flooding	416 %	326 %
B.A.T.M.A.N.	885 %	741 %
OLSR	56 %	36 %
Optimal performance	-53 %	-41 %
	Gains for Scenario 1 – Average Link Quality	Gains for Scenario 2 - Scalability