An Analytical Model for Fast and Verifiable Assessment of Large Scale Wireless Mesh Networks

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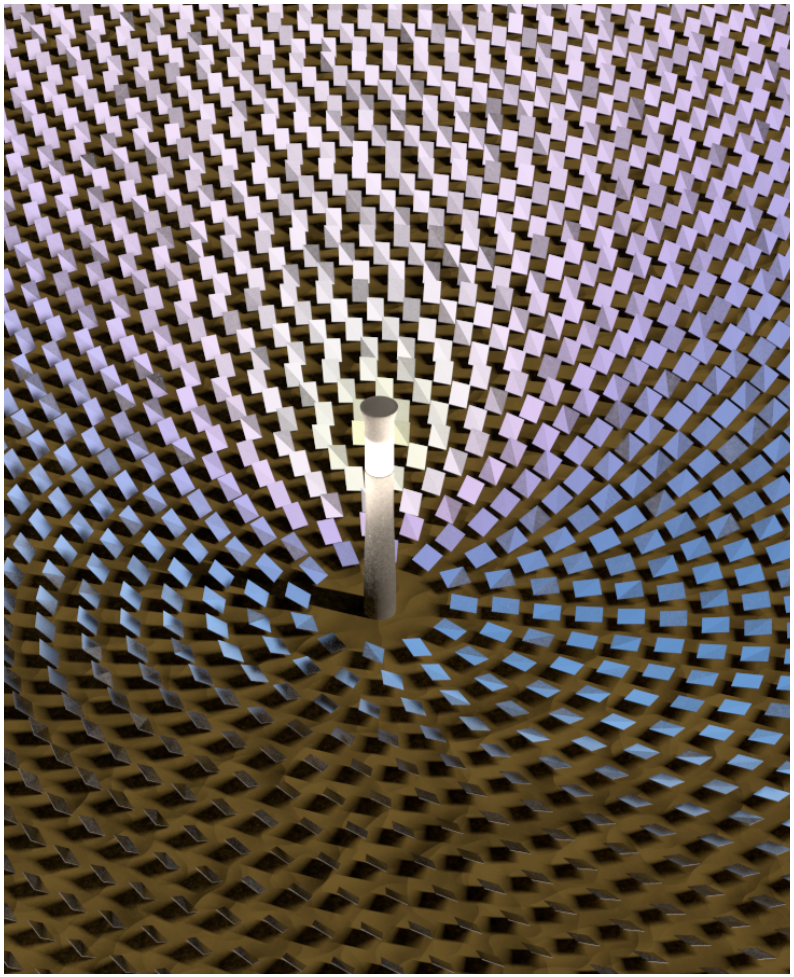
March 26th, 2015

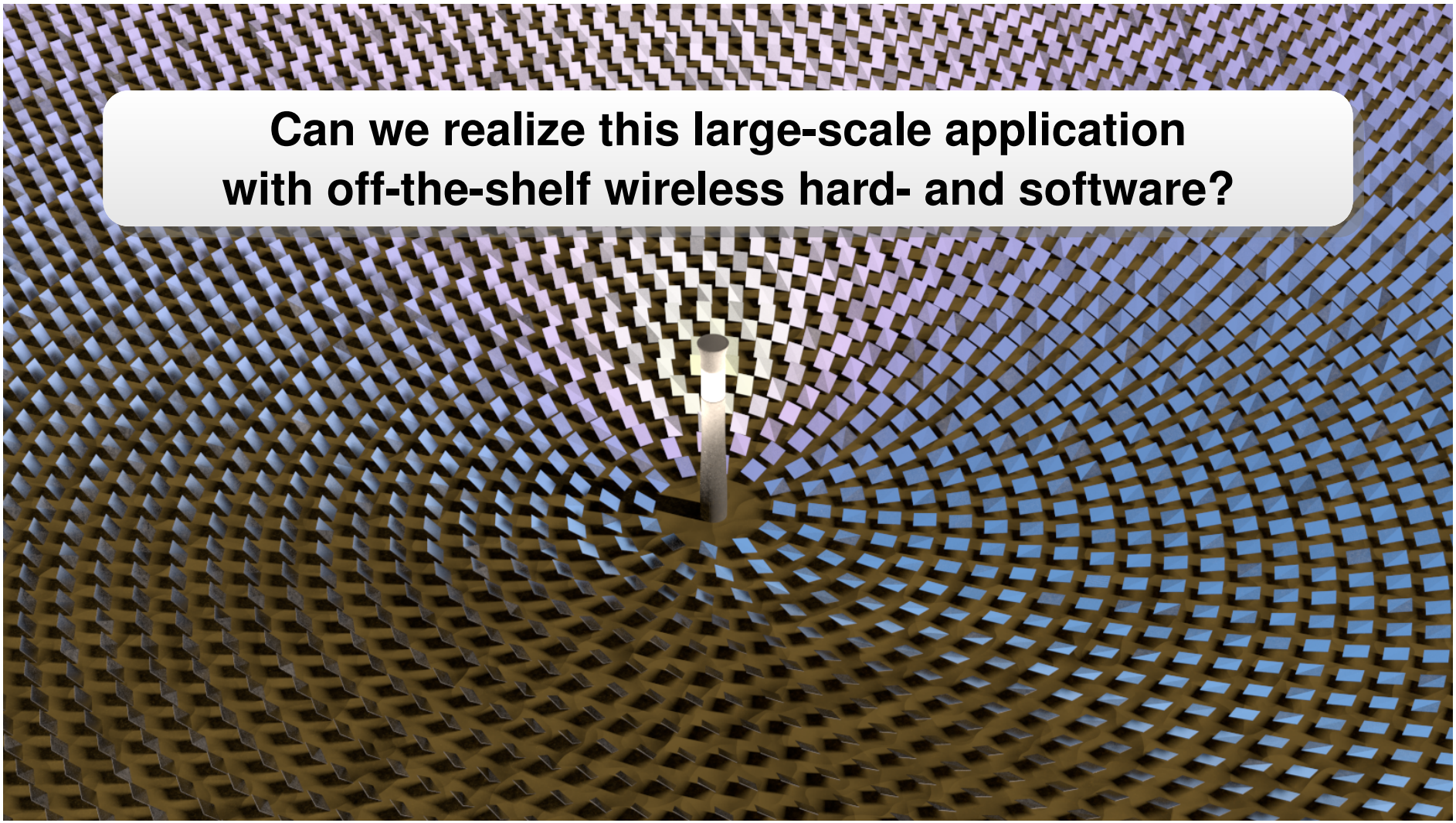
Institute of Telematics
Hamburg University of Technology
TUHH

Motivation



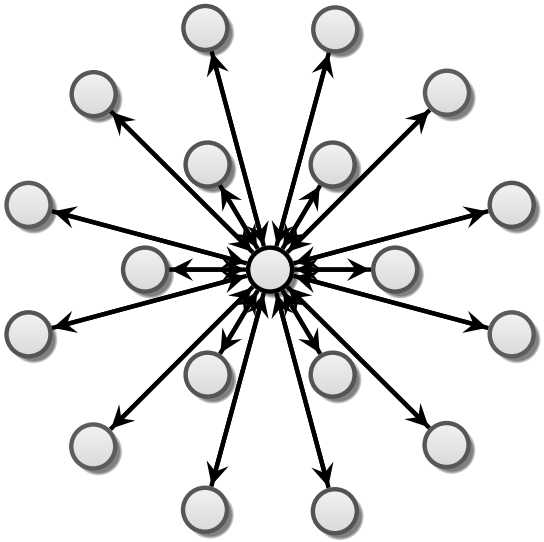
- Concentrated solar power plants
  - 1,000 - 1,000,000 heliostats
- Wireless control of heliostats
  - $\rightarrow$ Cost Reduction
- Small control packets from and to the central gateway

Motivation


Can we realize this large-scale application
with off-the-shelf wireless hard- and software?

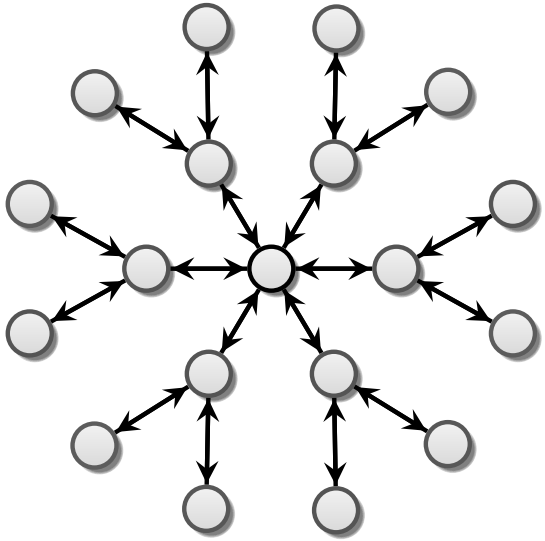
Approaches

Single-Hop



- ⊖ High power senders needed
- ⊖ Coordination very difficult, since the collision domain contains thousands of senders

Multi-Hop



- ⊕ Inexpensive hardware
- ⊕ Coordination easier since the density is reduced
- ⊖ Delivery probability decreases with the number of hops

2

Analytical Model

Why Analytical Model?

Simulation

- Step-by-step execution

- ⊕ Software same as on nodes
- ⊖ Slow execution

- ○ Parameters $\rightarrow$ Behavior
- ⊕ Useful for developing models

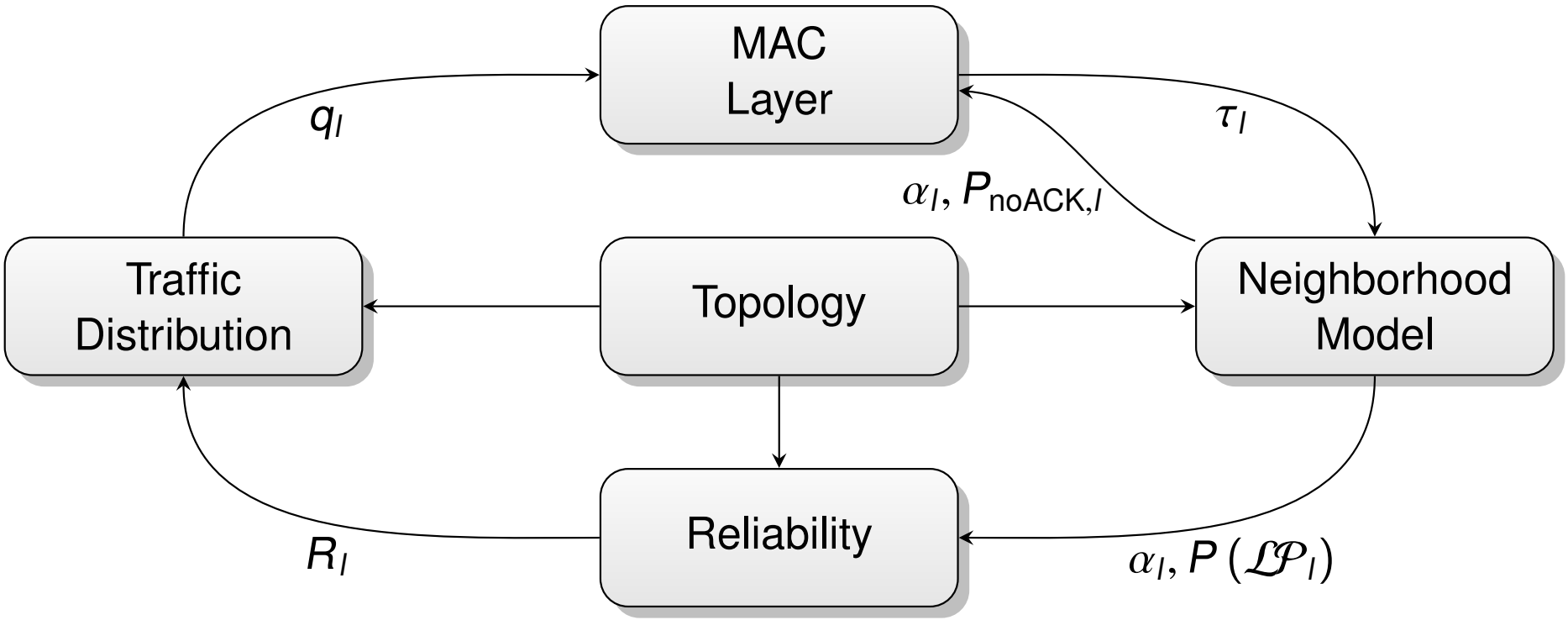
Analytical Model

- Solving a system of equations

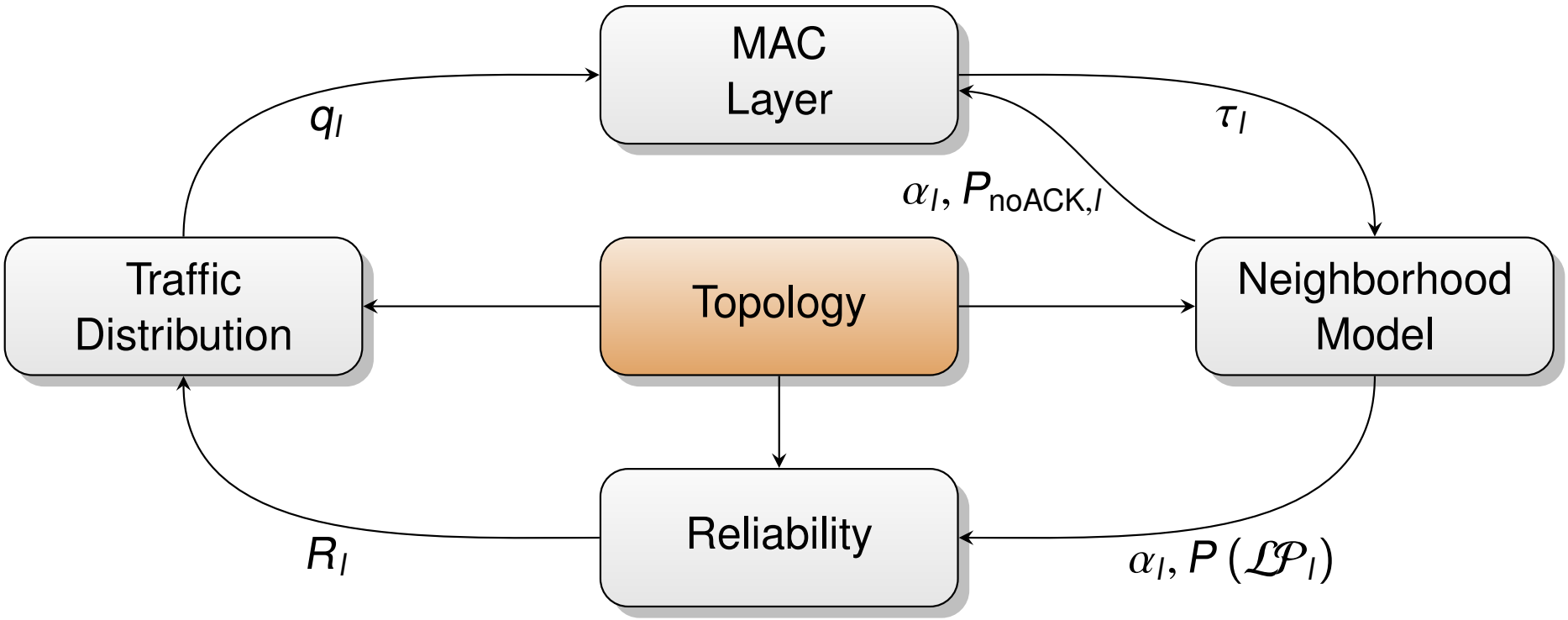
- ⊖ Complex modeling
- ⊕ Fast calculation

- ⊕ Parameters $\leftrightarrow$ Behavior
- ⊕ Can find parameters for simulations
- ⊕ Gives new insights

Overview


MAC
Layer
q_I
τ_I
$\alpha_I, P_{\text{noACK},I}$
Traffic
Distribution
Topology
Neighborhood
Model
Reliability
R_I
$\alpha_I, P(\mathcal{LP}_I)$

Overview


MAC
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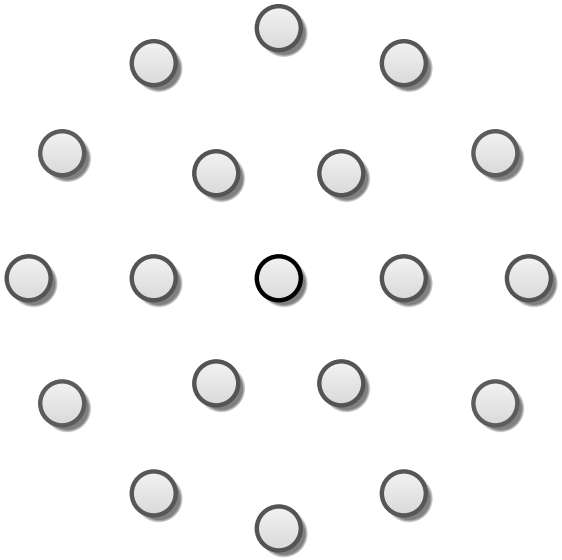
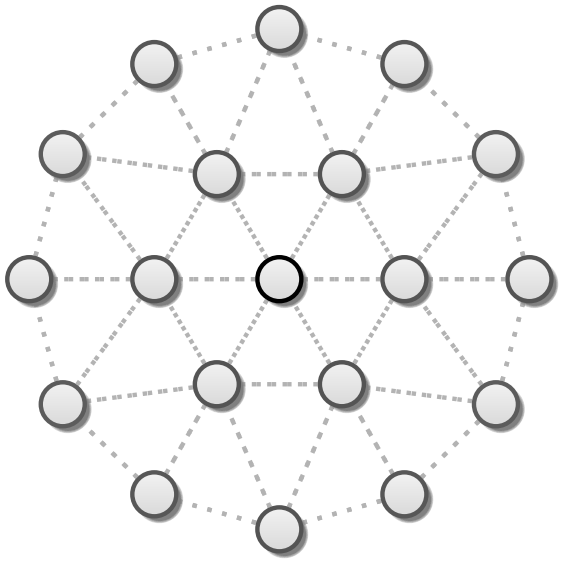
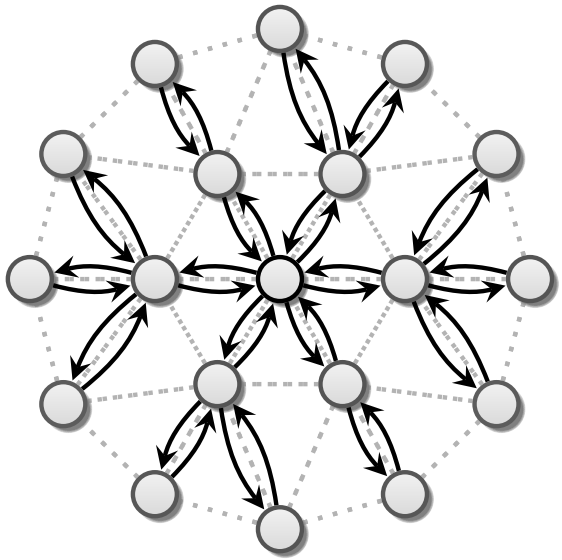
Topology



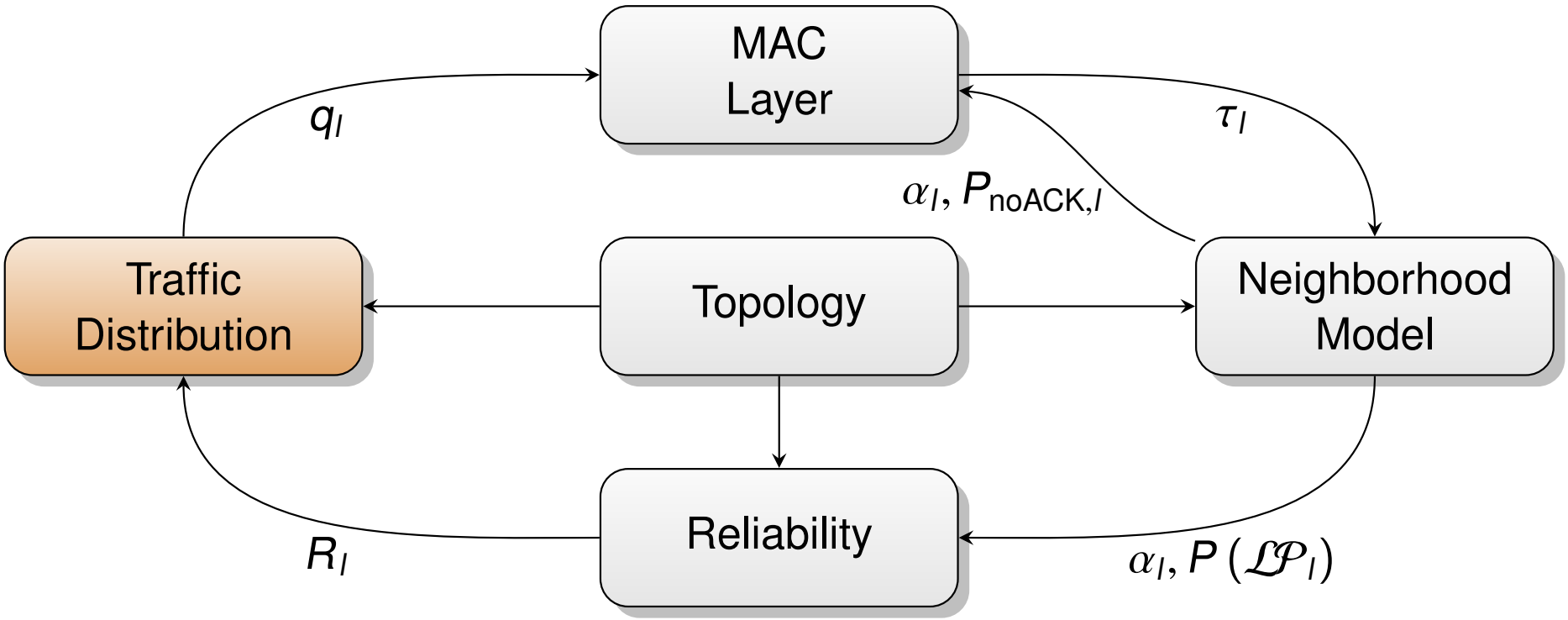
Log-Distance Path Loss Model



Dijkstra's Algorithm



Overview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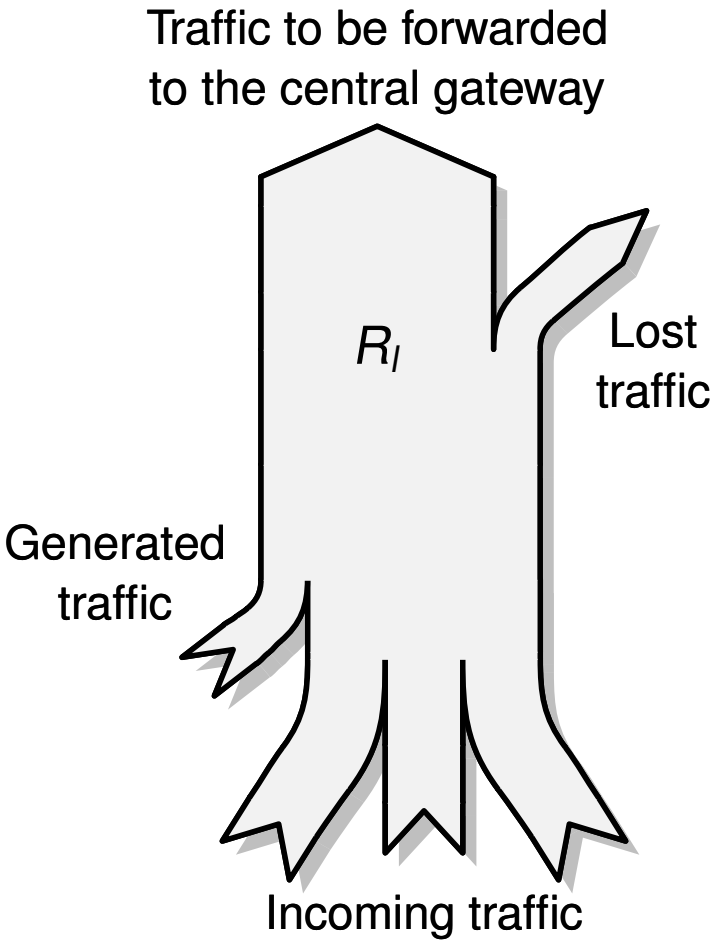
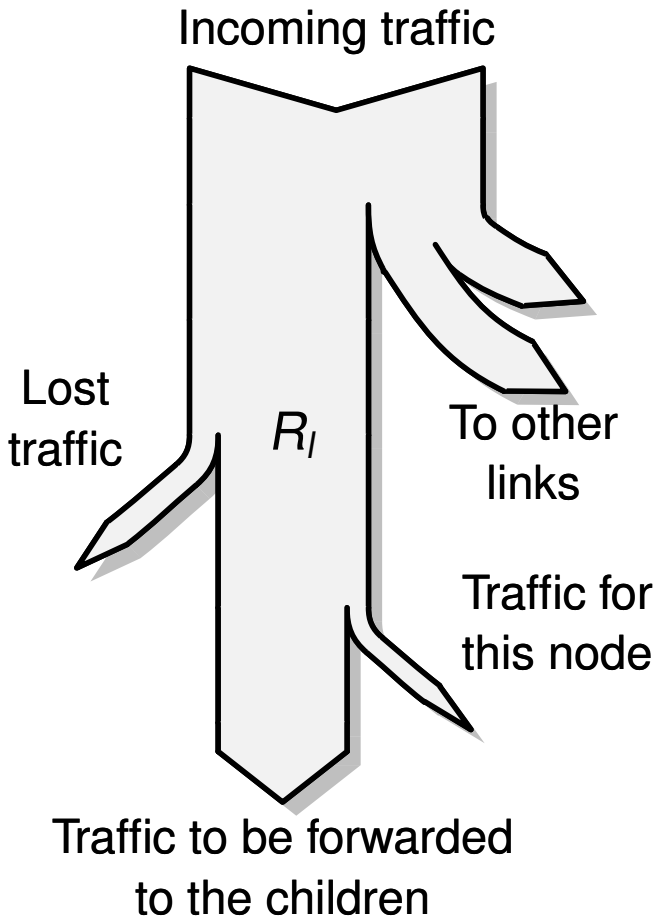
Traffic Distribution for a Single Link

Upstream

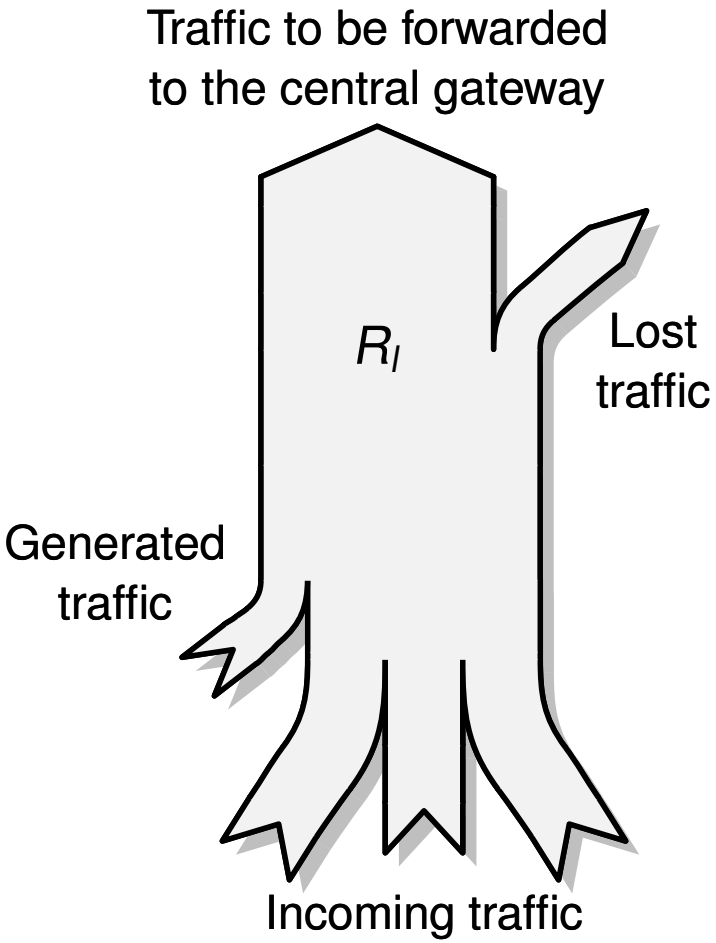


Downstream

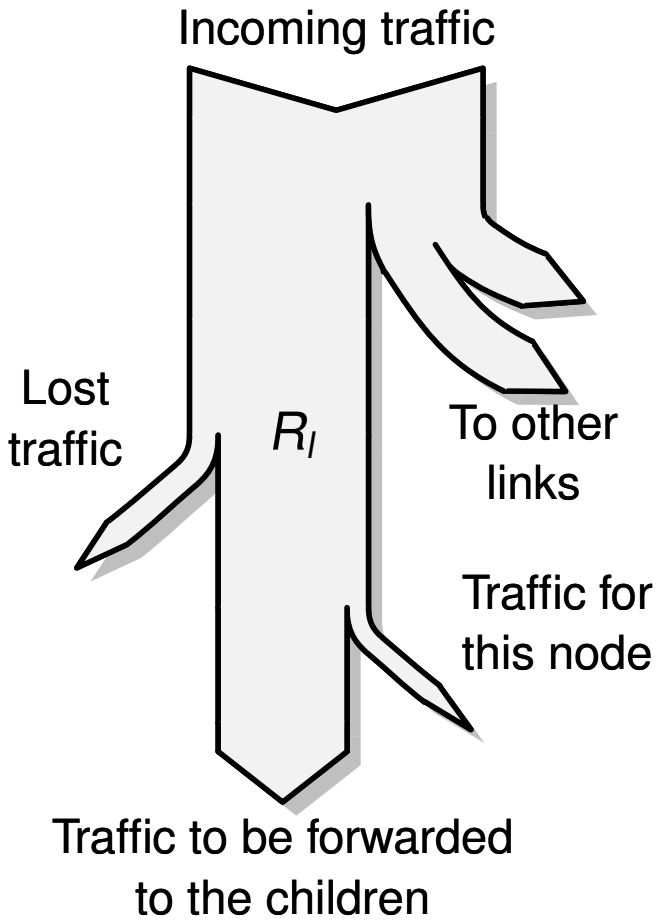


Traffic Distribution for a Single Link

Upstream

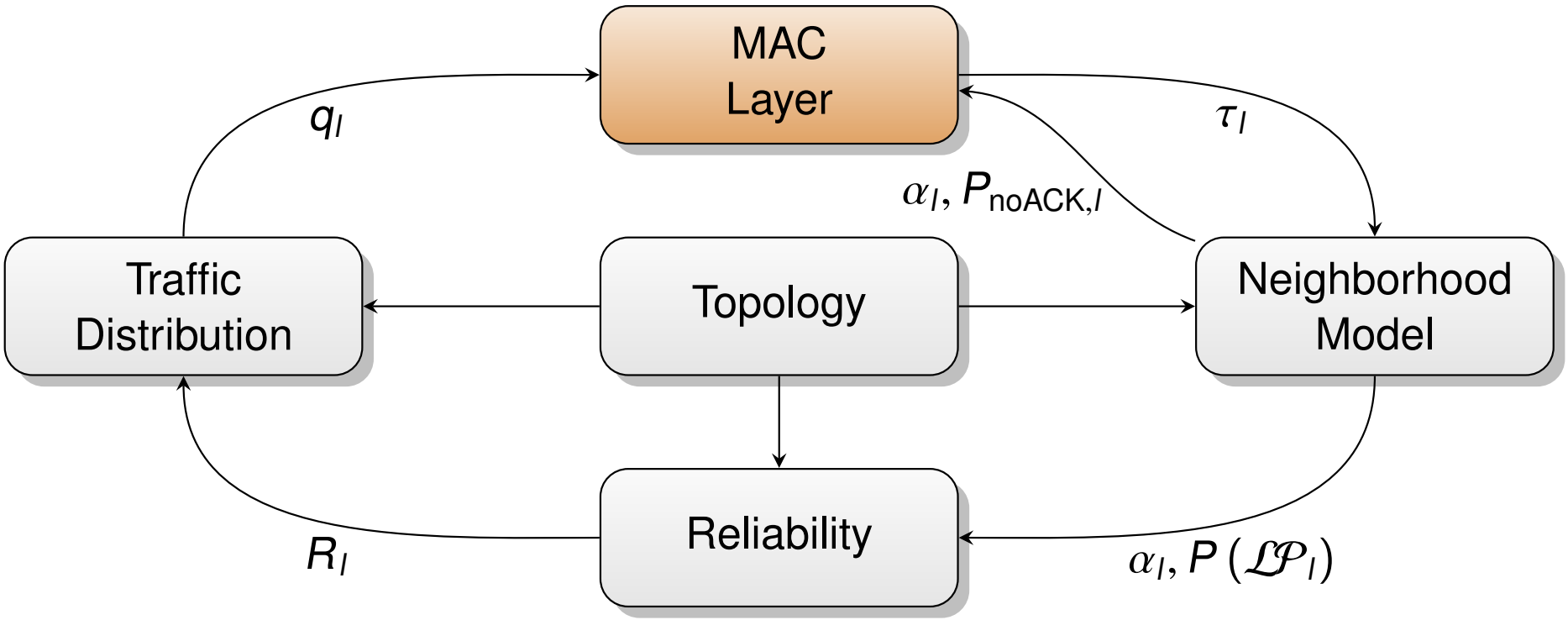


Downstream



$\Rightarrow$ Probability of a pending packet q_l

Overview

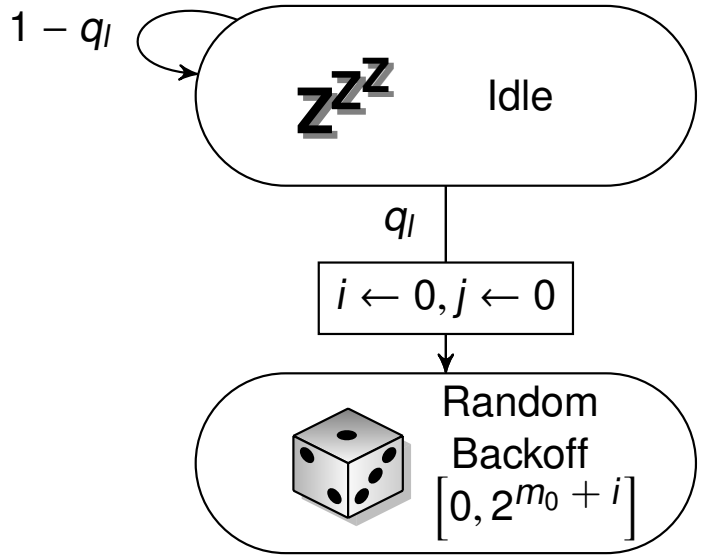

MAC Layer
q_I
τ_I
$\alpha_I, P_{\text{noACK},I}$
Traffic Distribution
Topology
Neighborhood Model
Reliability
R_I
$\alpha_I, P(\mathcal{LP}_I)$

MAC Layer

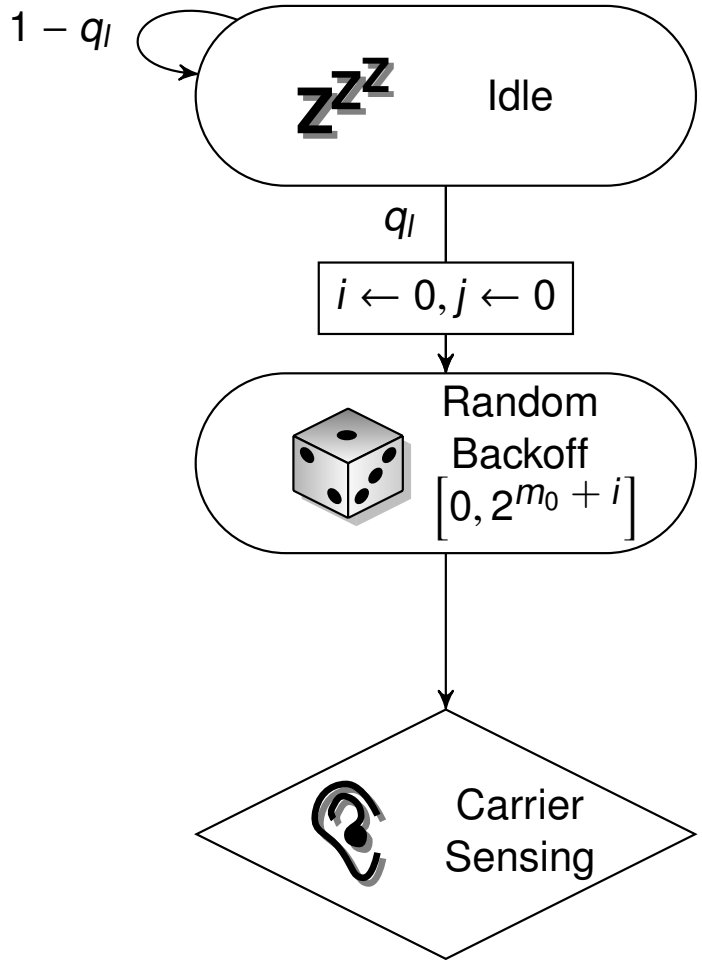
- IEEE 802.15.4 Standard
- Widely used for energy efficient, inexpensive multi-hop networks
- Uses Carrier Sense Multiple Access with Collision Avoidance
- Model based on

Di Marco, P.; Park, P.; Fischione, C.; Johansson, K.H.
Analytical Modeling of Multi-hop IEEE 802.15.4 Networks.
IEEE Transactions on Vehicular Technology, 2012.

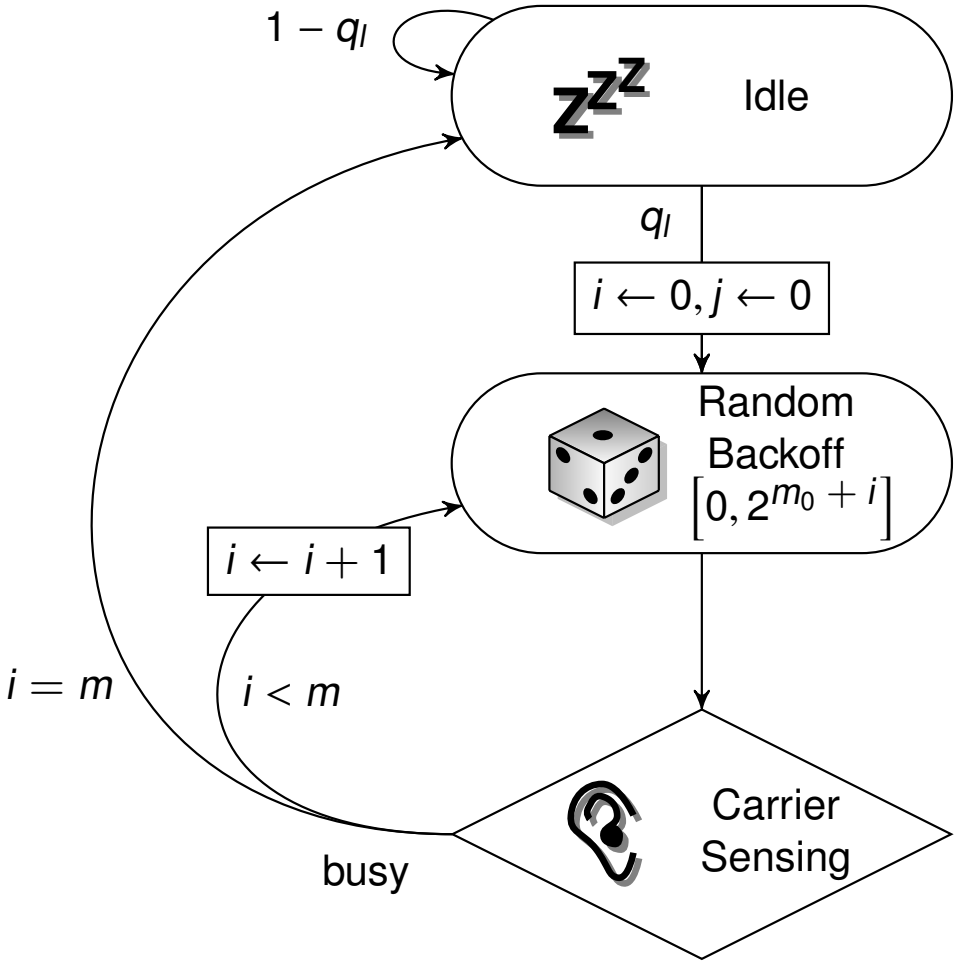
IEEE 802.15.4 CSMA/CA



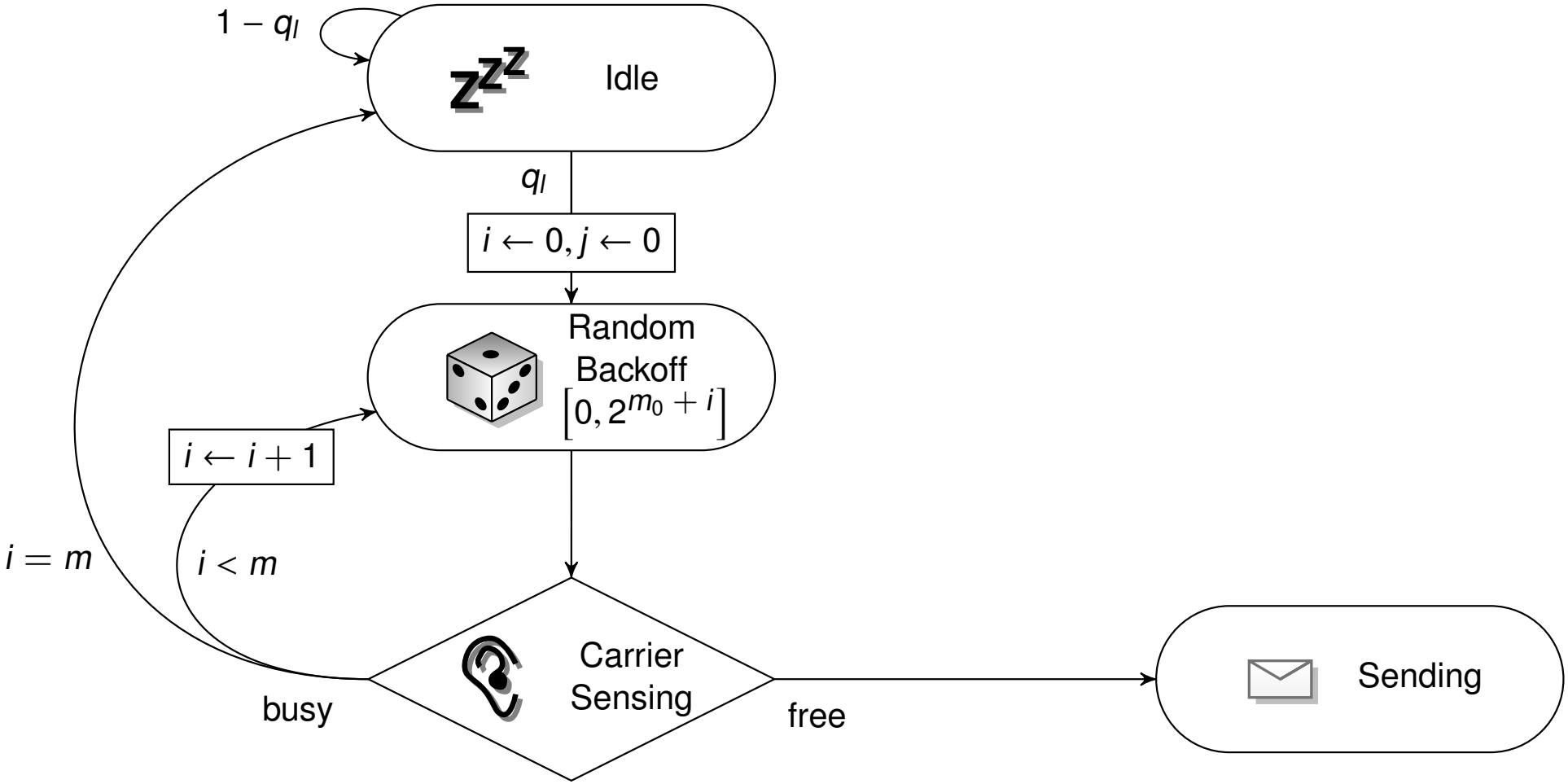
IEEE 802.15.4 CSMA/CA



IEEE 802.15.4 CSMA/CA



IEEE 802.15.4 CSMA/CA



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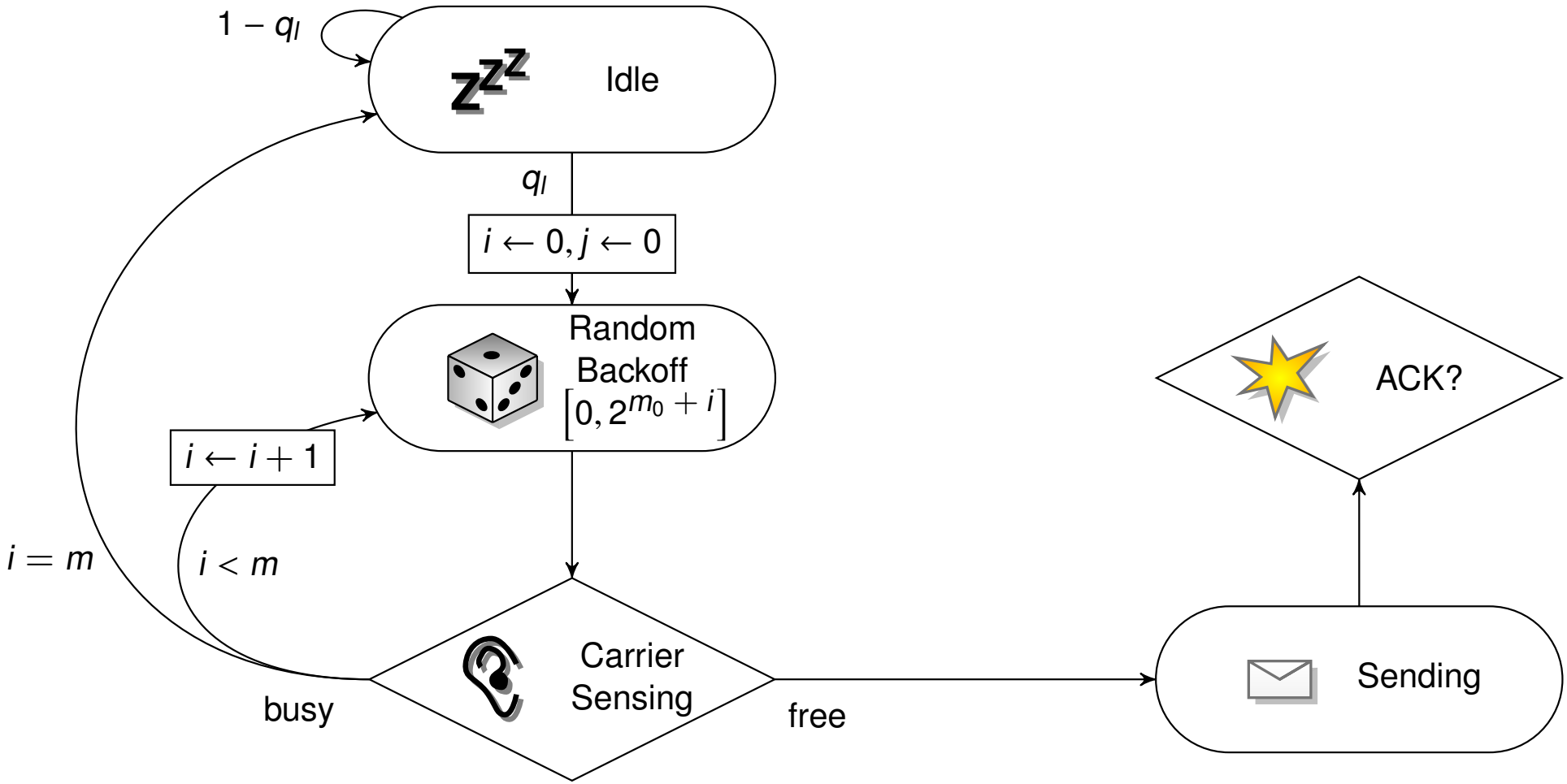

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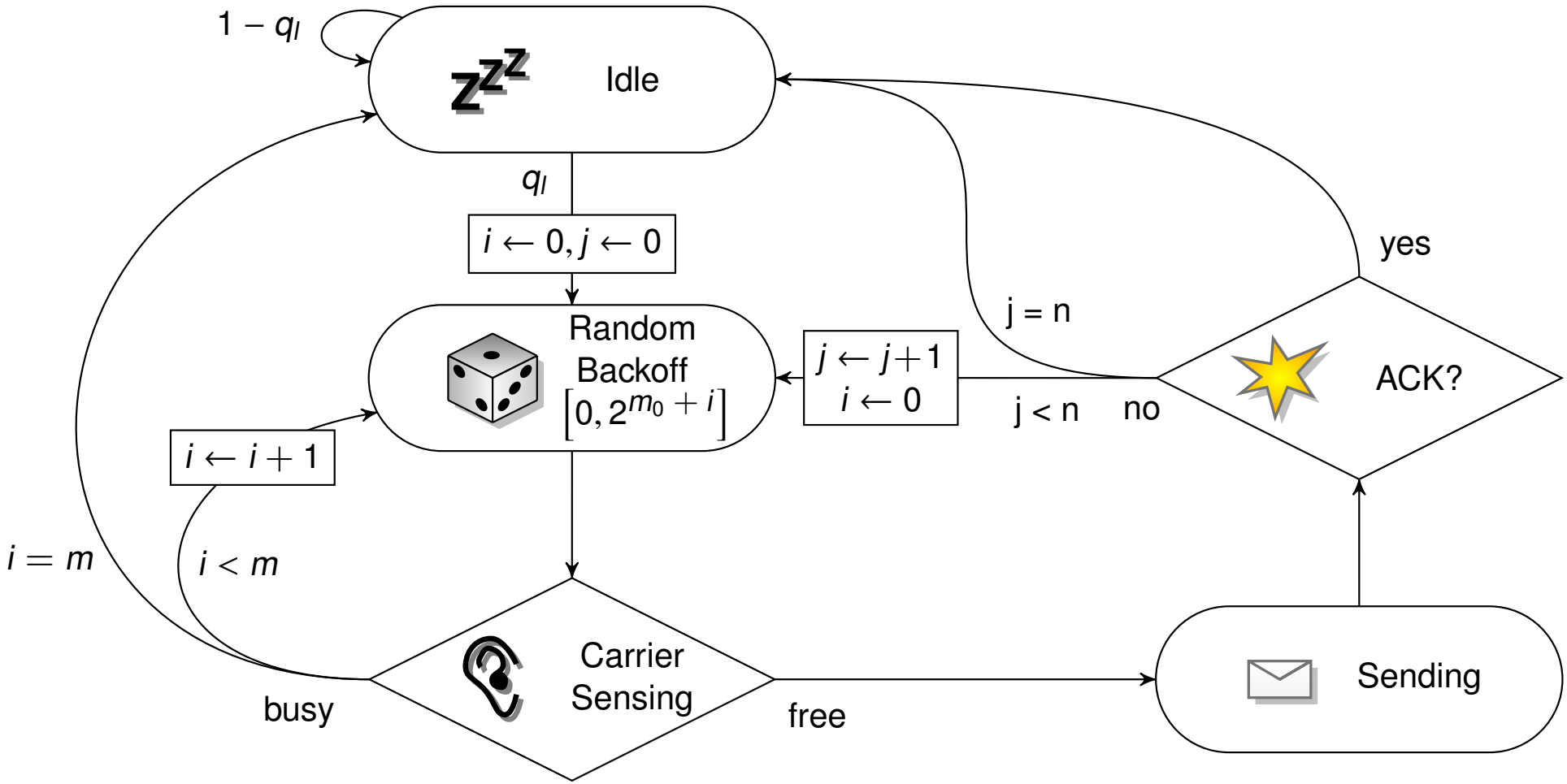

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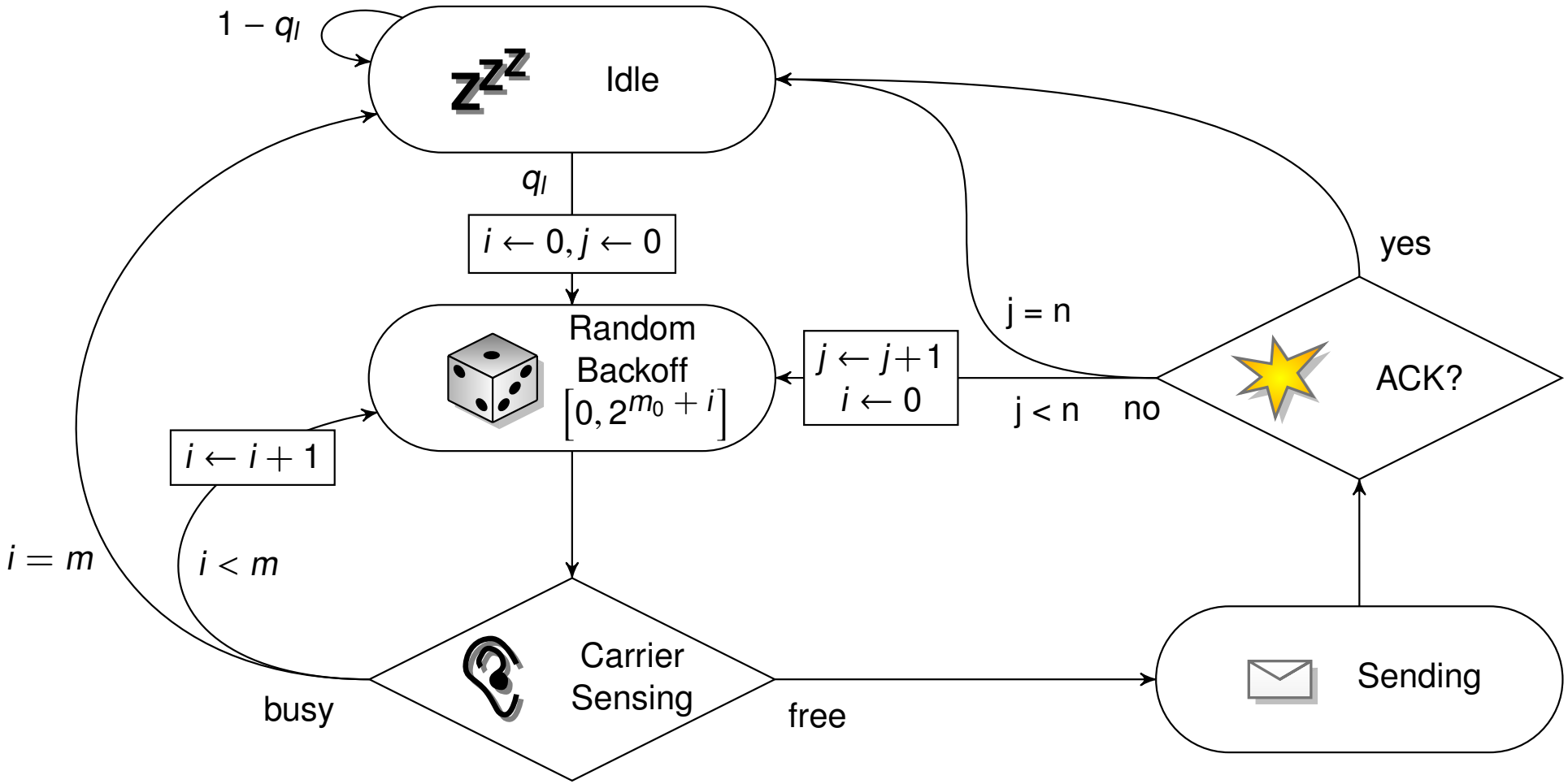
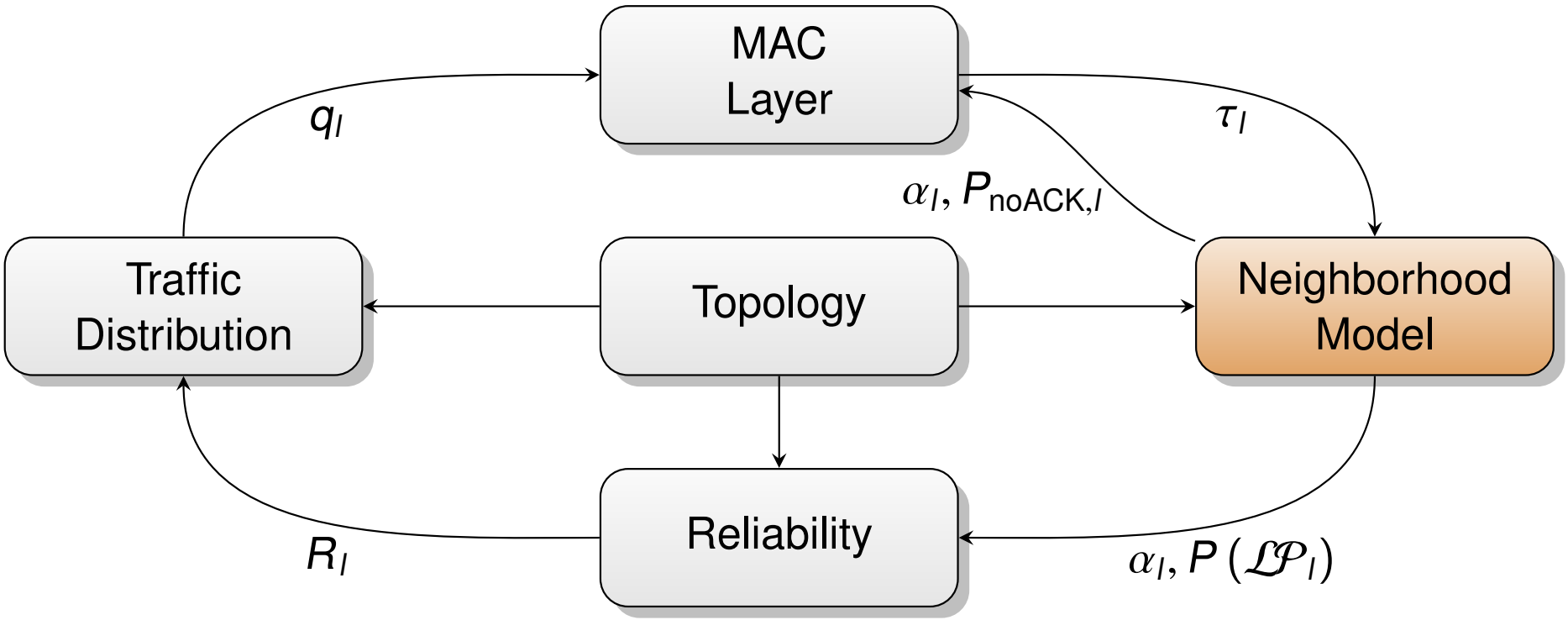


$\Rightarrow$ Probability of attempting a transmission τ_I from the stationary distribution of a Markov chain

Overview


MAC
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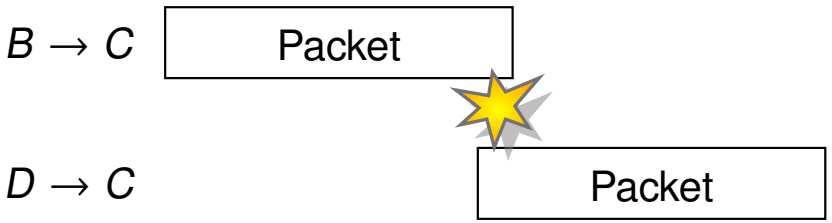
Neighborhood Model

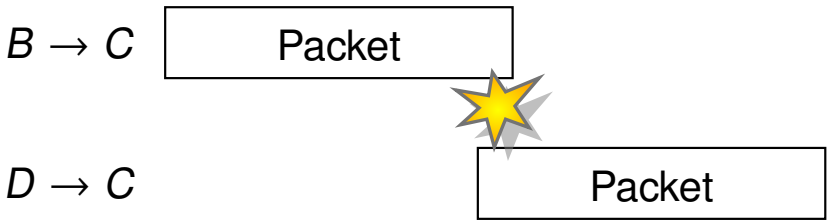
Example 1: Hidden Nodes



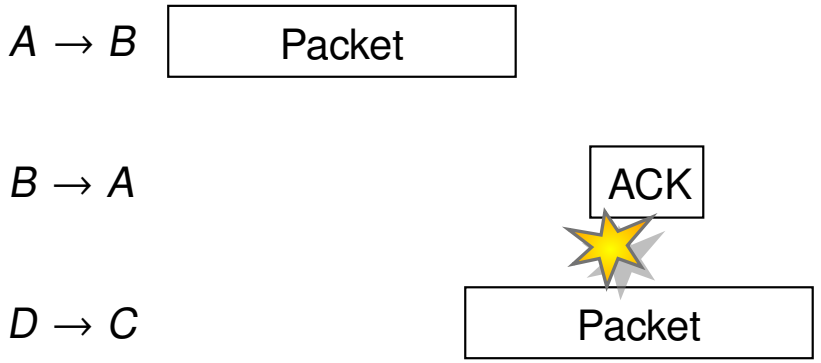
$\Rightarrow$ Probability of a lost packet $P\left(\mathcal{LP}_I\right)$,
a missing ACK $P_{\text{noACK},I}$ and a busy channel α_I.

Neighborhood Model

Example 1: Hidden Nodes

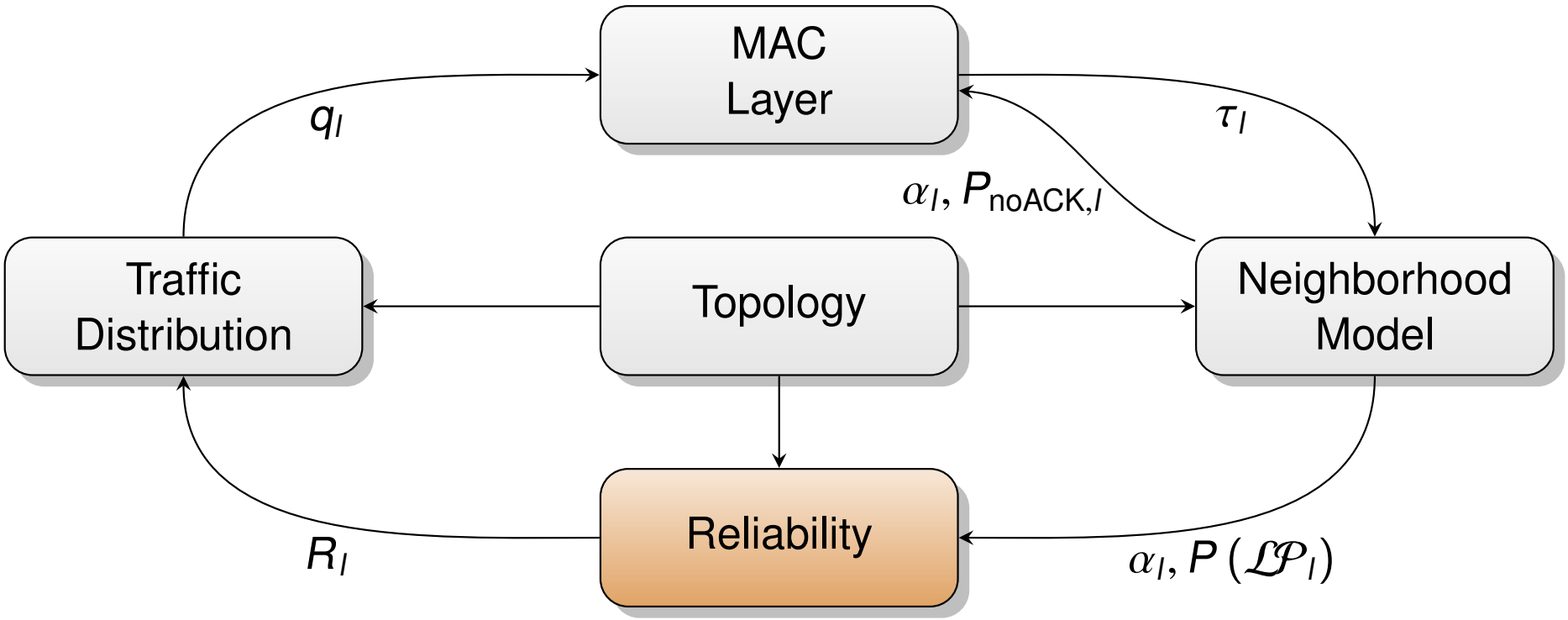


Example 2: ACK Collisions



⇒ Probability of a lost packet $P\left(\mathcal{LP}_I\right)$,
a missing ACK $P_{\text{noACK},I}$ and a busy channel α_I.

Overview


MAC
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q_l
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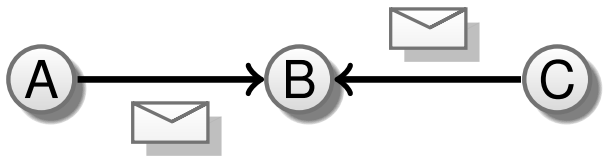
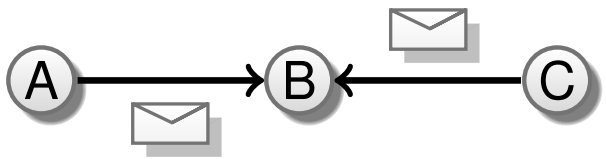
Link Reliability

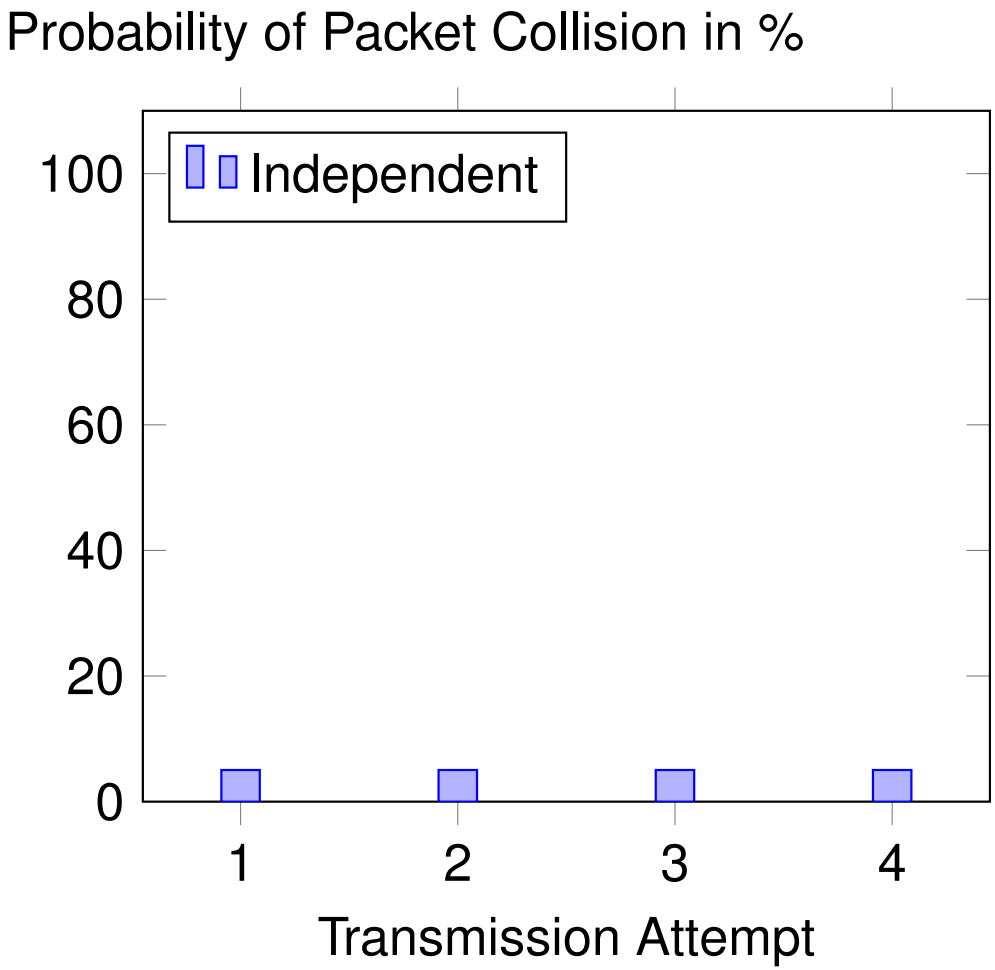


$$R_l = 1 - P\left(\mathcal{LP}_l\right)^{n+1}$$

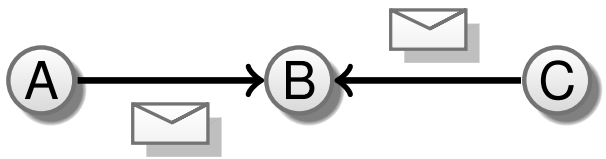
Link Reliability



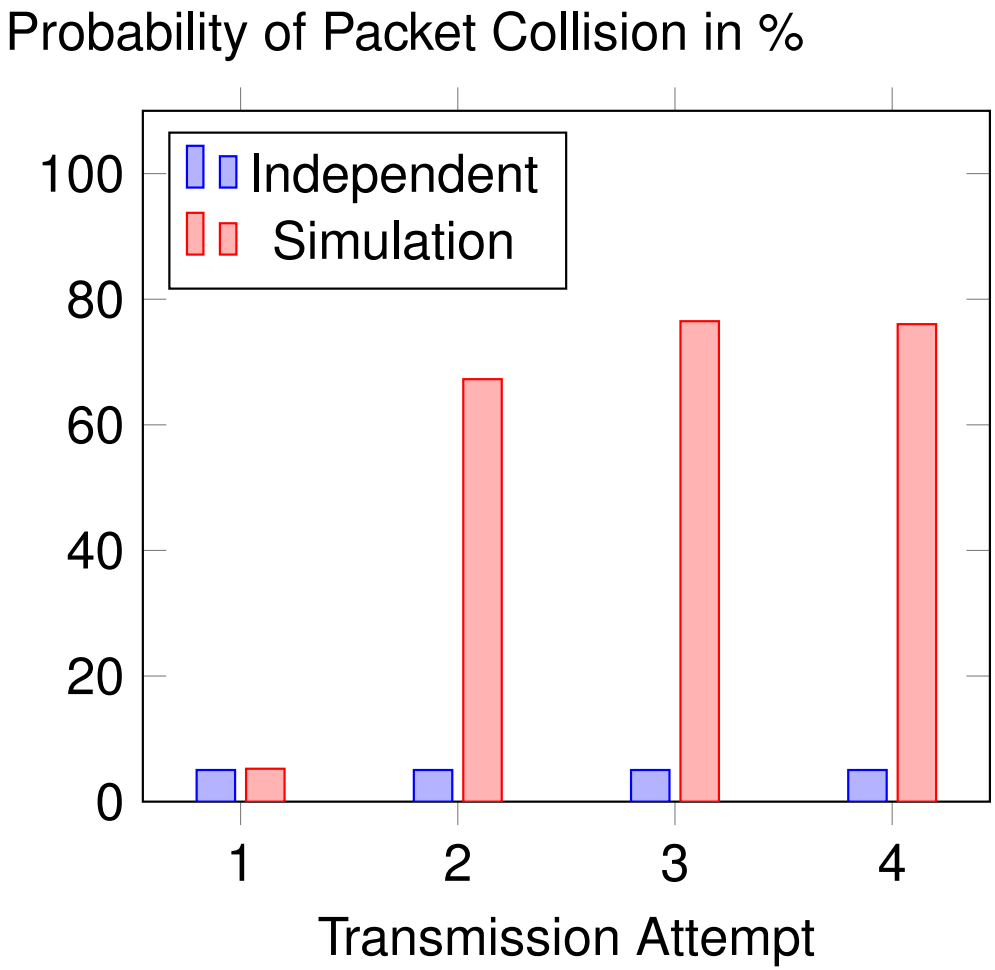
$$R_l = 1 - P\left(\mathcal{LP}_l\right)^{n+1}$$



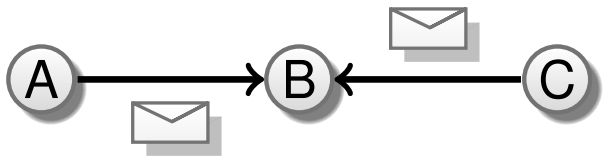
Link Reliability



$$R_l = 1 - P\left(\mathcal{LP}_l\right)^{n+1}$$

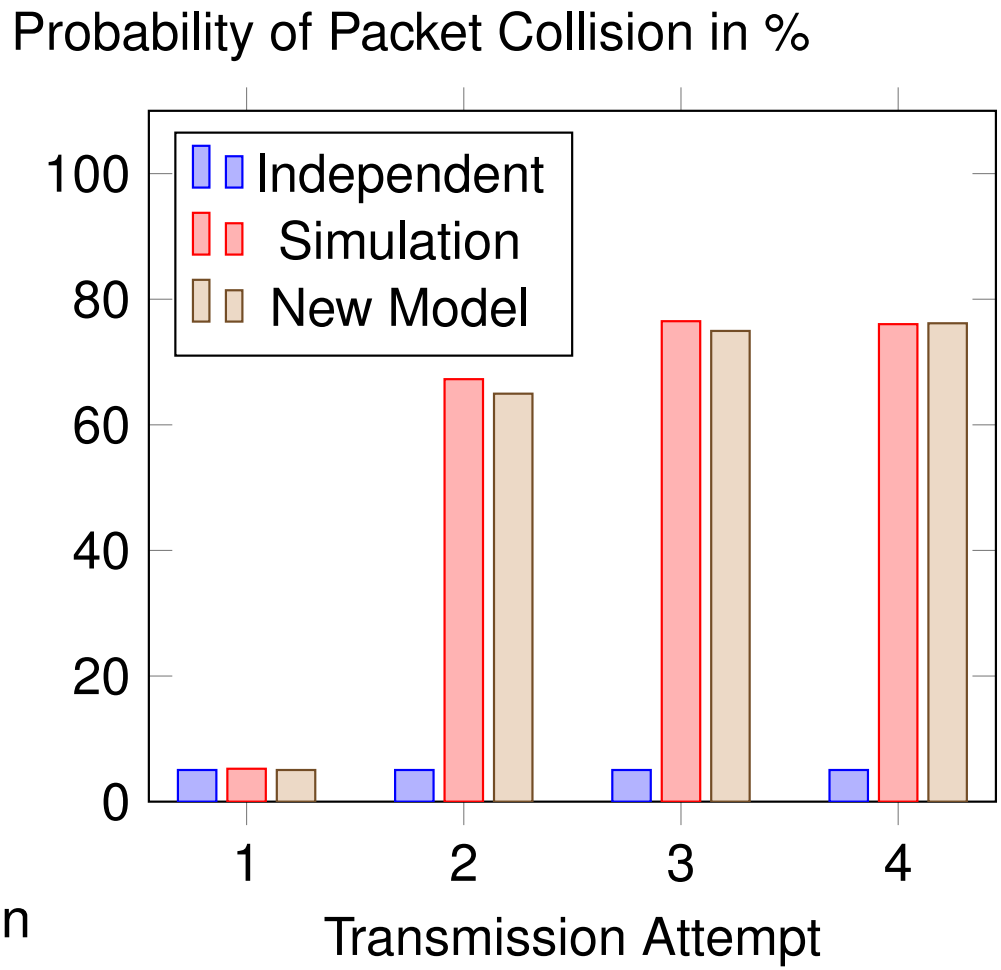


Link Reliability



$$R_l = 1 - (\mathcal{LP}_l)^{n+1}$$

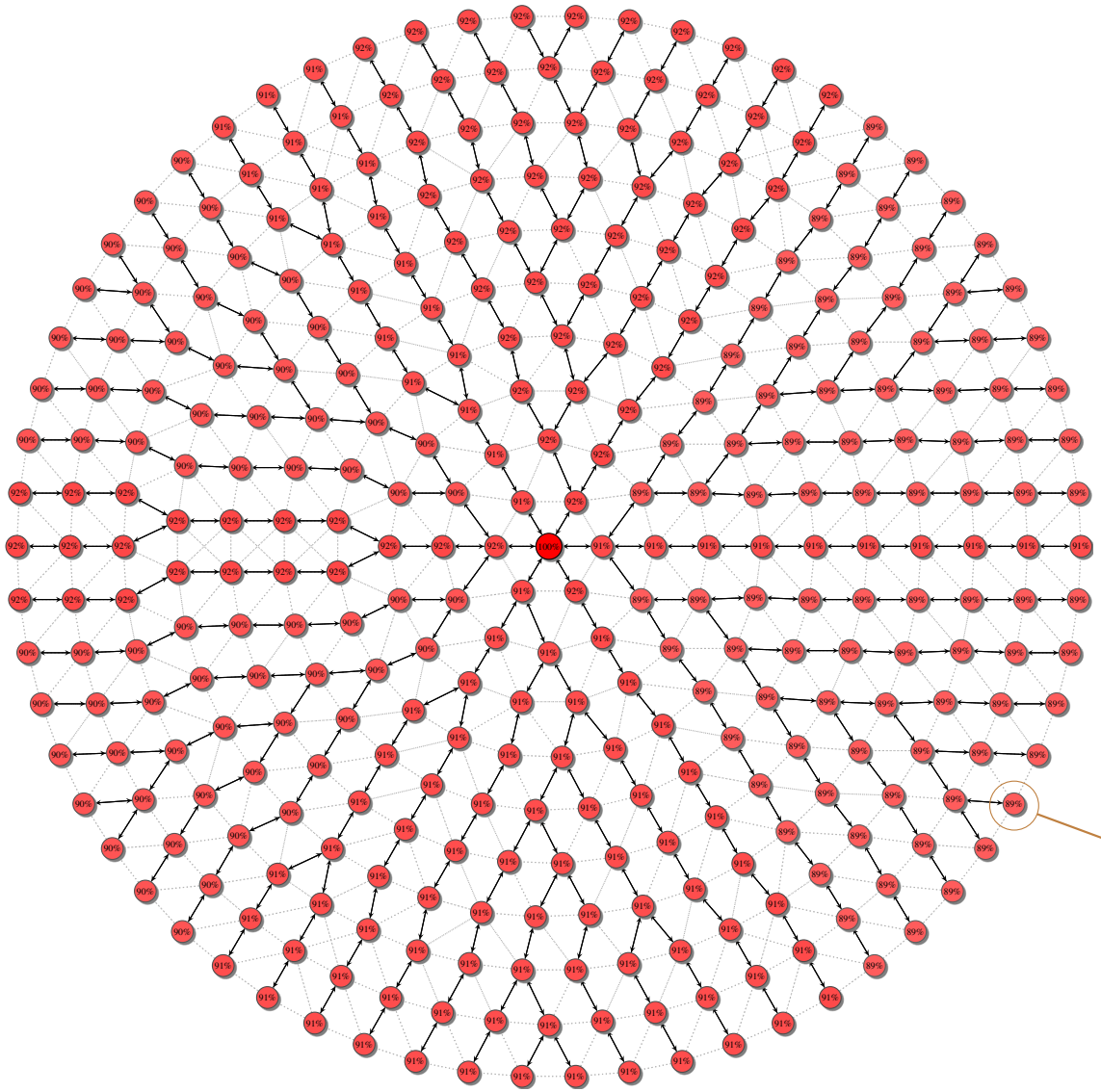
Instead: Absorbing Markov chain



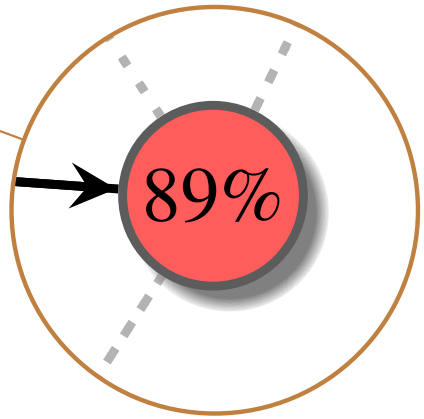
3

Results

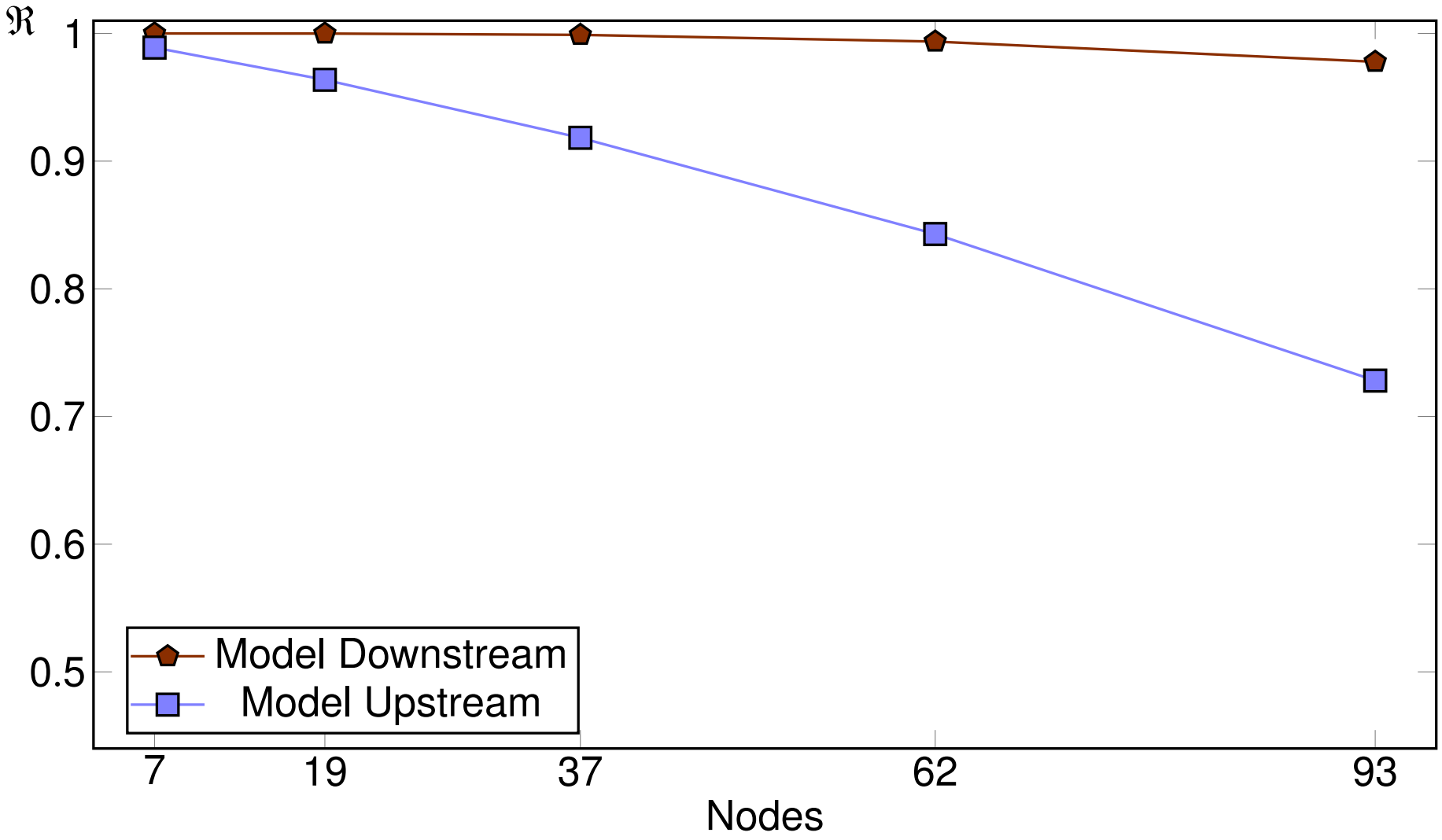
Reliability of Packet Delivery



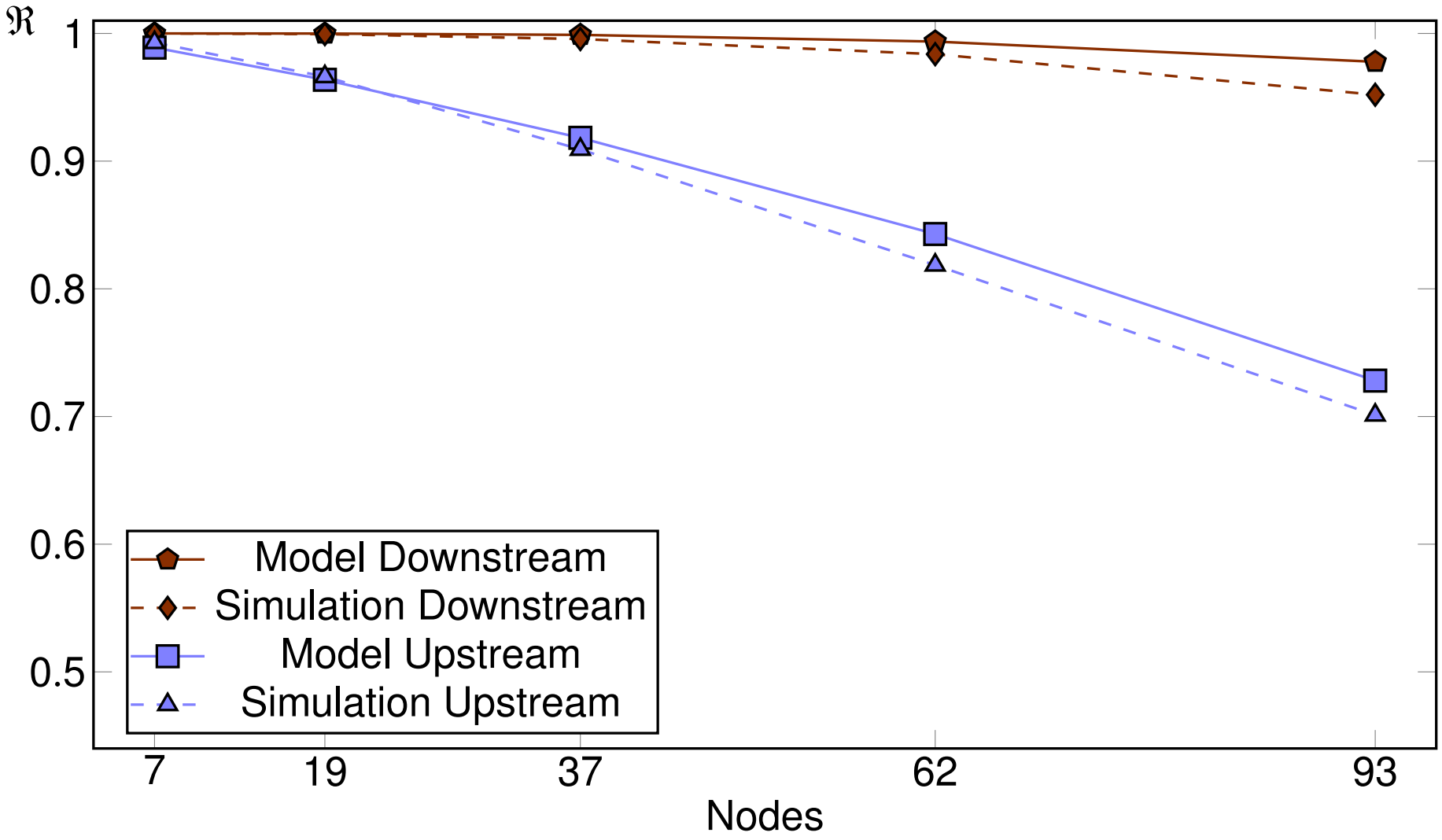
- 341 Nodes
- 60 Bytes per Packet
- Interval: 10 s



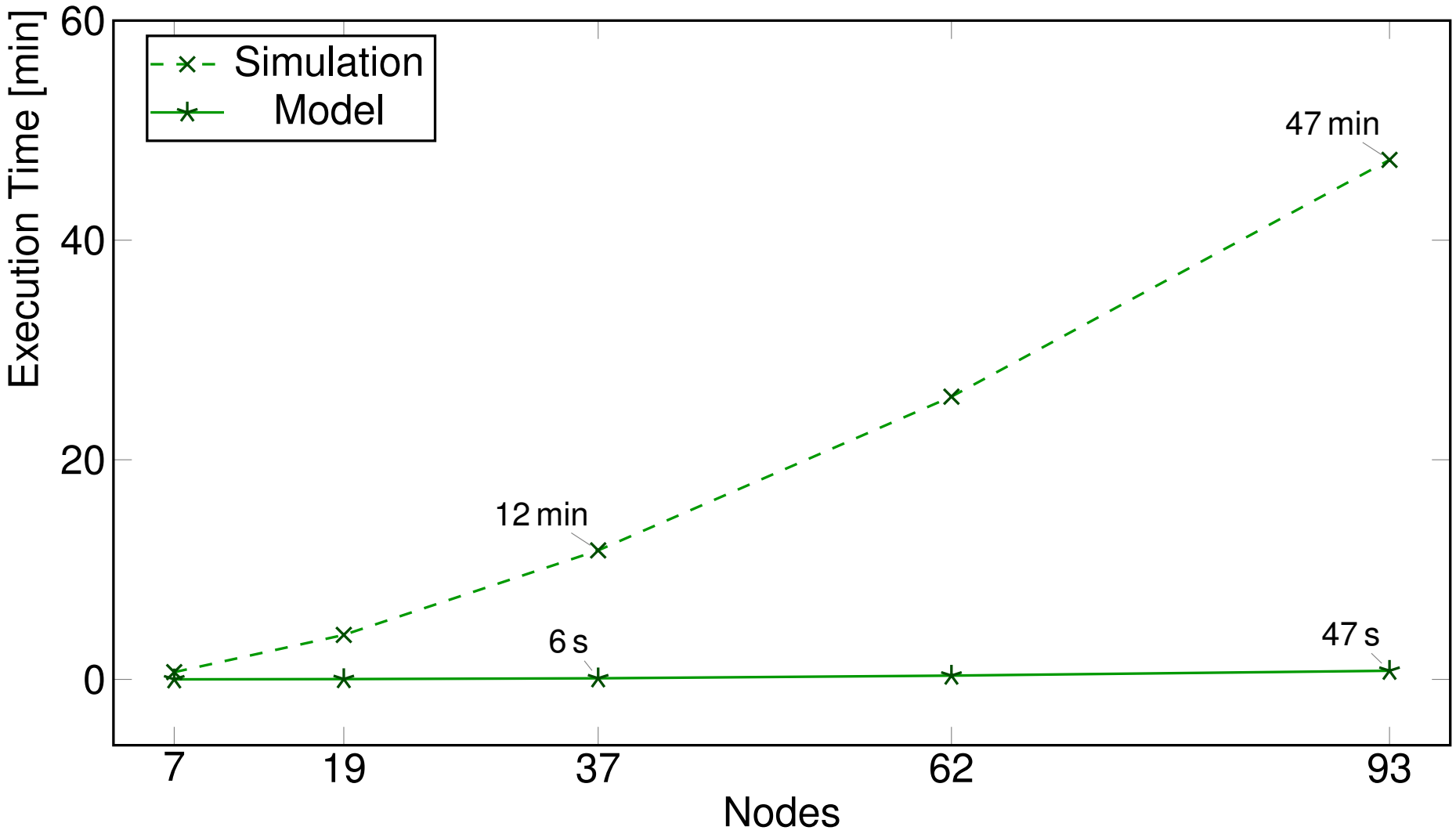
Network Scalability



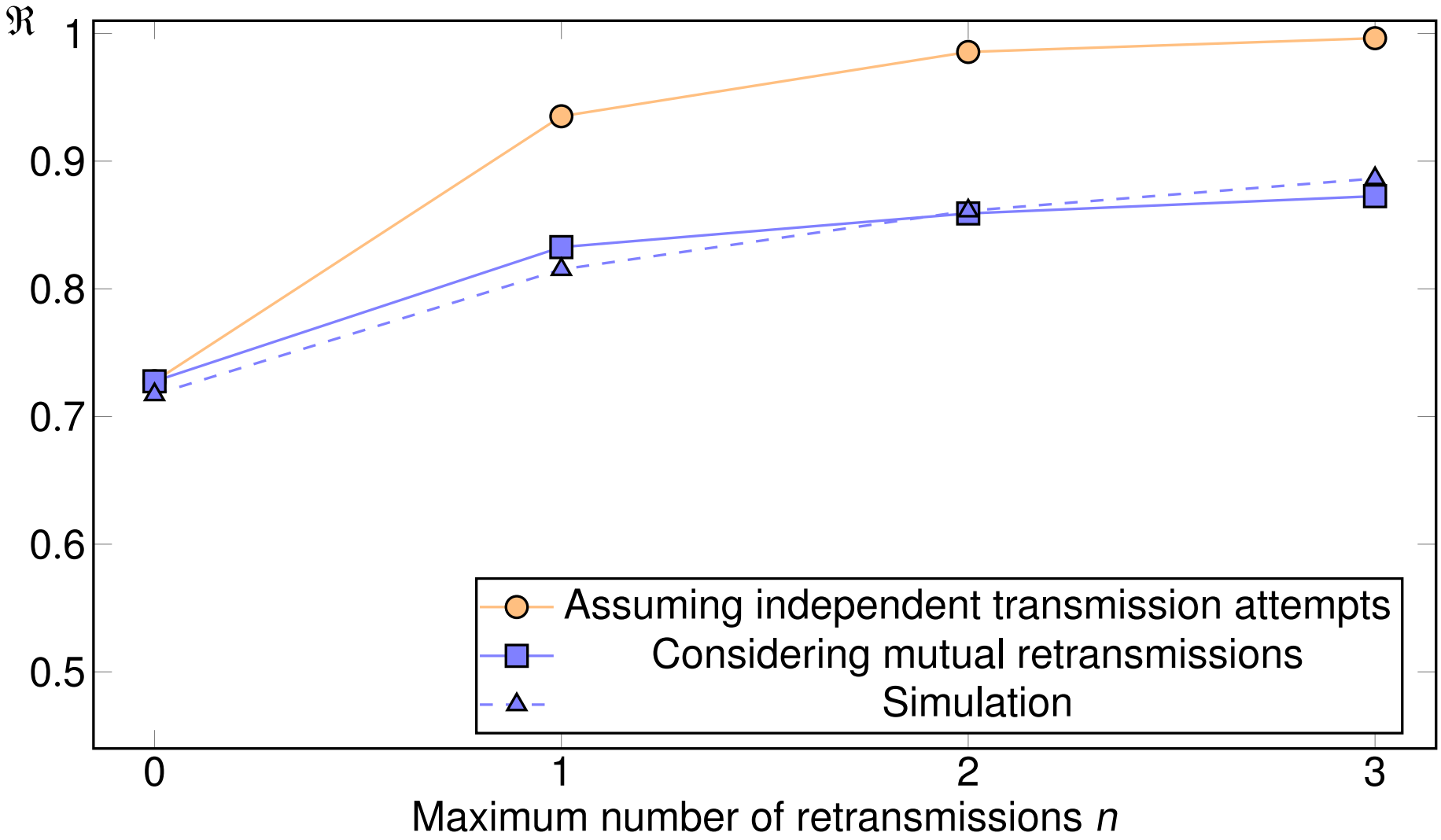
Comparison to Simulation



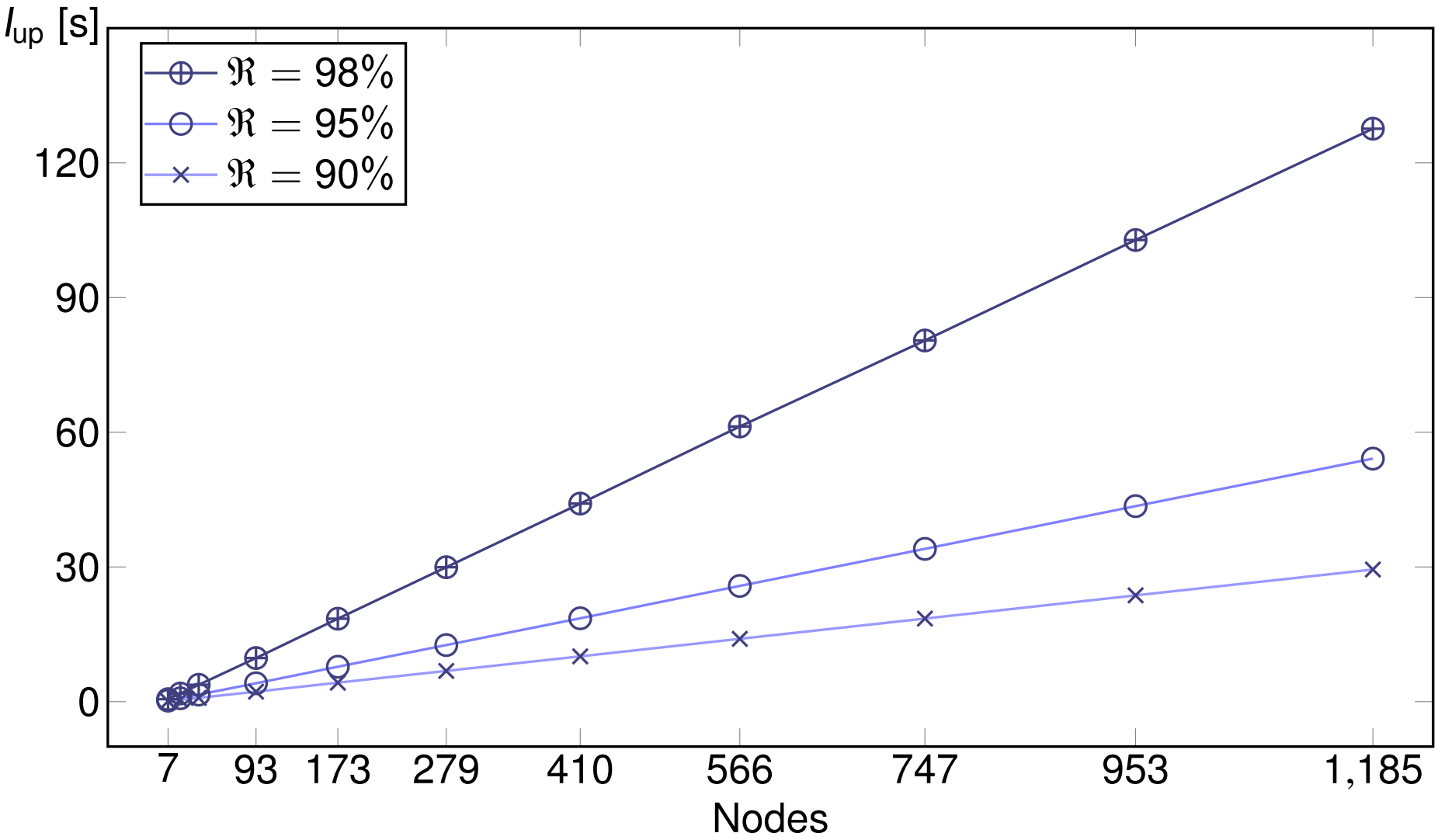
Computing the Model is Much Faster



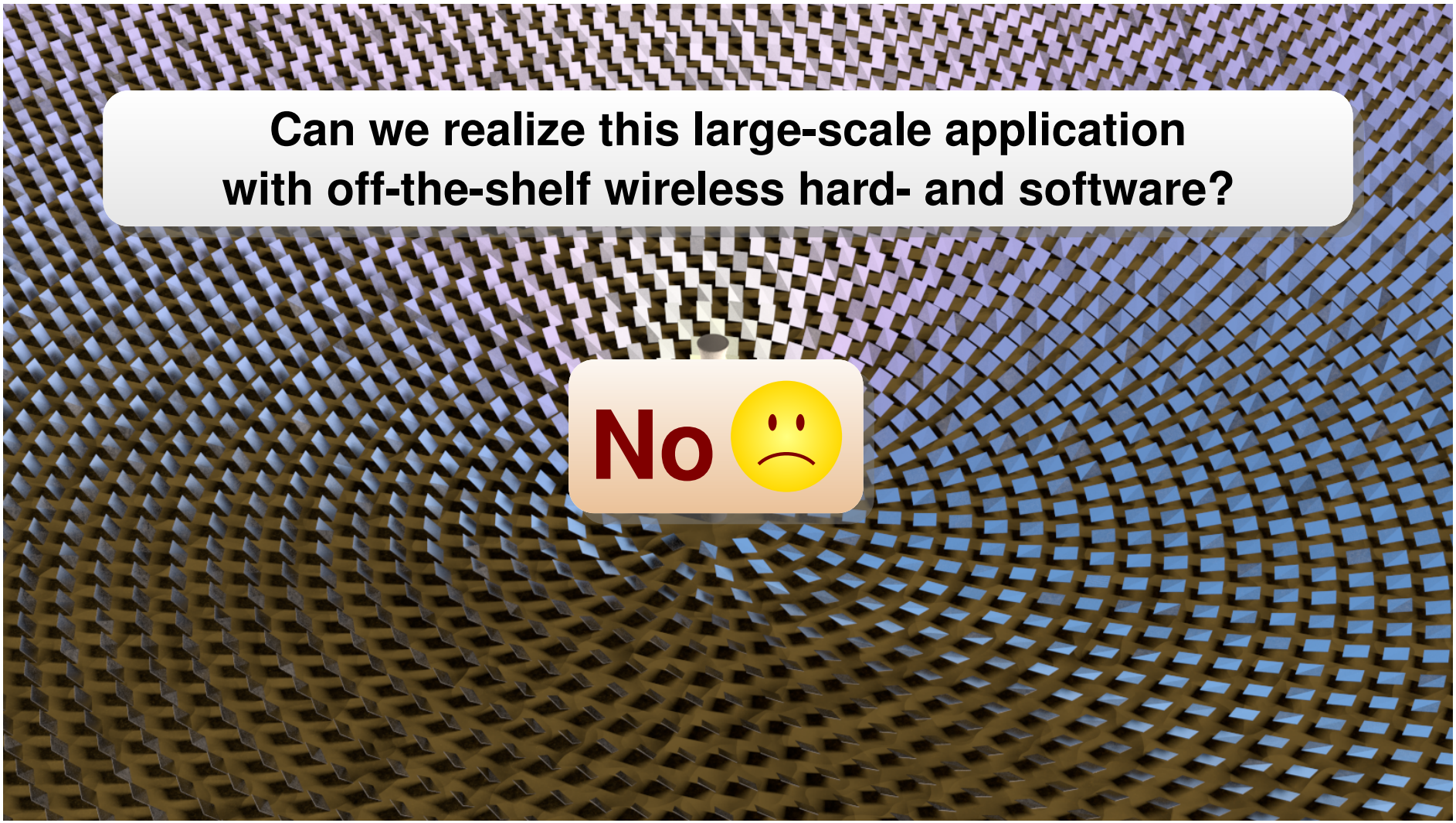
Retransmissions



Behavior → Parameters

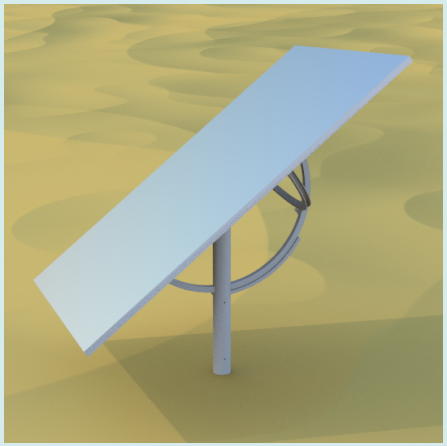


Conclusion

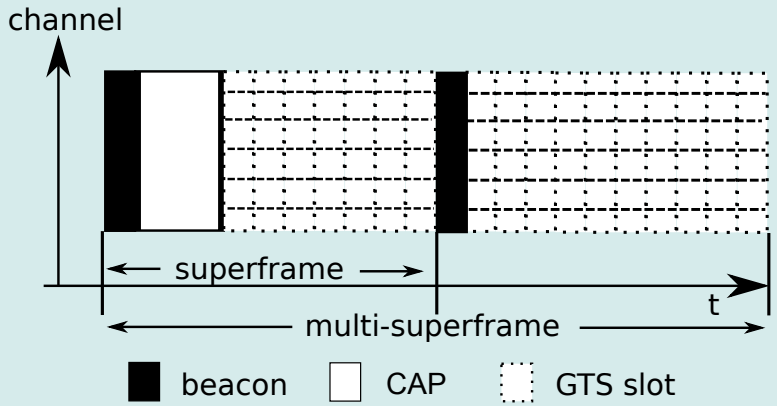

Can we realize this large-scale application
with off-the-shelf wireless hard- and software?
No

Possible Solutions

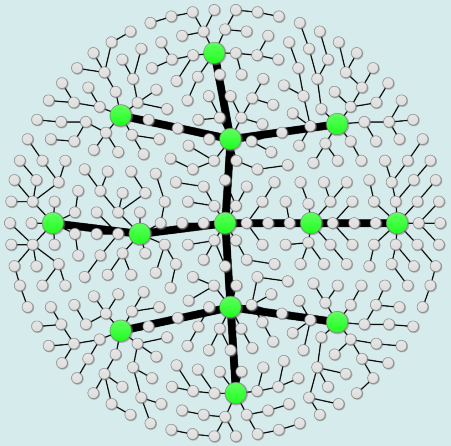
Intelligent Heliostats



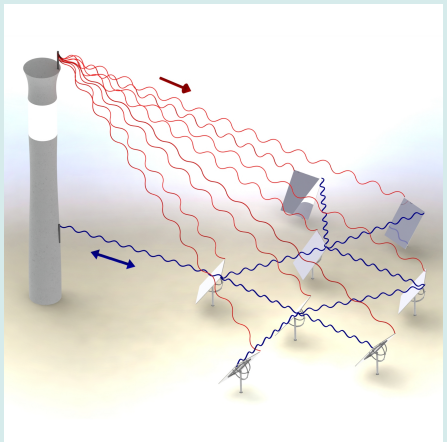
TDMA MAC Layer



Partitioning / Backbone



Emergency Channel



Conclusion

- Analytical model for IEEE 802.15.4 mesh networks

- Implemented in C++ using the PETSc framework
- Source code on Github

  `https://github.com/koalo/AnalyticalMultiHop`

- Fast assessment of large-scale networks
- Acknowledgements are significant for collisions
- Mutual retransmissions decrease the performance a lot
- The application is not realizable with off-the-shelf components, but there are ways out

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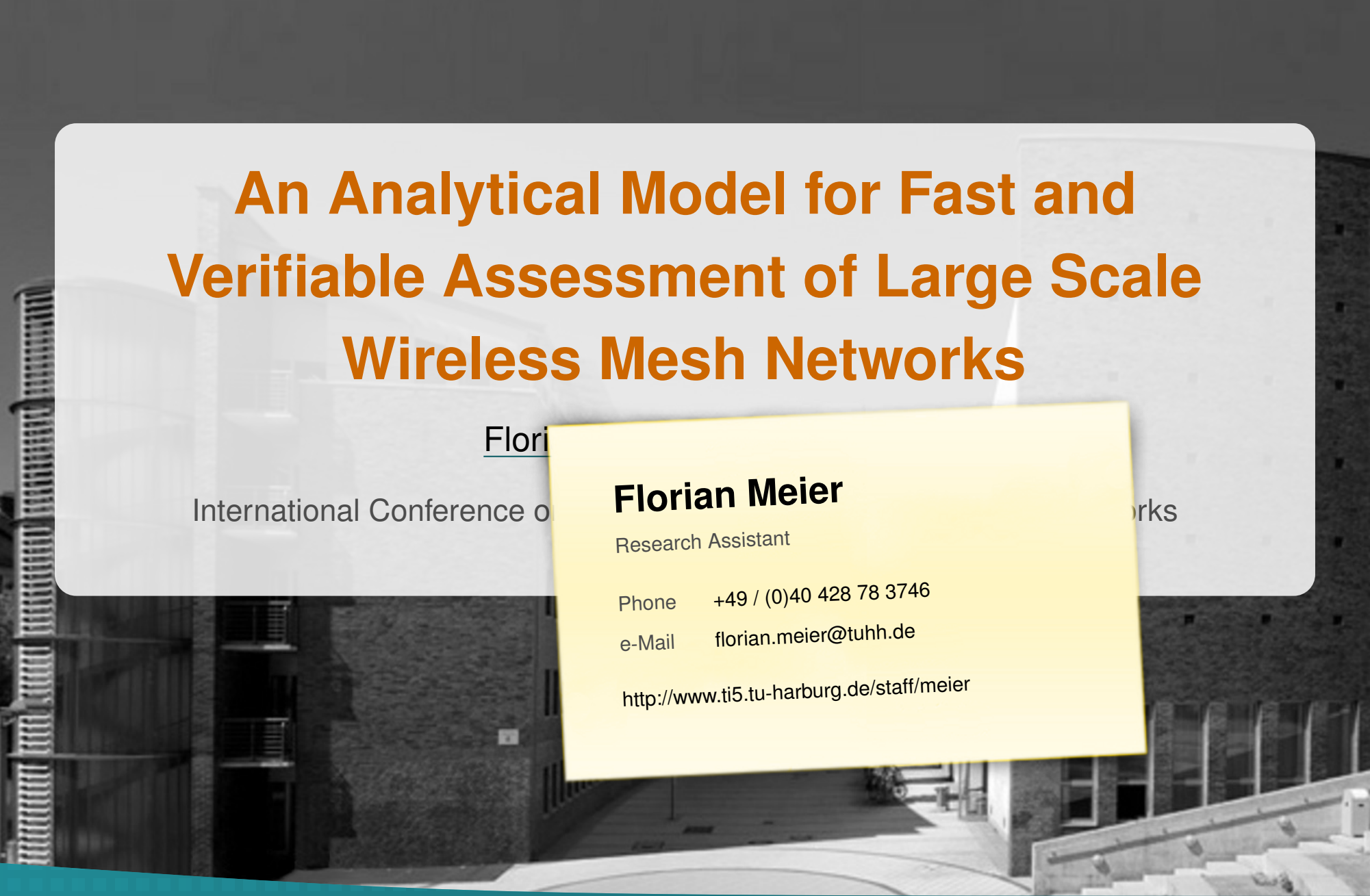
International Conference o rks



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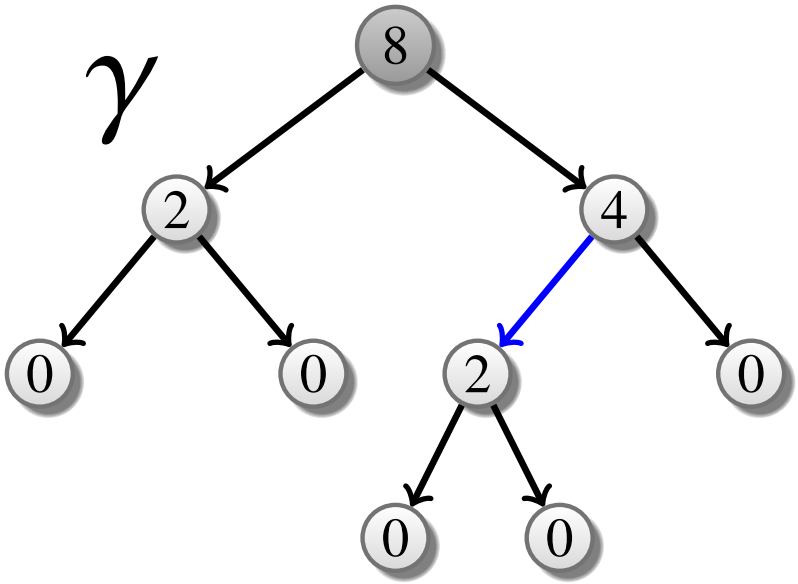
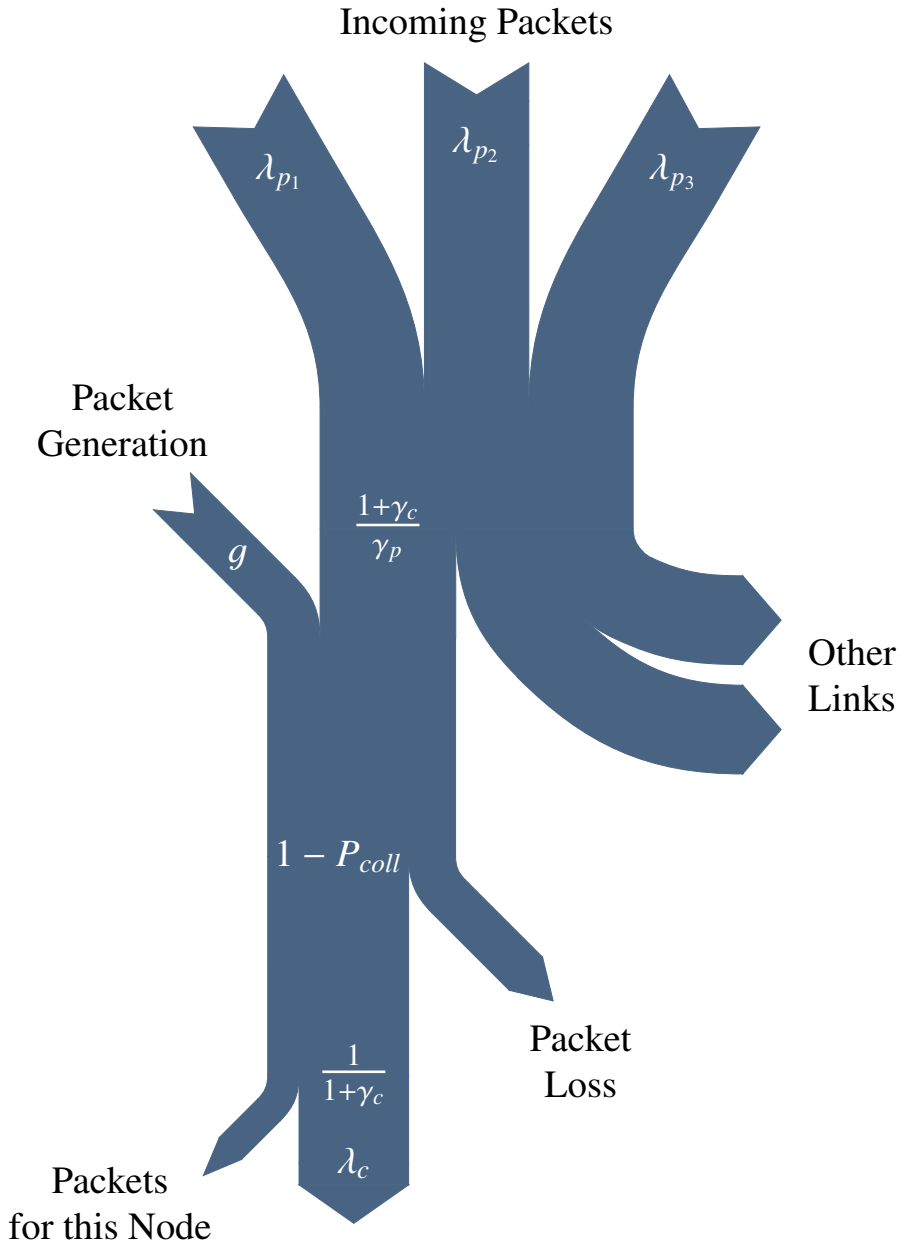
Appendix

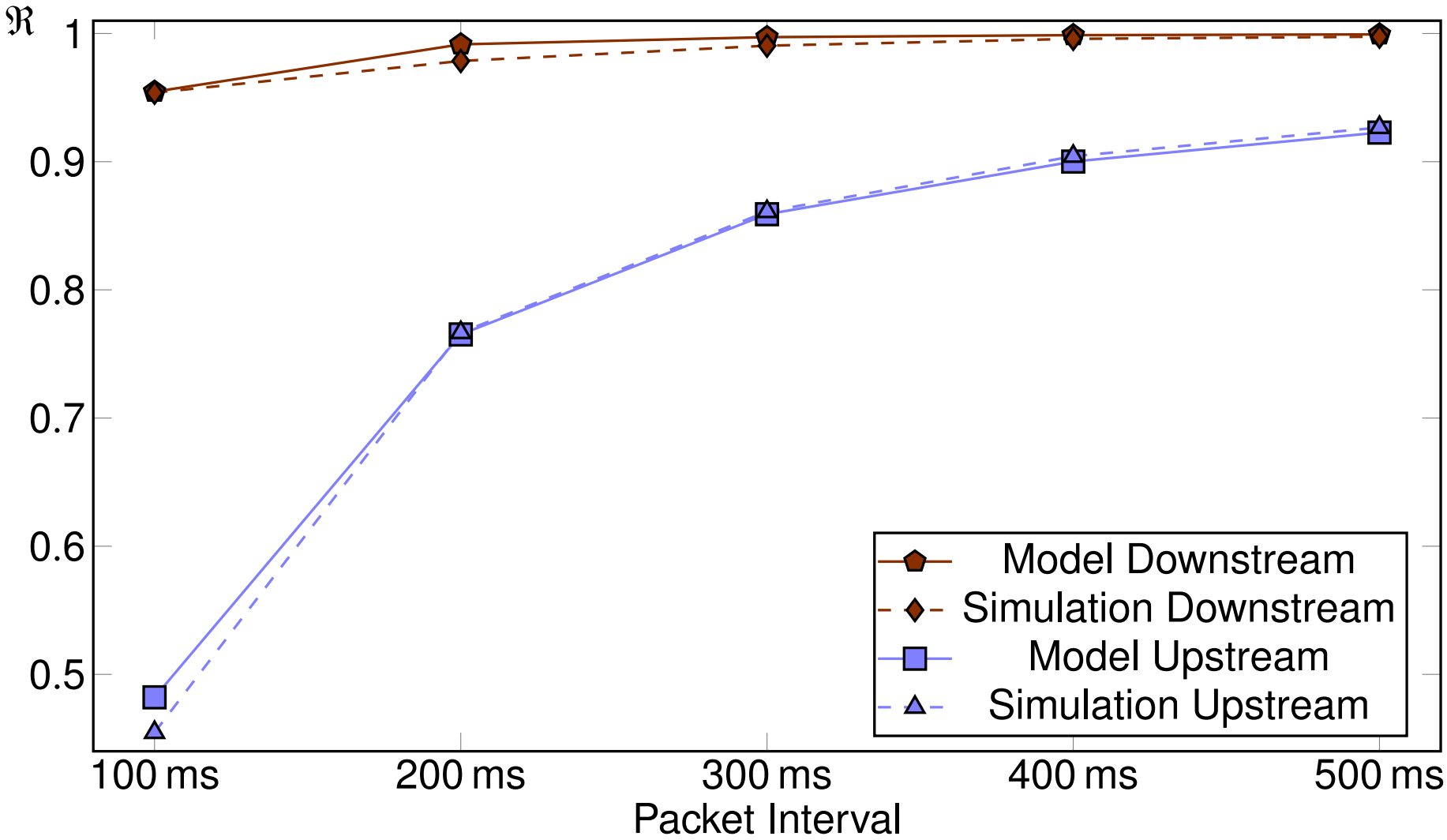
Data Flow



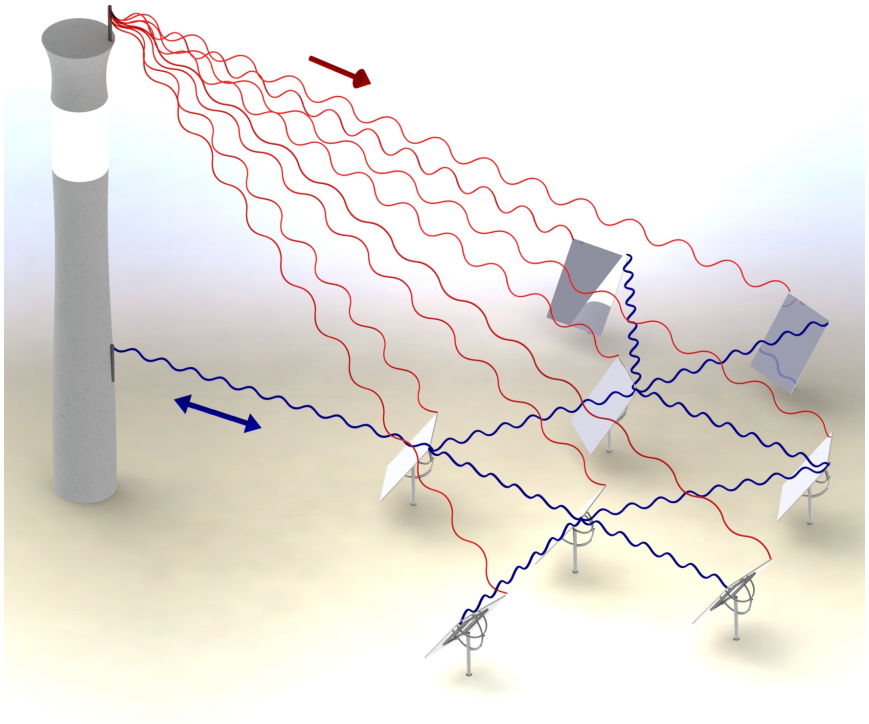
$$\lambda_c = \lambda_p \cdot \frac{1+2}{4} \cdot (1 - P_{coll}) \cdot \frac{1}{1+2}$$



Sending Interval

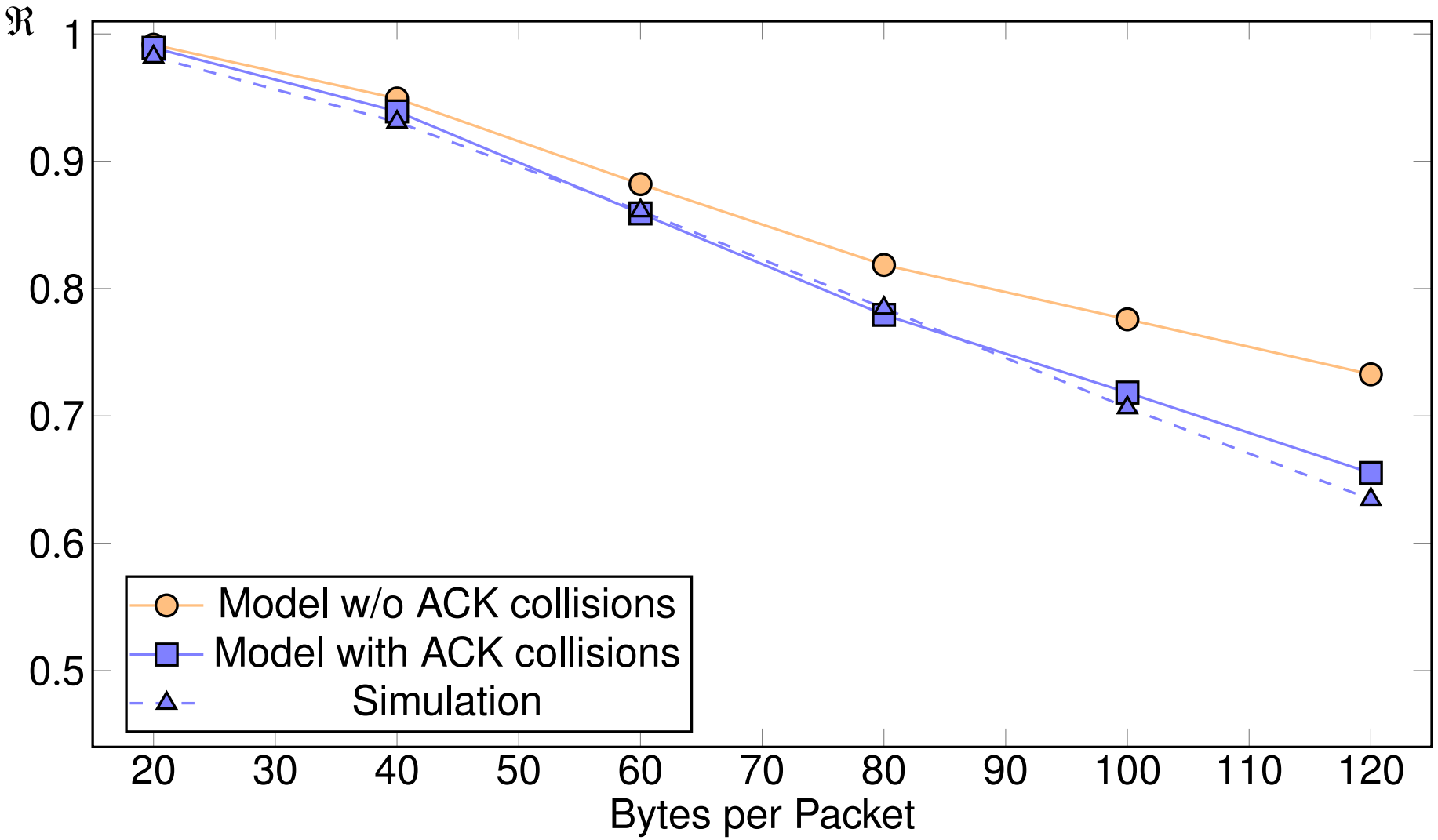


Two Wireless Channels

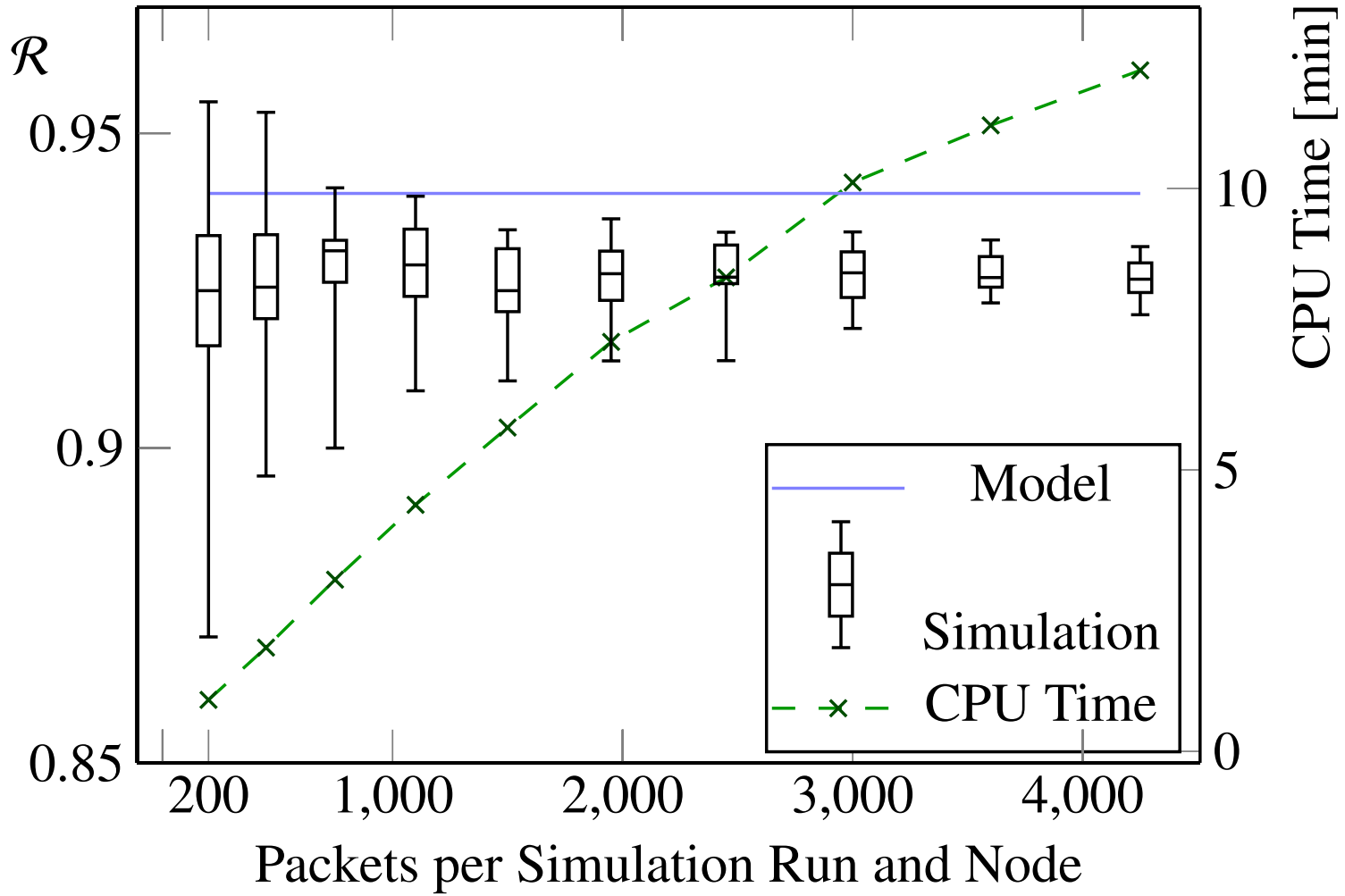


- Emergency Channel
  - ⊕ Long Range
  - ⊕ Reliable
  - ⊖ No Back Channel
- Wireless Mesh Network
  - ⊕ Inexpensive
  - ⊖/⊕ Short Range ($\rightarrow$ Mesh)
  - ⊖ Unreliable for High Data Rates

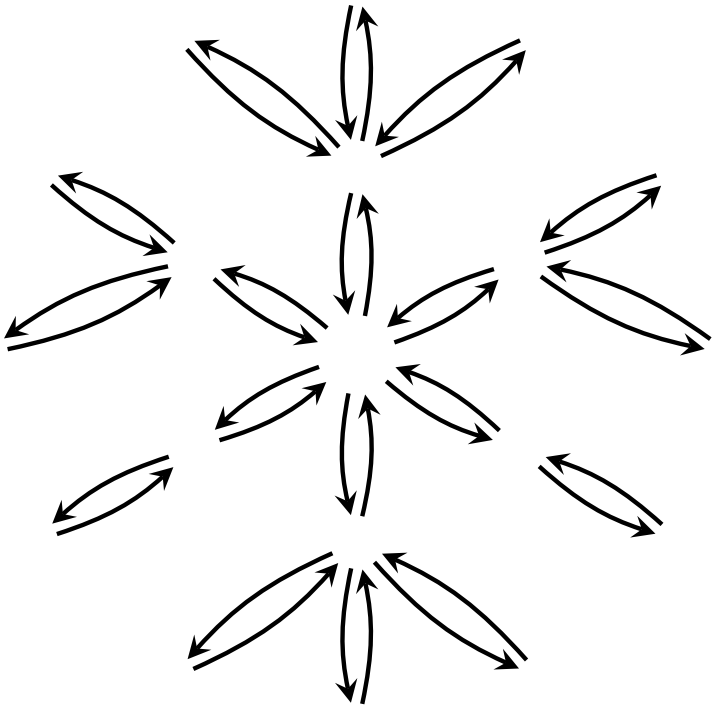
Acknowledgements



Number of Packets per Simulation



Link-Based Model

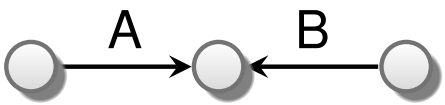


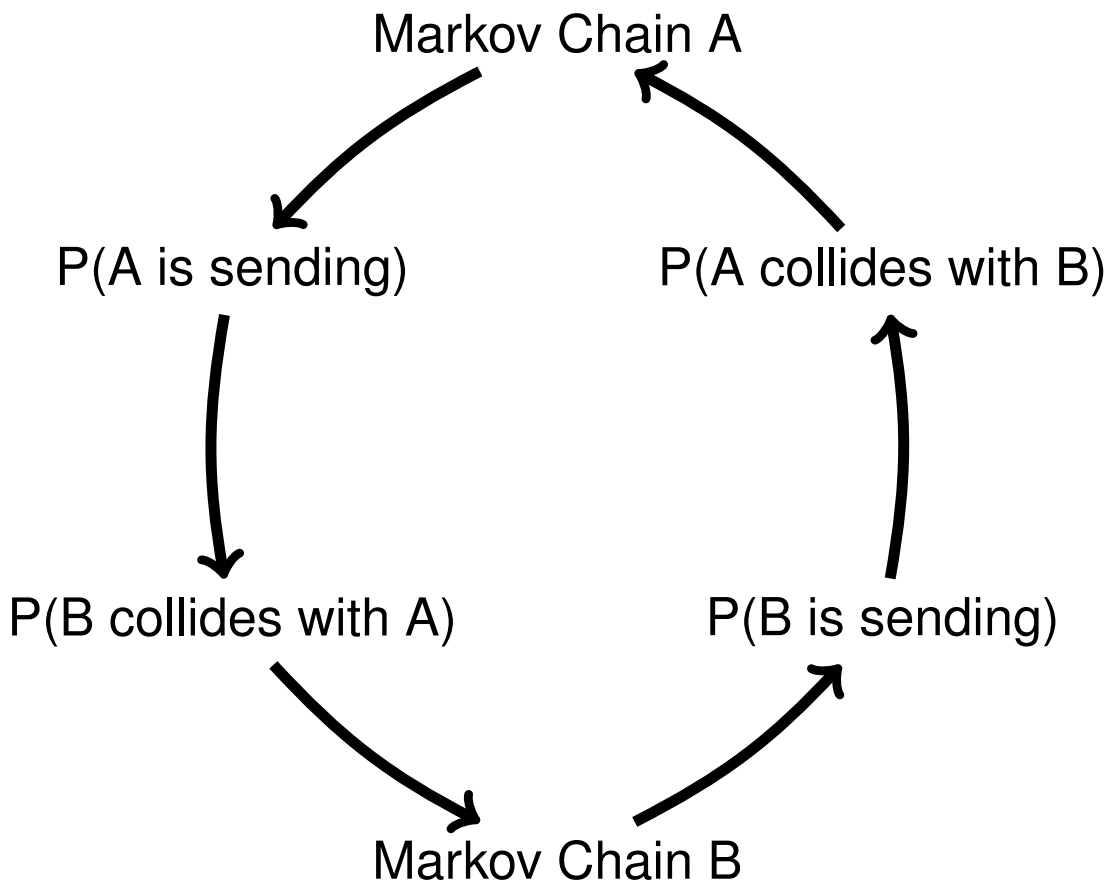
- Main entities: Links
- For example collision probablity per link, not per node
- Advantages
  - Easy implementation of multiple flows
  - More accurate modeling of packet collisions

Contributions

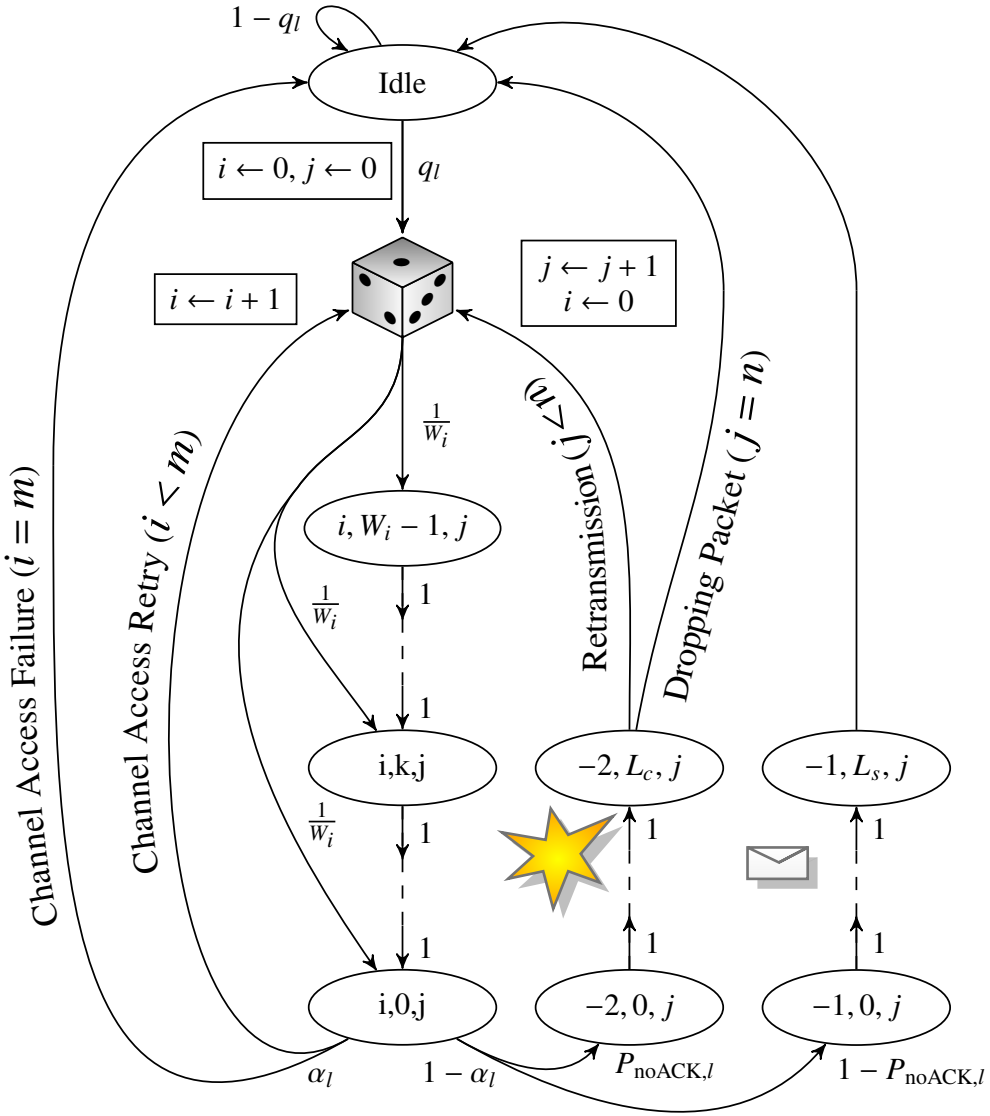
- Downstream traffic
- Collisions with acknowledgements
- Simultaneous retransmissions
- Enhancements for faster computation

Influence of Probabilities

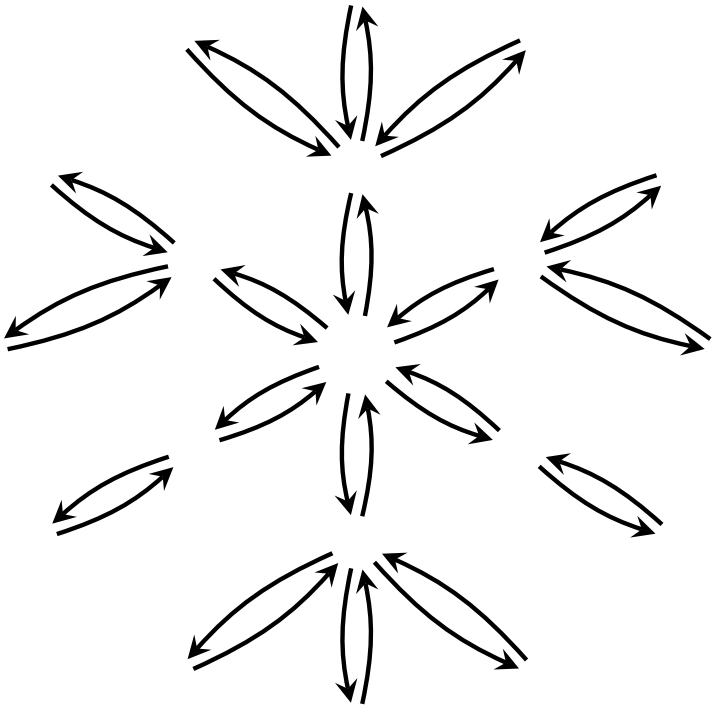




IEEE 802.15.4 MAC Layer



Scenario



- IEEE 802.15.4 mesh network
- Static routing tree
- Nodes $\rightarrow$ Gateway (upstream)
- Gateway $\rightarrow$ Nodes (downstream)
- Poisson packet generation
- Probability of packet arrival?