MobiCom 2005

Modeling Media Access in Embedded Two-Flow Topologies of Multi-hop Wireless Networks

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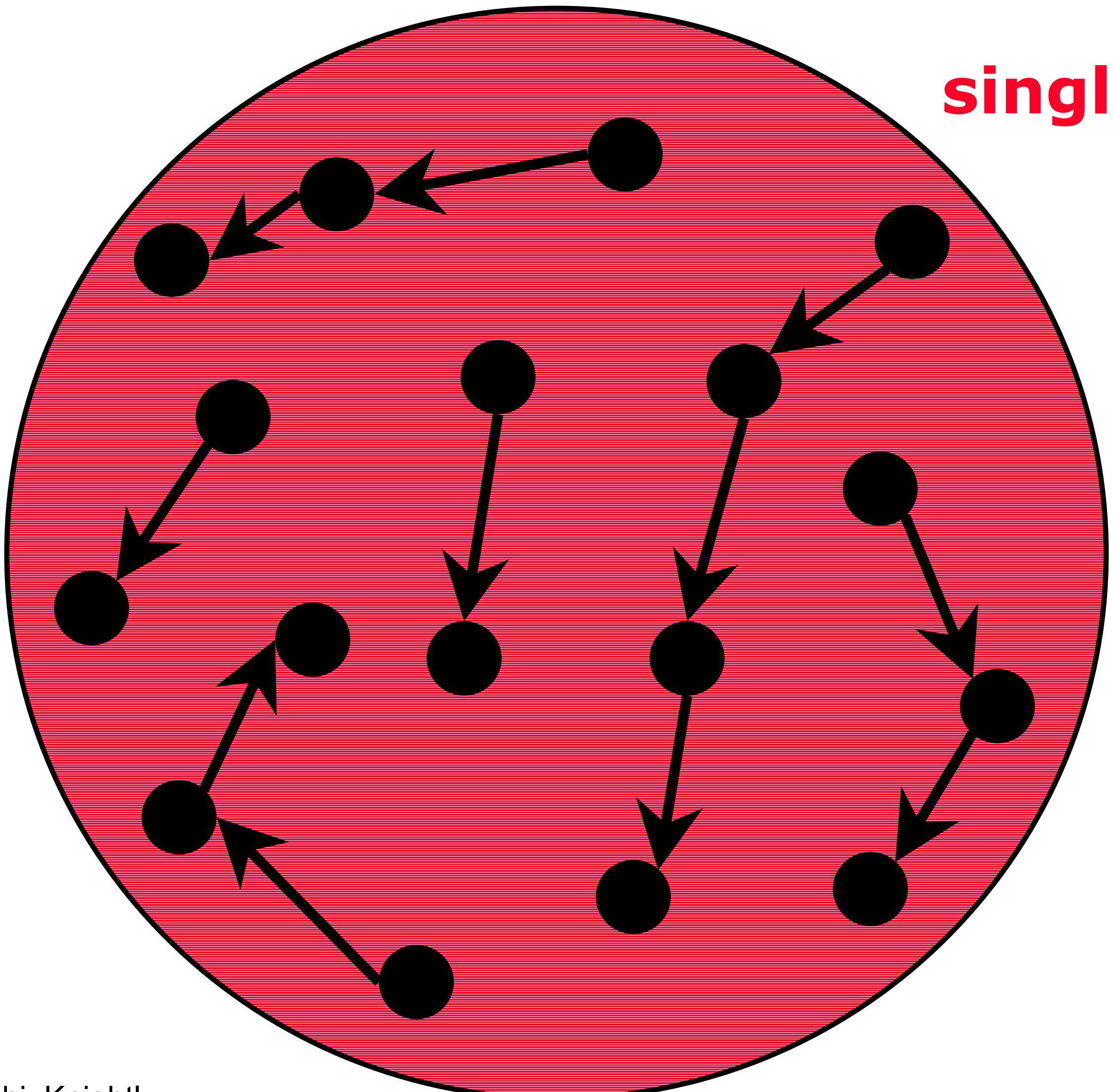
Motivation

- Multi-hop wireless networks with CSMA/CA protocols



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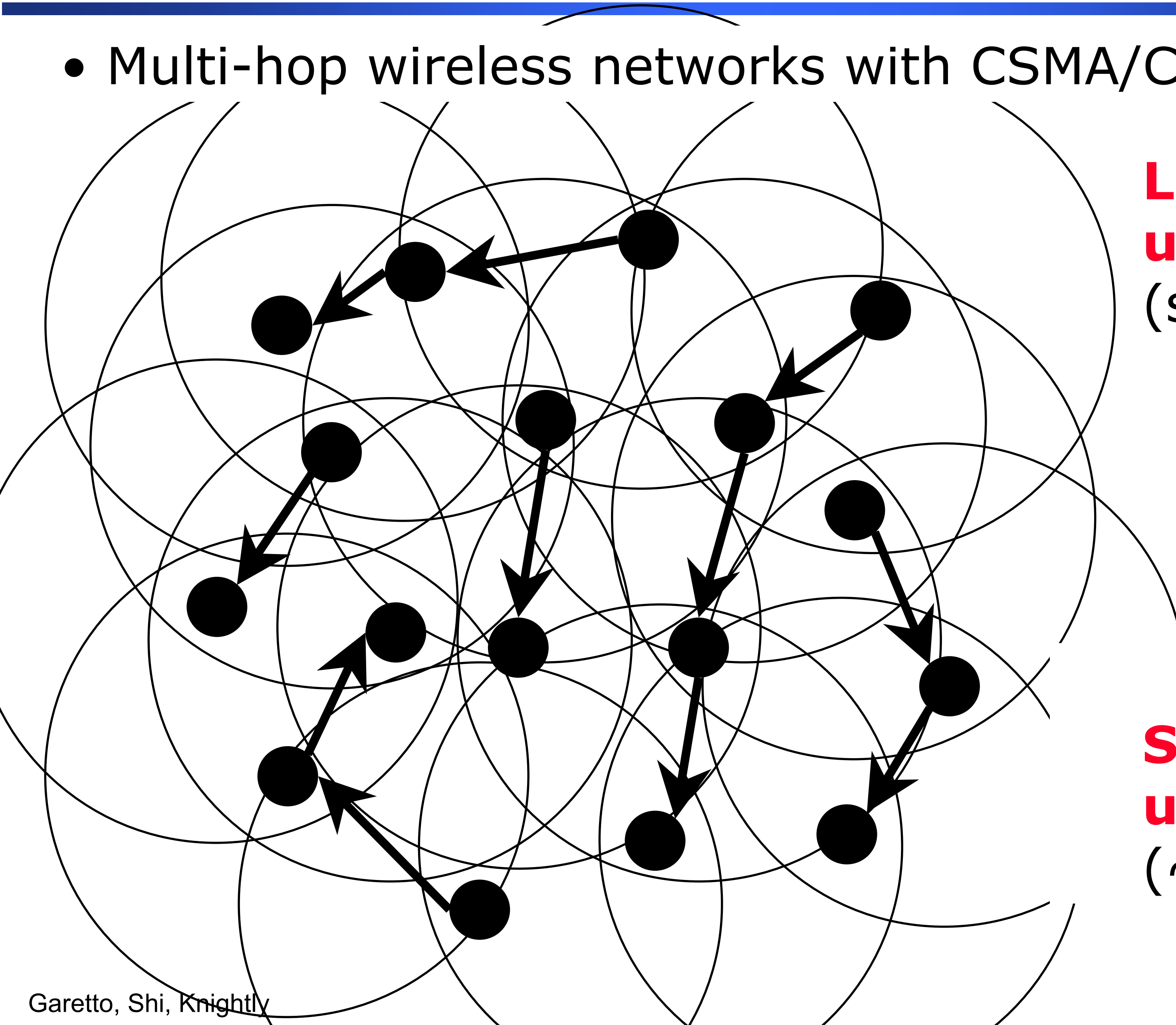

Long-term unfairness (starvation)

Short-term unfairness (~100 ms)

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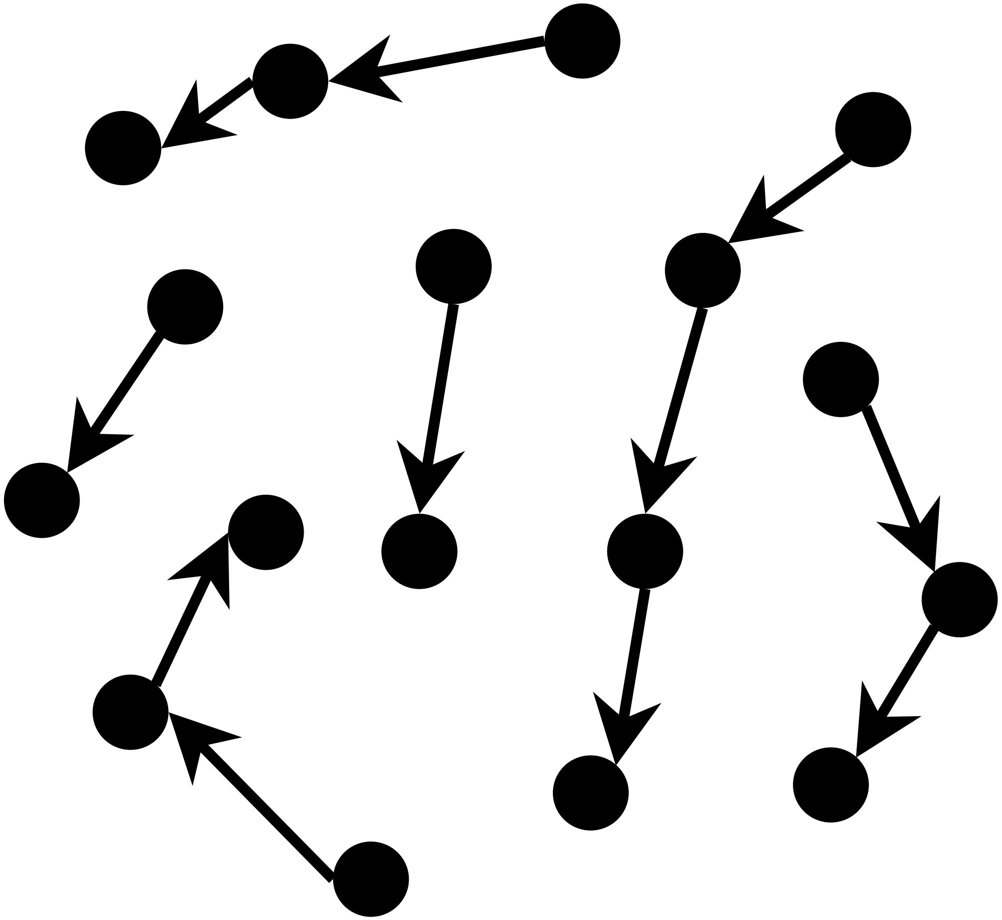
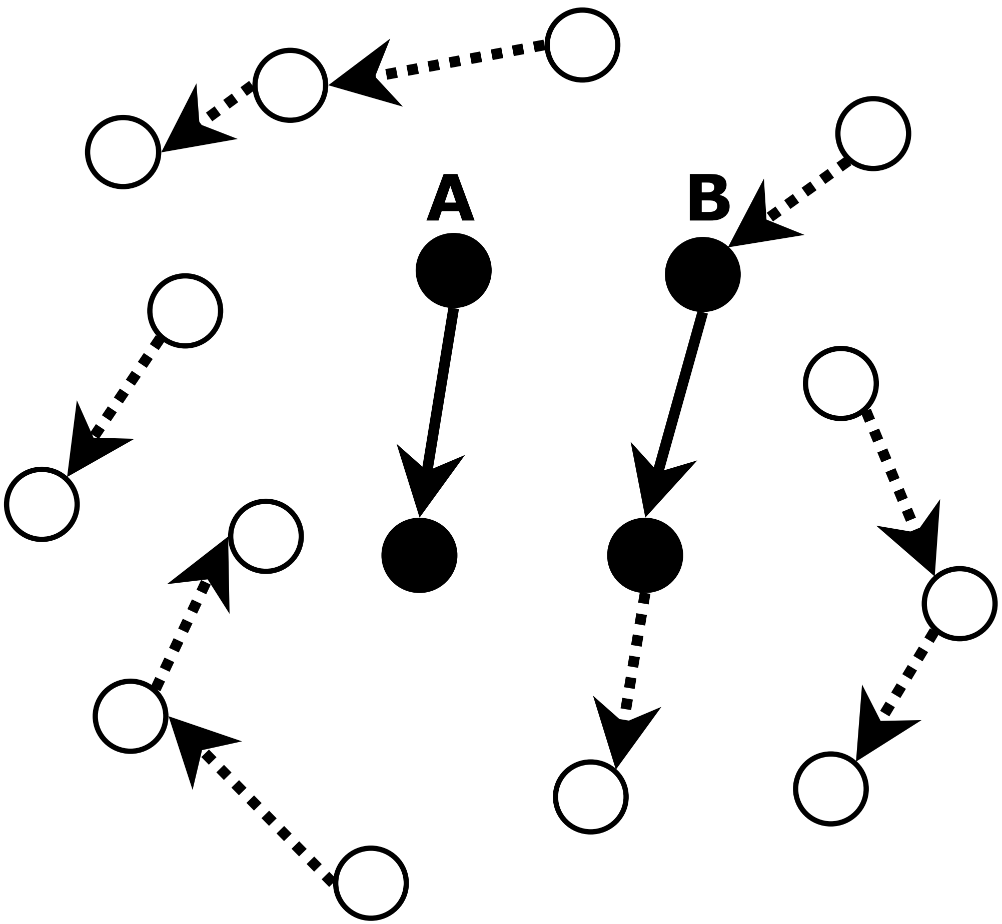


Motivation

- Multi-hop wireless networks with CSMA/CA protocols

2 contending link flows



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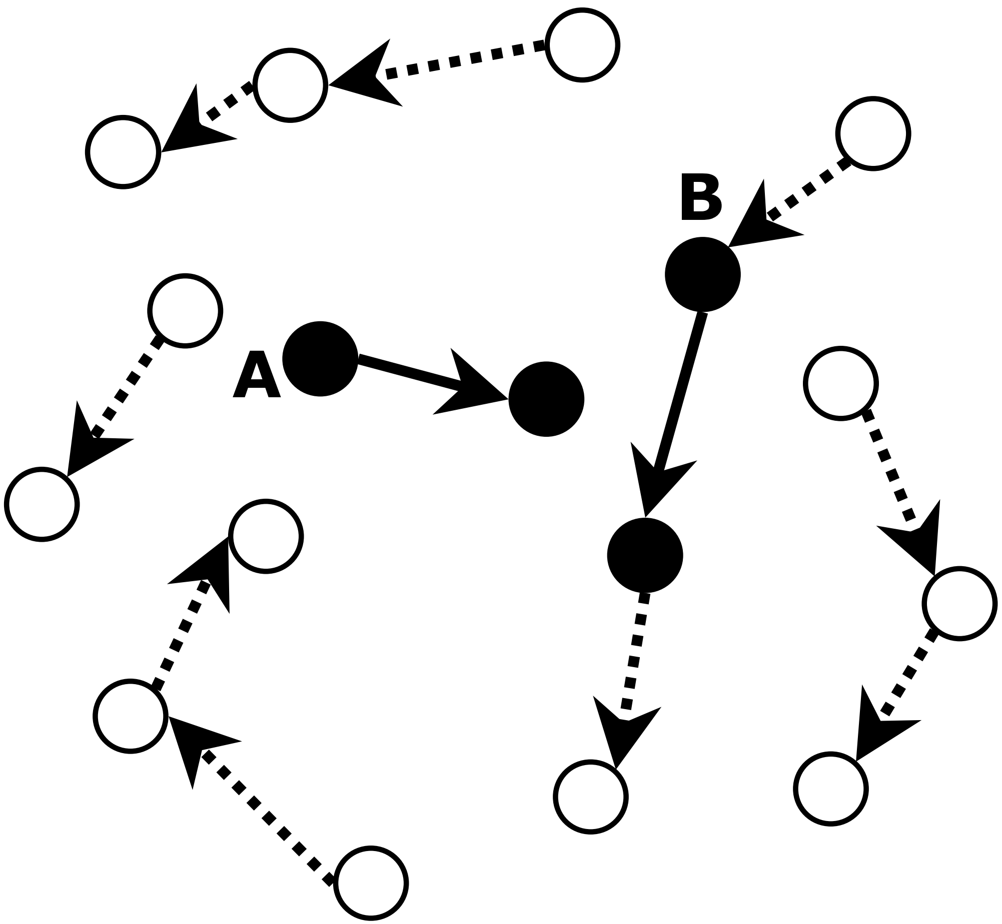
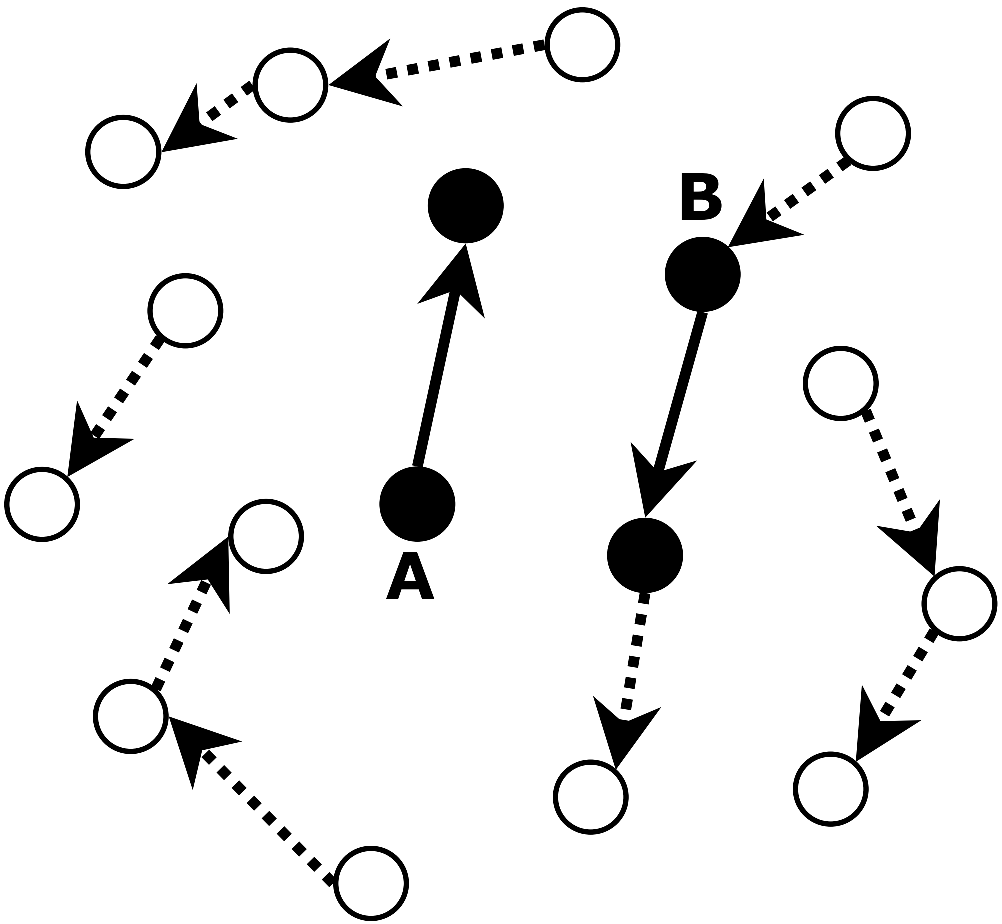
- Multi-hop wireless networks with CSMA/CA protocols



Long-term unfairness
(flow **A** starves)

Motivation

- Multi-hop wireless networks with CSMA/CA protocols



Short-term unfairness
(~100 ms)

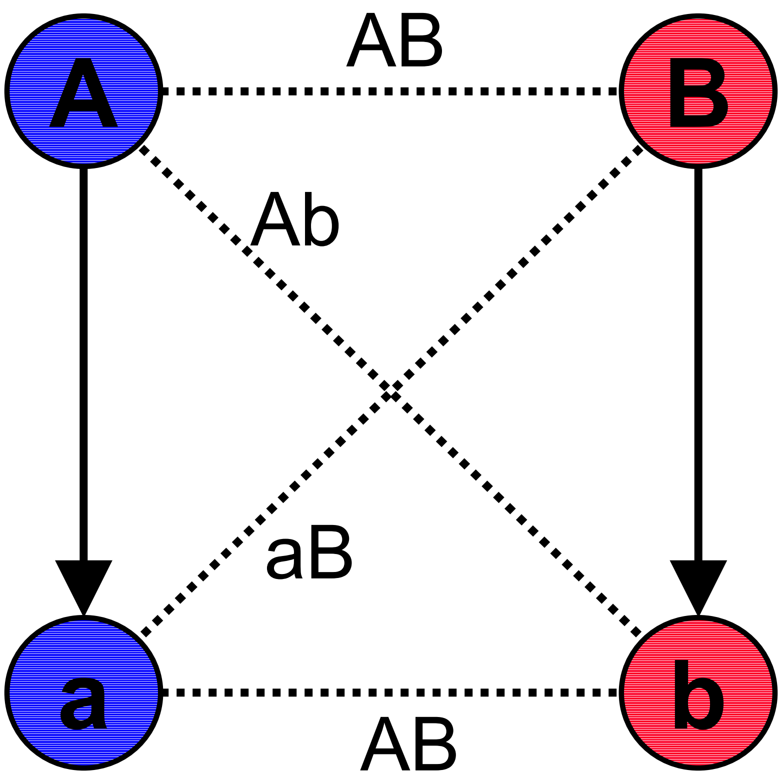
Motivation

- Multi-hop wireless networks employing CSMA/CA exhibit complex behavior and are difficult to analyze
  - Root cause: different and incomplete channel state information among flows
  - Most of existing modeling techniques only consider the single-hop case
- When stations are not all in radio range, severe unfairness can occur among flows:
  - Long-term unfairness and starvation
  - Short-term unfairness

Our contributions

- We decompose a large-scale network into embedded 2-flow subgraphs
- We identify all possible 2-flow scenarios and classify them
- Spatial analysis: we compute the occurrence probability of each scenario under random nodes deployment
- We accurately predict the performance of random access in all cases, quantifying long-term and short-term unfairness

Basic two-flow, four-node layout



- Senders **A, B**
- Receivers **a, b**
- **A-a, B-b** must be connected (= in radio range)

- Nodes from one flow may hear nodes from the other
- Four possible connections that can exist – or not

- $2^4 = 16$ combinations
- Ab, Ba interchangeable
  → 4 redundant scenarios

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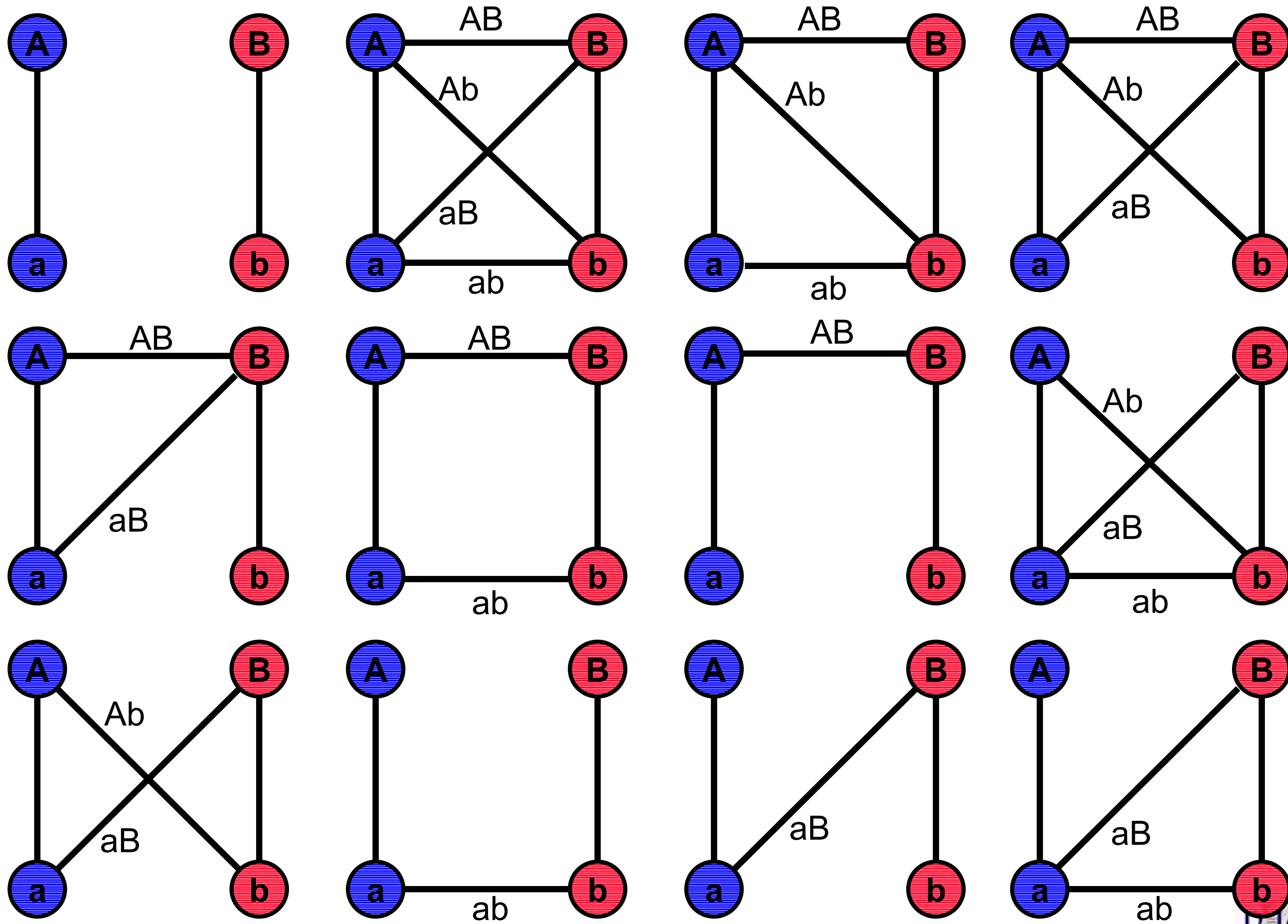
Twelve possible scenarios



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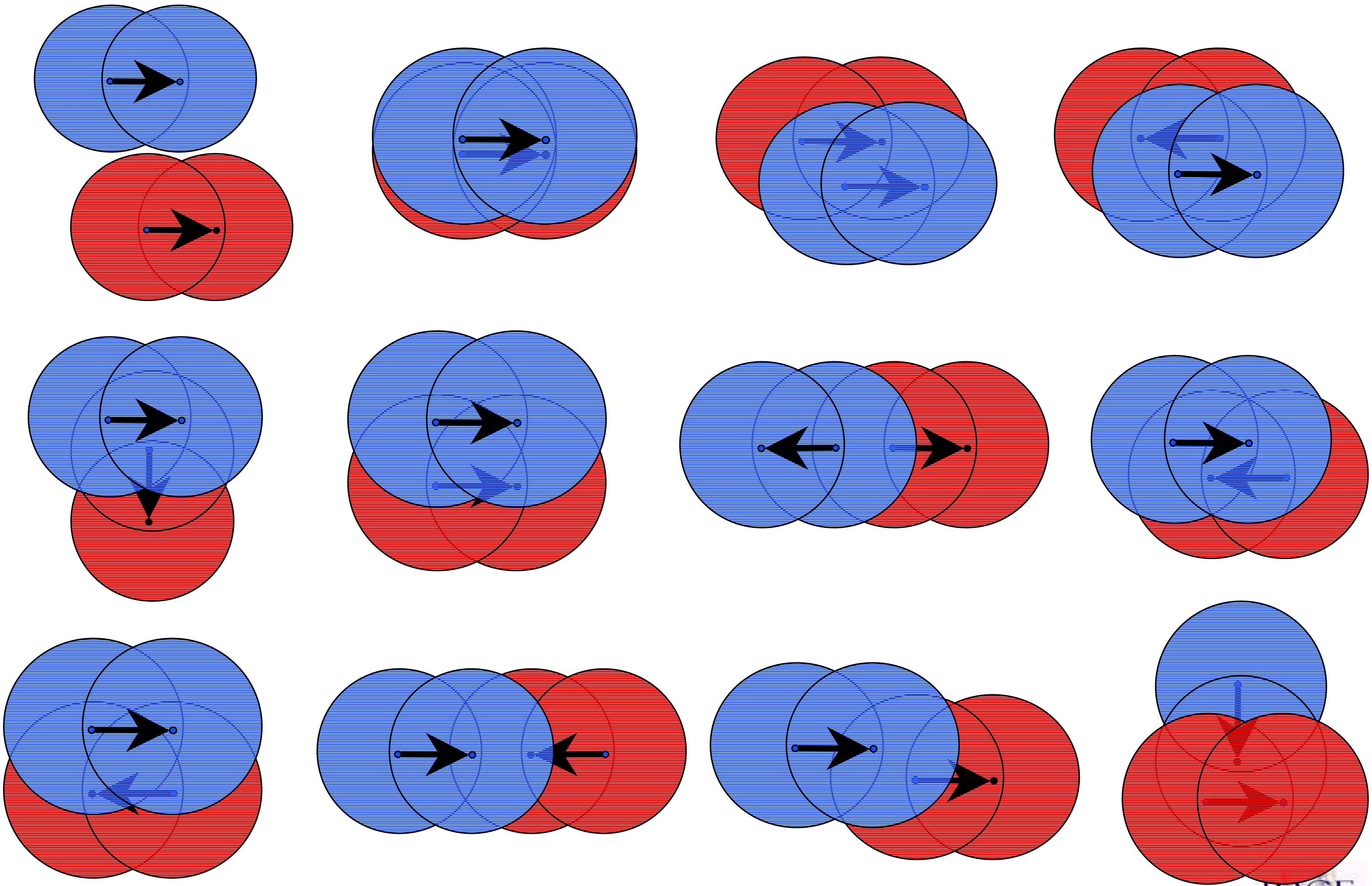
Example topologies



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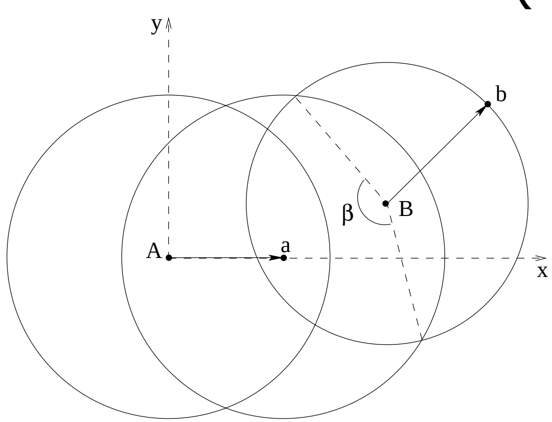
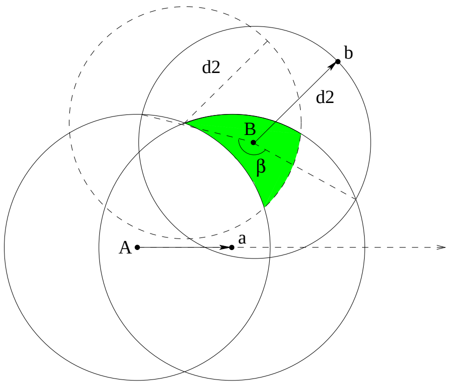
Spatial analysis

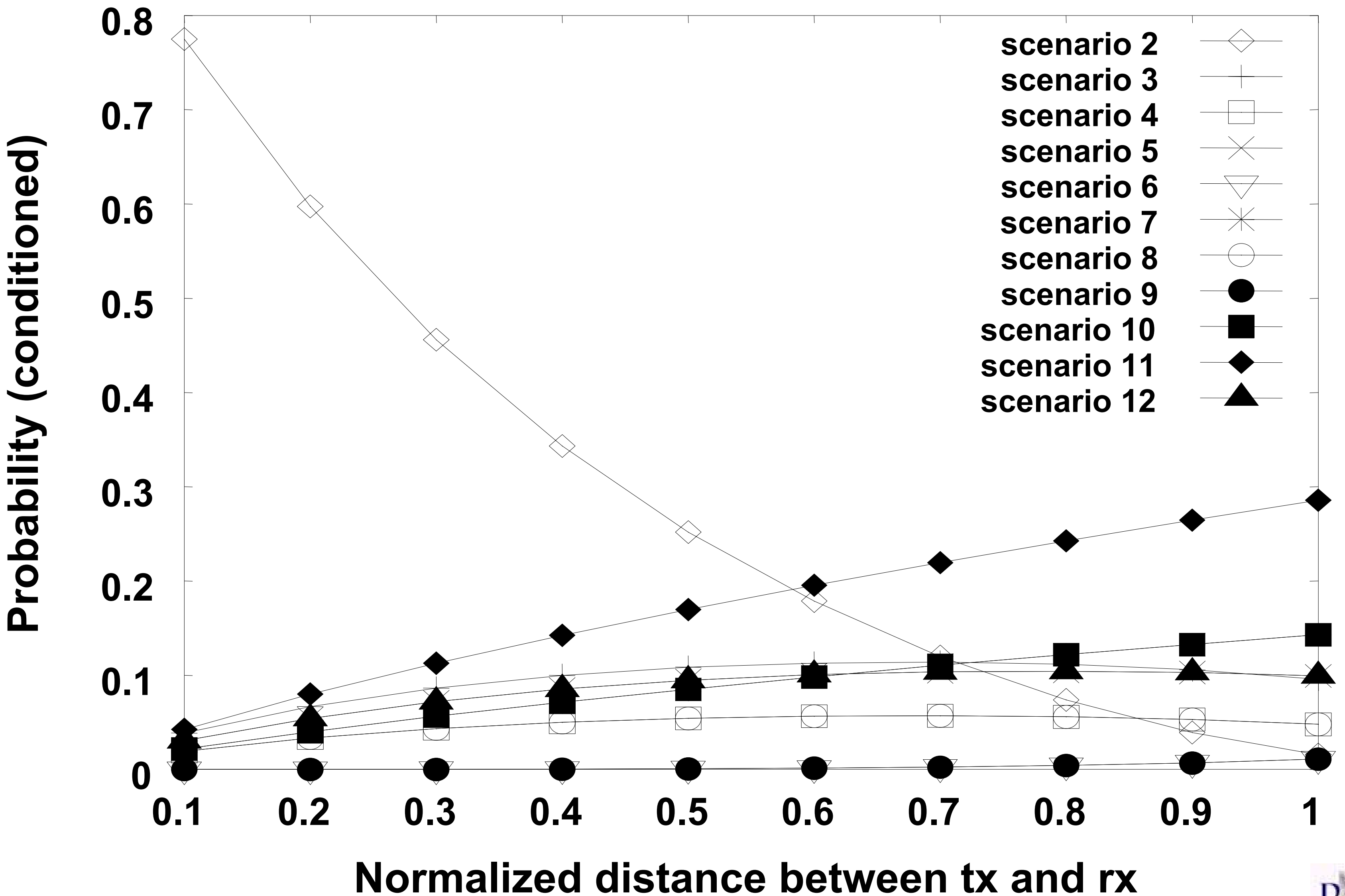
- We compute the **occurrence probability** of each scenario
- We assume nodes **uniformly** distributed in the area with **equal radio range**
- We discard the case in which flows are completely isolated from each other → **normalized probabilities**
  - insensitive to node density
  - insensitive to area size (no border effects)





$$p_{11} = \int_0^r \int_0^r \int_{\frac{d_1}{2}}^{r+d_1} \int_{f_1(d_1,x_B)}^{f_2(d_1,x_B)} 2 \times p'_{11} \, \mathrm{d}(y_B) \, \mathrm{d}(x_B) \, g(d_2) \, \mathrm{d}(d_2) \, g(d_1) \, \mathrm{d}(d_1)$$

Scenario Likelihood



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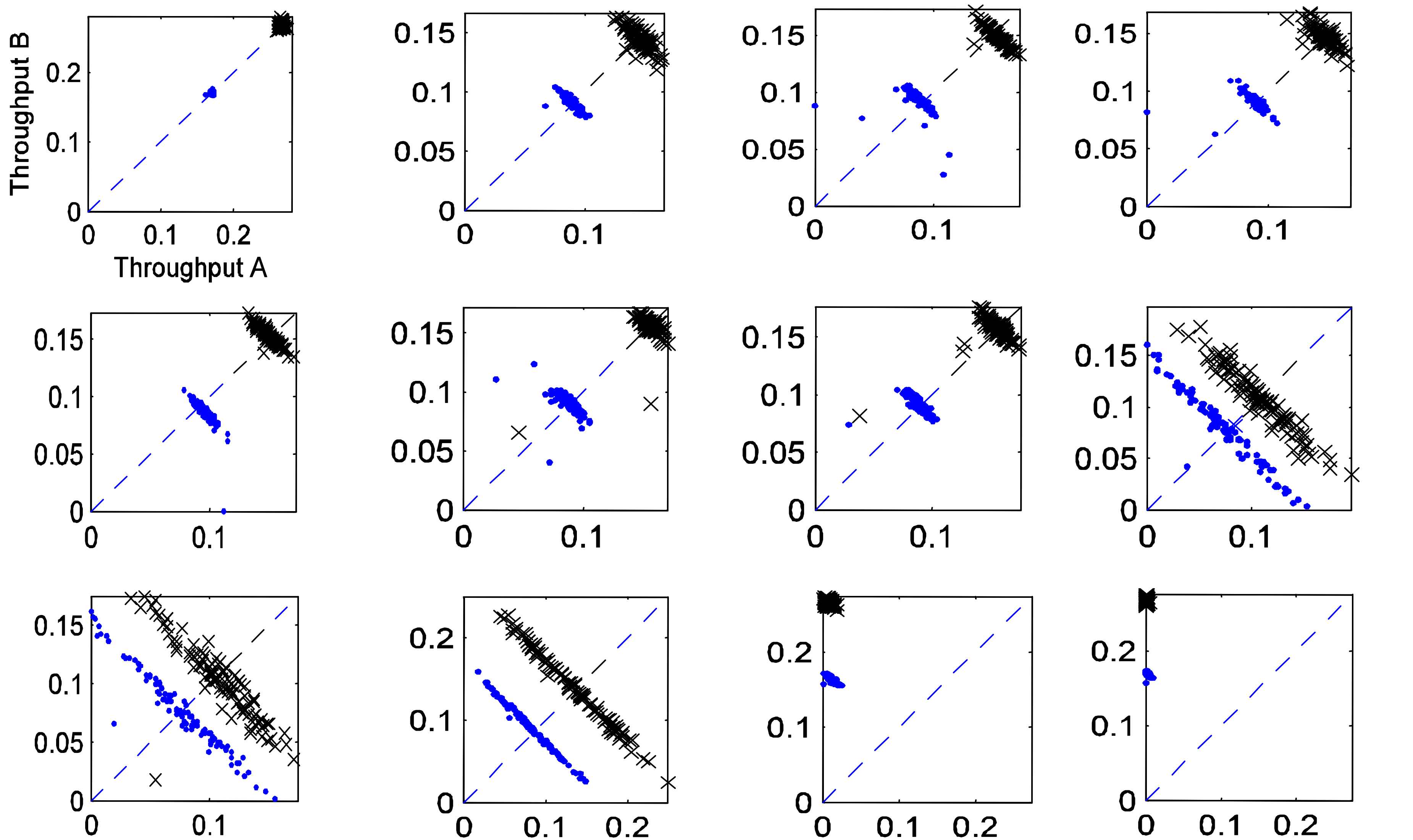
Performance simulations with CSMA/CA protocol

Throughput measurements every 400 ms

X = two-way handshake
• = four-way handshake



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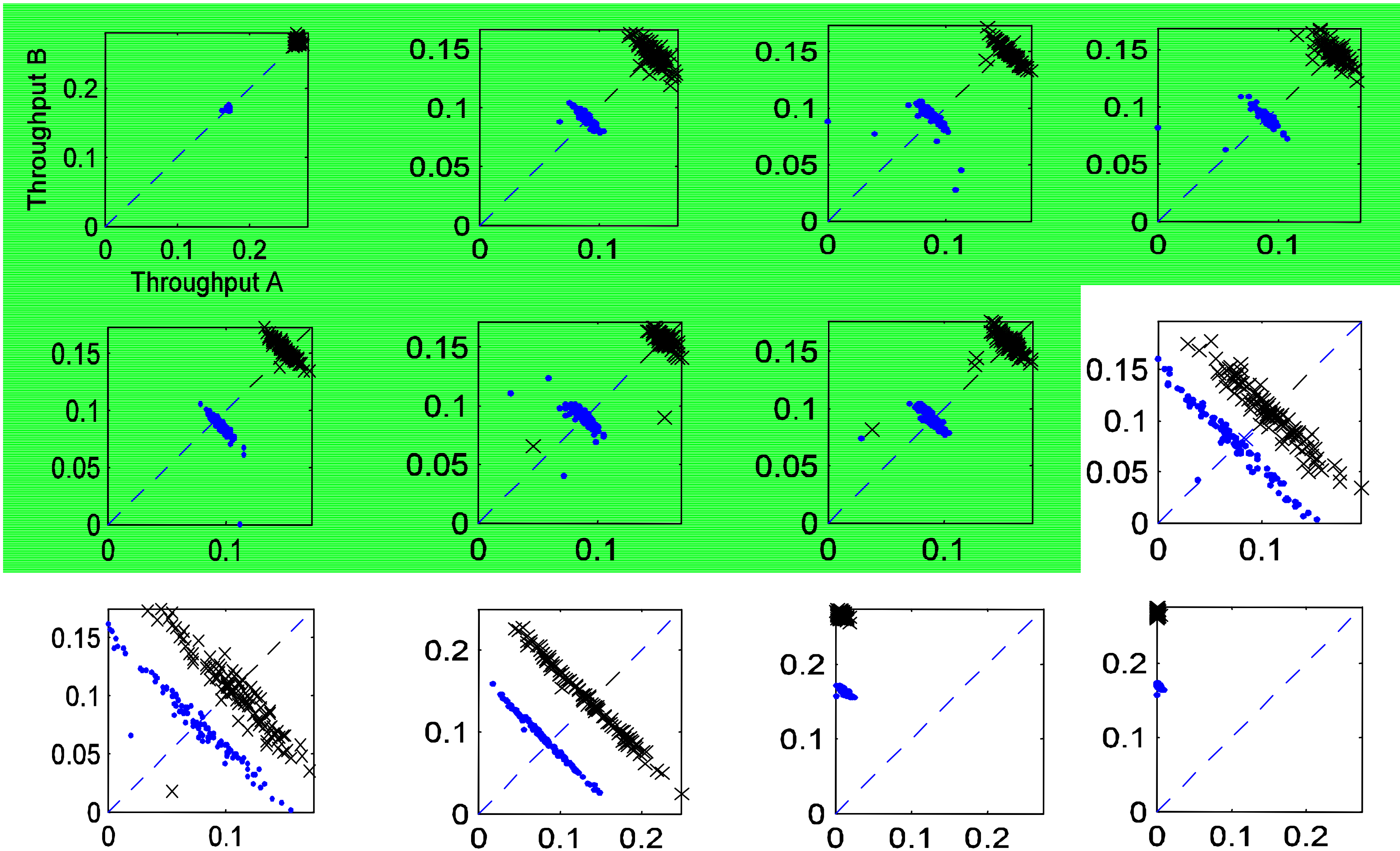

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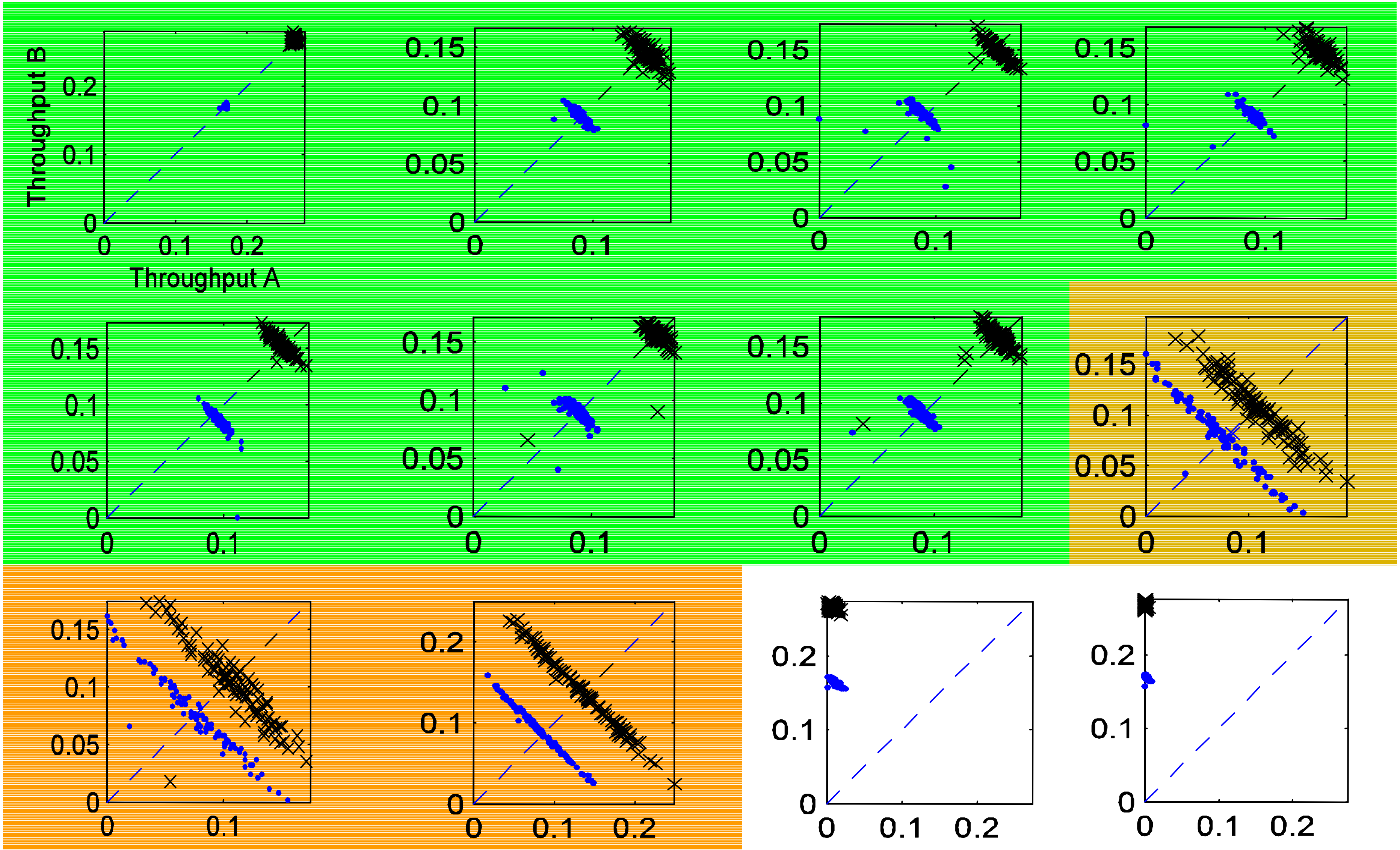

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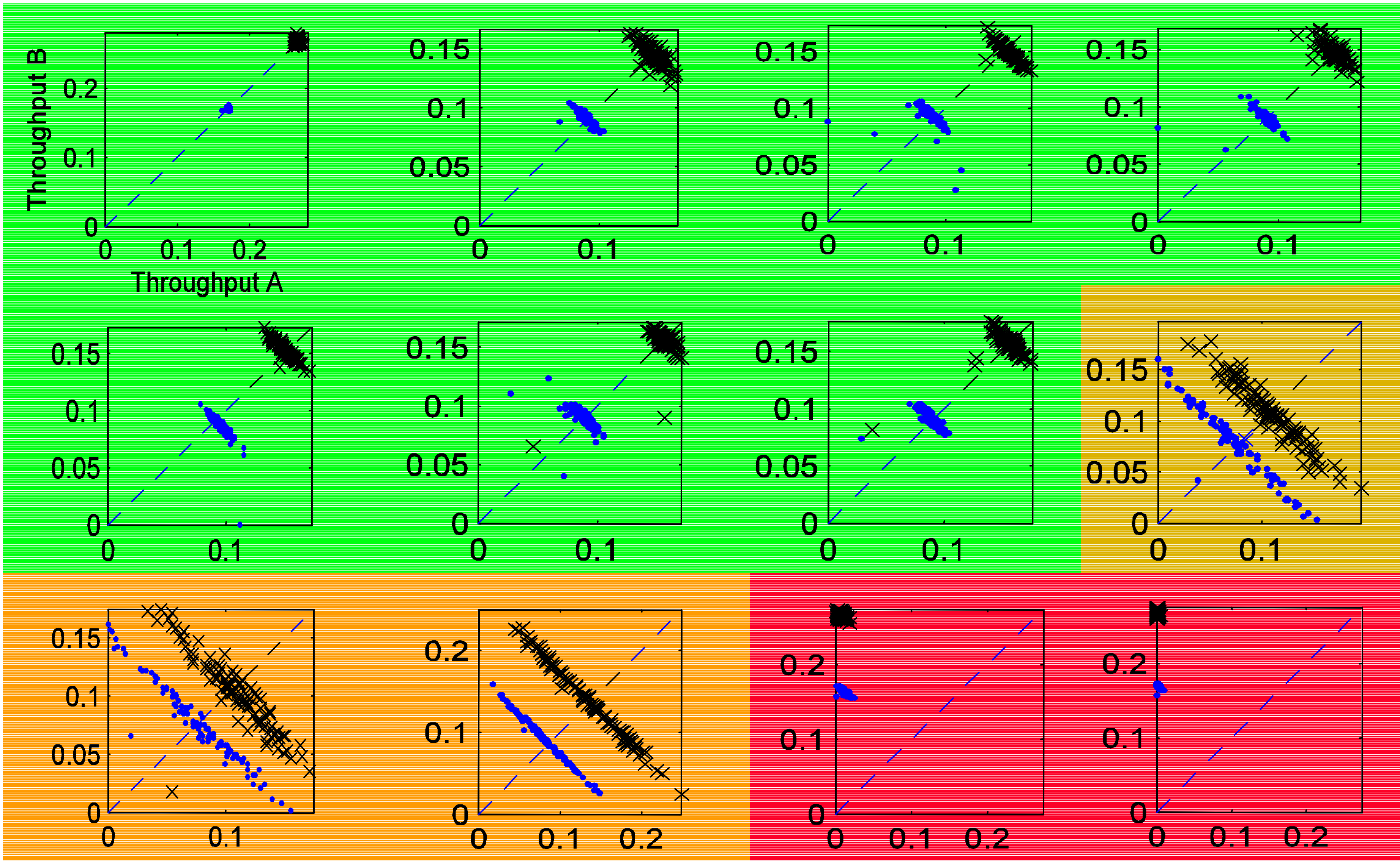
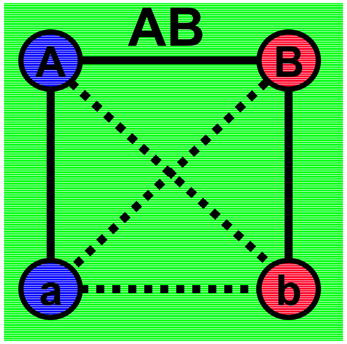
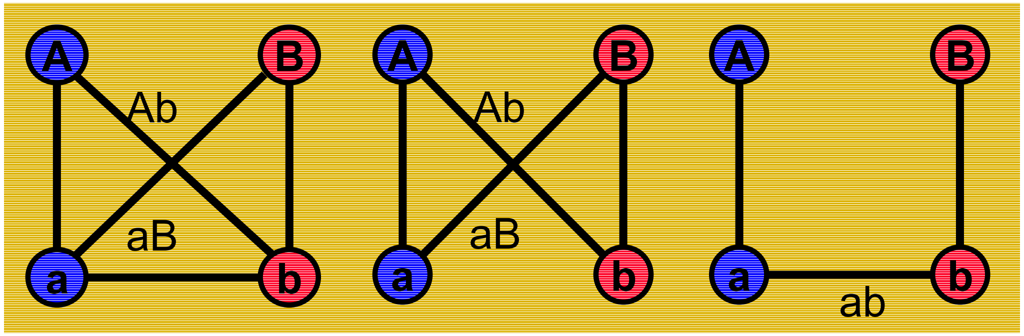


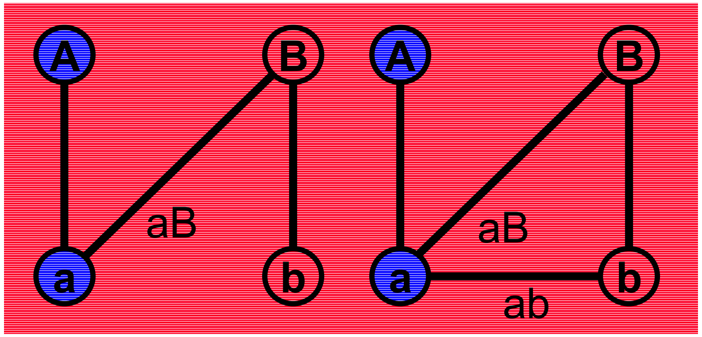
Scenarios classification : 3 groups



⇨ Senders Connected (**SC**)



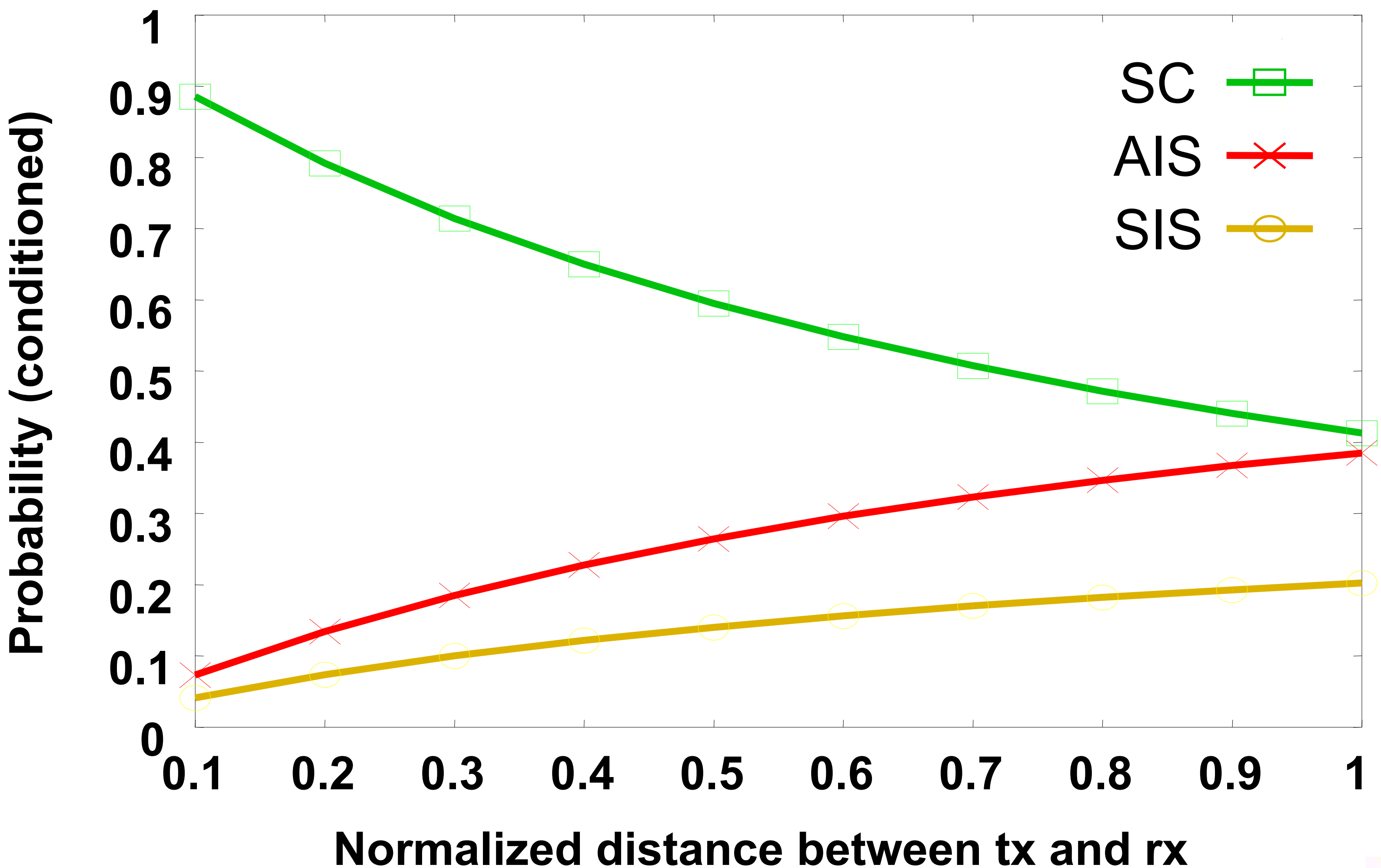
⇨ Symmetric Incomplete State (**SIS**)



⇨ Asymmetric Incomplete State (**AIS**)

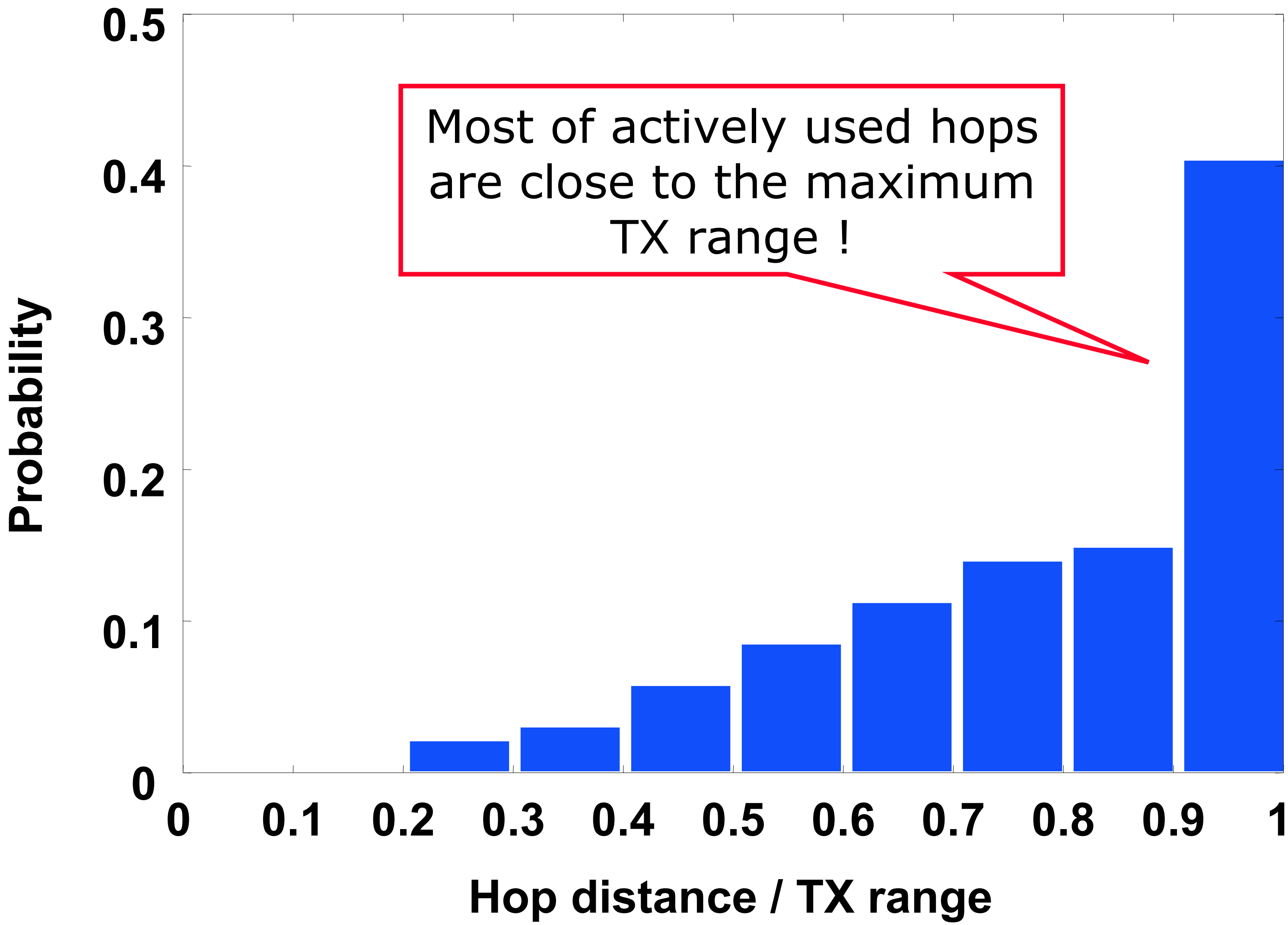
Probabilities of 3 groups of scenarios

- Problematic scenarios are highly likely to occur !



Hop distance distribution in a multi-hop network

300 nodes - 2000 m x 2000 m – Random waypoint – DSDV



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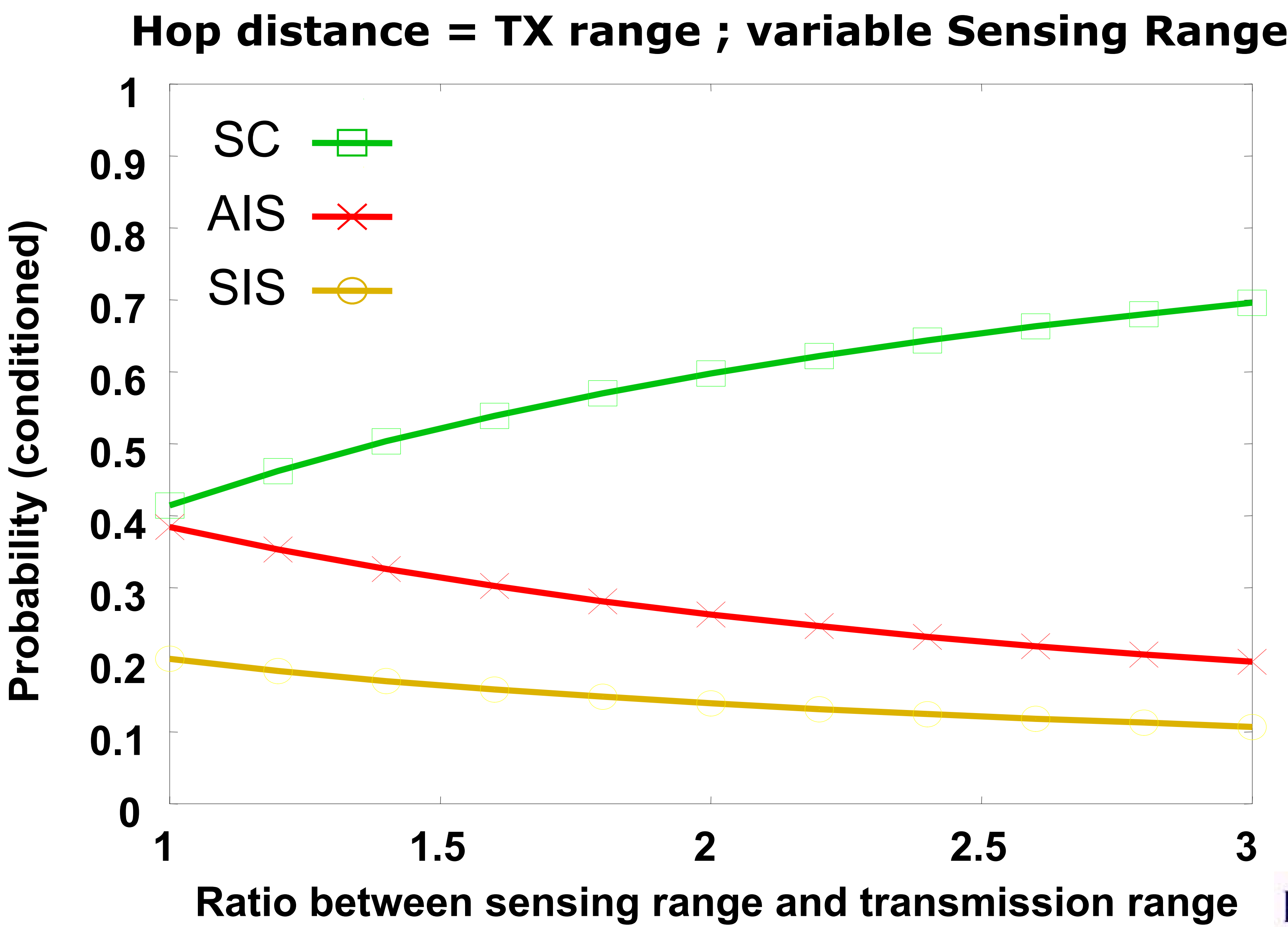
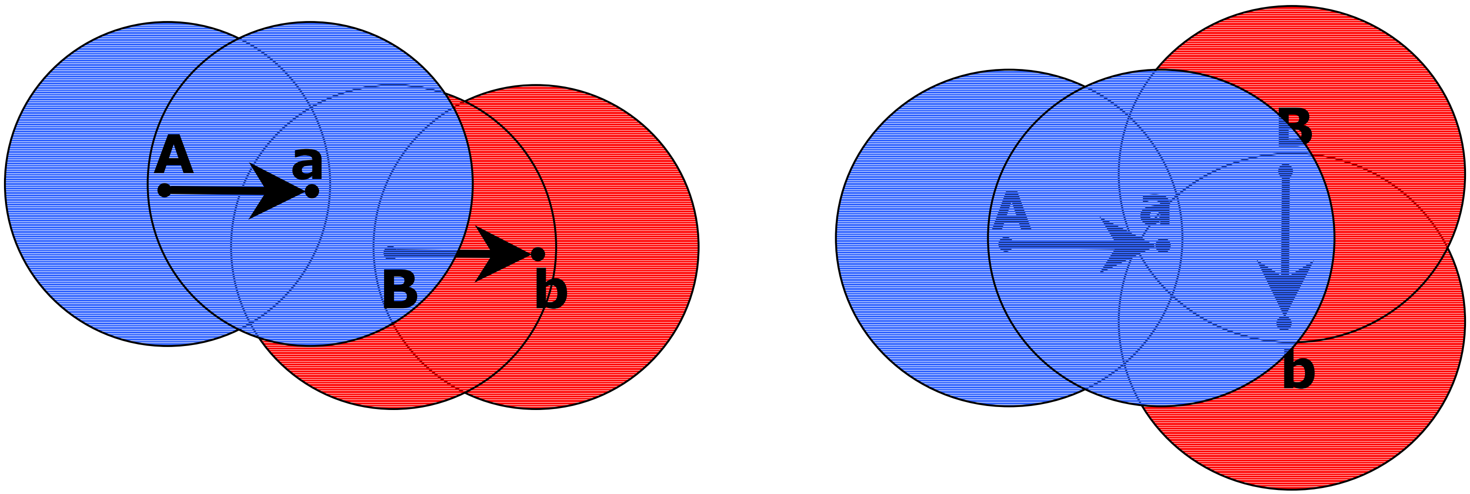


Analysis of Asimmetric Incomplete State scenarios (AIS)



- Known to be highly problematic for random access protocols: flow **A→ a** starves
  - V. Bharghavan, A. J. Demers, S. Shenker, L. Zhang, MACAW: A Media Access Protocol for Wireless LAN's, SIGCOMM '94
- RTS/CTS does not solve the problem
- RRTS does not help
- Not yet modeled analytically

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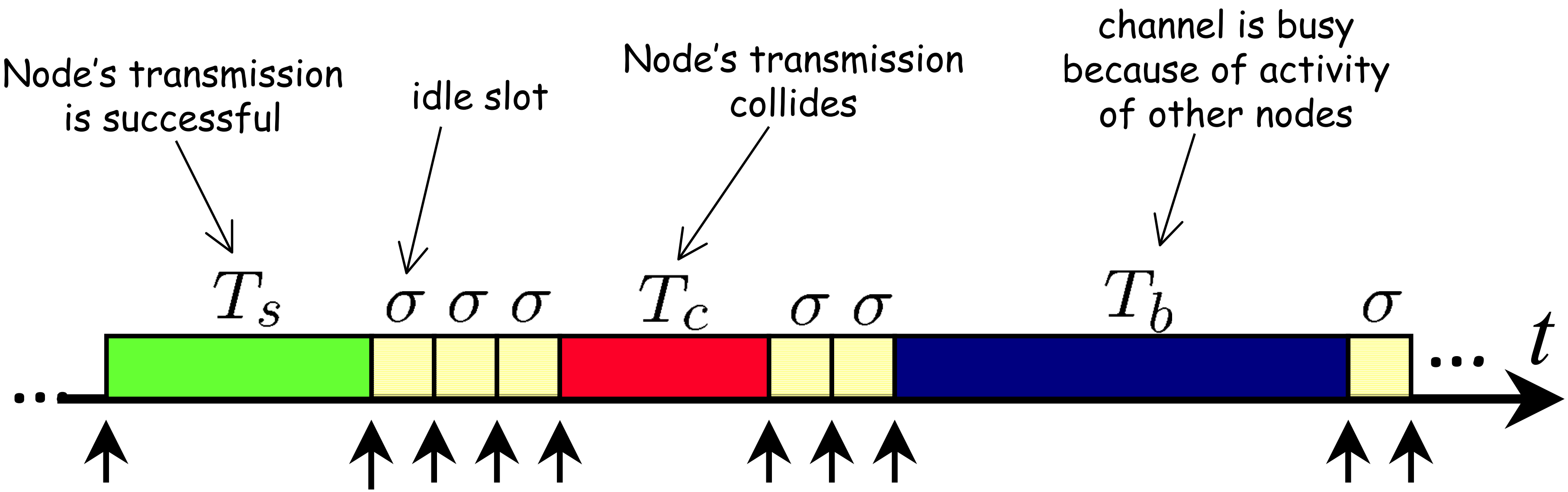
Decoupling technique (valid for general topologies)

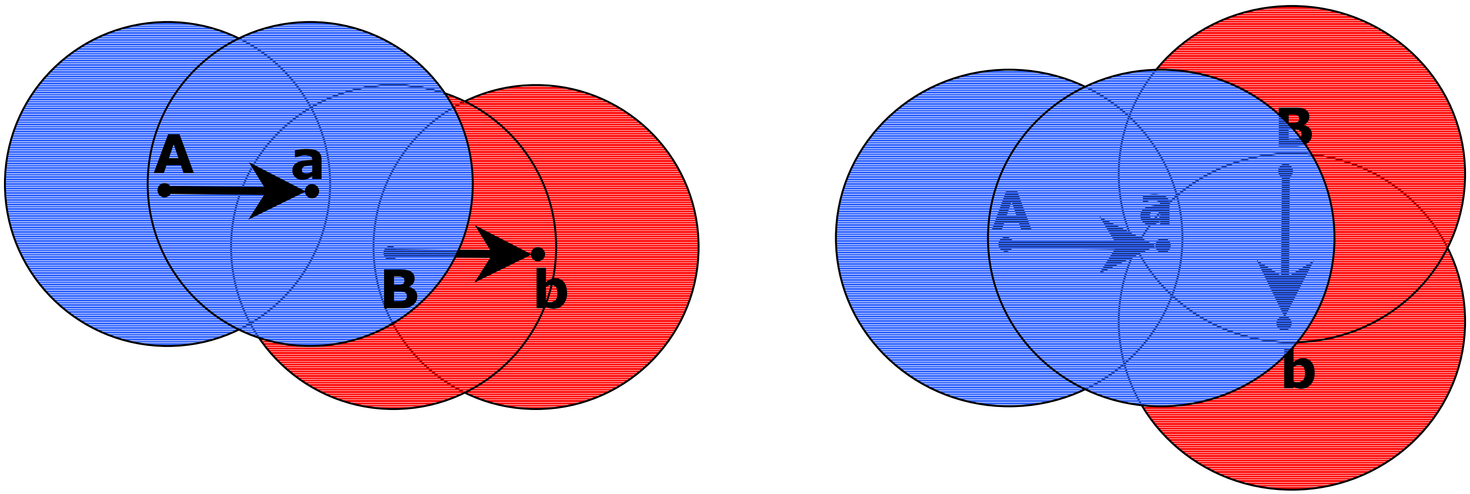
- The channel "private view" of a node:



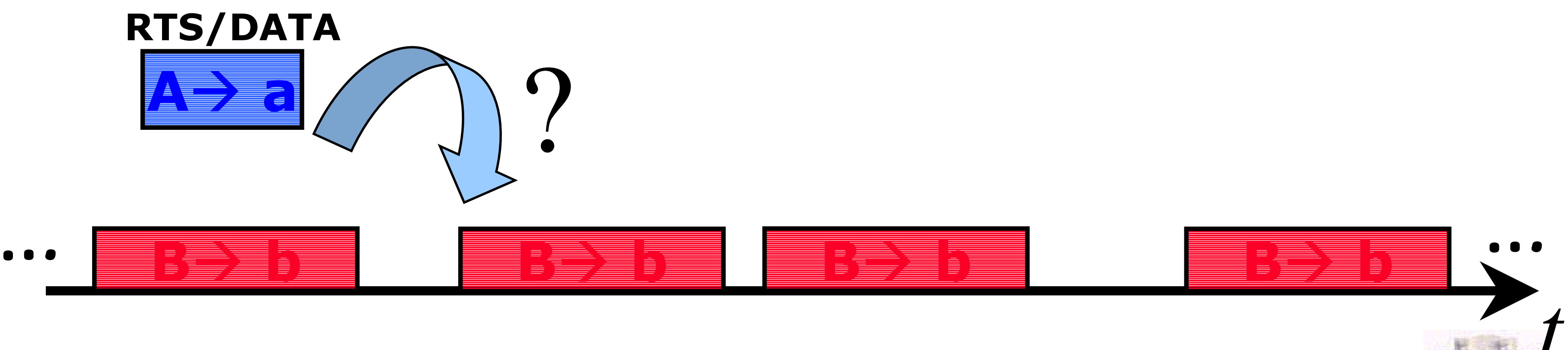
- Modelled as a renewal-reward process

$$\textbf{Throughput (pkt/s)} = \frac{\textbf{P [event } T_s \textbf{ occurs]}}{\textbf{Average duration of an event (s)}}$$

Analysis of Asymmetric Incomplete State scenarios (AIS)



- Flow **A→ a** does not know when to contend: it has to discover an available gap in the activity of flow **B→ b** randomly, where to place an entire RTS or DATA packet



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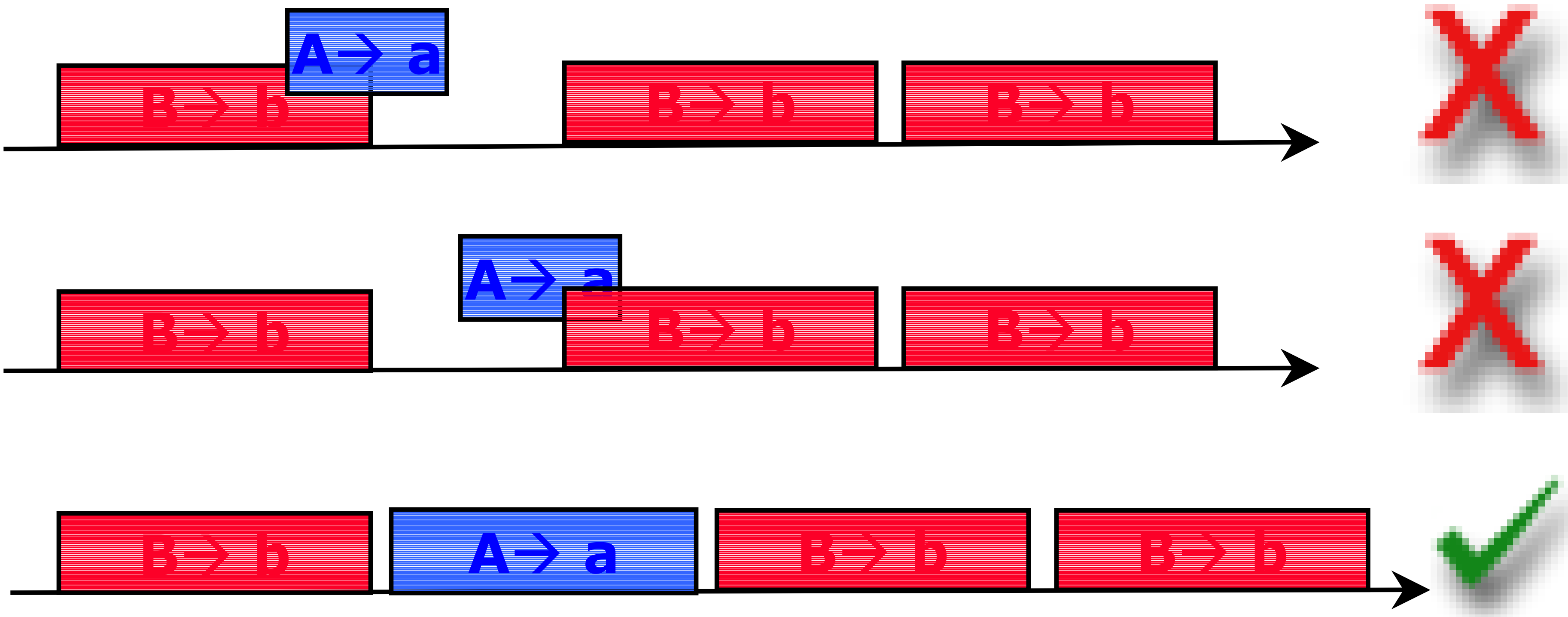
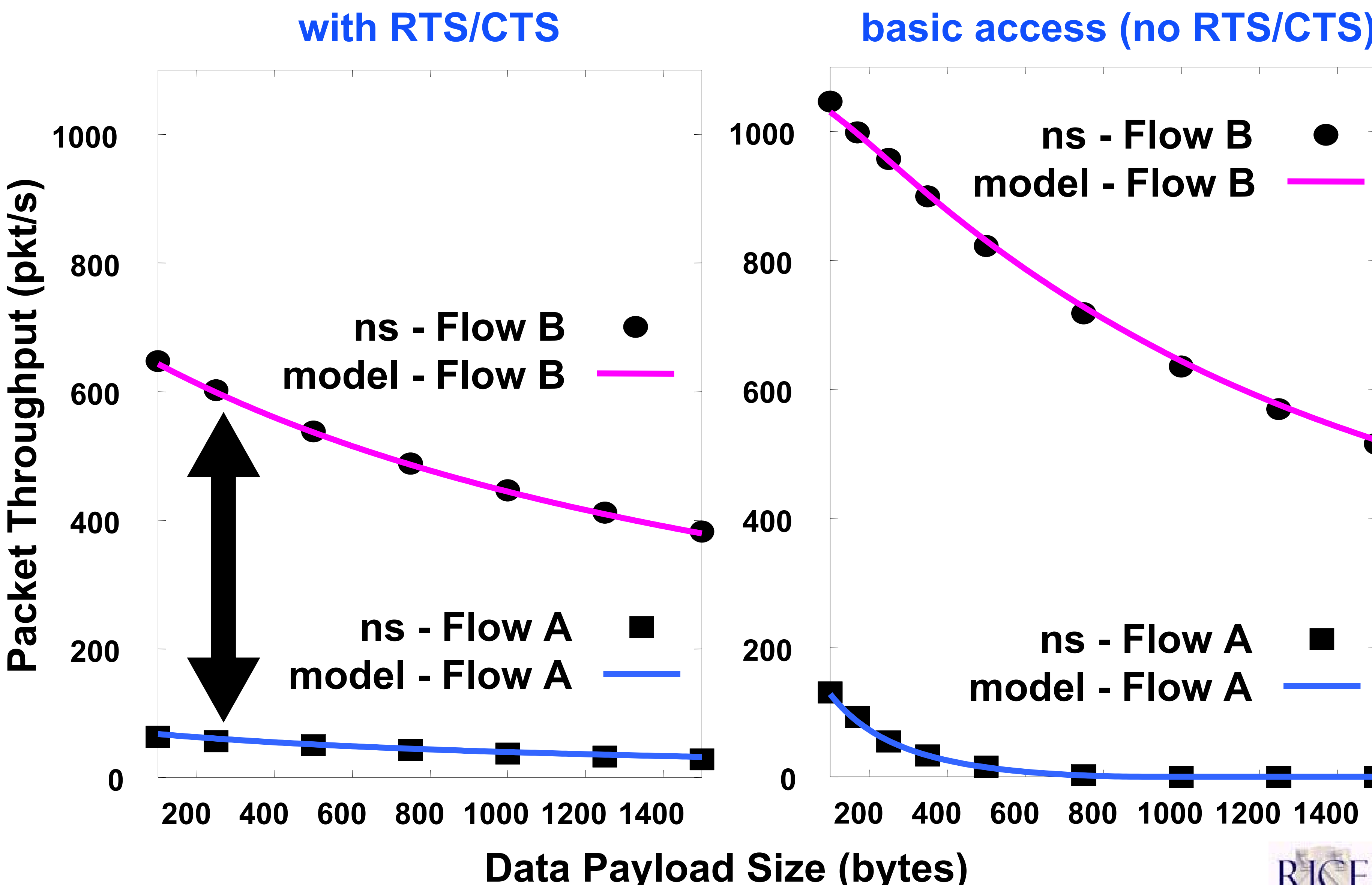


- The collision probability of flow **A→ a** can be accurately computed assuming that the first packet arrives at a random point in time
- The collision probability of flow **B → b** is zero

AIS scenario – model vs simulation



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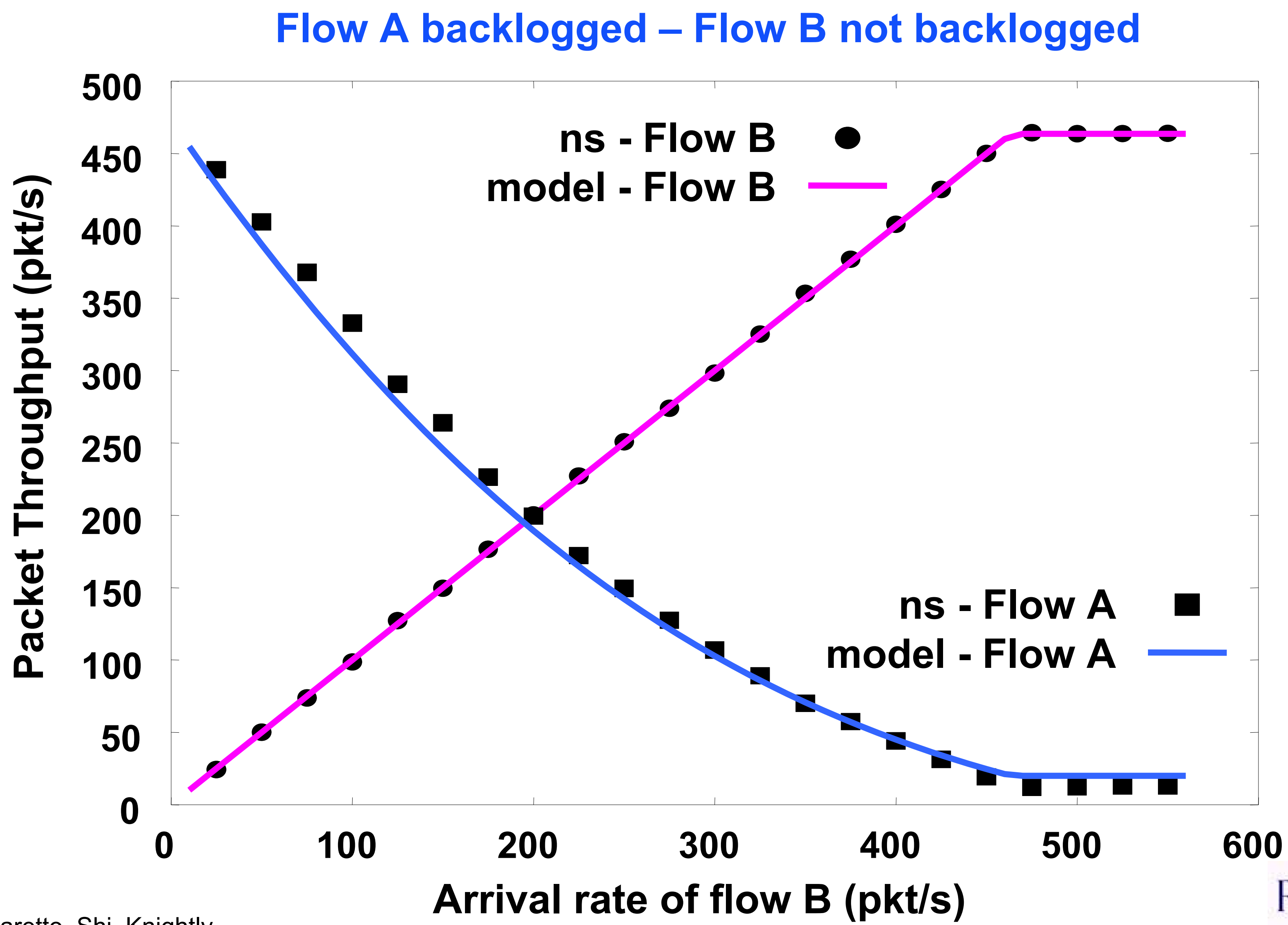
AIS scenario – model vs simulation



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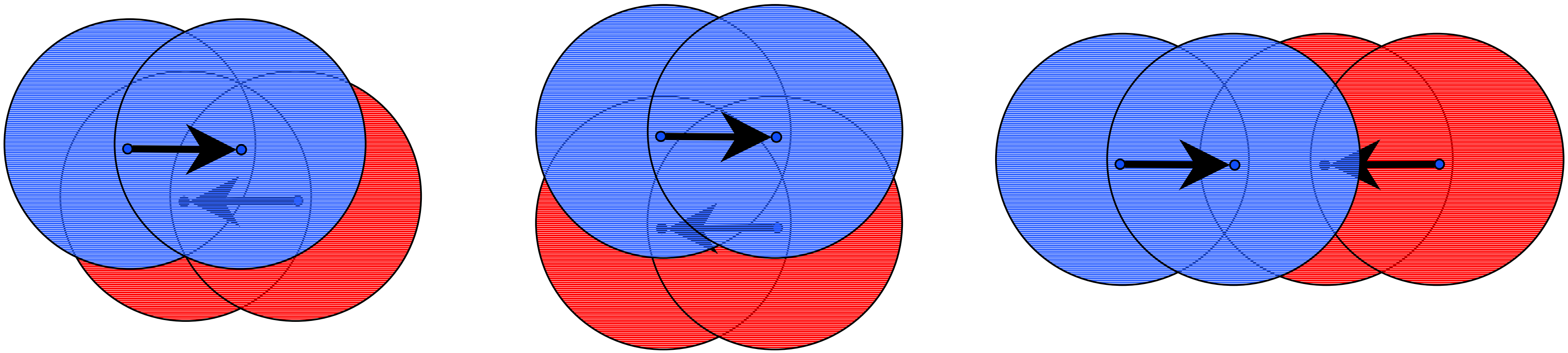
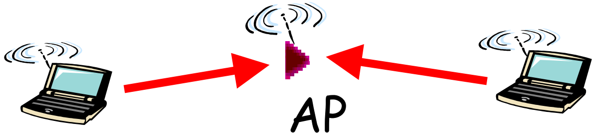
Analysis of Symmetric Incomplete State scenarios (SIS)



- Long-term fair, but short-term unfair
- One flow dominates over the other, until they switch their role (randomly)
- RTS/CTS does not help, and can even make things worse
- Not yet modeled analytically
- As a particular case, the receiver can be in common:



= the classic "hidden-terminal" scenario

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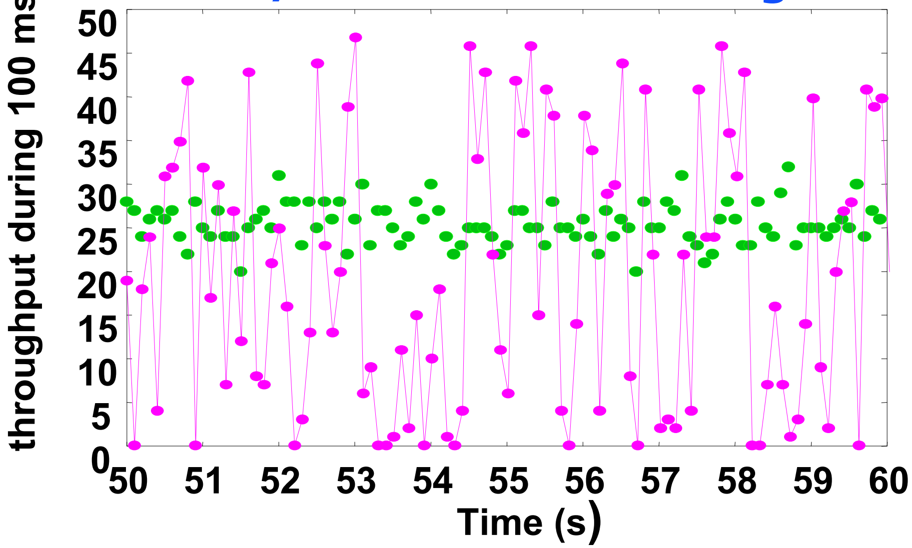
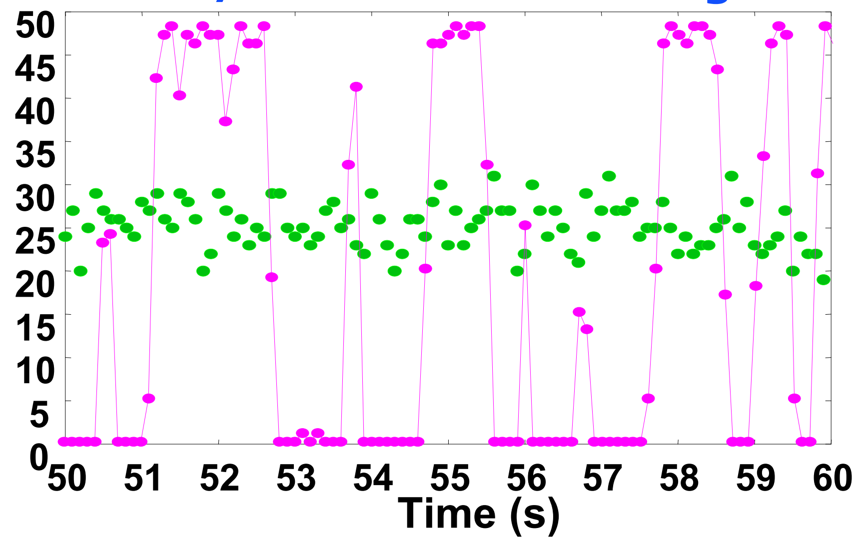
Simulation of short term unfairness – SC vs SIS

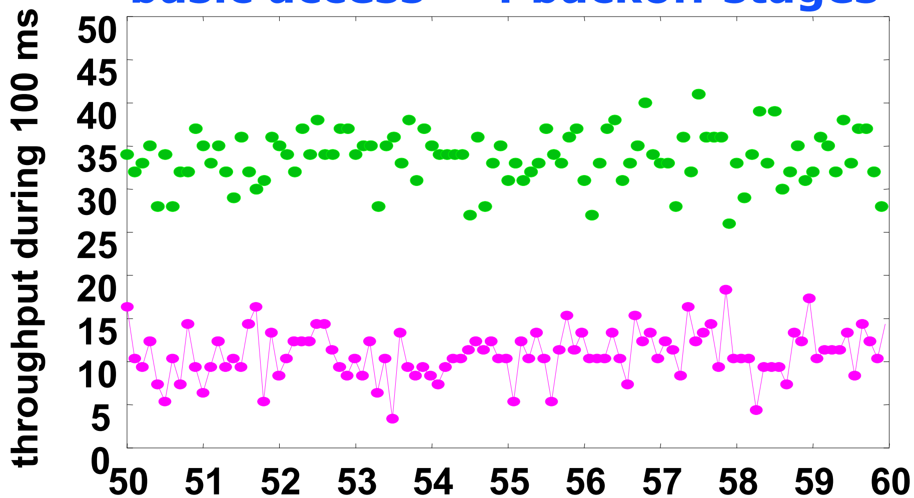
RTS/CTS – 7 backoff stages



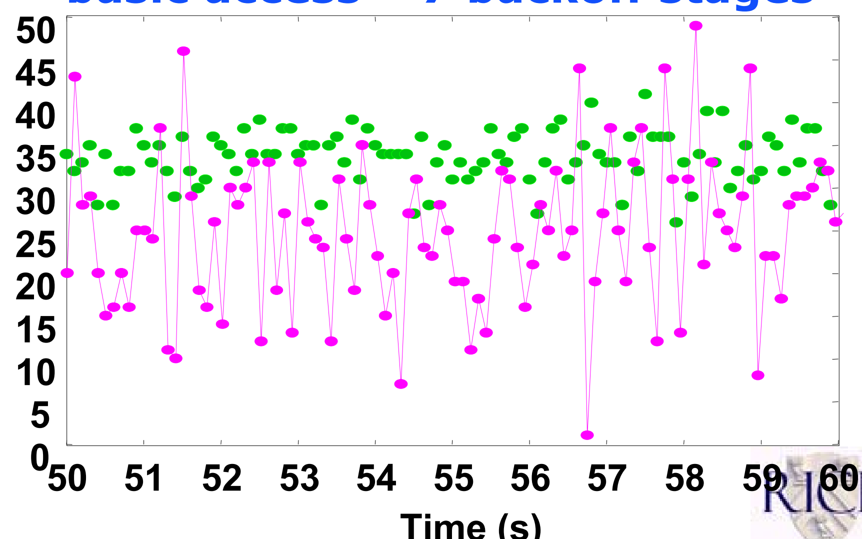
RTS/CTS – 9 backoff stages



basic access – 4 backoff stages



basic access – 7 backoff stages



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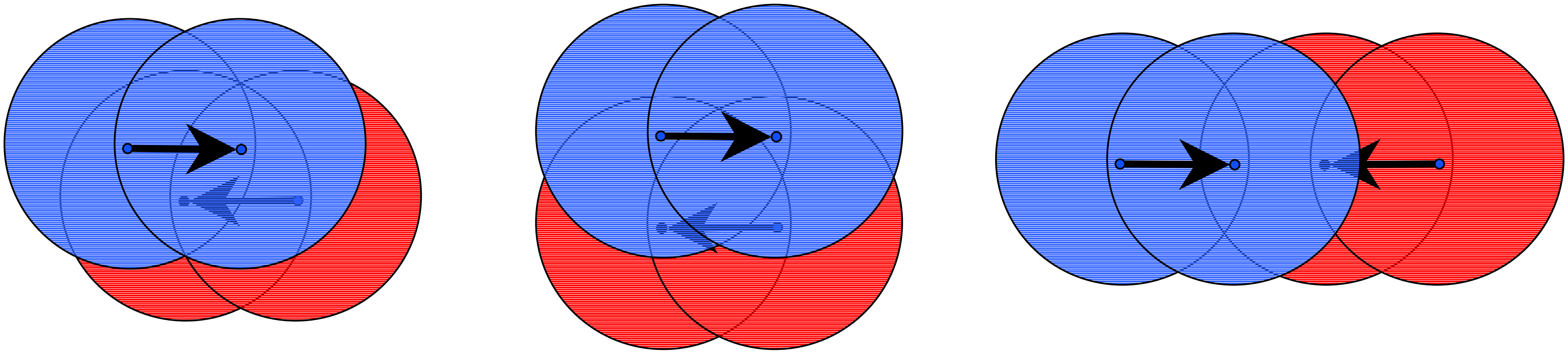

- To capture short-term behavior, we cannot apply the decoupling technique (i.e. assume independent states)
  - States of the two flows are tightly correlated !

- We use a markov model in which the state is:

  { backoff stage of **A**, backoff stage of **B** }

- The computation of the collision probability is the key point

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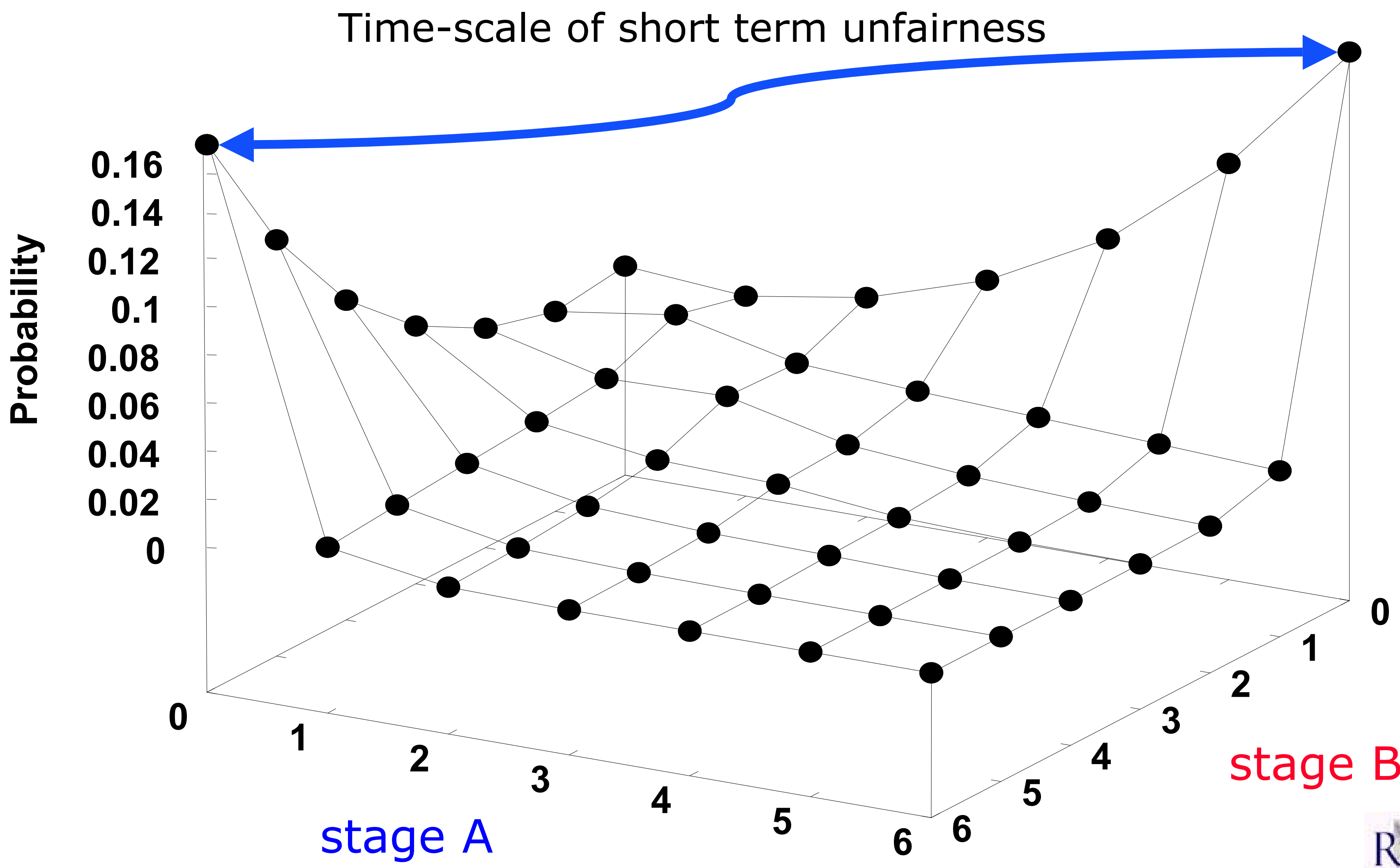
Analysis of Symmetric Incomplete State scenarios (SIS)

- Steady-state distribution of Markov Chain:



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SIS scenario – model vs simulation

Case	Throughput (pkt/s)	Collision probability	Time scale of unfairness (ms)	
RTS/CTS 7 stages	218 216	0.25 0.25	235 223	**ns** **model**
RTS/CTS 9 stages	229 230	0.11 0.09	982 1156	**ns** **model**
Basic access 4 stages	125 107	0.69 0.75	15 15	**ns** **model**
Basic access 7 stages	222 220	0.37 0.38	59 60	**ns** **model**

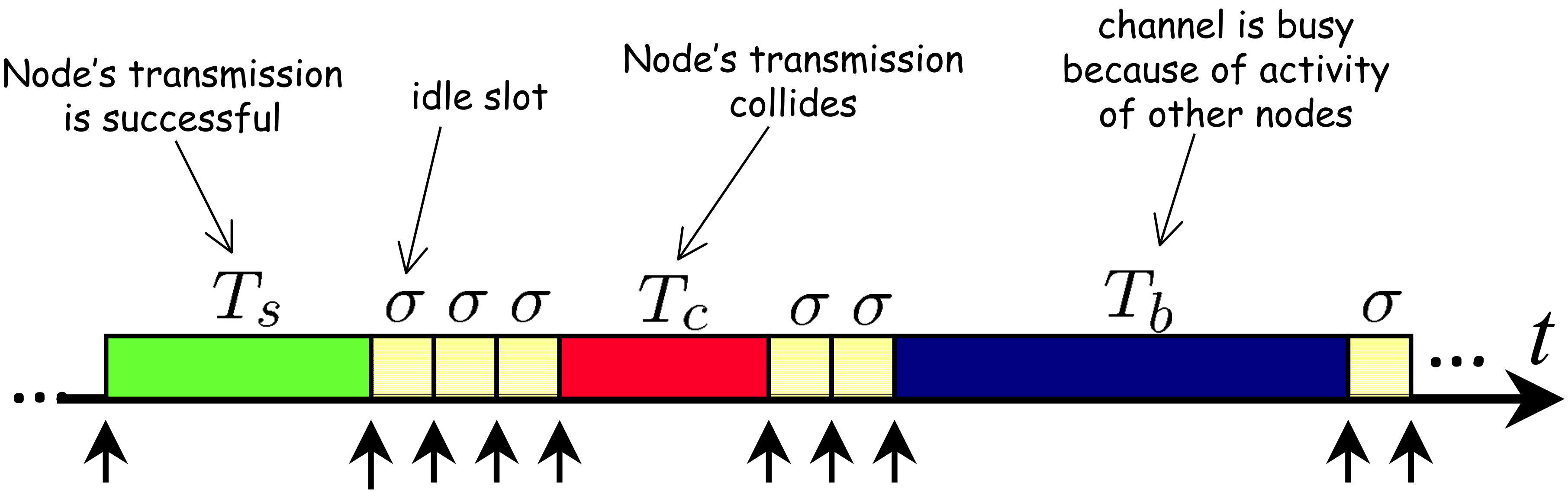
Conclusions

- We systematically studied all 2-flow scenarios of a multi-hop network
- We developed accurate analytical models to characterize throughput and fairness in all cases
- Spatial analysis reveals that problematic cases are not just "corner cases", but dominating scenarios occurring with high probability
- Deployment of wireless mesh networks using standard protocols (e.g. 802.11) incurs severe performance problems still to be solved

Thanks !

Decoupling technique (valid for general topologies)

- The channel "private view" of a node:



- Modelled as a renewal-reward process

$$\textbf{Throughput (pkt/s)} = \frac{\textbf{P [event } T_s \textbf{ occurs]}}{\textbf{Average duration of an event (s)}}$$

Modeling Media Access

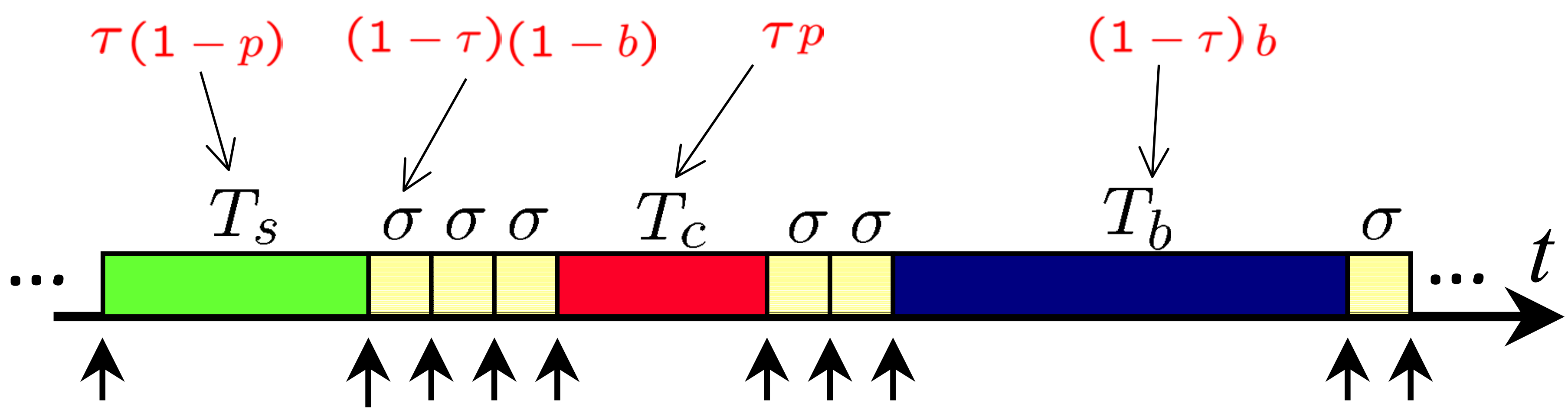
- Define the probabilities

τ = probability that the node sends out a packet in a slot

p = conditional collision probability

b = conditional busy channel probability

- Event probabilities:



Modeling Media Access

- $\tau = f_{bianchi}(p)$ (a decreasing function of p)
- The unknown variables are: p b T_b
- Throughput formula:

$$T = \frac{\tau(1-p)}{\tau(1-p)T_s + \tau p T_c + (1-\tau)(1-b)\sigma + (1-\tau) b T_b}$$

- The throughput of a node decreases if either:
  - p is large (if so, τ is small, also)
  - $b \, T_b$ is large (large fraction of busy time)

Mobility and Fairness

40 nodes (20 flows) - 1000 m x 1000 m – RWP [7,15] m/s

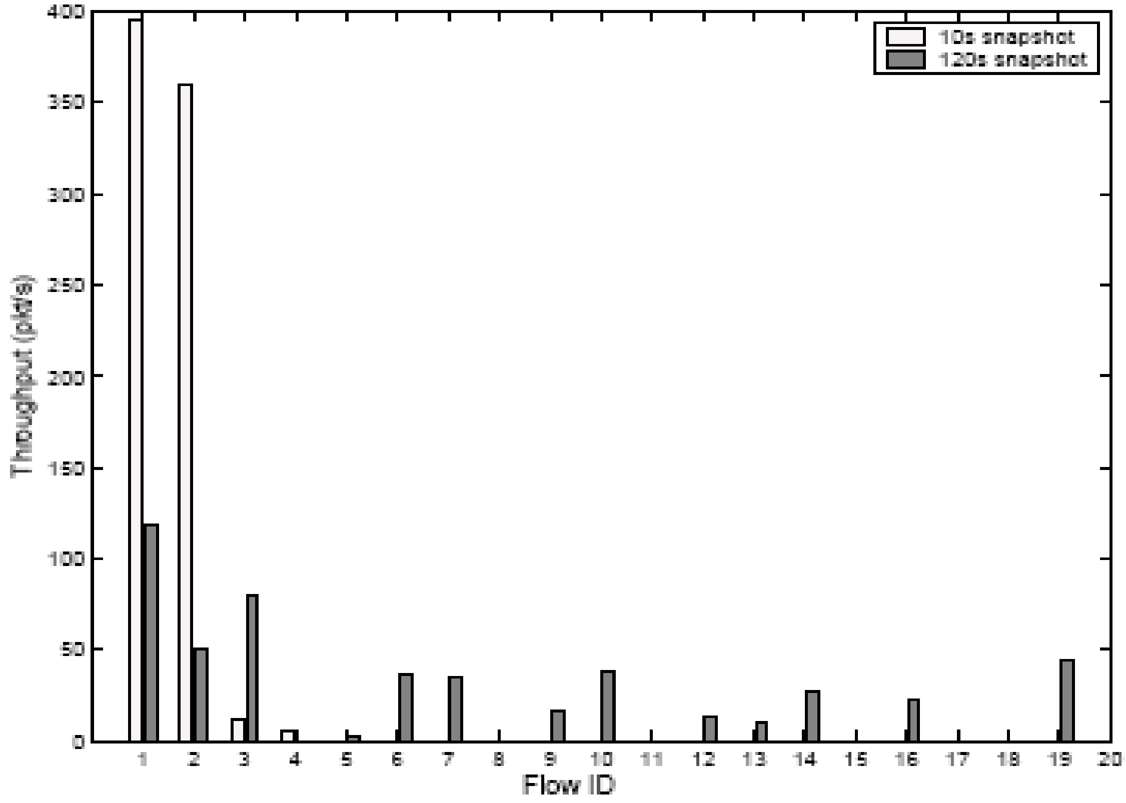


Figure 12: Flow throughput comparison between a 10 second snapshot and a 120 second snapshot.