Modeling Per-flow Throughput and Capturing Starvation in CSMA Multi-hop Wireless Networks

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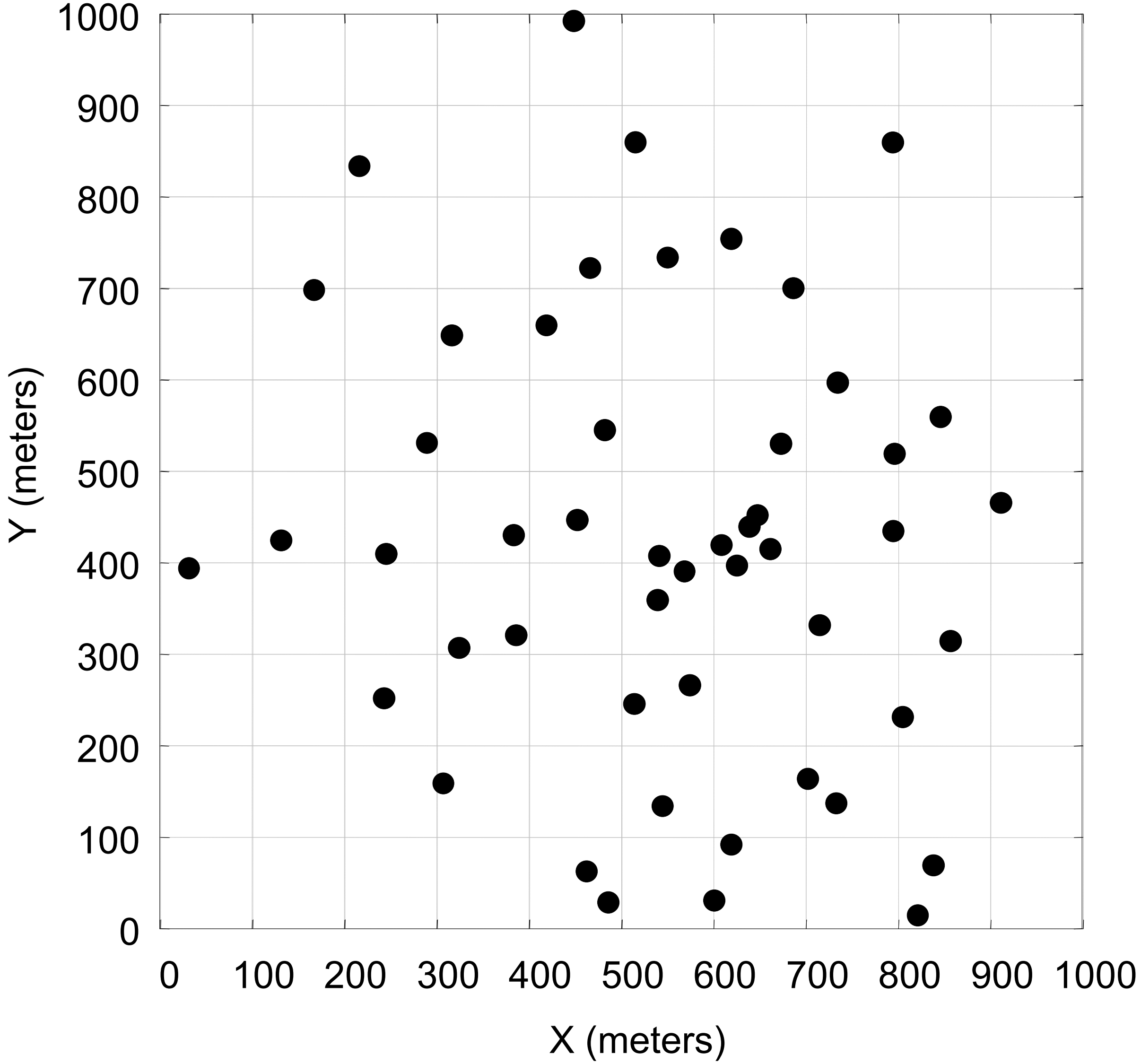
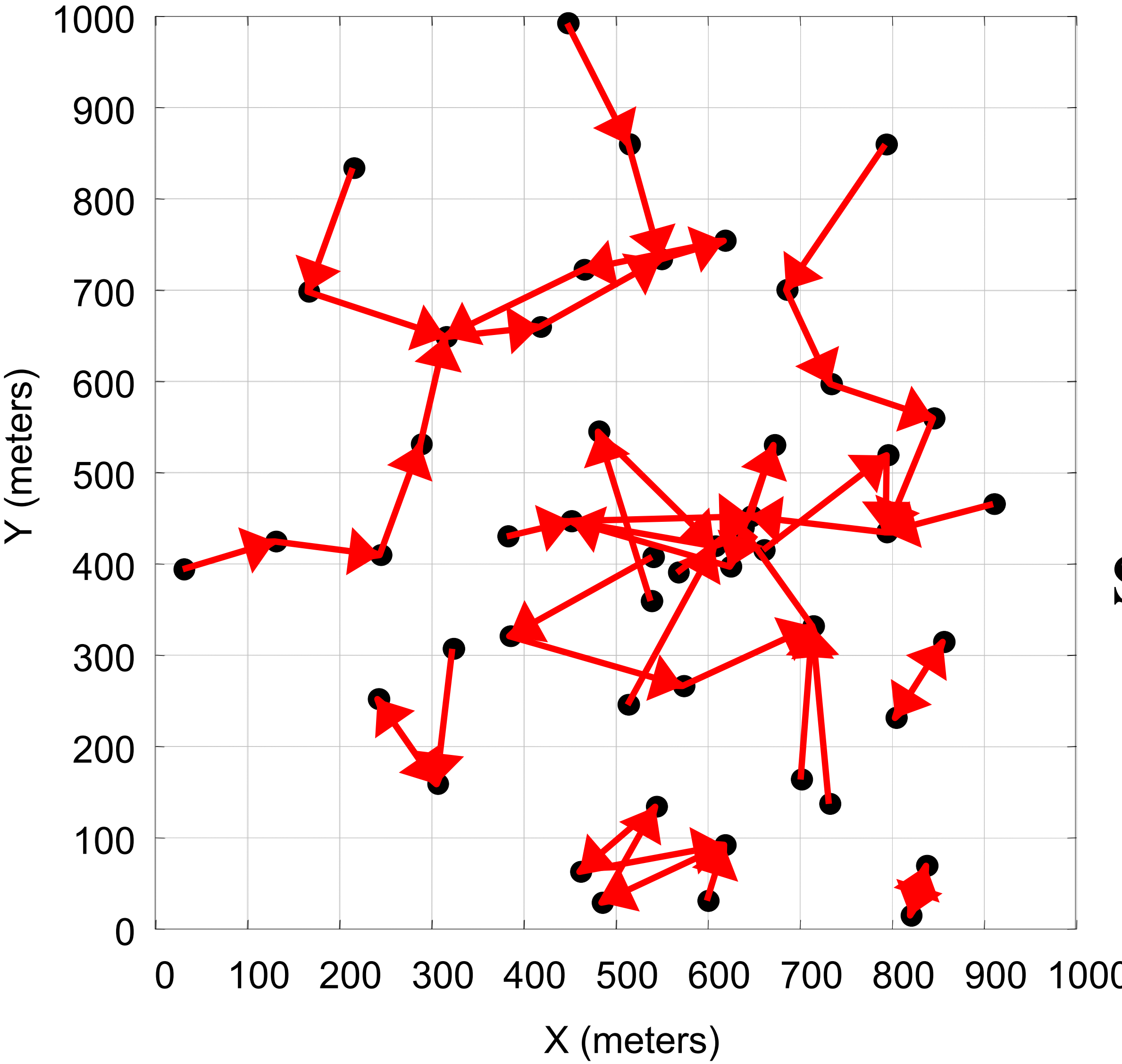
Example : 50 nodes



Example : 50 nodes



50 tx-rx pairs

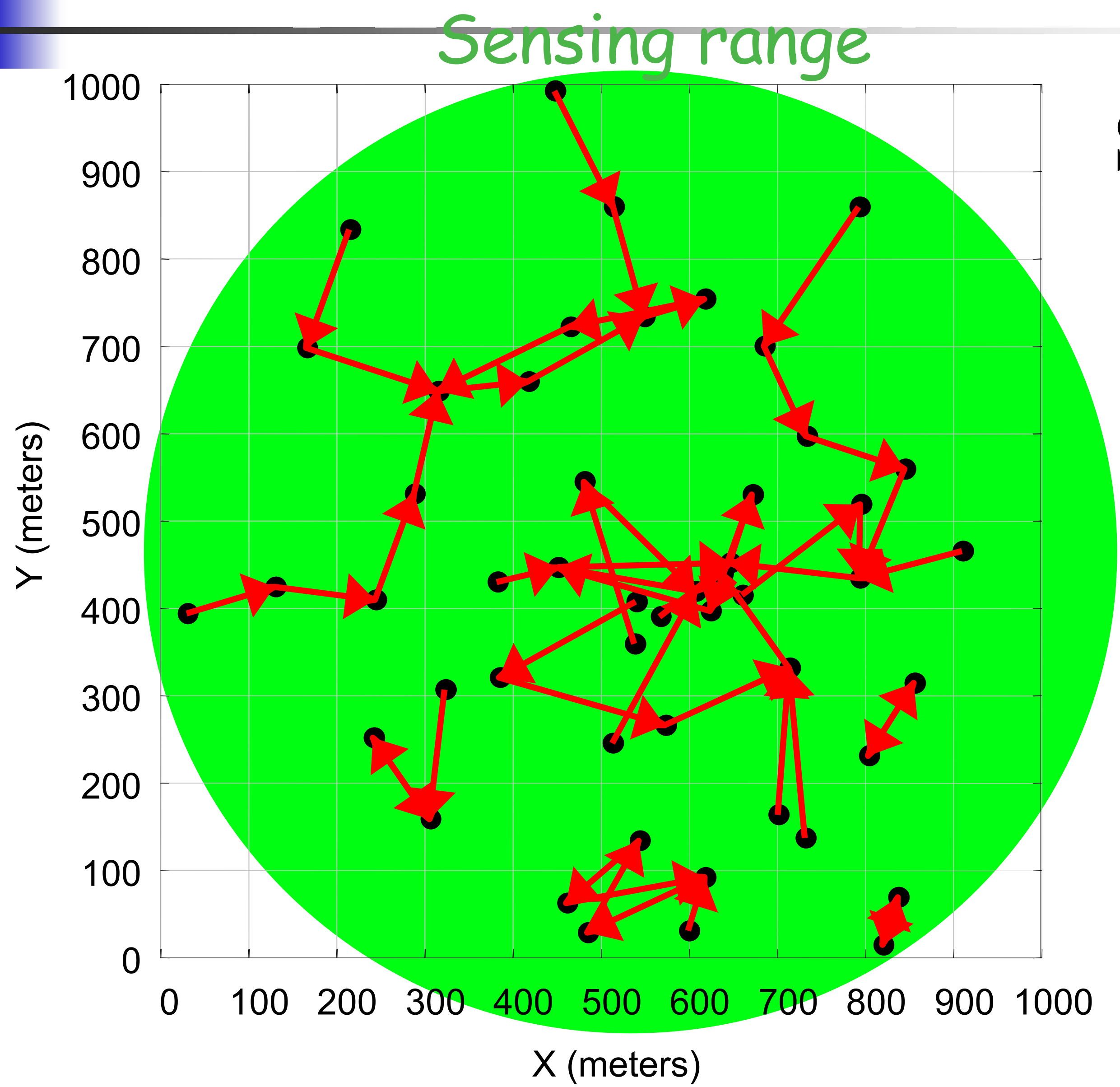
(link flows)

802.11 DCF (CSMA/CA)

Saturated traffic

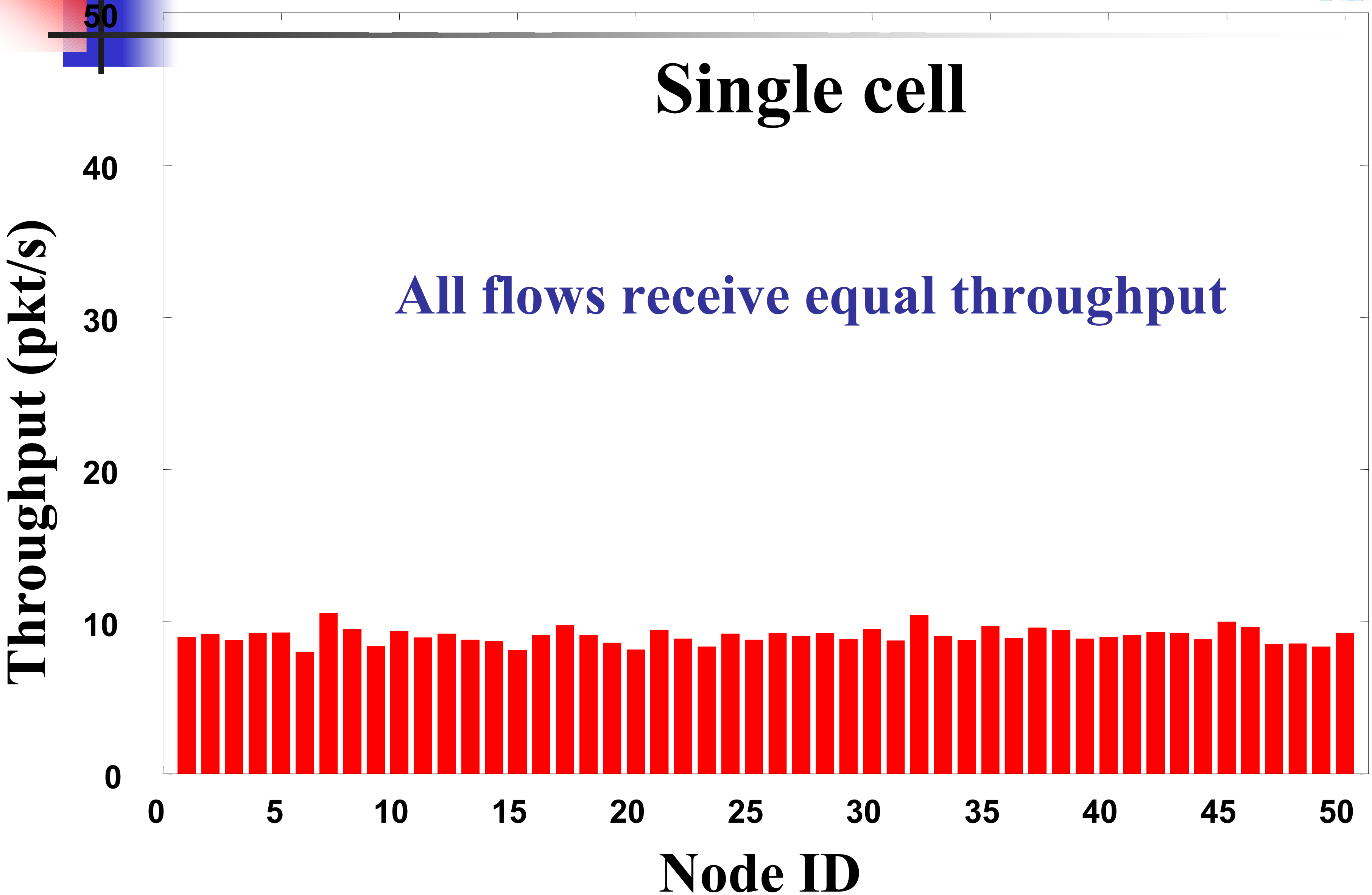
Perfect channel

Example : 50 nodes

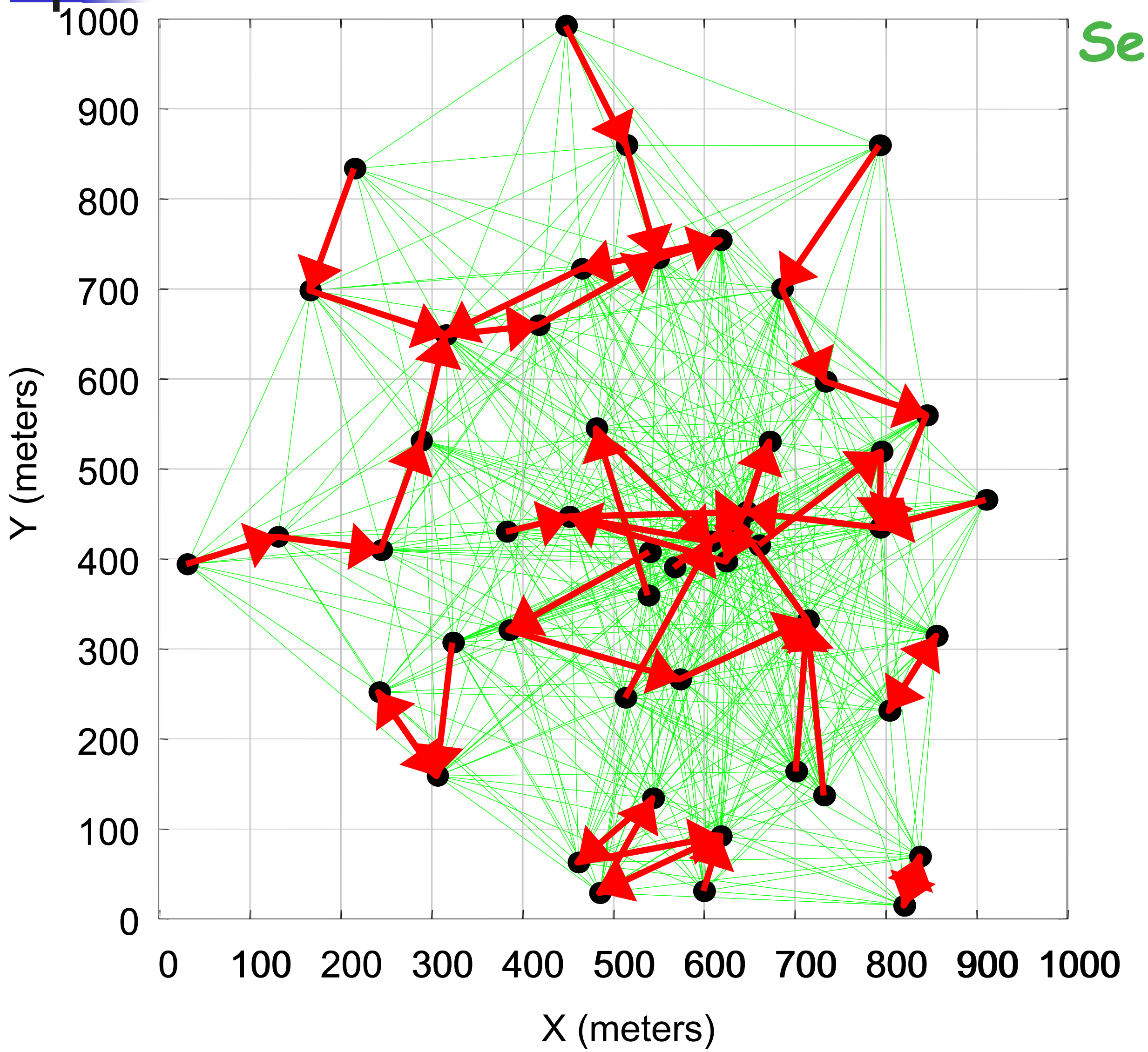


Single cell

Example : 50 nodes

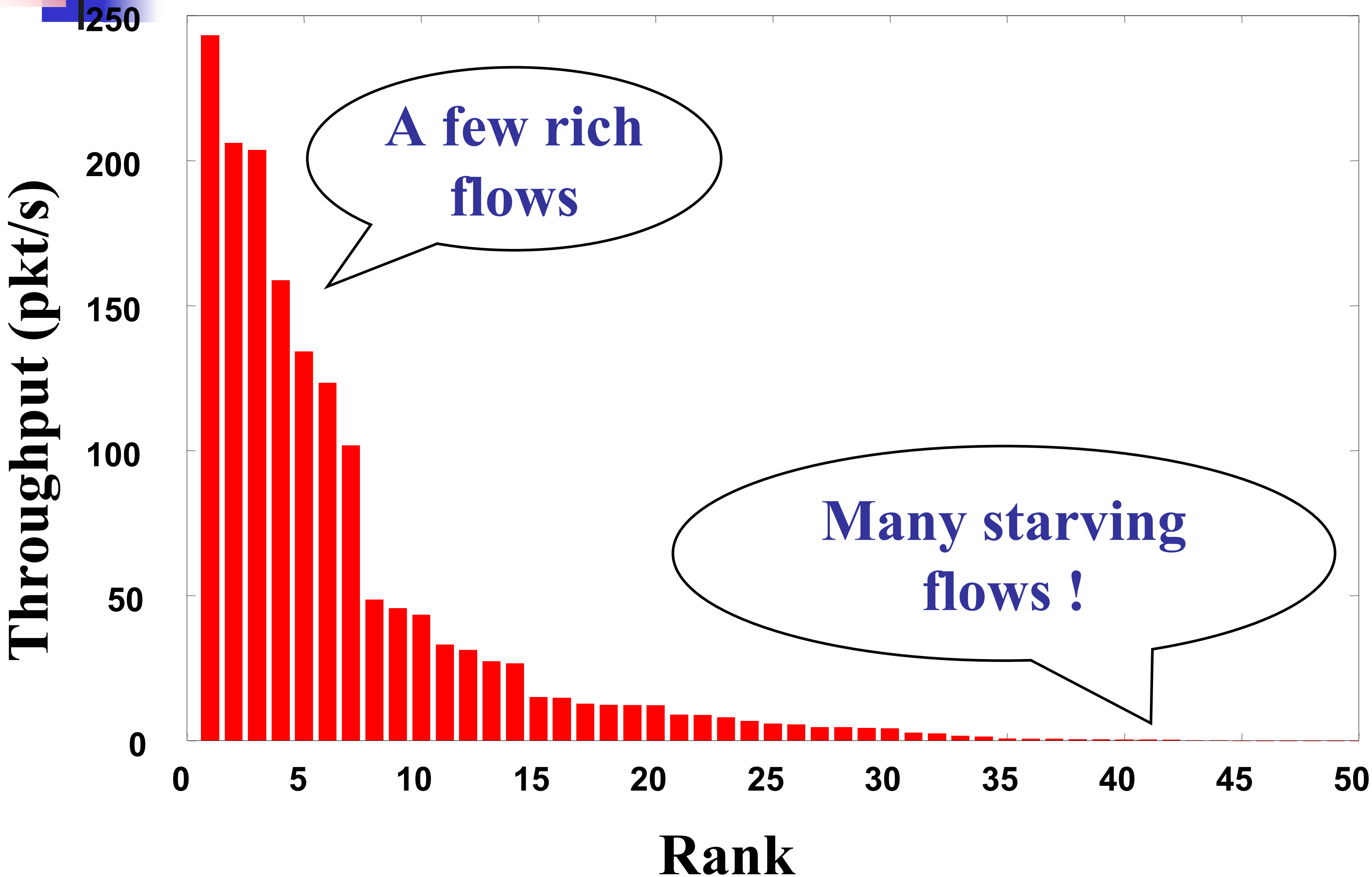


Example : 50 nodes



Sensing Range = 400m

Example : 50 nodes



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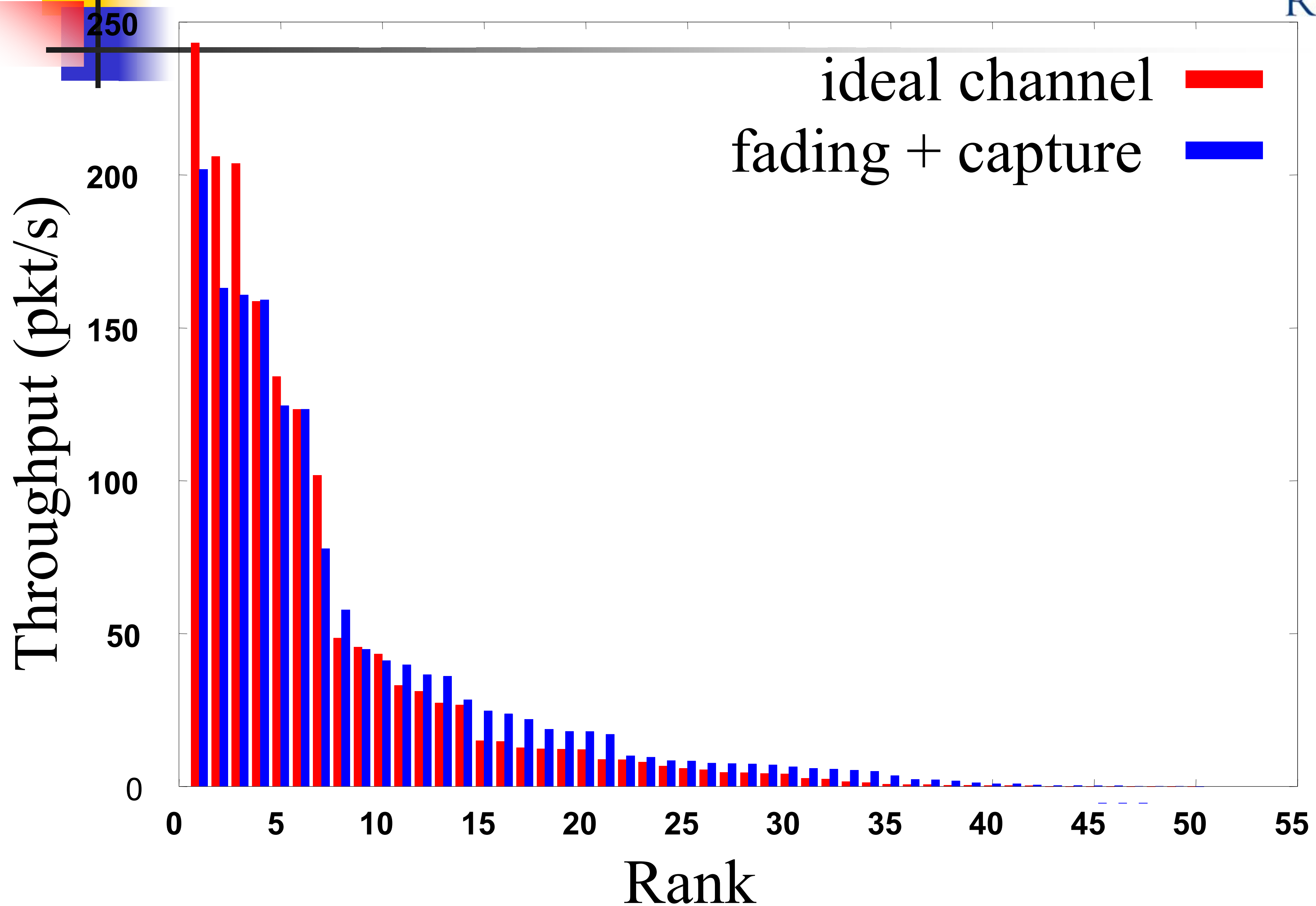


Our contributions

- Develop an analytical model to compute per-flow throughput in arbitrary network topologies employing 802.11 DCF
- Explain the origin of starvation in CSMA-based multi-hop wireless networks
- Propose metrics to quantify starvation due to the MAC protocol operation

Related work on CSMA models

- **Models for single-cell networks (WLANs)**
  - Leverage symmetric channel state
  - Accurately capture carrier sense, Binary Exponential Backoff, RTS/CTS (e.g. [Bianchi00])
- **Models for multi-hop networks**
  - **Assumption**
    - Throughput proportional to number of interferers [Boorstyn87, Carvalho04, Kar05]
  - **Cannot capture the CSMA "disproportionalities" or predict zero throughput**

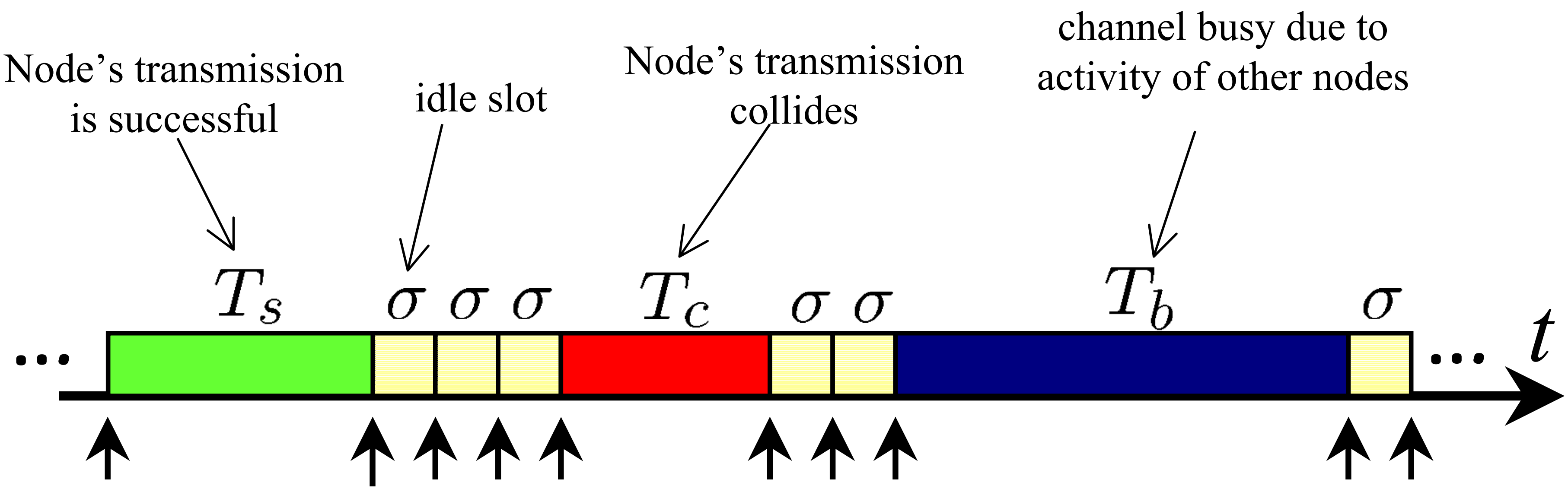
Our approach

RICE

- **Decoupling technique**
  - Describe behavior of each node based on its private view of the channel state.
- **Throughput expression**
  - Express throughput of each node as a function of its
    - Sensed fraction of busy time **(b, Tb)**
    - Collision probability **p**
- **Basic iteration**
  - Compute **p, (b,T_b)** variables of each node subject to the current variables of other nodes.
- **Iterative solution**
  - Perform basic iteration until convergence

Analytical model

- The "channel view" of a node:

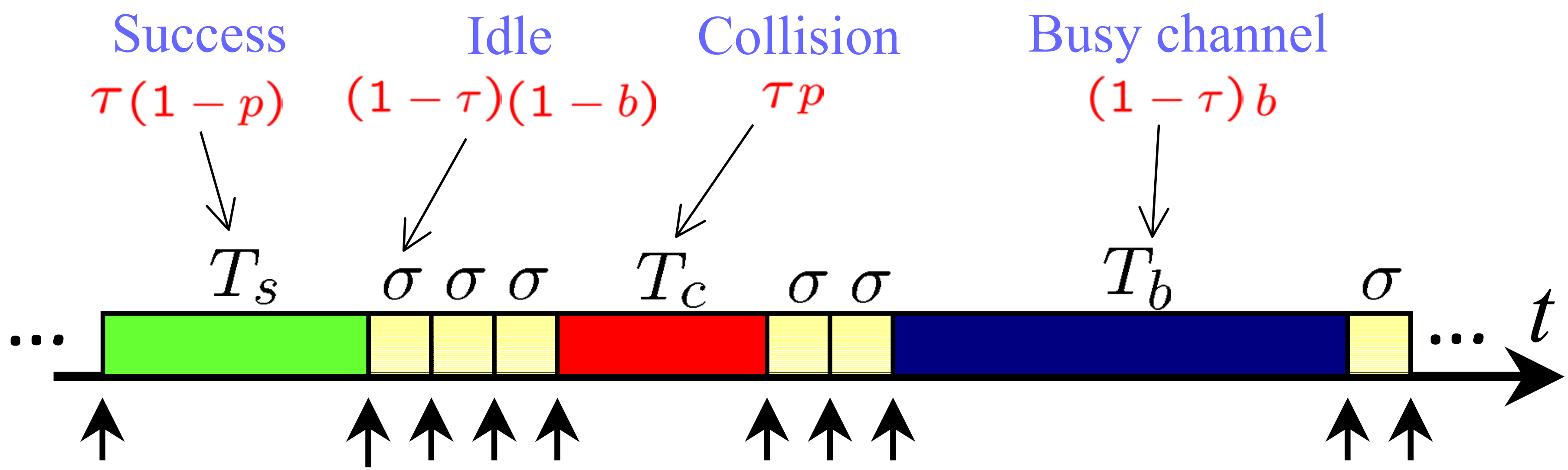


- Modeled as a renewal-reward process

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

Analytical model

- Define:
  - τ = **probability that the node sends a packet**
  - p = **conditional collision probability**
  - b = **conditional busy channel probability**
- Event probabilities:



Analytical model

- $\tau = f_{bianchi}(p)$
- $f_{bianchi}(\cdot)$
  - Deterministic decreasing function of p
  - Captures Binary Exponential Backoff
- **Throughput formula:**

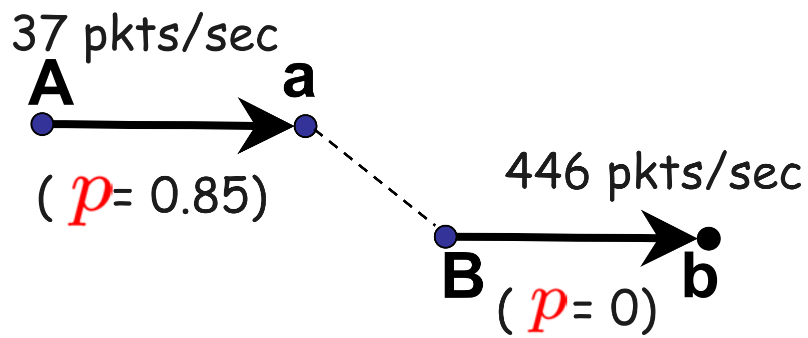
$$T = \frac{\tau(1-p)}{\tau(1-p)T_s + \tau p T_c + (1-\tau)(1-b)\sigma + (1-\tau) b T_b}$$

- **Unknown variables (different for each node)**
  - Collision probability p
  - Busy channel probability b
  - Average busy time T_b

How can collision probability *p* be disproportionately large ?

The "information asymmetry" scenario

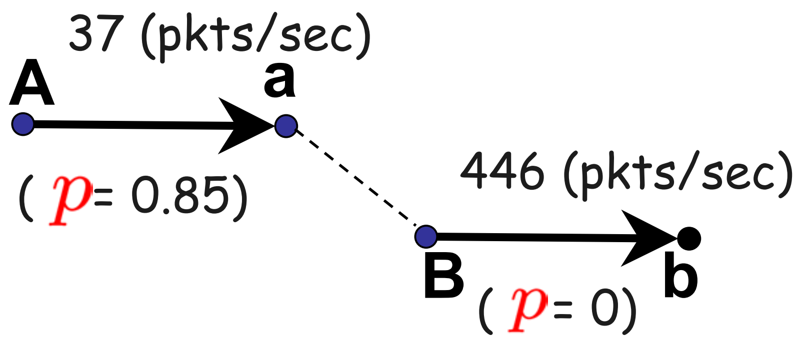
Flow A->a starves



Why is collision probability *p* disproportionately large ?

The "information asymmetry" scenario

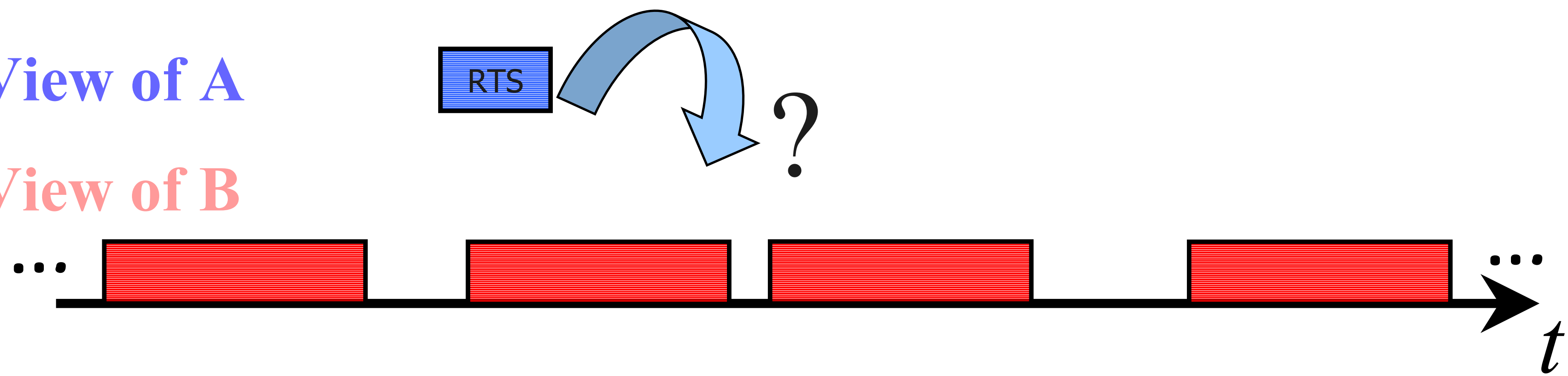
Flow A->a starves
due to high packet loss



Starvation cause:
A contends randomly
B knows when to contend

View of A

View of B

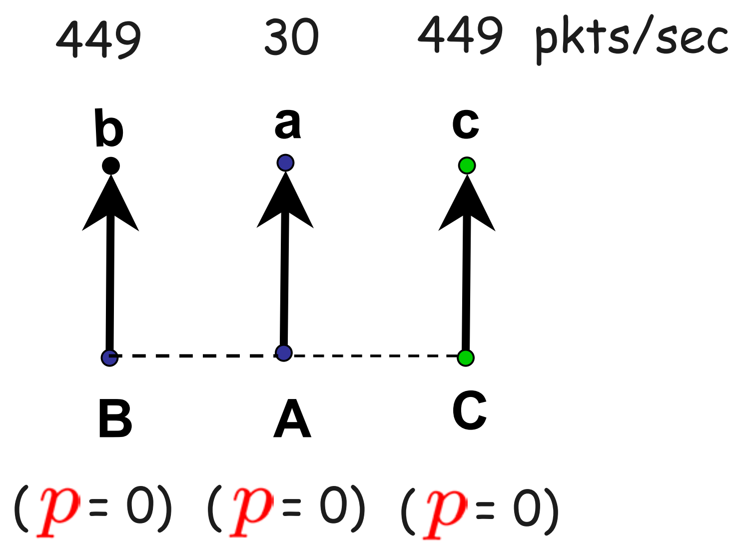


How can busy channel product bT_b be disproportionally large ?

The "flow-in-the-middle" scenario

No packet losses

Flow A->a starves



Why is busy channel product bT_b disproportionally large ?

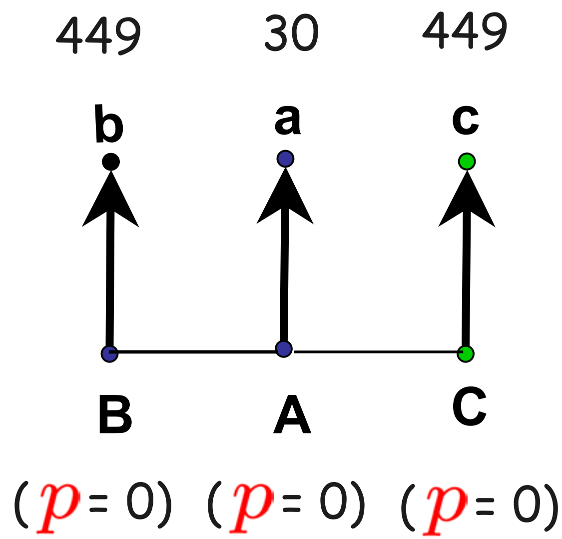
The "flow-in-the-middle" scenario

Flow A->a starves

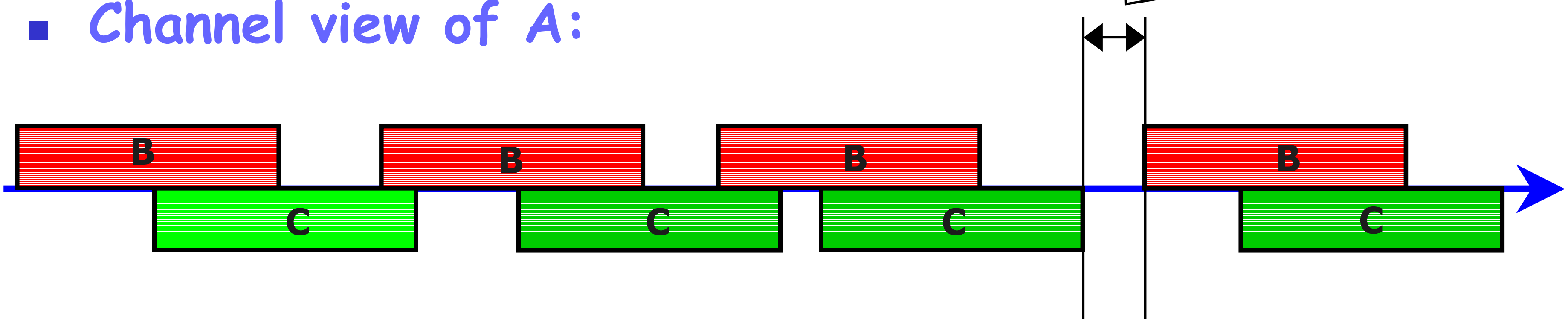
No packet losses

Starvation cause:

A senses busy medium for a very long time

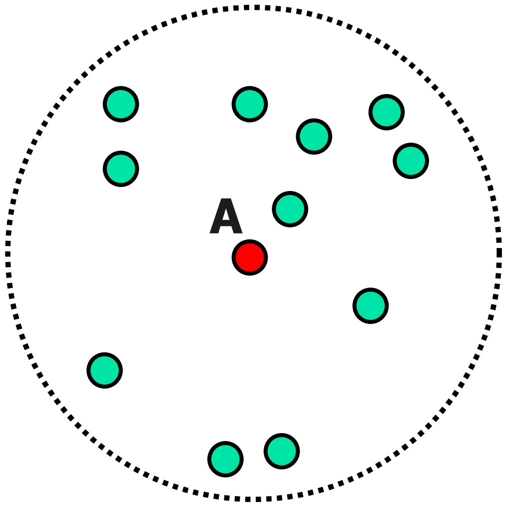


- *Channel view of A:*



Computation of busy channel parameters (b, T_b) for flow Aa

- **Challenge**
  - Not all neighbors of A are mutually within range and their activities are inter-dependent.
- **Clique computation**
  - Find minimum number of maximal cliques M covering all neighbors



Computation of busy channel parameters (b, T_b) for flow Aa

- **Challenge**
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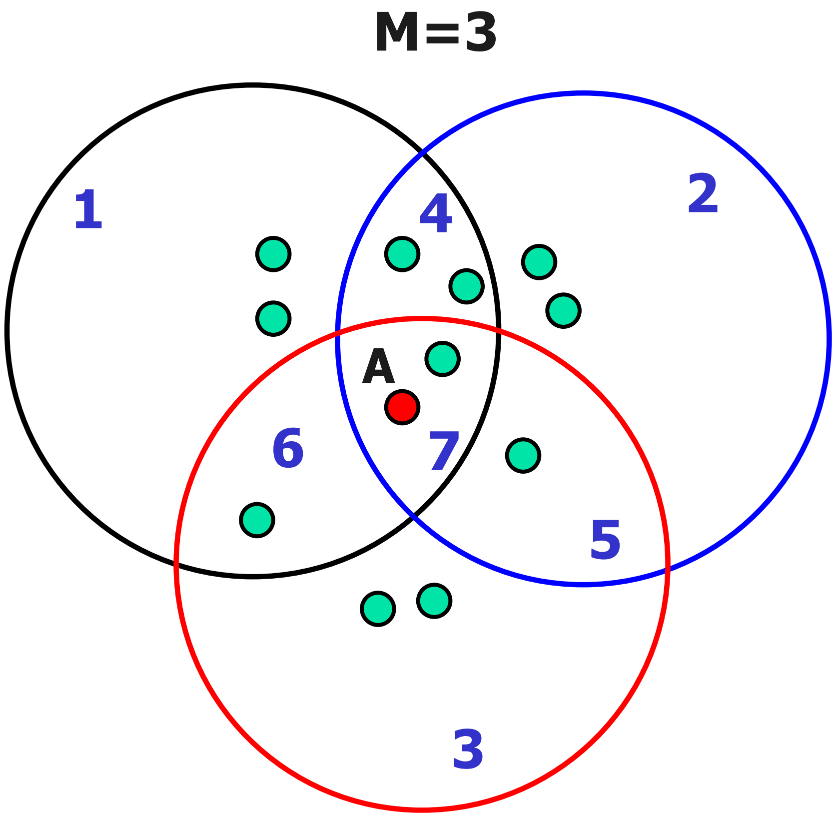
- **Virtual nodes (VN) graph**
  - **VN** = set of non-empty clique intersections
  - **VN Graph:** Connect two VNs if they share at least one clique



Computation of busy channel parameters (b,T_b) for link Aa

- **Challenge**
  - Not all neighbors of A are mutually within range and their activities are inter-dependent.
- **Clique computation**
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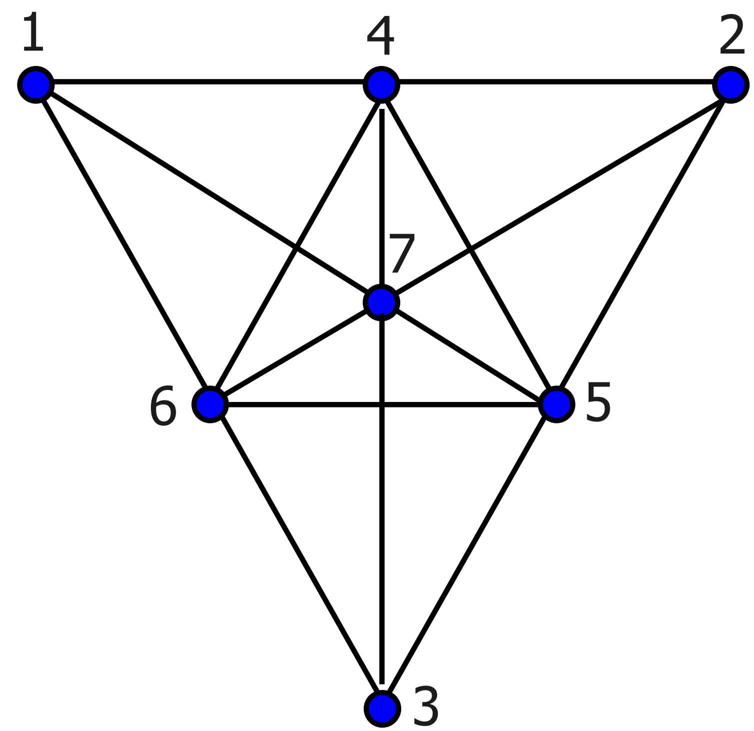
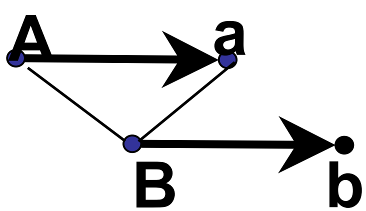
- **Virtual nodes (VN) graph**
  - **VN** = set of non-empty clique intersections
  - **VN Graph:** Connect two VNs if they share at least one clique
- **Computation of busy period**
  - Find the aggregate busy time around node i based on VN activities



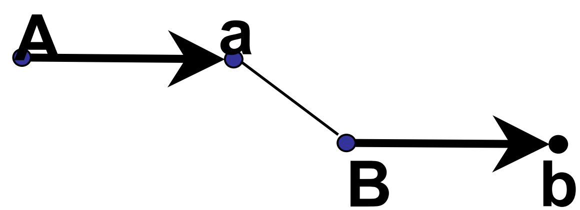
Computation of collision probability p for link Aa

- **4 classes of packet loss due to link Bb**

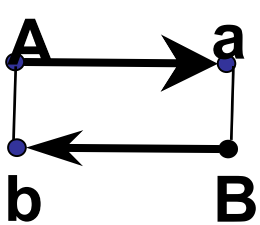
1) Coordinated losses: P_{co}



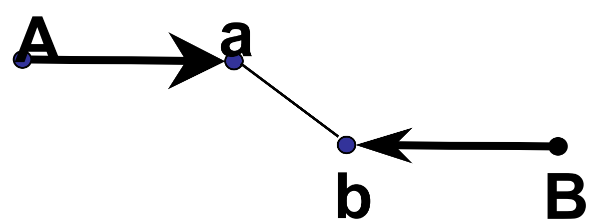
2) Information Asymmetry: P_{ia}



3) Near Hidden terminals: P_{nh}



4) Far Hidden terminals: P_{fh}

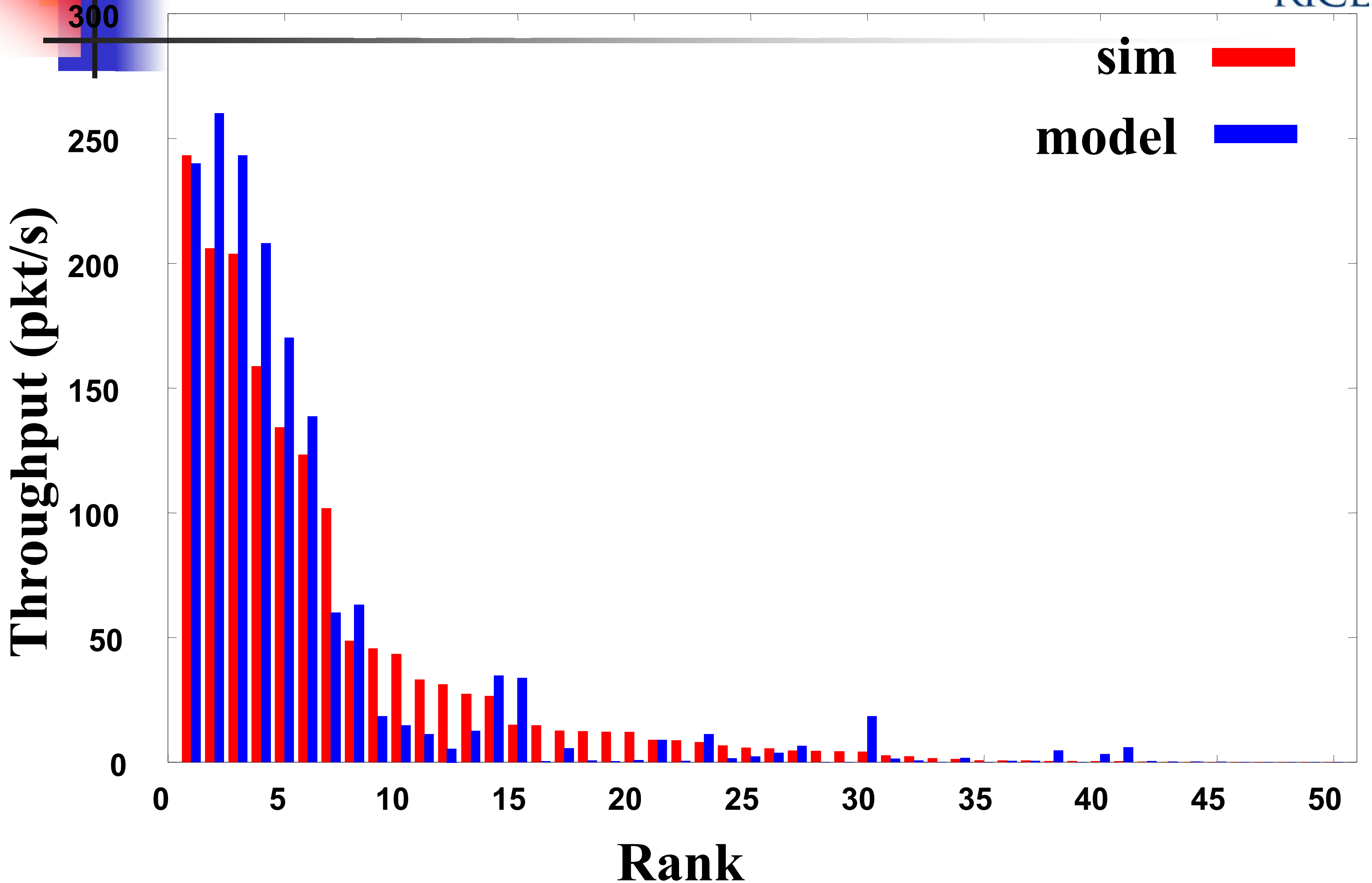


$$p = 1 - (1-P_{co})(1-P_{ia})(1-P_{nh})(1-P_{fh})$$

Network solution

- **Basic iteration**
  - Compute p, (b,Tb) of each node subject to the variables of other nodes.
- **Network solution**
  - Multivariate system of coupled non-linear equations
  - Perform basic iteration until convergence
- **Model features**
  - Incorporates all starvation effects due to CSMA MAC
  - Can analyze arbitrary topology
  - Predicts individual flow throughput
  - Supports non-saturated flows

Model vs Sim – 50-nodes example



Measuring Starvation

- **Objectives**
  - Capture how individual flows are treated by different solutions
  - Distinguish between imbalance due to topology (number of contenders) and starvation due to the MAC protocol
- **Reference system: Slotted Aloha**
  - Starvation structurally eliminated

Conclusions

- Multi-hop wireless networks employing 802.11 (or other variants of CSMA) are subject to severe starvation (under high load)
- This is a fundamental problem CSMA due to lack of coordination between out-of-range transmitters
- We developed an analytical model to predict per-flow throughput in arbitrary topologies and characterize starvation

Thank you

For more information: www.ece.rice.edu/~thsalon