Capacity of Ad Hoc Networks

- Quality of Wireless links
  - Physical Layer Issues
  - The Channel Capacity
  - Path Loss Model and Signal Degradation
- 802.11 MAC for Ad-hoc Networks
  - DCF (Distributed Coordination Function)
- Analysis of Network Capacity
- Enhancement Of Network Capacity

Physical Layer Issues

- Bandwidth of 802.11 b/g
  - upto 30 MHz, centered at 2.4GHz
- Data Rates
  - 802.11 b : 11Mbps (~5.5 Mbps practically)
  - 802.11 g : 54Mbps (~35 Mbps practically)

Layer 1 Capacity

- Theoretical Upper bound

$$C = W_c \log (1 + SNR/W_c) \text{ bits/sec}$$

Where

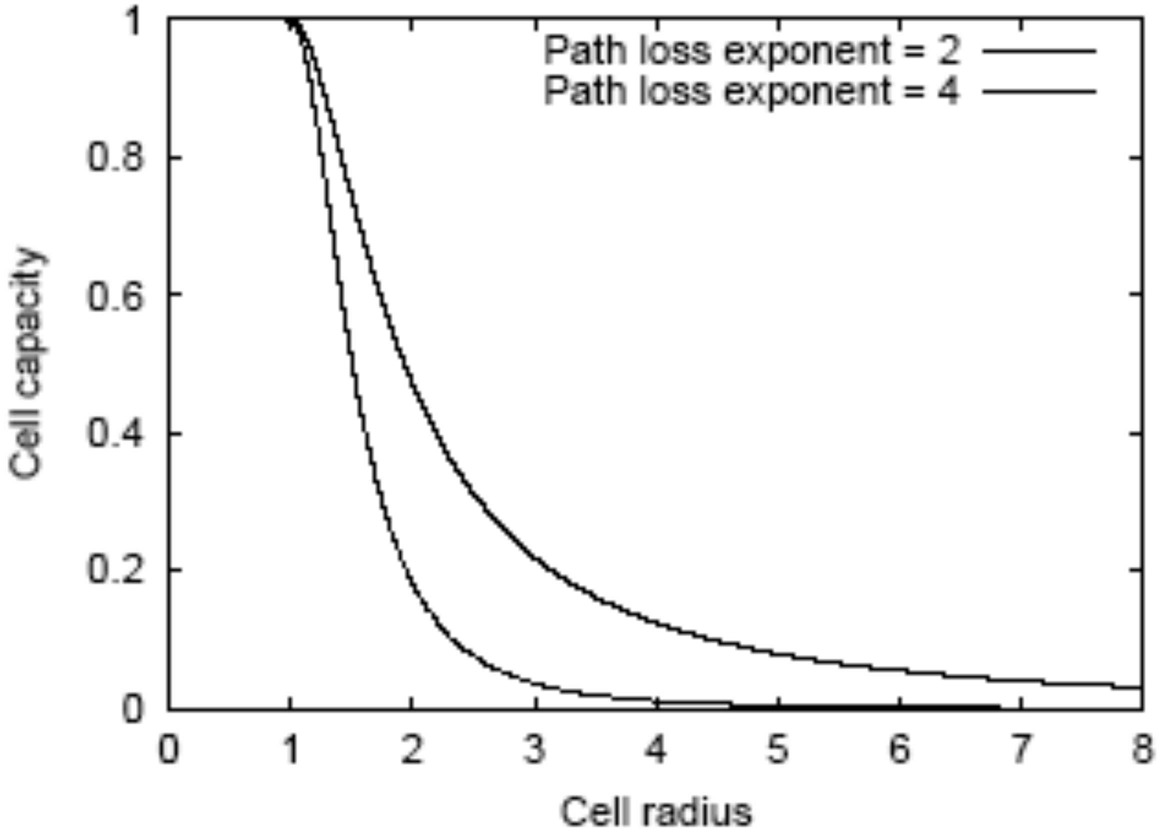
W_c : Bandwidth in Hz

Path Loss Model

Assume C_0 is the maximum realizable data rate

$$C(r) = \begin{cases} C_0 & \forall \quad r \le r_0 \\ C_0\left(\dfrac{r_0}{r}\right)^{\alpha} & \forall \ r > r_0 \end{cases}$$

Path Loss Model



Distributed Coordination Function

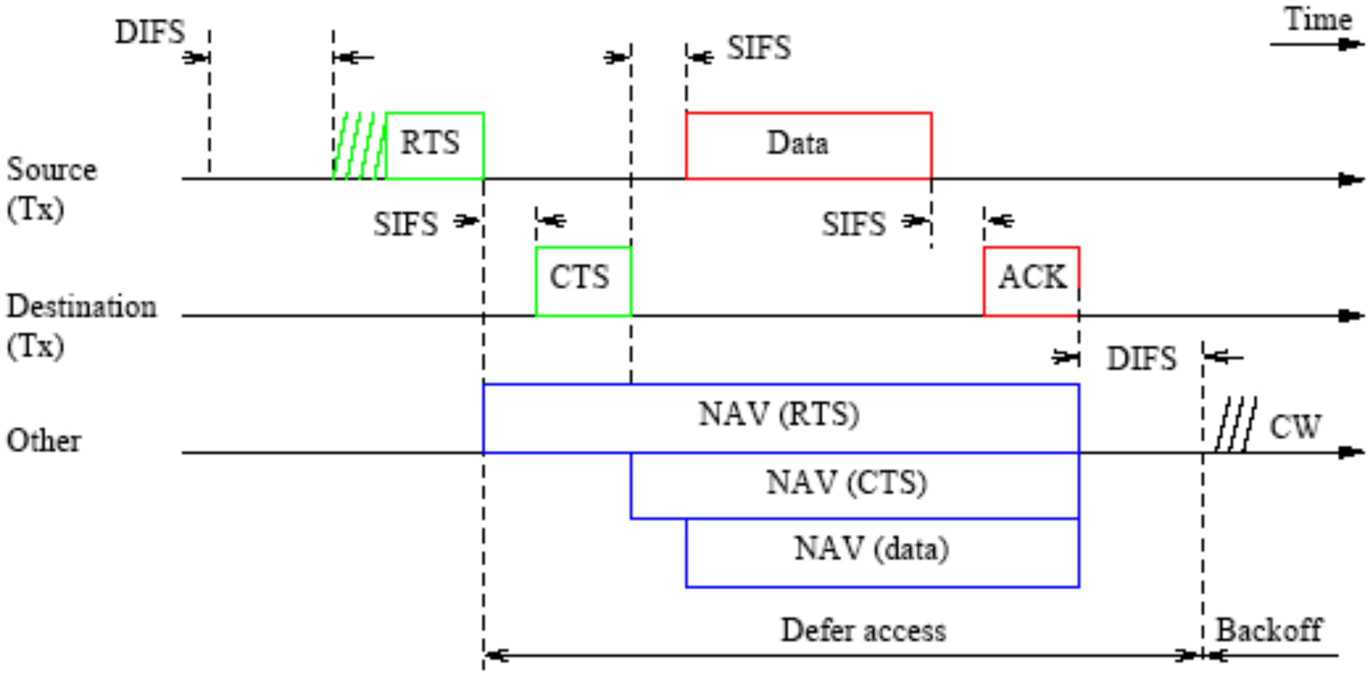
- Overview of DCF
  - NAV : Network Allocation vector : tracks the time for which the channel is reserved
  - Sender transmits RTS (40 bytes)
  - If destination node's NAV = 0, destination responds with a CTS message (39 bytes)

Overview Of DCF

- Both RTS and CTS packets specify the time for which the channel is being reserved.
- All other nodes that can listen to RTS or CTS, update their NAV to

  NAV_{new}= max (NAV_Curr, time in RTS/CTS)
- Each data packet is acknowledged (ACK : 39 bytes)

Timing Diagram for DCF



RTS: Request To Send
CTS: Clear To Send

Efficiency Of DCF

- Consider a data packet of size 1500 bytes
- Link Capacity of 2Mbps
- Effective data throughput

$$T_c = \frac{1500}{1500 + 40 + 39 + 39 + 47} * 2.0 \text{ Mbps}$$

$$\sim = 1.80 \text{ Mbps}$$

With inter-frame timing, $T_c \sim= 1.7$ Mbps

Assumptions

- Sources generate data at rate lower than the link capacity
  - essential to ensure that the network is not ‘over-loaded’
- In some of the plots, it is assumed that packets are routed along pre-determined routes – in order to neglect the effects of the network layer over-head

Capacity Of Ad-Hoc Networks

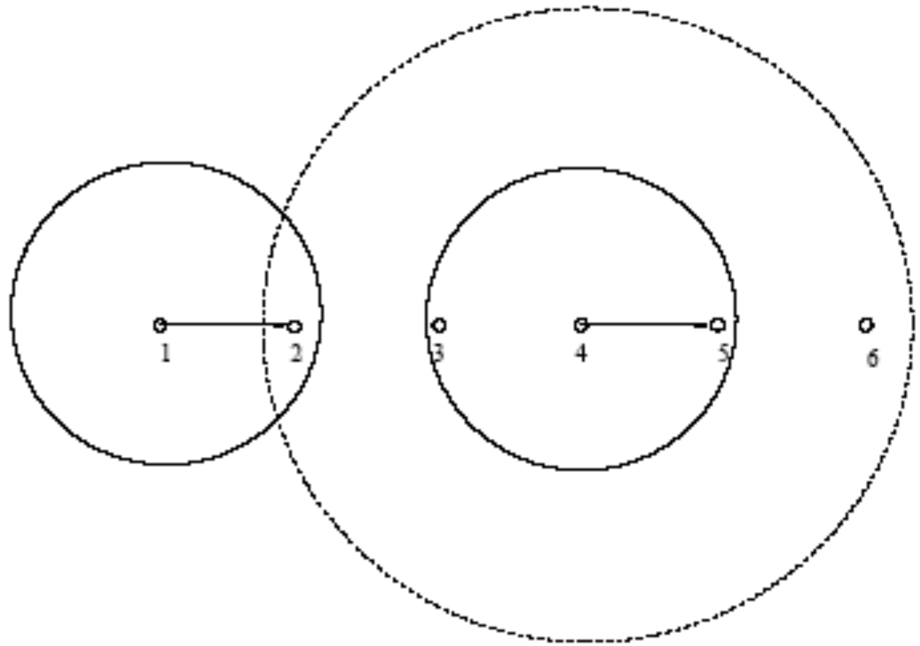
- Radios that are sufficiently separated can transmit simultaneously [2]
  - Hence, total one-hop capacity is O(n) for a network with ‘n’ nodes
  - If node-density is fixed, we expect the average number of hops in each link to grow as a function of radial distance

$$or,$$

$$Path\ Length = O(\sqrt{n})$$

$$\Rightarrow C = O(\frac{n}{\sqrt{n}}) = O(\sqrt{n})$$

Multi-Hop Performance



MAC Interference among a chain of nodes. The Solid-line circle denotes transmission range (200m approx) and the dotted line circle denotes the interference range (550m approx)

Capacity Of A Chain of Nodes

- Since a node interferes with up to 4 other nodes, only ¼ links in the chain can be operational at any time instant
- Hence, effective end-end throughput is given by 0.25*1.7 = 0.425 Mbps

Chain Throughput

802.11 MAC : Problems

- Node 1 experiences interference from 2 other nodes
- Nodes in the middle of the chain experience interference from 4 other nodes each
- Hence node 1 can pump data in to the chain at a higher rate than can be relayed by the chain

802.11 MAC : Problems

- This rate discrepancy leads to higher packet loss rate and retransmissions
- During the time that these extra packets are transmitted, other nodes in the interference range cannot transmit leading to even lower efficiency

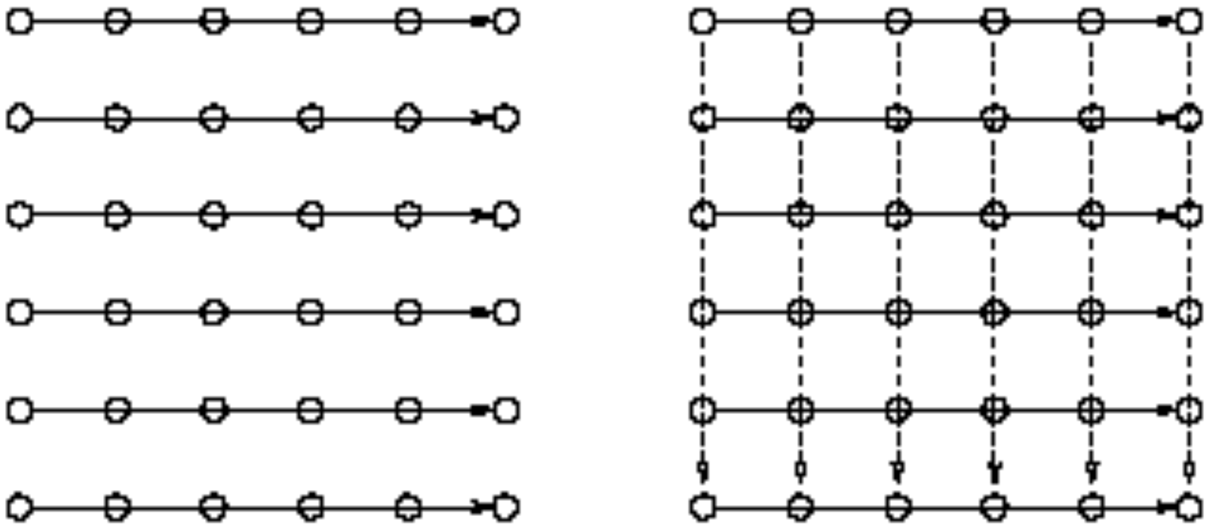
Inefficiency of Exponential Backoff

- If a sender doesn't receive a CTS in response to RTS, the sender retransmits RTS after an exponential backoff
- Consider a transmission between Nodes 4 and 5
- Node 1 would repeatedly poll Node 2 and the exponential back-off period would increase drastically before the end of the transmission

Inefficiency of Exponential Back-off

- After the end of transmission by node 4, node 1 would still remain in the ‘exponential back-off’ State, leading to bandwidth under-utilization
- Hence, exponential back-off is unsuitable for ad-hoc networks

The Lattice Layout



Lattice Network Topologies showing just horizontal flows (left) and both vertical and horizontal flows (right)

Performance in Lattice Topologies

- Minimum vertical separation of 200 m (interference range) for lattice layout with horizontal data flows
- For a chain spacing of 200m, 1/3 of all chains can be used simultaneously
- Hence capacity = 1/4*1/3* 1.7Mbps

  ~= 140 Kbps/flow

Performance In a Lattice Network

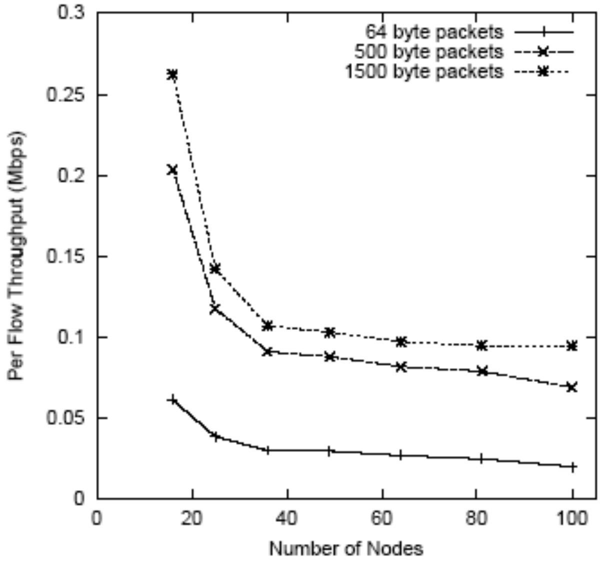


Figure 8: Average per flow throughput in square lattice networks with horizontal data streams only, as a function of network size. There are as many parallel chains as there are nodes per chain. The X axis value is the total number of nodes. Each node is separated from its four neighbors by 200 meters.

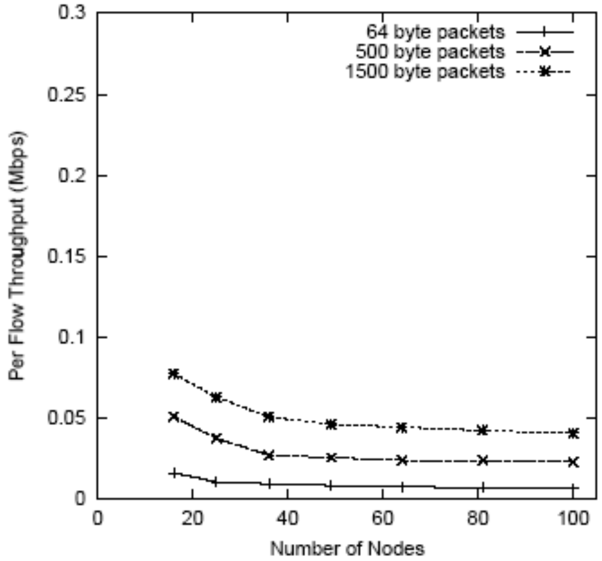


Figure 9: Average per flow throughput in square lattice networks with both horizontal and vertical data streams. This configuration has twice as many chains of traffic sharing the same network as Figure 8, which explains most of the difference between the two results.

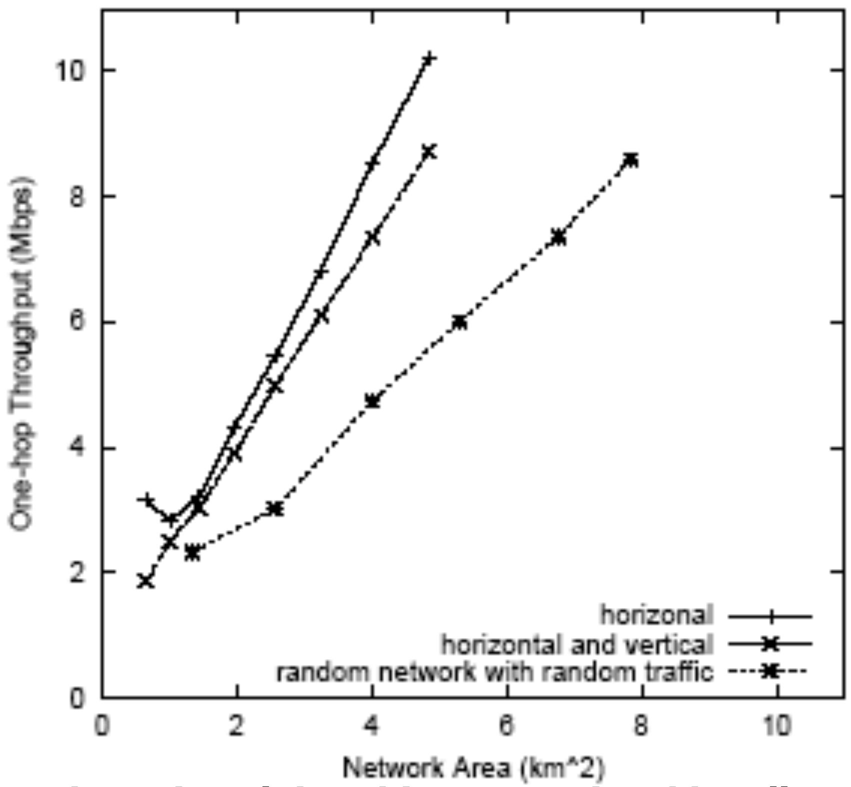
Random Layout With Random Traffic

- Uneven node density
  - Some areas may have very few nodes
- Average node density is set at thrice that of regular lattices to ensure connectivity (75 nodes/km^2)
- Packets are forwarded along pre-computed shortest paths (no routing)

Random Layout With Random Traffic

- Due to random choice of destinations, most packets tend to be routed through the centre of the network
  - Capacity of the center is network's capacity bottleneck

Random Networks With Random Traffic



Total one-hop throughput (total data bits transmitted by all nodes per second) for lattice networks with just horizontal flows, both horizontal and vertical flows and networks with random node placement and random source-destination pairs. Packet size :1500 bytes

Factors Affecting Capacity

- Physical channel conditions
- Efficiency of the MAC protocol
  - Overheads
  - back-off
- Degree of Contention amongst the nodes

Non-Pipelined Relaying

- Only one packet per flow is ‘in the network’ at any point in time
- Reduces the degree of contention drastically
- Provides temporal de-coupling between flows that enables effective load-balancing

Performance of NPR Scheme

$$TC(PR) = \frac{W.M}{l_{av}}$$

$$TC(nPR) = \sum_{k=1}^{\max_l} \frac{p_h(k).W.M}{k}$$

where

k : *No. of hops*

$\max_l$: Max. no of hops in any path (max hop length)

$p_h(k)$: hop - length distribution

W : Capacity of any contention region

M : Total number of contention regions in the network

l_{av} : Average length of flows in the network

Relative Performance of nPR

For a uniform distribution of hop lengths

$$\rho = \frac{\max_l + 1}{2} \cdot \frac{\log(\max_l)}{2}$$

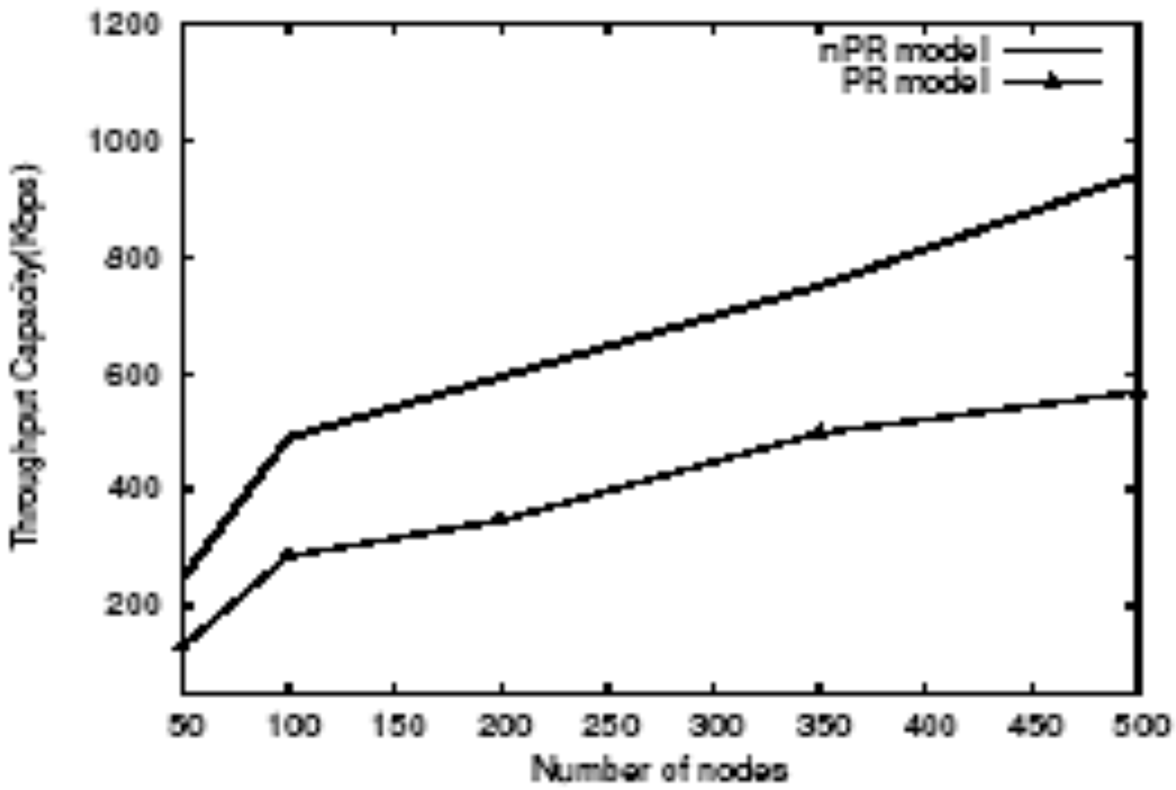
$$or,$$

$$\rho = O(\log(\max_l))$$

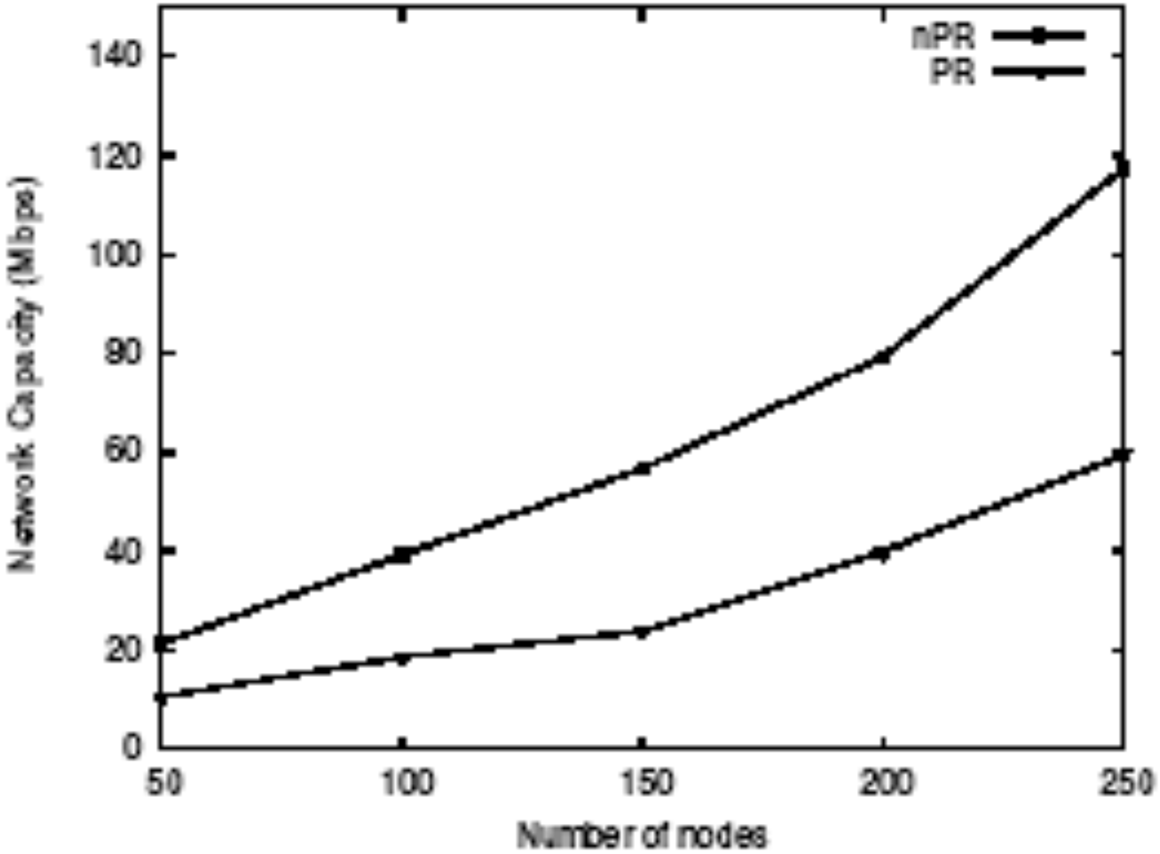
$$where$$

$$\rho = \frac{TC(nPR)}{TC(PR)}$$

Performance of nPR



Performance of nPR



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