Non-pipelined Relay Improves Throughput Performance of Wireless Ad-hoc Networks

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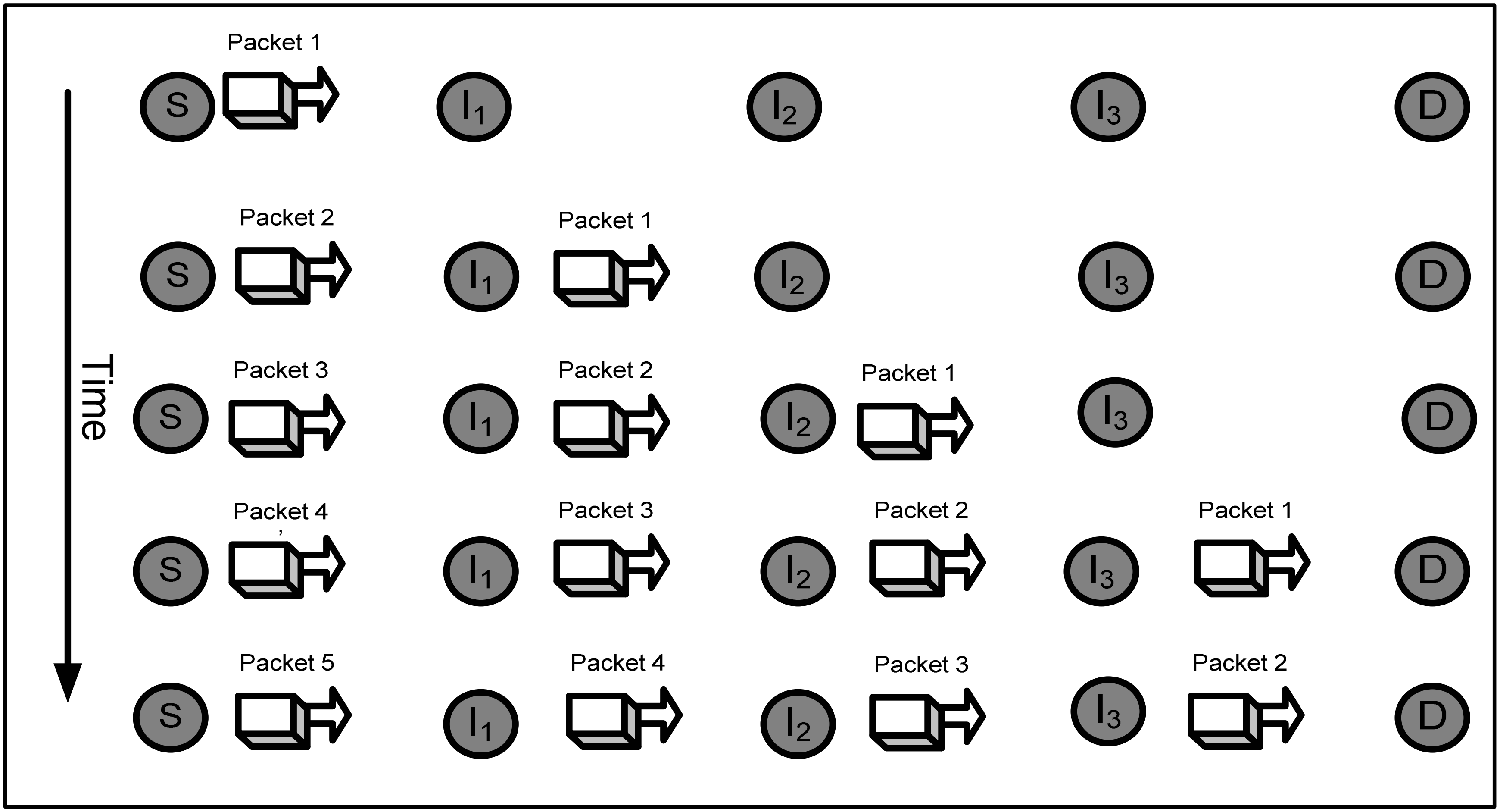
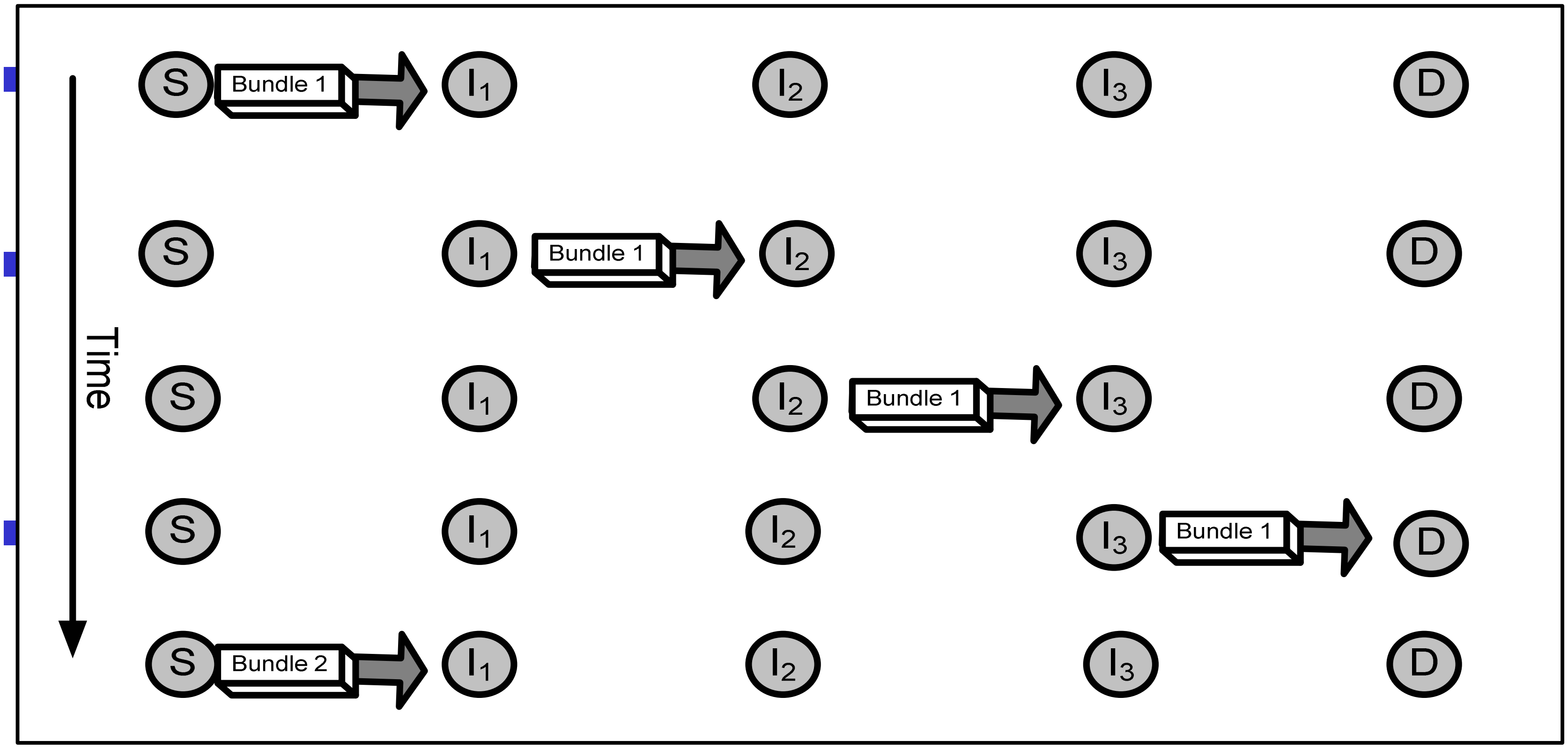
Overview

- Non-pipelined relay (*nPR*)
  - alternative to conventional pipelined strategy
- Benefits of *nPR* under idealized conditions
- Benefits of *nPR* under practical conditions
- Distributed Forwarding Protocol (DFP)
  - Instantiation of nPR under practical conditions
- Performance evaluation

Pipelined Relay (*PR*)



Non-Pipelined Packet Relay (*nPR*)



Overview

- Non-pipelined relay (*nPR*)
- Analysis of *nPR* under idealized conditions
  - Throughput Capacity
  - Network Transport Capacity
  - Fairness
- Benefits of *nPR* under practical conditions
- Distributed Forwarding Protocol
- Performance evaluation

Theoretical Analysis

- Model
  - Network topology : 3-D sphere of unit surface area
  - n nodes randomly distributed in the network
  - Every node is a source : total of n flows in the network
  - The network is assumed to be minimally connected
- Notations
  - W : capacity of the channel (or contention region)
  - M : Total number of contention regions in the network
  - l_{av} : Average hop-length of flows
  - max_l : maximum hop-length of flows in the network
  - $p_h(k)$: number of flows with hop-length k
- Experimental verification of the theoretical results using centralized MAC protocol without contention and centralized scheduler.

Throughput Capacity

- C_{PR} : Contention level using pipelined relay model

$$C_{PR} = \frac{\text{No. of mini-flows in the network using the PR model}}{\text{No. of contention regions in the network}} = \frac{n \,.\, l_{av}}{M}$$

λ_{PR} : Throughput achieved by a single flow using pipelined relaying

$$\lambda_{PR} = \frac{W}{C_{PR}} = \frac{W \,.\, M}{n \,.\, l_{av}}$$

TC_{PR} : Throughput capacity using pipelined relaying

$$TC_{PR} = n \,.\, \lambda_{PR} = \frac{W \,.\, M}{l_{av}}$$

Throughput capacity

- *nPR*'s single packet-in-transit principle => favors shorter hop flows at the cost of longer hop flows

- Given the hop distribution of the flows to be $p_h(k)$, we can derive the throughput capacity, TC_{nPR}, using non-pipelined relaying:

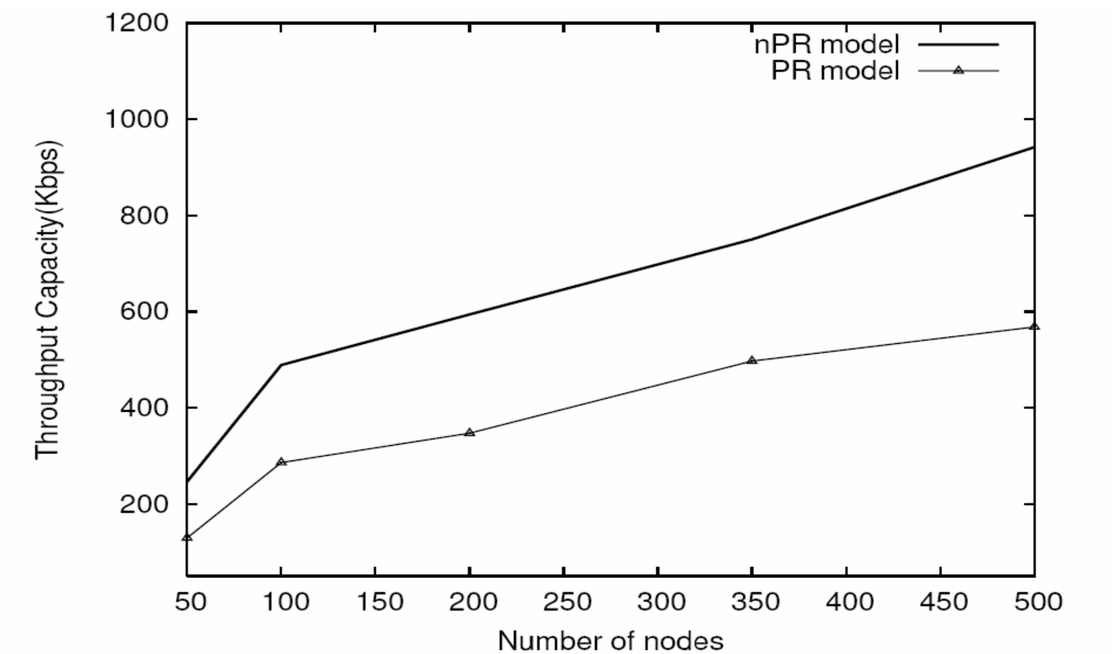
$$TC_{nPR} = \sum_{k=1}^{max_l} p_h(k) \cdot \frac{W \cdot M}{k}$$

- Ratio of the throughput capacities achieved using the two models :

$$\rho = \frac{TC_{nPR}}{TC_{PR}} = \frac{max_l + 1}{2} \cdot \frac{\log(max_l)}{max_l} = O(log(max_l))$$

Throughput capacity

- In nPR, every unit of throughput that a longer hop flow of hop-length l_{av} sacrifices increases the throughput of l_{av} single hop flows
- Improving aggregate throughput performance



Transport Capacity

- Number of bits transported in one second per meter by the network
- Using PR, the flows are constrained by the bottlenecked region through which they flow
- If all the flows in a contention region are bottlenecked in other regions, then the specific contention region is under-utilized using the pipelined model
- Using *nPR,* every mini-flow of each end-to-end flow achieves the fair-share capacity of the contention region it flows through

Transport Capacity

- $c_{\max}$: maximum contention level in any contention region
- Consider a contention region with contention level *c*
- Probability that all the flows are bottlenecked somewhere else is :

$$\{1 - (\frac{c}{c_{max}})^{h-1}\}^c$$

- Probability that a contention region is under-utilized using *PR* is given by :

$$\sum_{c=1}^{c_{max}} \frac{c}{c_{max}} \cdot \{1 - (\frac{c}{c_{max}})^{h-1}\}^c$$

Fairness

- Measure of the deviation among the throughputs of the flows in the network
- Conventional pipelined model achieves max-min fairness
- Using *nPR*, flows obtain end-to-end throughput inversely-proportional to their respective hop-length
- Kelly et. al have shown that rate vectors inversely proportional to utilities achieve proportional fairness
- Hence using this as the underlying model we show that *nPR* achieves proportionally-fair allocation of throughputs to the end-to-end flows

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- Non-pipelined relay (*nPR*)
- Benefits of *nPR* under idealized conditions
  - Throughput Capacity
  - Network Transport Capacity
  - Fairness
- Benefits of *nPR* under practical conditions
  - MAC utilization
  - Potential for Load Balanced routing
- Distributed Forwarding Protocol
- Performance evaluation

Impact on MAC Performance

- Under practical conditions, MAC protocols are contention based protocols
- Performance decreases with increased load (contending flows) due to the increase in distributed inefficiencies such as backoffs and collisions
- *nPR* decreases the effective load in the network by decreasing the number of mini-flows contending for network resources
- This in turn reduces the average number of contending mini-flows in each contention region
- Hence nPR achieves better MAC utilization than PR

Impact on Load Balanced Routing

- Load balanced routing (LBR) finds routes which have shortest length as well as having the least contention along the path from the source to destination
- Such routes are called shortest-widest routes
- Conventional pipelined strategy has been shown to have very low potential for LBR because of the strong coupling among the flows in the network
- But nPR achieves temporal decoupling among the flows
- This increases the potential of load balanced routing in finding widest-shortest routes than *PR*

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- Distributed Forwarding Protocol
  - Practical instantiation of the nPR model
- Performance evaluation

Distributed Forwarding Protocol (DFP)

- Realizes non-pipelined relay model under practical conditions
- Sits on top of the routing layer and beneath the transport layer in the protocol stack
- Every packet forwarded by intermediate node passes through the DFP layer
- Three key elements of the protocol
  - Proactive Acknowledgments
  - Proportional Rate Adaptation
  - Load Balanced Routing

Proactive Acknowledgments

- *nPR* implements the non-pipelined strategy of one packet per flow
- Require a mechanism to ensure that one data unit is *always* in transit for every flow in the network
- Cannot be achieved using simple destination based acknowledgements
  - No data packet in transit until the destination generated acknowledgement reaches the source
- DFP design consists of the mid-point ACK strategy where the temporal mid-point of the end-to-end flow sends back an ACK to the source.
- The source would receive the ACK at the same time the destination receives the data packet
- Temporal mid-points are calculated using timestamps on packets.

Proportional Rate Adaptation

- MAC protocol optimization curve has an under-utilization region
- Ensure that *nPR* operates in the optimal region of the utilization curve
- Monitor the utilization of the network
  - Marking-based feedback mechanism for monitoring
- Increases the number of packets in transit if the network is underutilized
- The increase in the number of packets in transit by each flow is done
  - to adhere to the proportional fairness model established by *nPR*
  - Avoid self-contention between packets in transit for the same flow

Load Balanced Routing

- *nPR* provides temporal separation between the mini-flows
- High potential for improvement using Load Balanced Routing (LBR)
- DFP design consists of a load-balanced routing element
- Nodes keeps track of number active flows passing through them
- Apart from number of hops, route response packets contain the maximum contention along the route from the source to the destination
- Sources select routes based on both hop-count and maximum contention level of the candidate routes

Overview

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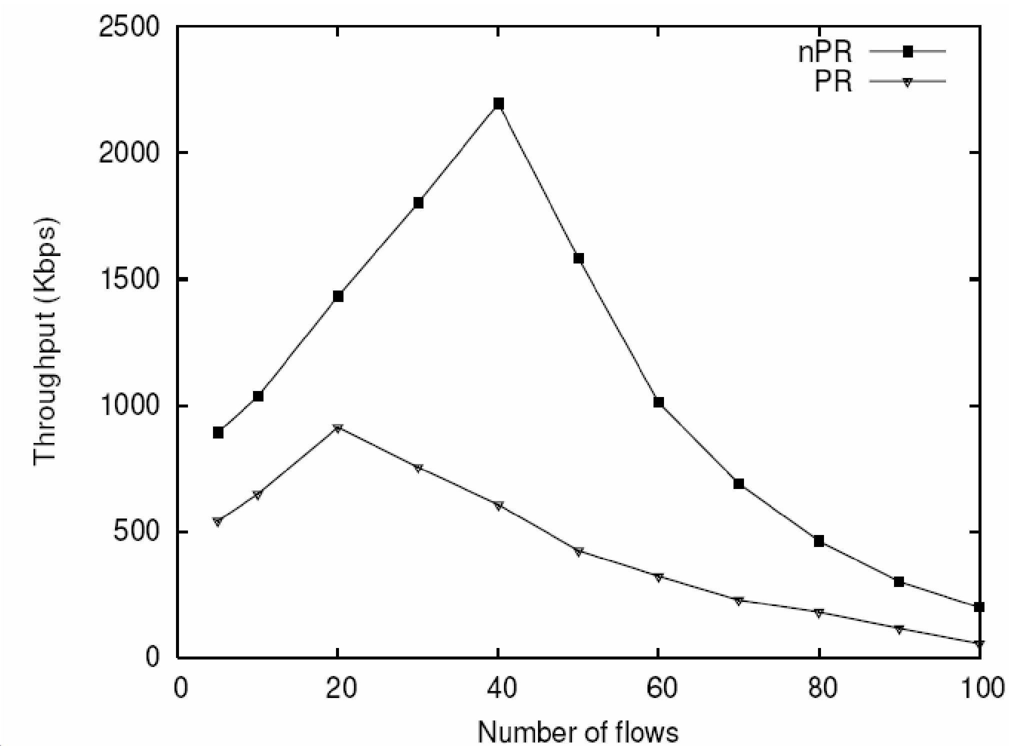
- Benefits of *nPR* under idealized conditions
- Benefits of *nPR* under practical conditions
- Distributed Forwarding Protocol : nPR instantiation in practical conditions
- Performance comparison of DFP and conventional forwarding scheme

Evaluation model

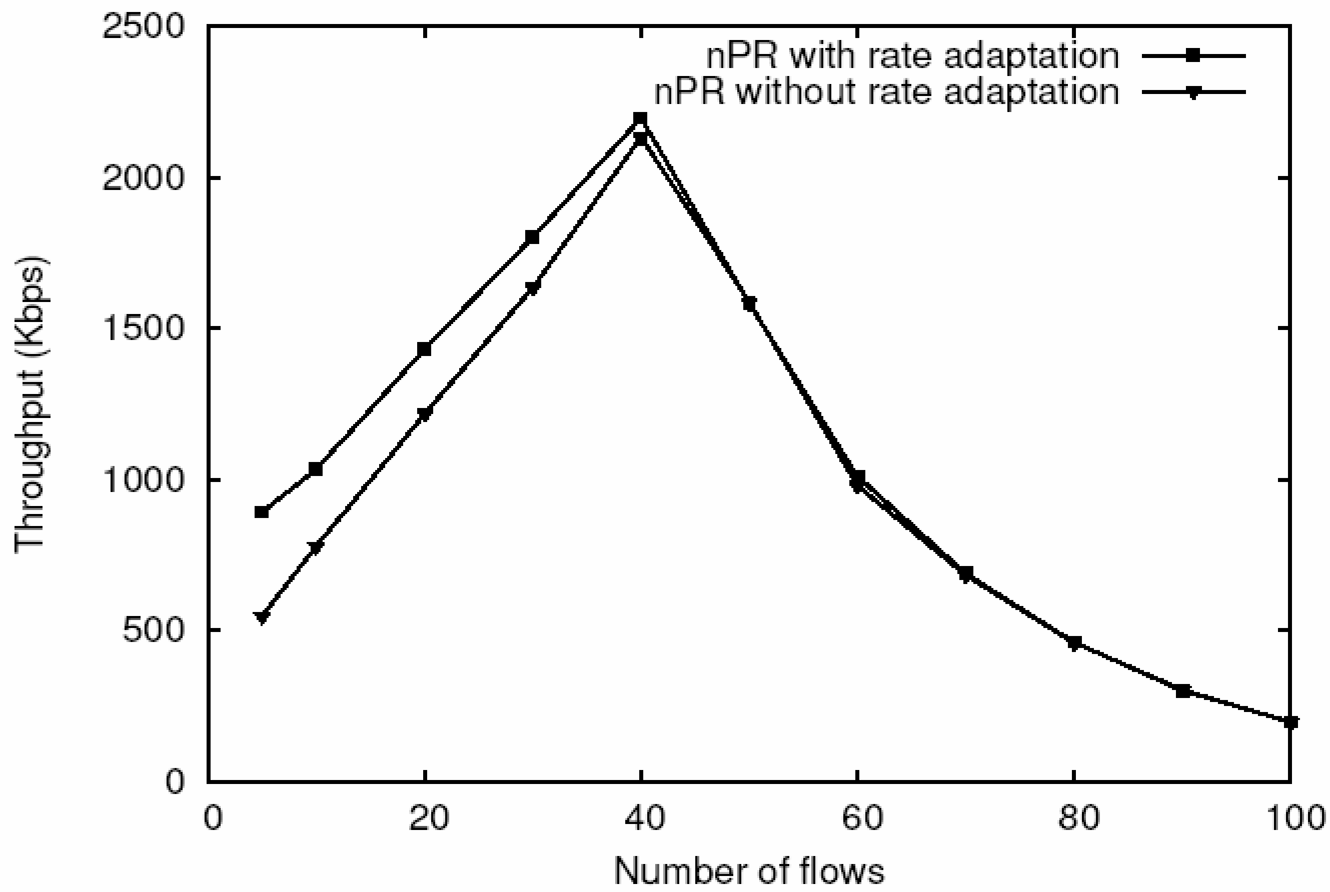
- ns2 based simulations
  - 100 nodes
  - 1000x1000 network grid
  - Application traffic : CBR traffic
  - DSR used for PR routing
  - CSMA/CA used for MAC
  - Random waypoint mobility model
  - Data points averaged over 20 simulations

Impact of Load

- Peak of utilization occurs at a higher load using *nPR*
- Scalability due to the reduction in the number of mini-flows contributed by end-to-end flows



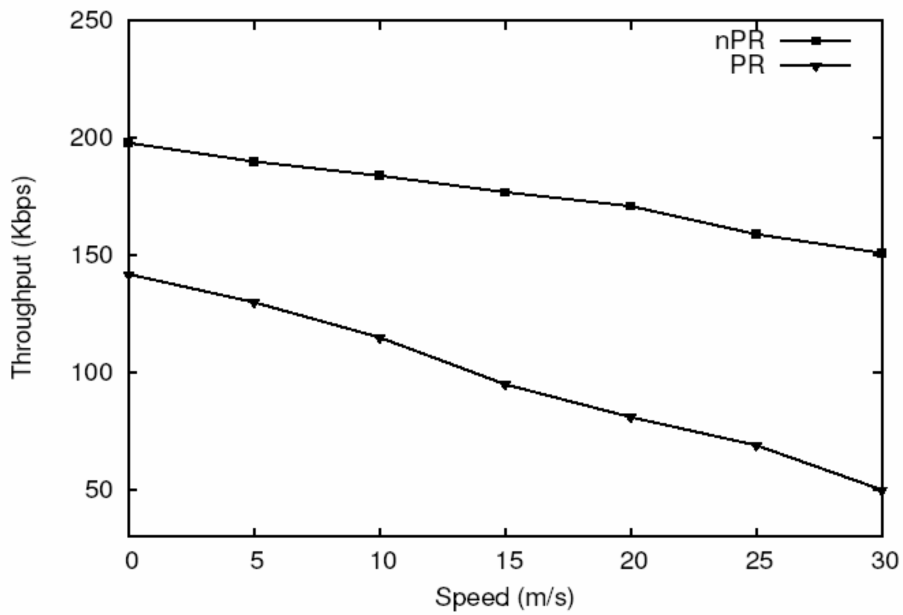
Low loads



nPR with rate adaptation
nPR without rate adaptation
Throughput (Kbps)
Number of flows
0
500
1000
1500
2000
2500
20
40
60
80
100

Impact of mobility

- *nPR* increases the throughput of the end-to-end flows and hence reduces lifetime of flows with finite amount of data to transmit
- Lesser number of mobility induced route errors using *nPR*



Summary

- Non-pipelining brings in benefits both under idealized and practical conditions
- Practical instantiation of the nPR strategy : Distributed Forwarding Protocol (DFP)
- Performance evaluation of DFP to compare against conventional forwarding policies

- For more information:
  - http://www.ece.gatech.edu/research/GNAN

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