جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
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Quality of Service and Resource Optimization in Wireless Multihop Networks

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KAUST-NSF Conference
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YAHOO!

400 ms slowdown resulted in a traffic decrease of 9%

[Yslow 2.0; Stoyan Stefanov]

Google

100 ms slowdown reduces # searches by 0.2-0.4%

[Speed matters for Google Web Search; Jake Brutlag]

AOL

Users with lowest 10% latency viewed 50% more pages than those with highest 10% latency

[The secret weapons of the AOL optimization team; Dave Artz]

mozilla Firefox

2.2 sec faster web response increases 60 million more Firefox install package downloads per year

[Firefox and Page Load Speed; Blake Cutler]

Walmart

Users with 0-1 sec load time have 2x conversion rate of 1-2 sec

[Is page performance a factor of site conversion? And how big is it; Walmart Labs]

amazon.com

YAHOO!

Google

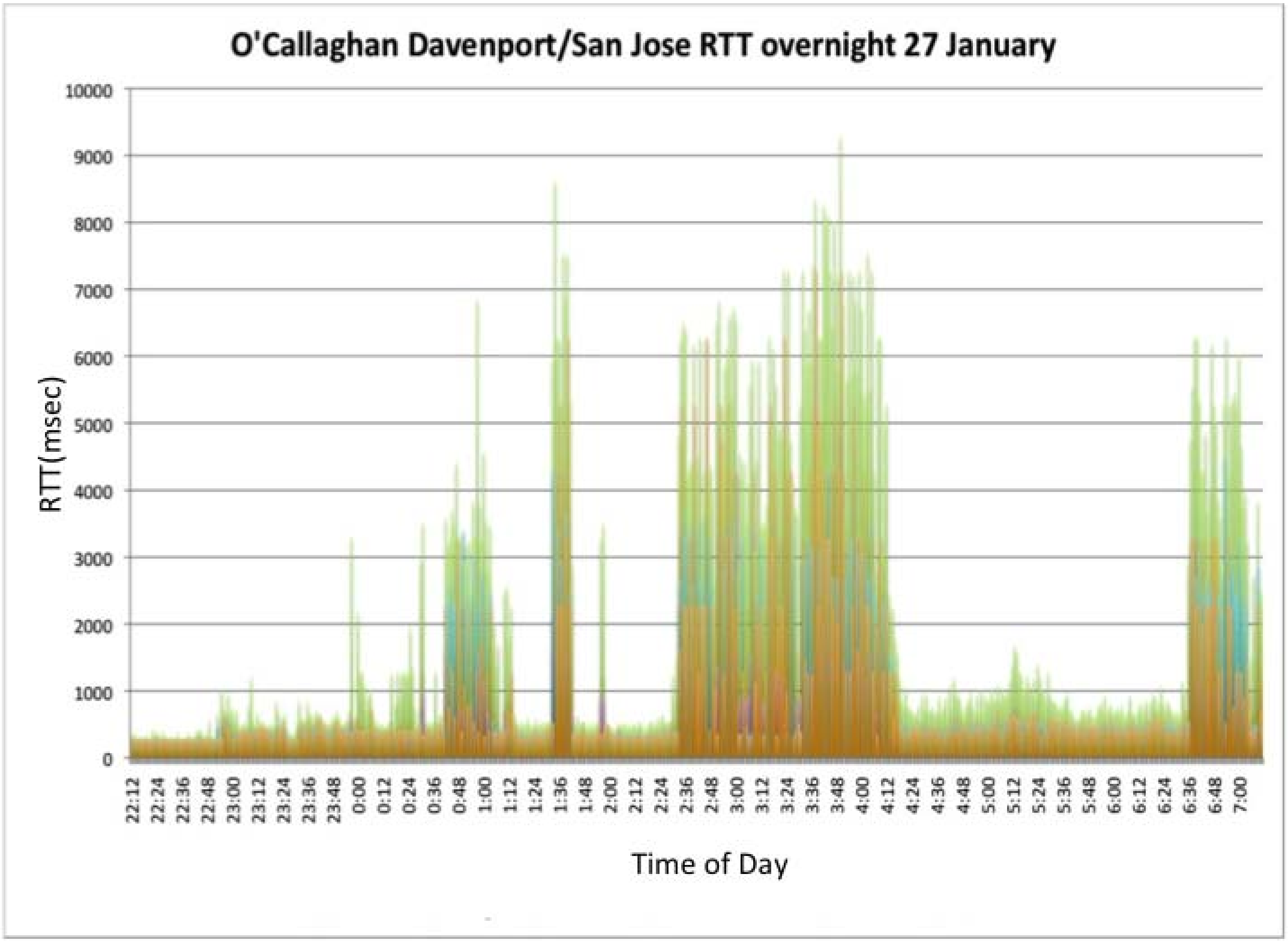
AOL

Firefox

Walmart

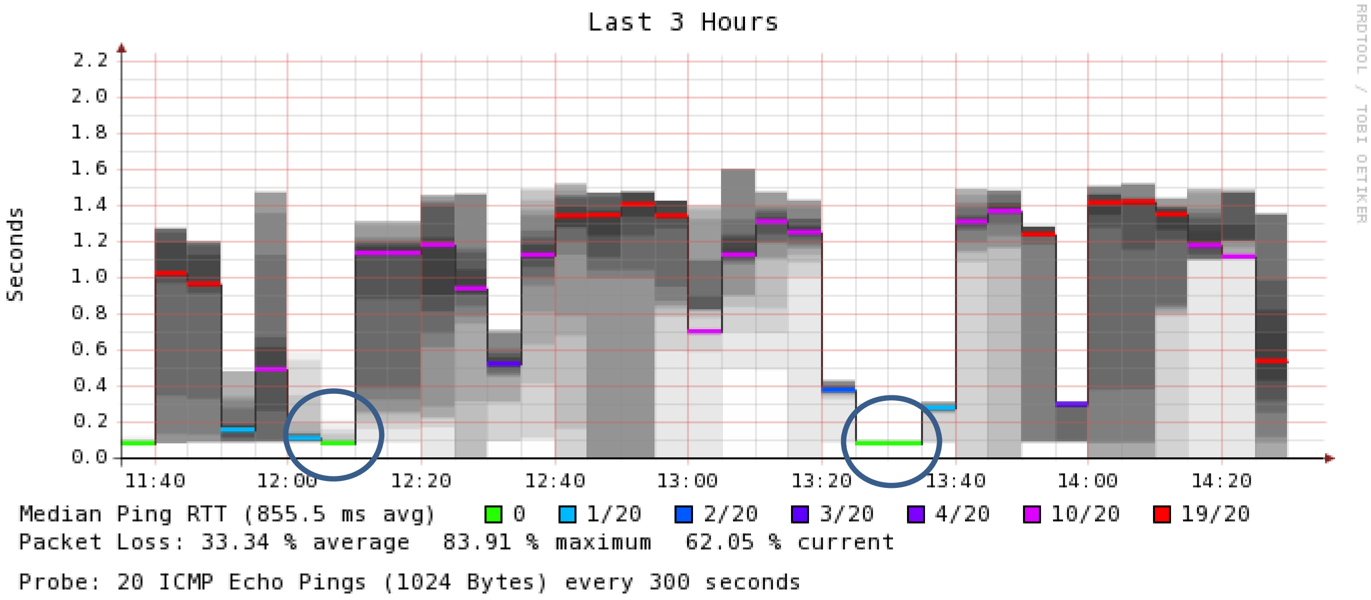
Users Respond to LATENCY!

How Bad are the Delays?



Pan, Rong, et al. "PIE: A Lightweight Control Scheme to Address the Bufferbloat Problem.". In Proceedings of the 2013 IEEE Conference on High Performance Switching and Routing, July 2013

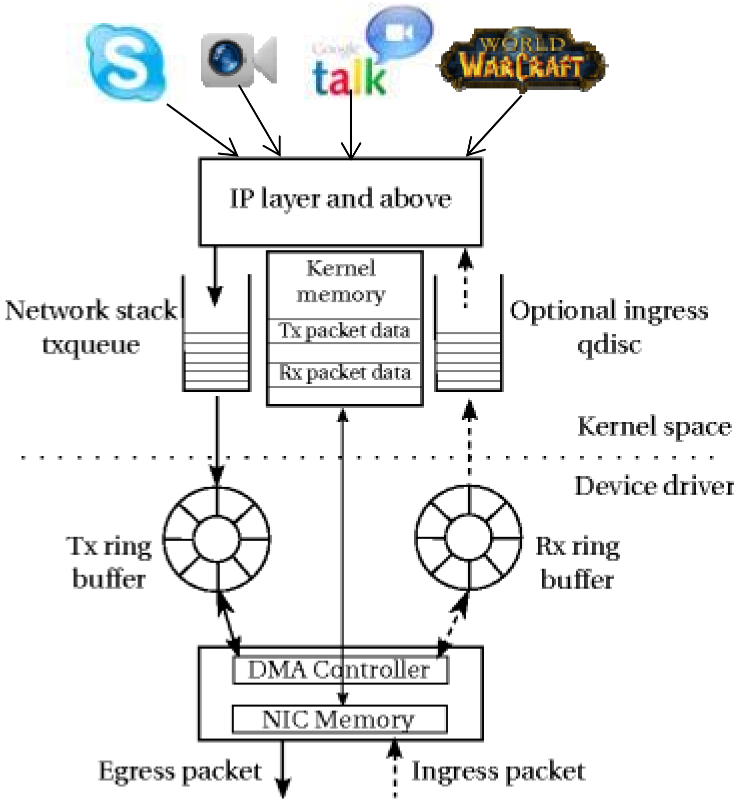
How Bad are the Delays?



Measurements in a wired access network with system backup to a remote server. Consistent delays of over 1 sec.

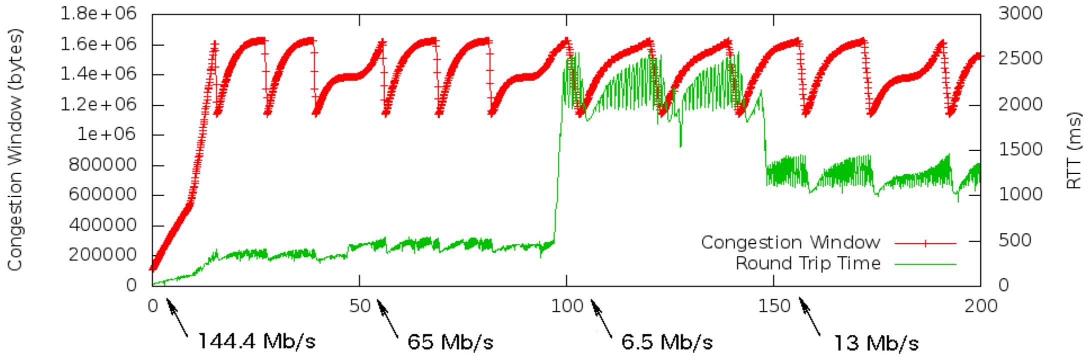
Where are the Bloated Buffers?

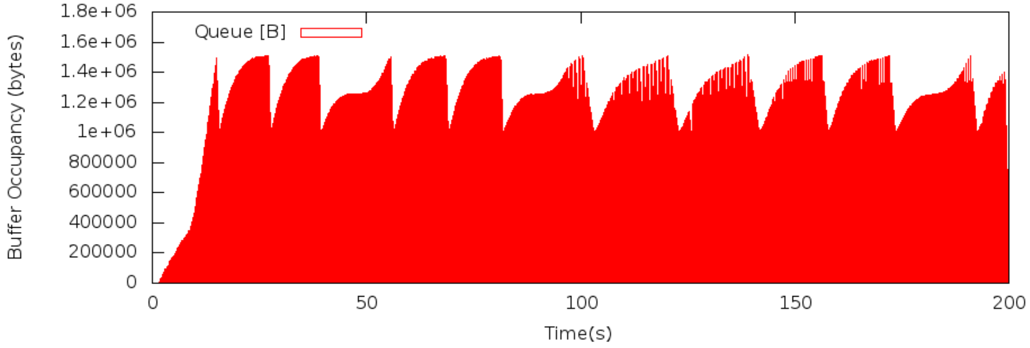
- Buffers exist at multiple layers in the stack
  - Application layer buffers
  - TCP socket buffers
  - Txqueue buffers
  - Device driver ring buffers
  - Hardware buffers

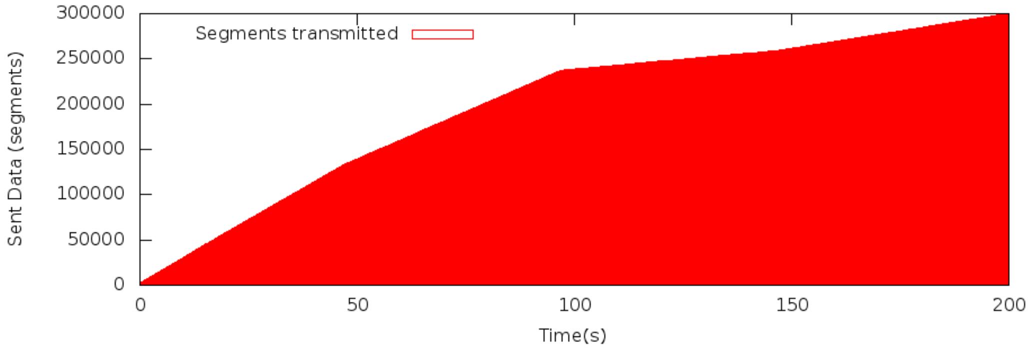


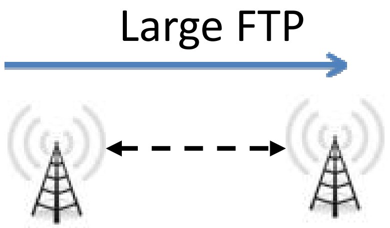
K. Jamshaid, B. Shihada, A. Showail, and P. Levis, “Deflating link buffers in Wireless Mesh Networks", *Elsevier Journal of Ad-Hoc Networks*, Accepted, 2014.

Txqueue buffers are Bloated





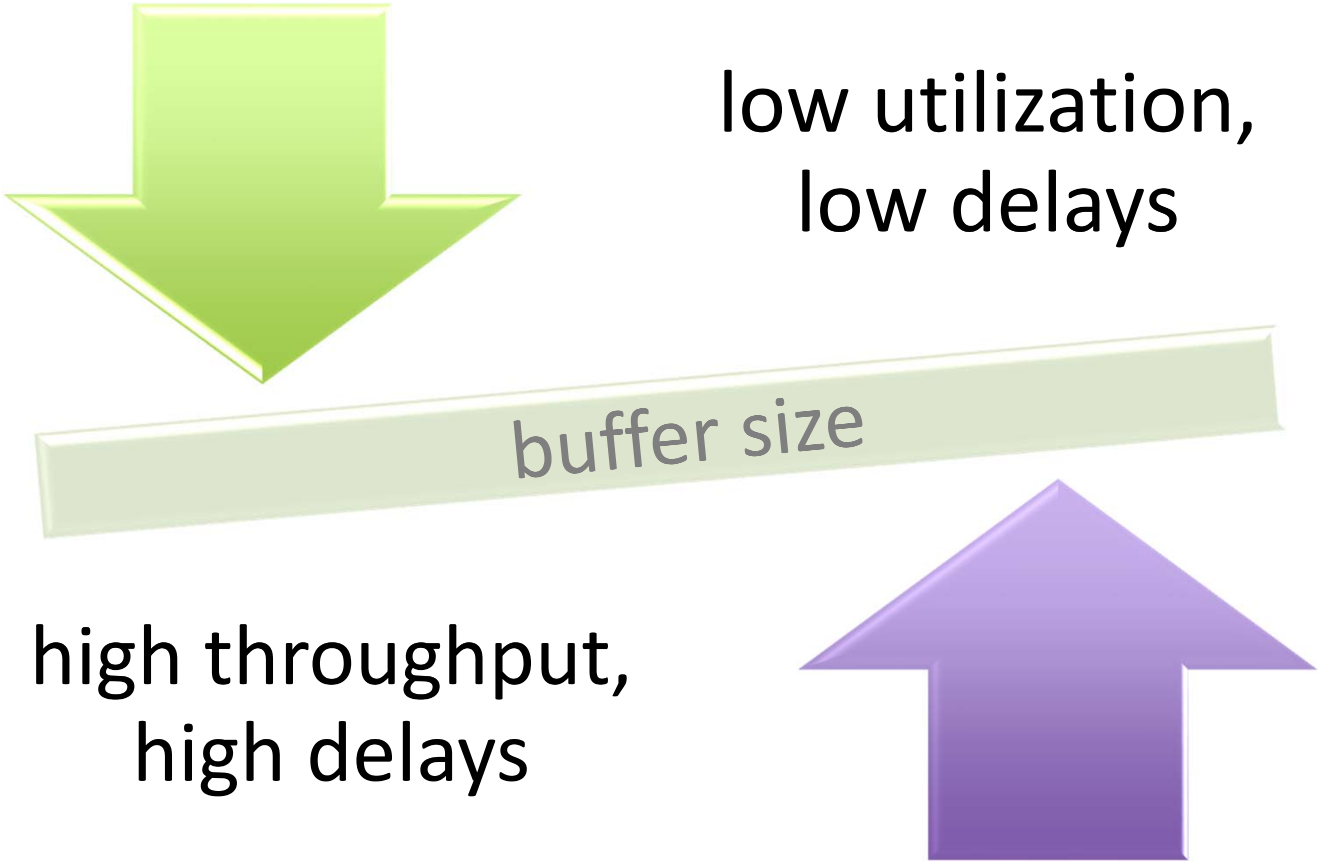




← 1000 packets

(packet→1500B)

Problem Statement



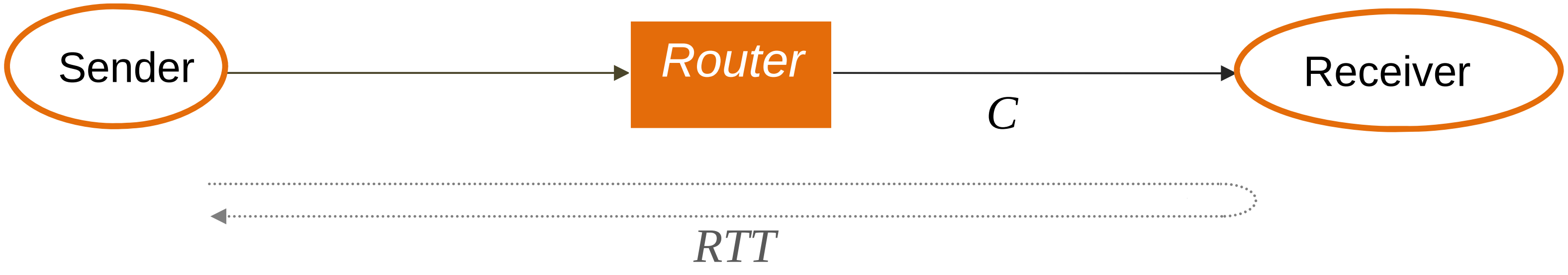
low utilization,
low delays

buffer size

high throughput,
high delays

Determine buffer size to balance throughput and delay tradeoff

Buffer Sizing Rule of Thumb



Router needs a buffer size of

$$B = RTT \times C$$

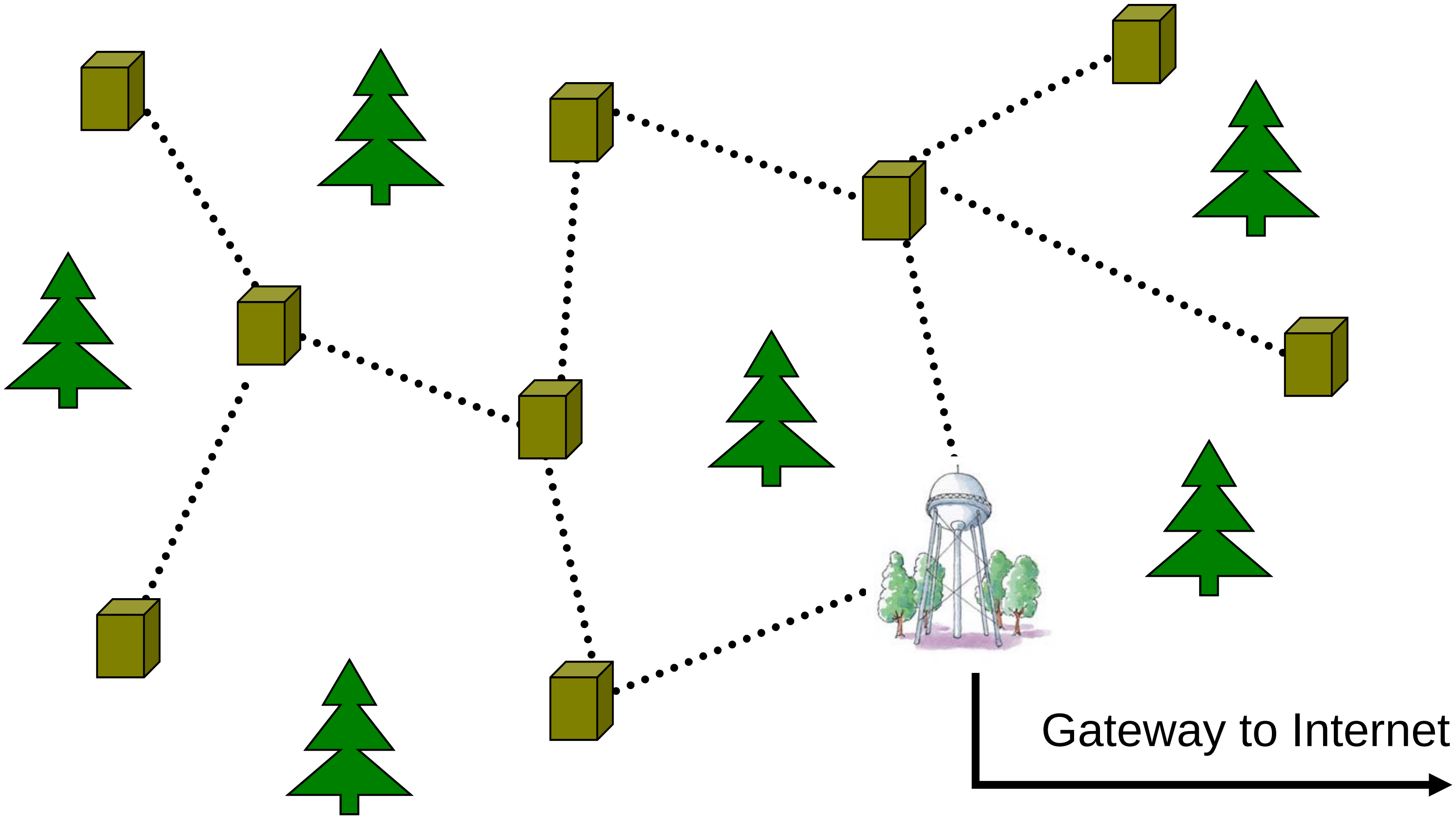
- *RTT* is the two-way propagation delay
- *C* is the bottleneck link capacity

Rule of Thump Exception in Wireless Networks

- Wireless link: abstraction for shared spectrum
- Variable Frame Aggregation
- Variable Packet Inter-Service Rate
- Adaptive link rates

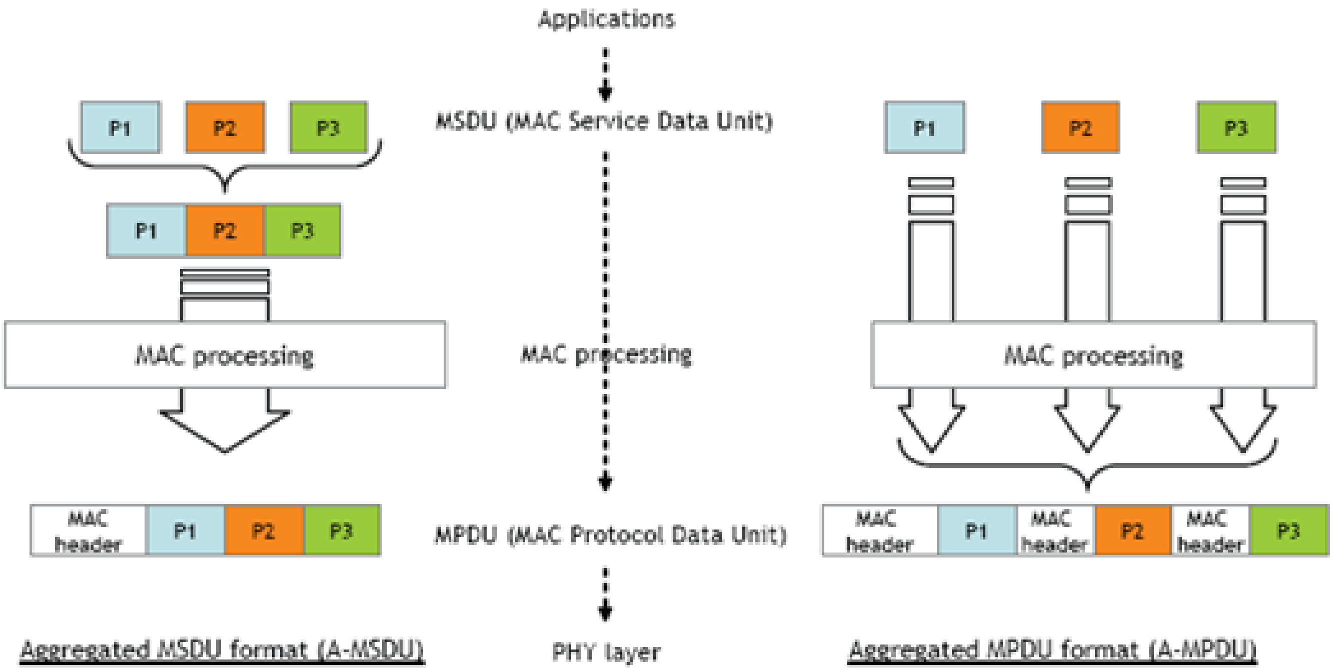
Challenges in Wireless Networks

- Wireless link: abstraction for shared spectrum
  - Bottleneck spread over multiple nodes



Challenges in Wireless Networks

- Wireless link: abstraction for shared spectrum
  - Bottleneck spread over multiple nodes
- Variable Frame Aggregation
  - Impact of large aggregates with multiple sub-frames

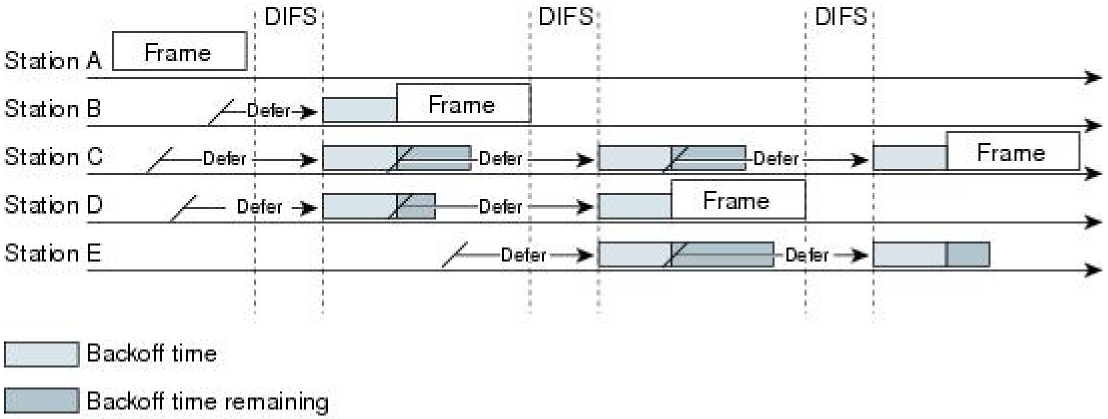


Challenges in Wireless Networks

- Wireless link: abstraction for shared spectrum
  - Bottleneck spread over multiple nodes

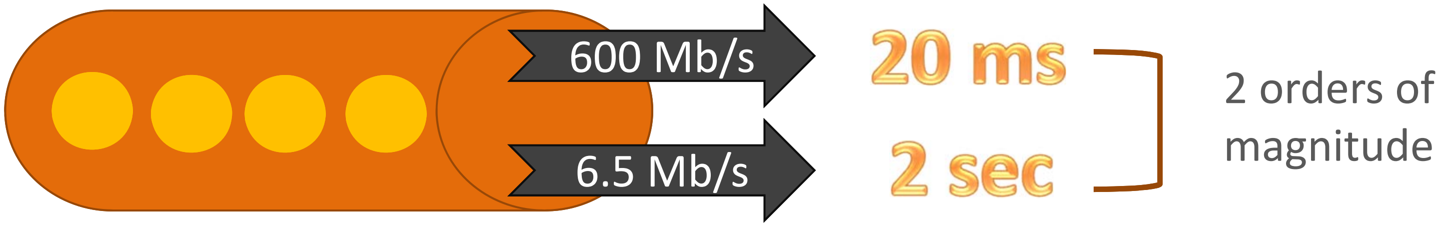
- Variable Frame Aggregation
  - Impact of large aggregates with multiple sub-frames

- Variable Packet Inter-Service Rate
  - Random MAC scheduling
  - Random noise and interference



Challenges in Wireless Networks

- Wireless link: abstraction for shared spectrum
  - Bottleneck spread over multiple nodes
- Variable Frame Aggregation
  - Impact of large aggregates with multiple sub-frames
- Variable Packet Inter-Service Rate
  - Random MAC scheduling
  - Sporadic noise and interference
- Adaptive link rates
  - With the default Linux buffer size, the time to empty a full buffer:



A. Showail, K. Jamshaid, B. Shihada, “Buffer sizing in wireless networks: Challenges and Opportunities", IEEE Communication Magazine, Submitted, 2014.

What about Wireless Multihop?

- Wireless link: abstraction for shared spectrum
- Variable Frame Aggregation
- Variable Packet Inter-Service Rate
- Adaptive link rates

Severe performance degradation on
throughput, delay, dropping

Solution Framework

- Wireless link: abstraction for shared spectrum
- Variable Frame Aggregation
- Variable Packet Inter-Service Rate
- Adaptive link rates

DNB

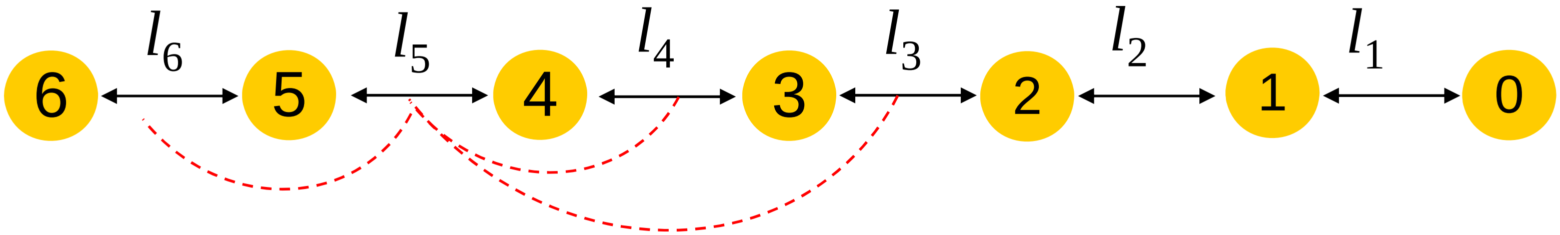
Severe performance degradation on throughput, delay, dropping

B. Shihada and K. Jamshaid†, "Buffer Sizing for Balancing Throughput and Delay Requirements in Multi-hop Wireless Networks," U.S. Patent No.: 8,638,686. 2014.

Collision Domains

Set of interfering links that contend for channel access

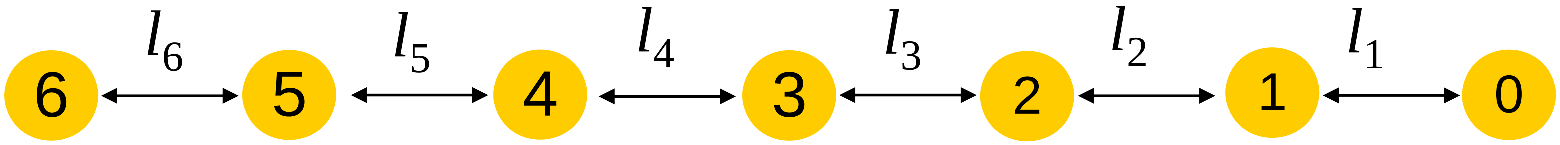
2-hop interference model: approximates RTS/CTS use in 802.11



Bottleneck Collision Domain

Set of links that contend with max. no. of links

  - Limits the end-to-end rate of a flow



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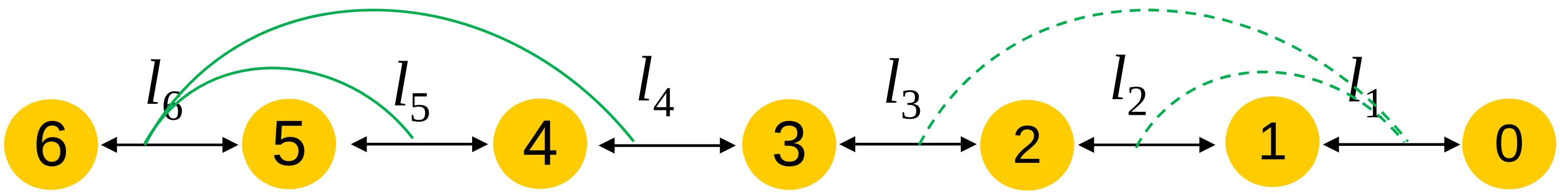

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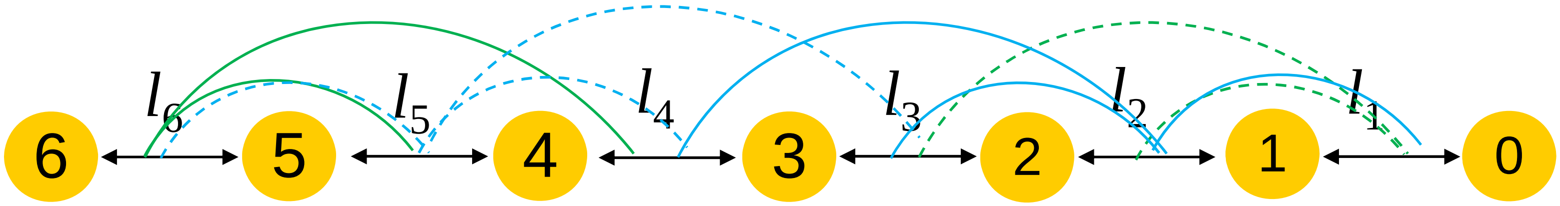

Bottleneck Collision Domain

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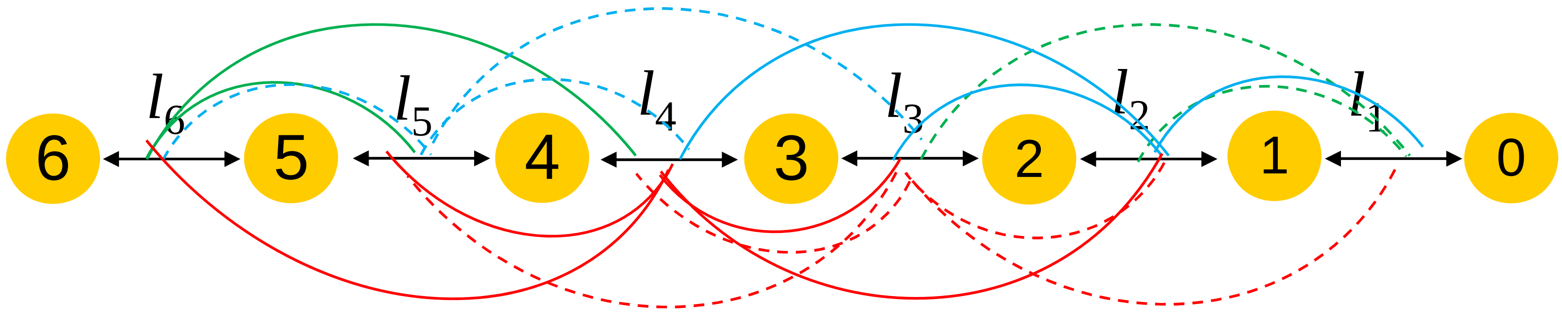
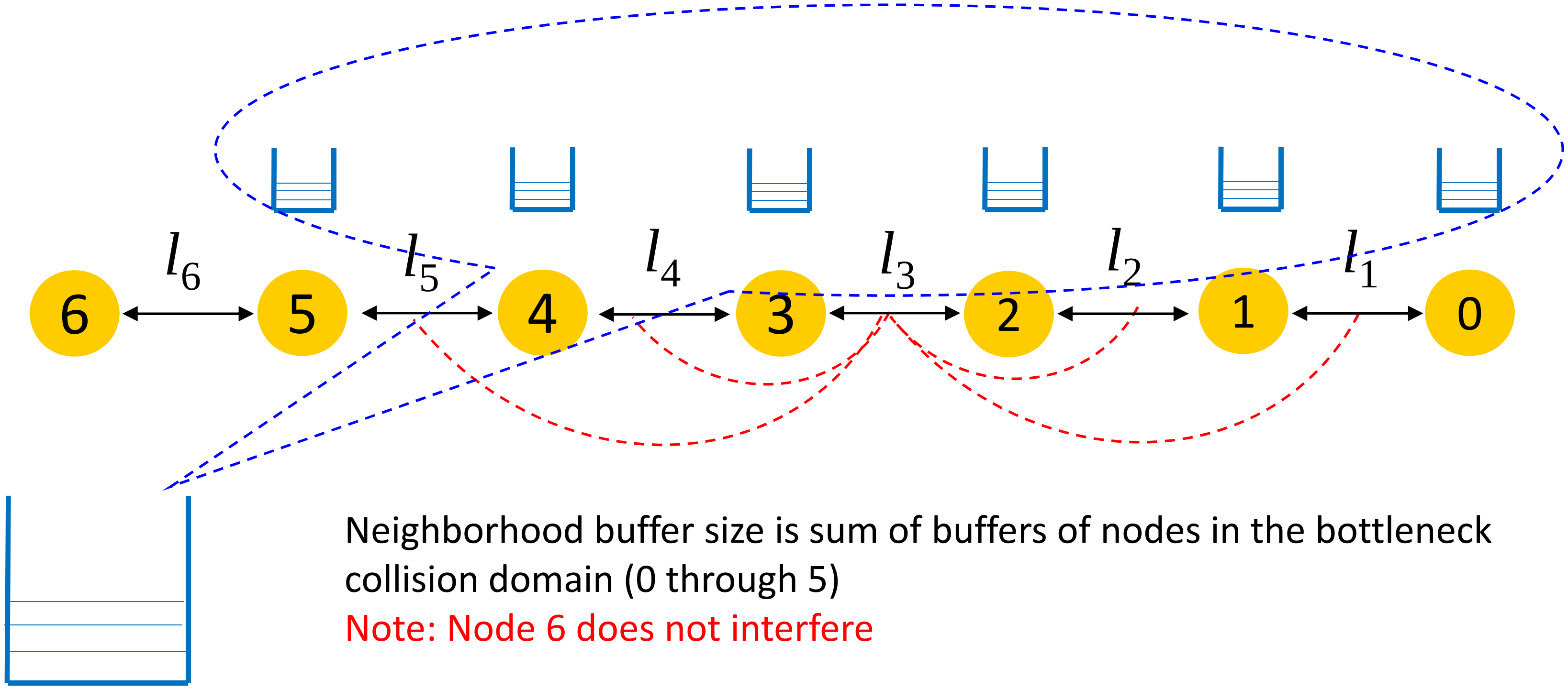


Neighborhood Buffer

Instead of having big local buffers at each node consider the combined effect of interfering nodes when sizing the buffer:

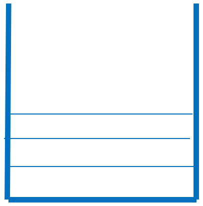


Neighborhood buffer size is sum of buffers of nodes in the bottleneck collision domain (0 through 5)

Note: Node 6 does not interfere

DNB
Distributed Neighborhood Buffer

1) Determine bottleneck buffer B



$$B = R * RTT$$

1) Assign b_i to nodes s. t. $B = \sum_{i \in bottleneck} b_i$

Assigning Per-node Buffer

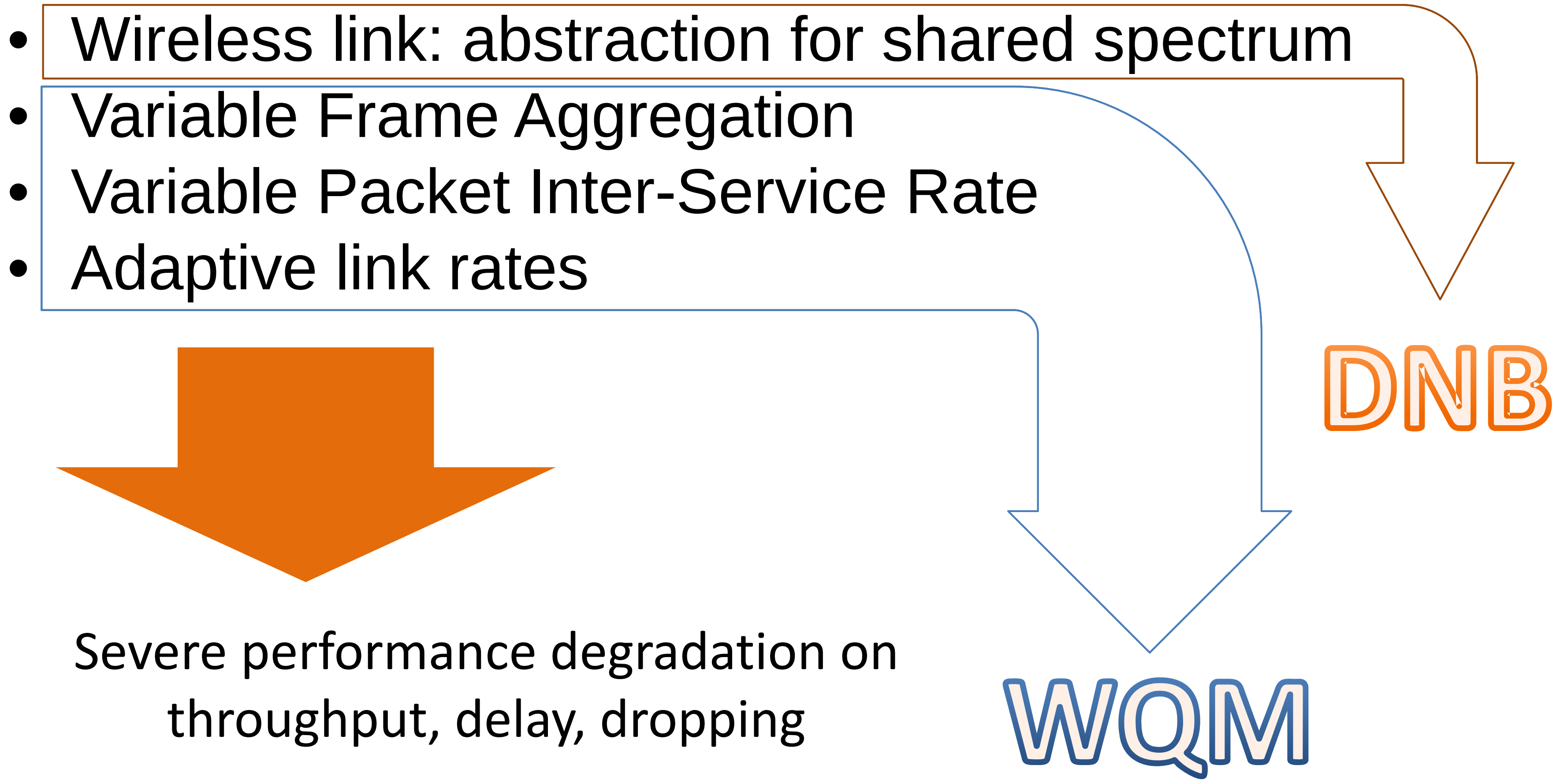
- Drops close to source are preferable
- Introduces a generic cost function
  - cost of drop increases with hop count

$$\min \sum_{i=1}^{M} Drop\ probability\ \times cost\ function$$

$$\begin{array}{cl} \text{subject to} & \sum_{i=1}^{M} b_i = B \\ \text{and} & b_i \geq 0, \forall\ i \in M \end{array}$$

M is the # of nodes in the bottleneck collision domain

Solution Framework



- Wireless link: abstraction for shared spectrum
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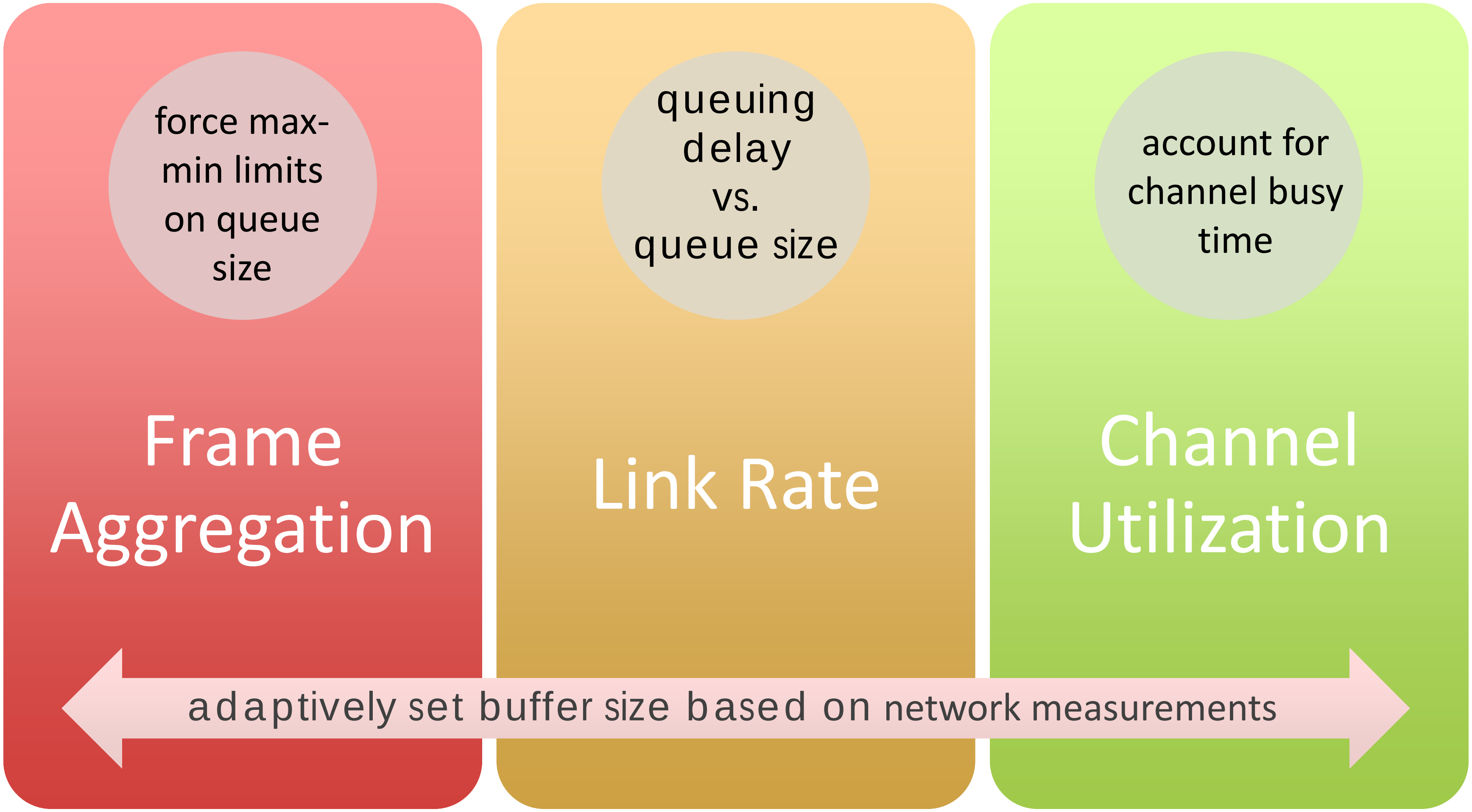
Severe performance degradation on throughput, delay, dropping

DNB

WQM

A. Showail, K. Jamshaid, B. Shihada, "An Empirical Evaluation of Bufferbloat in IEEE 802.11n Wireless Networks", IEEE Wireless Communications and Networking Conference (WCNC), Accepted, 2014

WQM
Wireless Queue Management



force max-min limits on queue size

Frame Aggregation

queuing delay vs. queue size

Link Rate

account for channel busy time

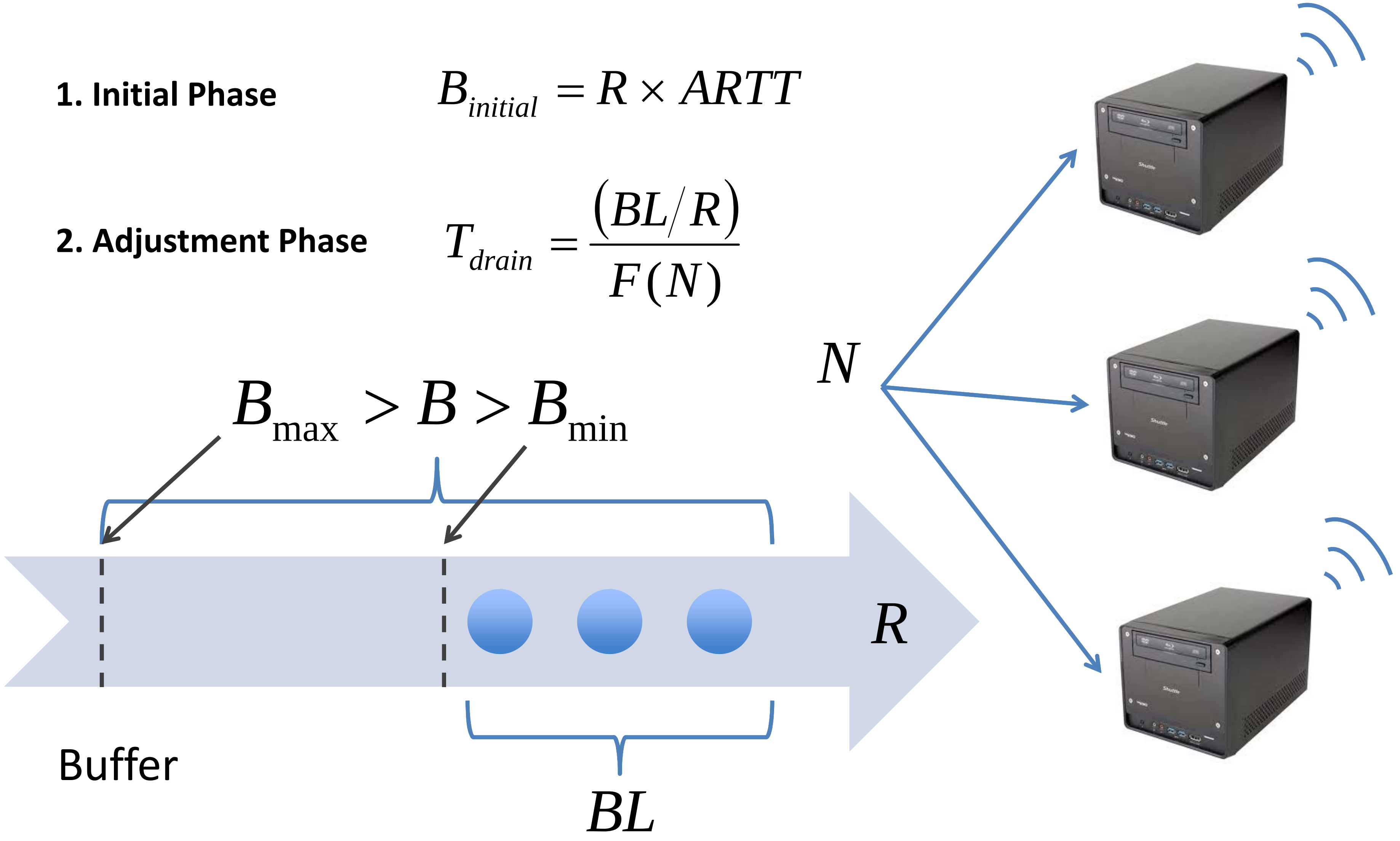
Channel Utilization

adaptively set buffer size based on network measurements

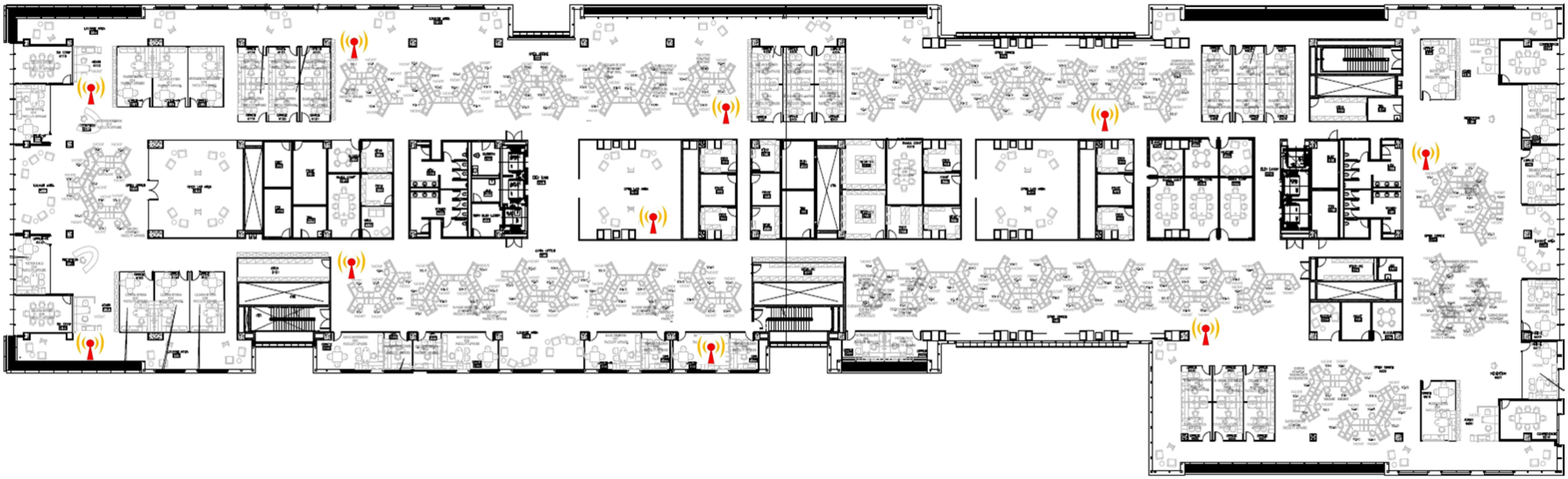
WQM Operations

1. Initial Phase $B_{initial} = R \times ARTT$

2. Adjustment Phase $T_{drain} = \dfrac{(BL/R)}{F(N)}$

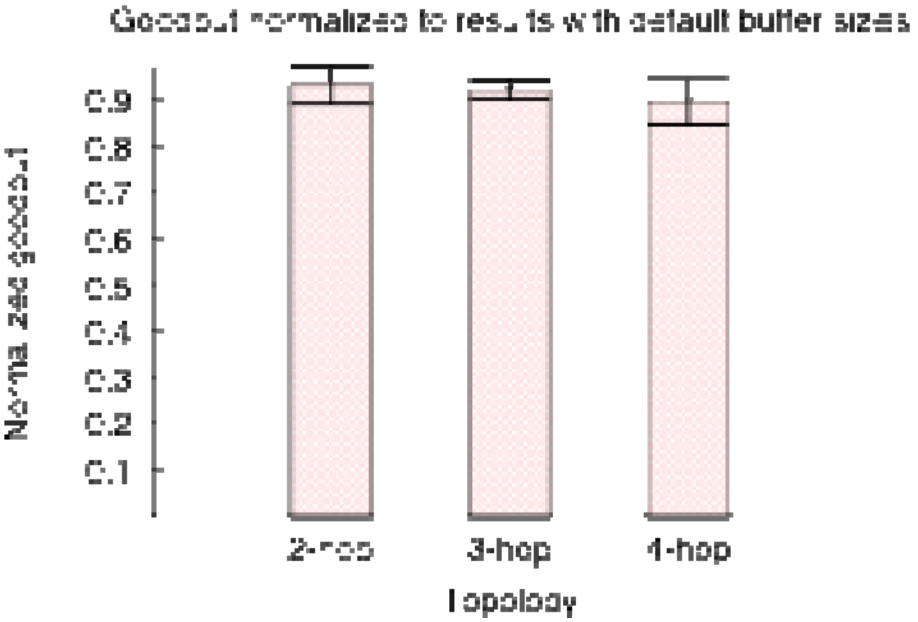


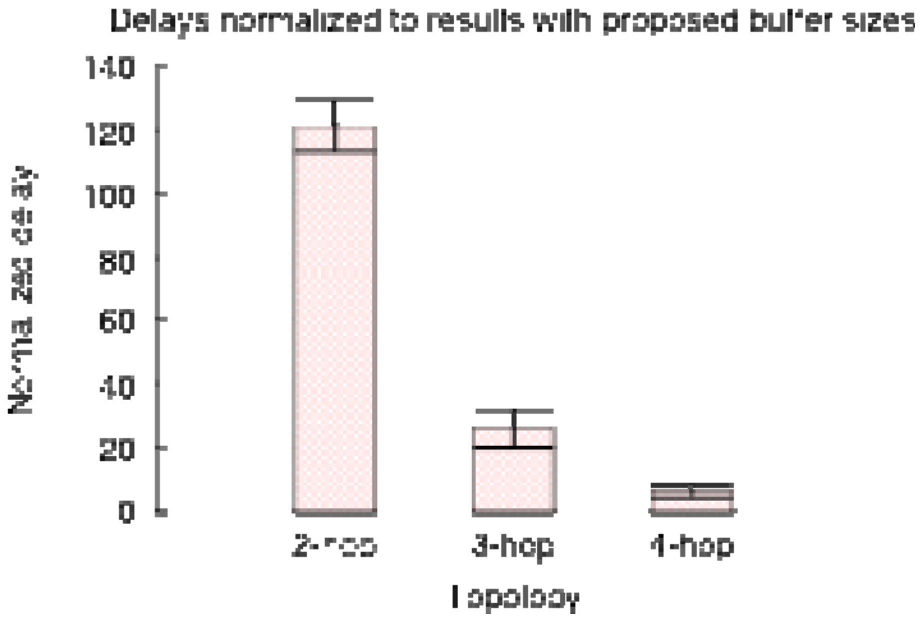
Testbed Topology



Node setup: 10 Distributed Shuttle Nodes at Building 1, Level 4.
Software setup: Customized Linux kernel for statistics collection
Network traffic setup: Large file transfers

DNB with Single-flow





Two-orders of magnitude improvement in delay while achieving 90% goodput

DNB with Multi-flows

Intersecting 3-hop & 4-hop flows in our 10-nodes testbed

Scheme	Avg. goodput	Mean RTT
Default buffer size	786	1653
Proposed buffer sizing	712	91

Average RTT is reduced by a factor of 20 at the cost of 9% drop in goodput

WQM over a Single-hop

Num. of Flows	Default Buffer Size		WQM	
	Throughput (Mb/s)	RTT (ms)	Throughput (Mb/s)	RTT (ms)
1	155.7	61.51	134.35	13.1
2	78.43	65.8	69.21	13.47
3	51.96	420.66	45.77	14.19
4	39.22	213.19	33.96	14.91
5	31.38	937.56	27.41	14.93

Latency improvement of > 5x with around10% throughput drop

WQM prevents flows from filling up the buffers quickly while starving others

Num. of Flows	Jain’s fairness index (JFI)	
	Default Buffer Size	WQM
2	0.99	0.99
3	0.7	0.99
4	0.89	0.99
5	0.69	0.99

WQM over Multi-hops

Num. of Flows	Default Buffer Size		WQM	
	Throughput (Mb/s)	RTT (ms)	Throughput (Mb/s)	RTT (ms)
1	68.32	169.44	61.08	33.76
2	34.52	165.3	32.1	35.32
3	22.89	177.09	20.4	38.83
4	17.06	186.29	15.94	38.55
5	13.76	193.47	12.54	38.2

WQM reduces RTT by 5× with the cost of 10% drop in throughput in the worst case

Audio demo

- Network traffic setup: 1 file transfer in the background + 1 real-time audio stream

Wireless - Default

wireless-default.mp3

Wireless - Proposed

wireless-proposed.mp3

Wired

wired-network.mp3

Video demo

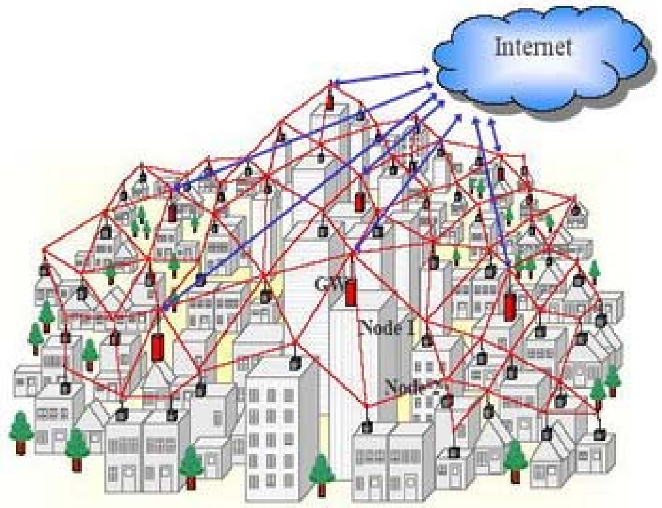
- Network traffic setup: 1 file transfer in background + real-time video streaming

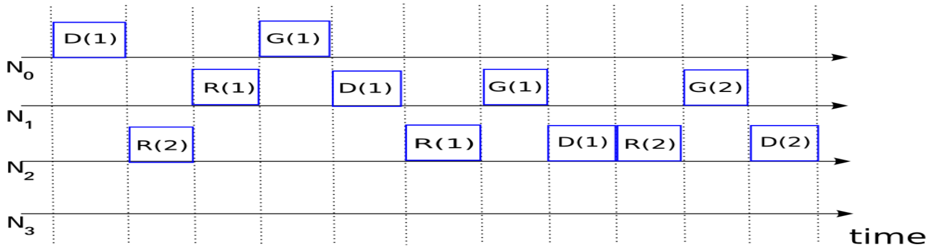
Concluding Remarks

- Challenge: Choosing the optimal queue size in wireless networks
- Proposed Solutions:
  - DNB: sizing bottleneck buffers and distributing it among nodes
  - WQM: chooses the queue size based on network load and channel condition
- Performance: Improvements in *latency* by at least 5*x* over default Linux buffers
- Feature: Improvements in network fairness by limiting the ability of a single flow to saturate the buffers

Fairness in Wireless Multi-Hop

- The objective is to “fairly” allocate channel resources among WMN nodes [1,2,3].
- Proposed a distributed MAC layer protocol, called T-MAC, which extends Lamport’s mutual exclusion algorithm to frame scheduling in WMN.
- Using analytical modeling of TCP streams, we derive a closed-form solution for throughput[2]
- T-MAC implemented in ns-3. Our results achieve fairness while maintaining high network utilization[3]





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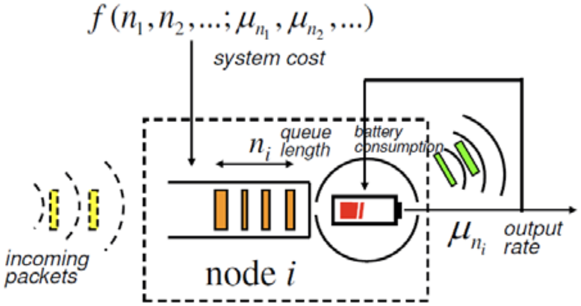
[1] F. Nawab, K. Jamshaid, B. Shihada, and P-H. Ho, "TMAC: Timestamp-ordered MAC for CSMA/CA Wireless Mesh Networks", In Proc. *IEEE ICCCN* 2011.

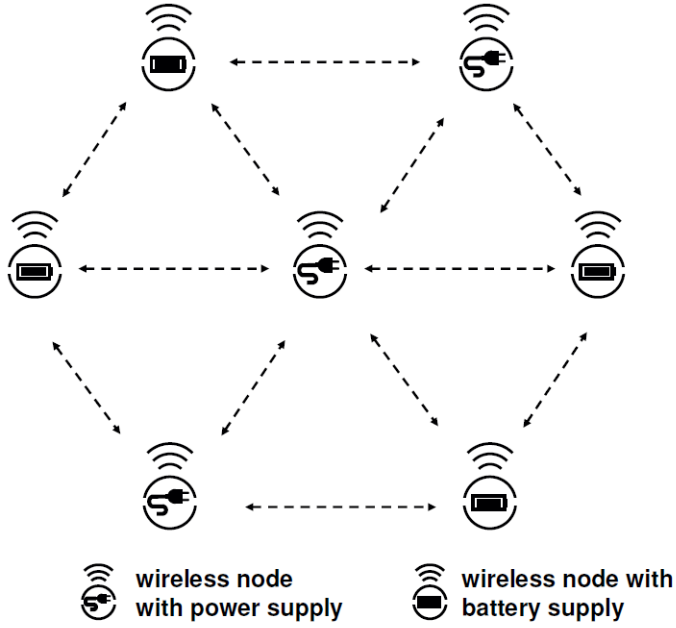
[2] F. Nawab, K. Jamshaid, B. Shihada, and P-H. Ho, "MAC-Layer Protocol for TCP Fairness in Wireless Mesh Networks", In Proc. *IEEE ICCC* 2012.

[3] F. Nawab, K. Jamshaid, B. Shihada, and P-H. Ho, " Fair Packet Scheduling in Wireless Mesh Networks", *Elsevier Journal of Ad-Hoc Networks*, Vol. 13, Part B, pp. 414-427, 2014.

Energy in Multi-Hop Networks

- The objective is to minimize the energy consumption at the energy-critical nodes and the overall network transmission delay[1,3].
- The transmission rates of energy-critical nodes are adjusted according to its local packet queue size.
- We proved that there exists a threshold type control which is optimal[1].
- We implemented a decentralized algorithm to control the packets scheduling of these energy-critical nodes[2].





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[1] L. Xia and B. Shihada, "Decentralized Transmission Scheduling in Energy-Critical Multi-Hop Wireless Networks" *in Proc. American Control Conference* pp. 113-118, 2013..

[2] L. Xia and B. Shihada, "Max-Min Optimality of Service Rate Control in Closed Queueing Networks," *IEEE Transactions on Automatic Control*, Vol. 58, No. 4, pp. 1051-1056, 2013.

[3] Li Xia and B. Shihada, "Power and Delay Optimization for Multi-Hop Wireless Networks," *International Journal of Control*, Accepted, 2014.

Questions/Comments/Feedback