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Deflating Wireless Link Buffers

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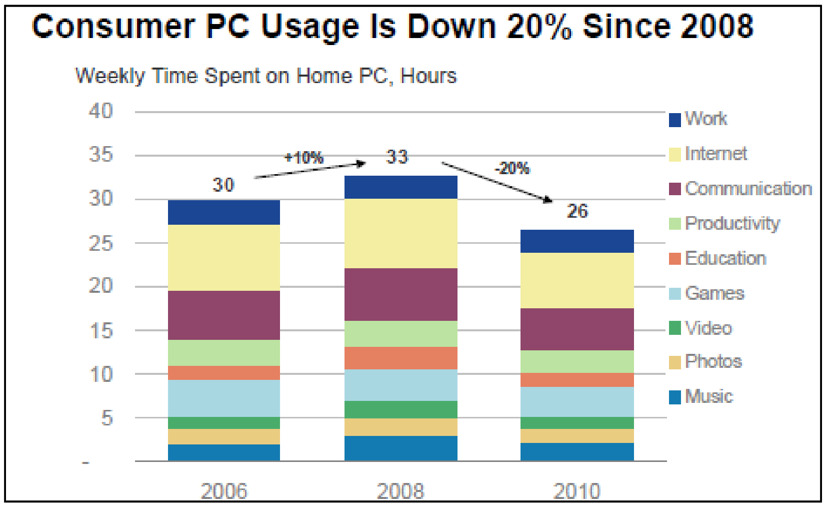
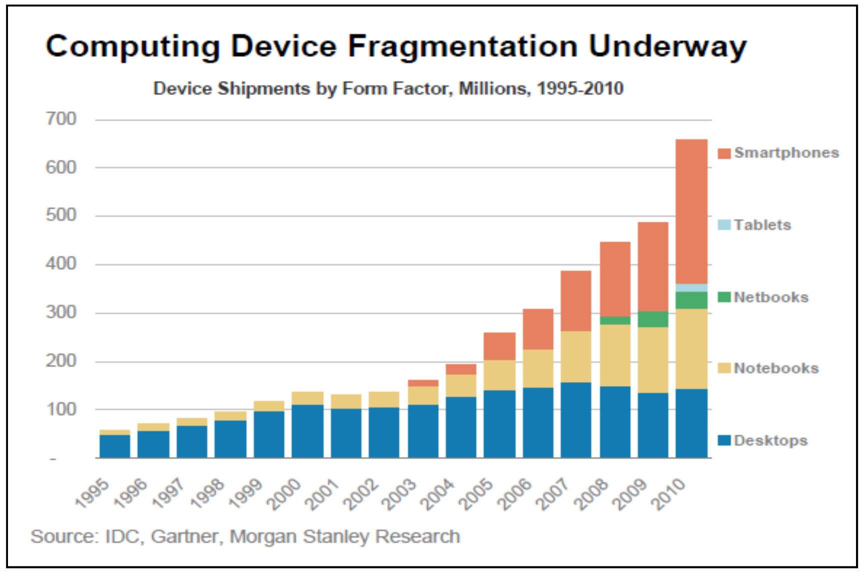
Computing and Networking Trends

- ❑ Bell's Law*: Every decade sees a change in the class of computing devices
  - ❑ 1990s saw the emergence of the laptop;
  - ❑ 2000-2010 saw the mobile phones
  - ❑ Next decade, desktops will disappear. End-user computers will be almost entirely laptops & tablets.
  - ❑ Data and applications will live in the cloud.



- ❑ Ubiquitous high-speed wireless connectivity is a must.
  - ❑ Dense, small-range wireless access points (AP) will become more important than today.
  - ❑ Spectrum is limited, neighboring APs will likely have to operate on the same spectrum.
  - ❑ Interference between neighboring APs will become the dominating factor.
  - ❑ Small cells connectivity and load will fluctuate rapidly, both in space and time.



* Bell's Law of Computer Classes formulated by Gordon Bell in 1972, describes how types of computing systems (referred to as computer classes) form, evolve and may eventually die out.

400 ms slowdown resulted in a traffic decrease of 9%

[Yslow 2.0; Stoyan Stefanov]

100 ms slowdown reduces # searches by 0.2-0.4%

[Speed matters for Google Web Search; Jake Brutlag]

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]

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

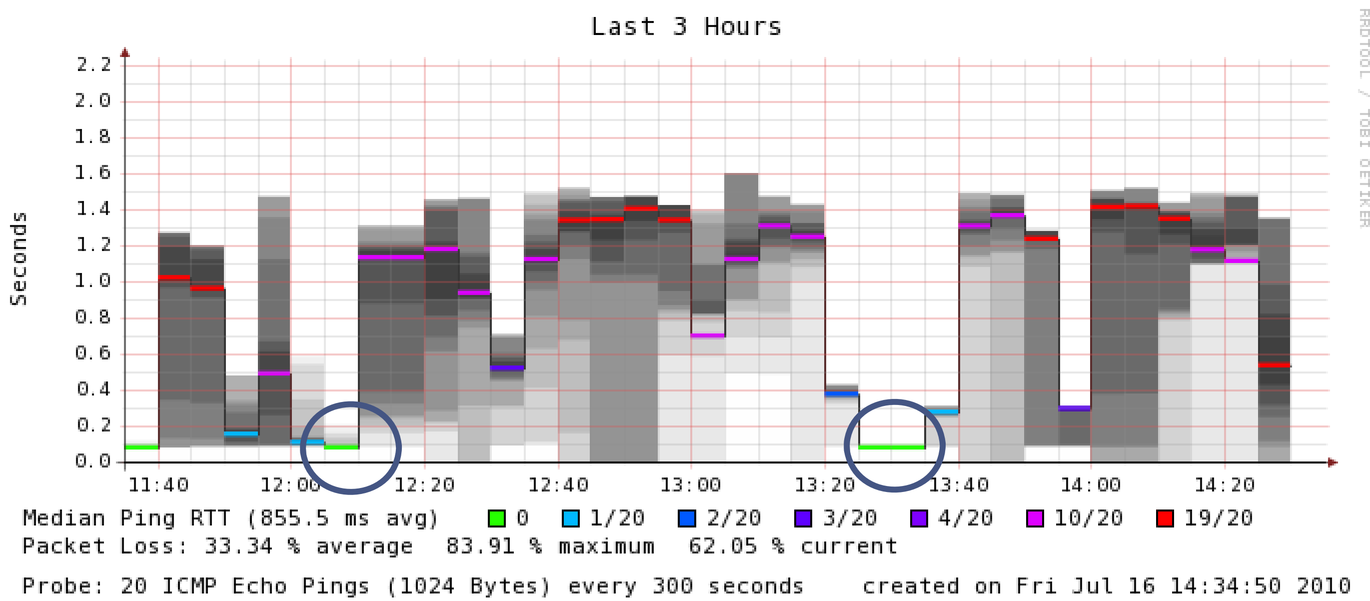
[Firefox and Page Load Speed; Blake Cutler]

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] users really respond to latency!

Bufferbloat: Wired Networks

- Large buffers add to queueing delay without increasing flow throughput



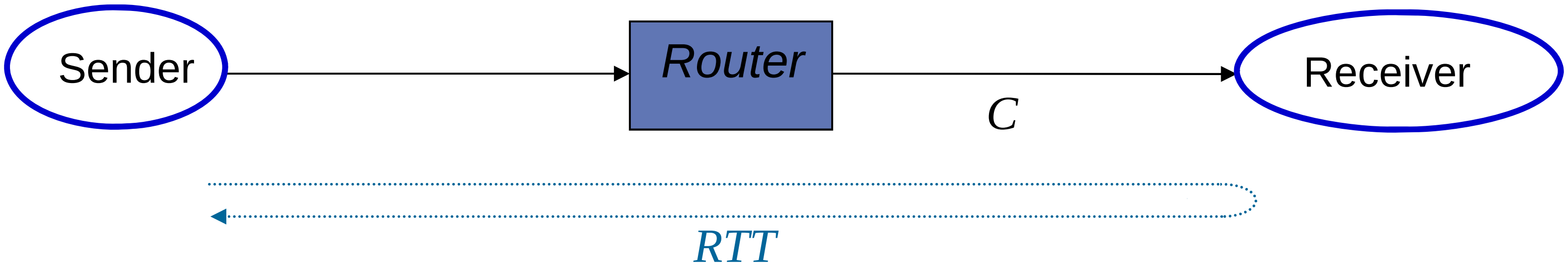
Measurements in a wired access network with system backup to a remote server. Consistent delays of over 1 sec.

Problem Definition

- Large buffers ⇒ high throughput, high delay
- Small buffers ⇒ low utilization, low delays

Problem statement: determine buffer size to balance throughput and delay tradeoff

Buffer Sizing General Rule



Router needs a buffer size of $Buffer = RTT*C$

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

What about Wireless Networks?

- Wireless link: abstraction for shared spectrum
  - Bottleneck spread over multiple nodes
- Variable network capacity
  - Sporadic noise and interference
  - Random MAC scheduling
- Aggregate frame scheduling
  - Impact of large frame with multiple frame aggregates
- Adaptive link rates
  - 802.11n can connect from 600 Mb/s to 1 Mb/s

What about Wireless Multi-Hop Networks?

- Wireless link: abstraction for shared spectrum
- Variable network capacity
- Aggregate frame scheduling
- Adaptive link rates

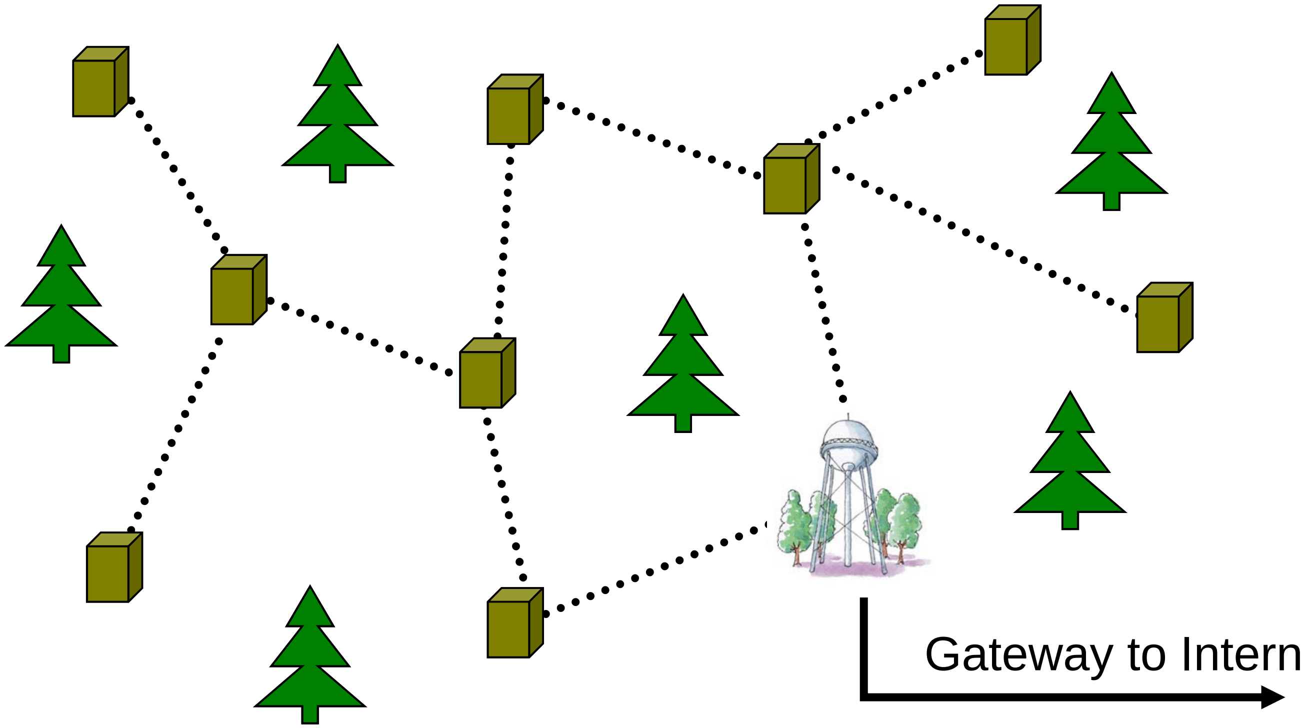
Severe performance degradation on throughput, delay, dropping

A. Showail, K. Jamshaid, and B. Shihada, “Buffer sizing in wireless networks: Challenges and Opportunities", IEEE Network, Minor Revision, 2013.

Why Multi-Hop is of Interest?

- Convenient network access
  - Connection can be made from any available close-by AP
  - No extra equipment required
- Multiple connection paths
  - Improve connection reliability
  - QoS and better data routing
- Scalable network deployment
  - Can start with few AP and increase upon device availability
  - Large-scale network can be created easily.
  - Large number of clients can be served easily
- Growing deployment
  - Mountain view city, CA by Google
  - Waterloo city, ON by UW
  - Cambridge city, MA by MIT

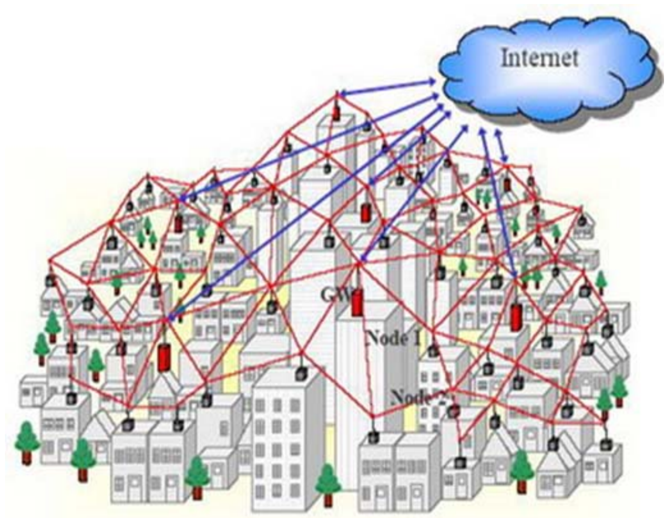
Typical Wireless Multi-Hop



- Multi-hop routing between mesh nodes
  - Increases range
  - Goes around obstructions
- Connectivity to a gateway router to bridge traffic to the public Internet

Wireless Multi-Hop Characteristics

- Fixed nodes
- No power constraints
- Traffic directed towards and away from gateway
- Node traffic may be aggregate of multiple end-hosts

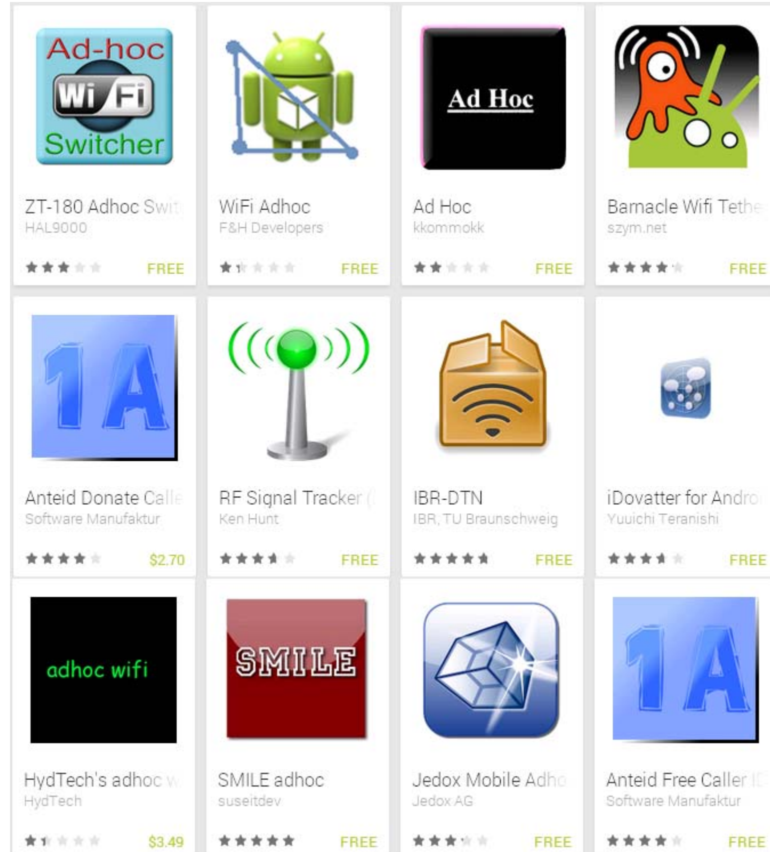


Wireless Multi-Hop Technology

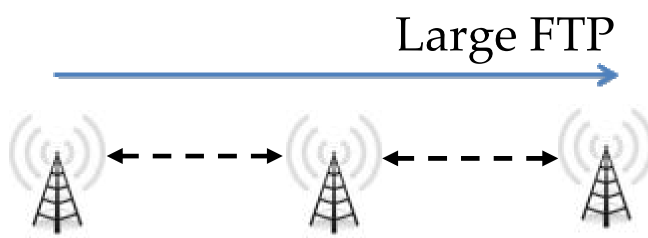
- Last mile access network
  - Commodity mass-produced radios
  - Globally license-exempt frequency bands
  - Thriving ecosystem of open source software

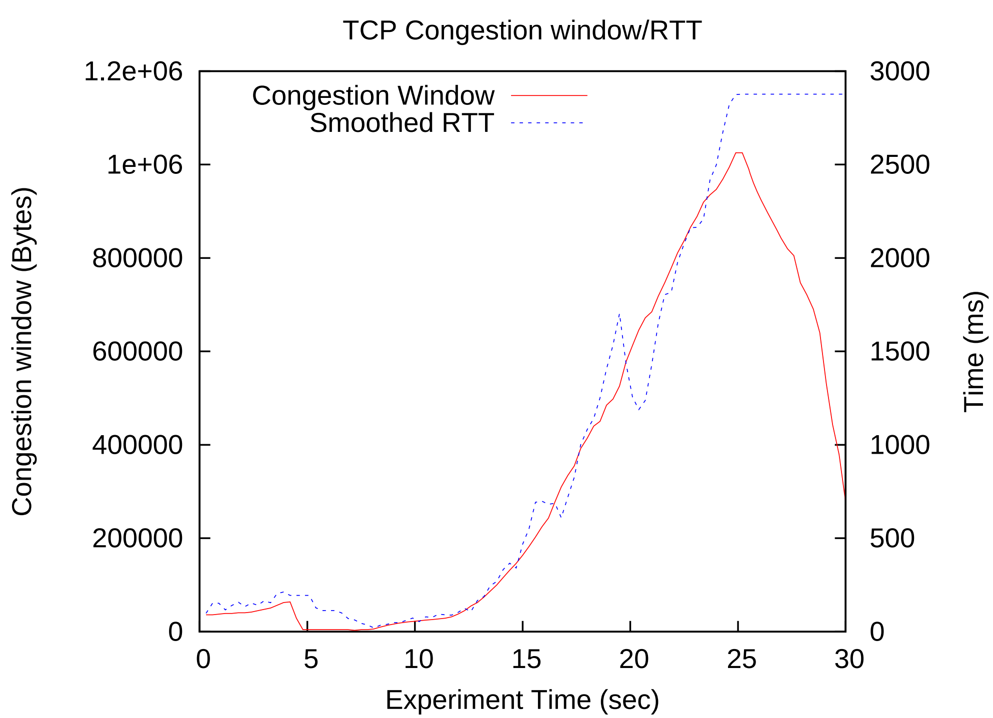
- 802.11s: amendment adds mesh capability to 802.11 WLAN

- Preferred approach by commercial vendors
  - Arrowspan, BelAir Networks, Firetide, Meraki (now Cisco), Motorola, Tropos, and others



Revisiting Bufferbloat in Wireless networks

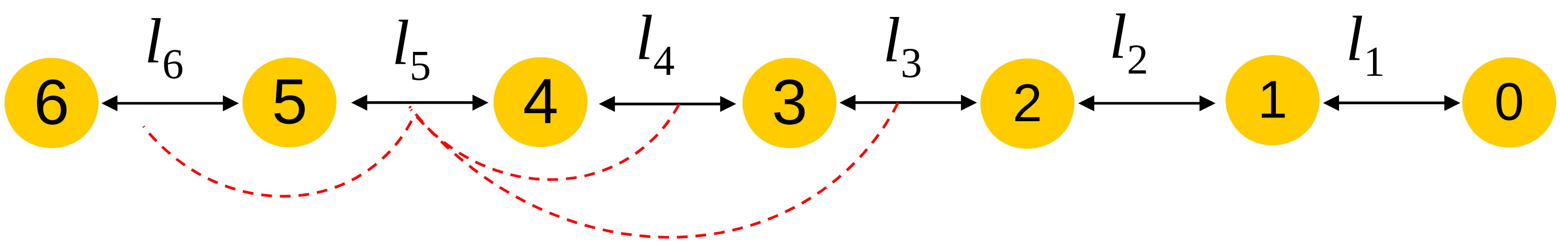




Collision Domains

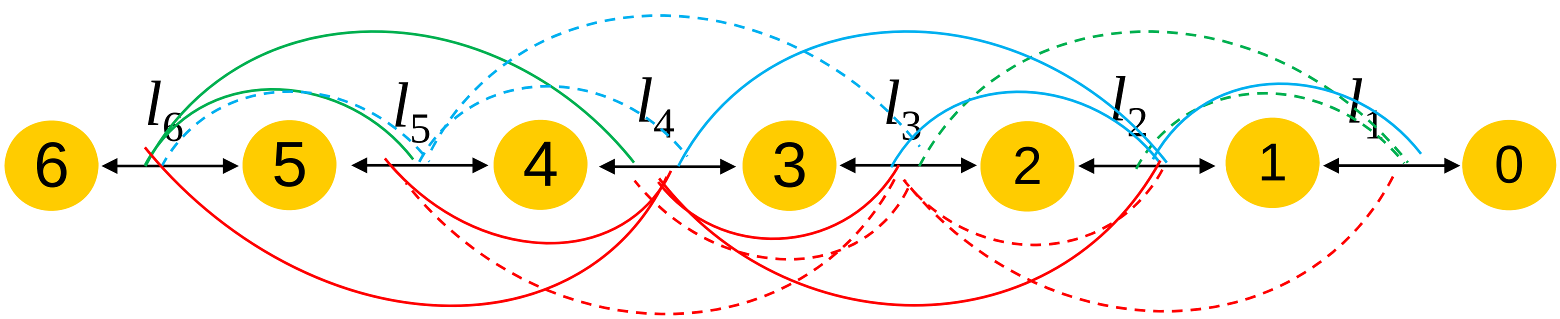
Set of interfering links that contend for channel access

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



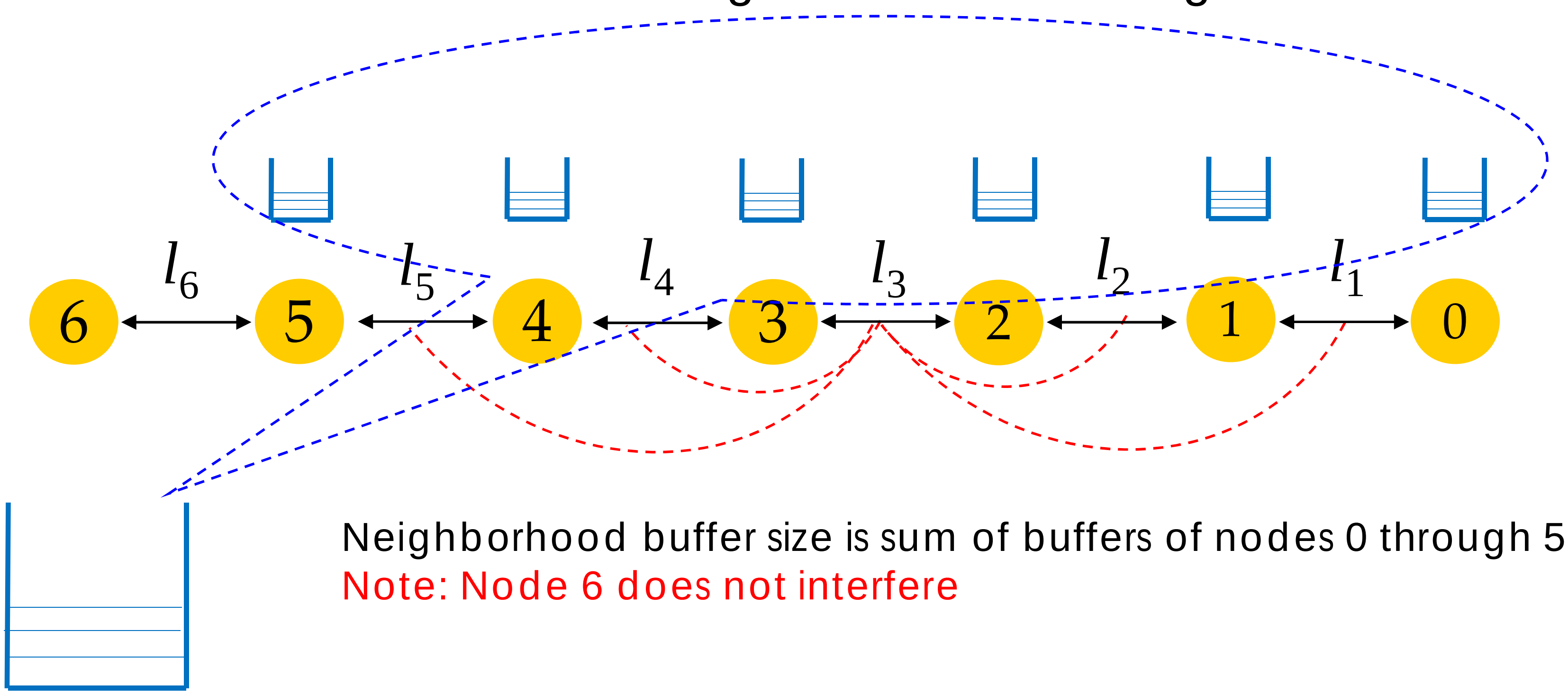
Bottleneck Collision Domain

- Set of links that contend with max. no. of links
  - Limits the end-to-end rate of a flow



Bottleneck Collision Domain Buffer

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



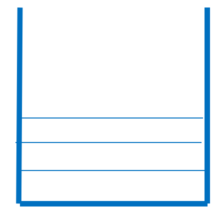
Neighborhood buffer size is sum of buffers of nodes 0 through 5

Note: Node 6 does not interfere

B. Shihada and K. Jamshaid, "Buffer Sizing for Balancing Throughput and Delay Requirements in Multi-hop Wireless Networks," U.S. Patent and Trademark Office, 20,120,236,726, 2012.

Two Parts of the Problem

1) Determine bottleneck buffer B



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

Part 1: Bottleneck Buffer Size

$$B = RTT \times C$$

- Bottleneck fully utilized as long as any node in the bottleneck has a packet to transmit
- Account for channel variations by using loose bounds on *RTT* and *C*

Part 2, Strategy 1: Per-node Buffer

- Equal division: $\frac{B}{\#\, nodes}$

- But drops closer to source are preferable to drops closer to destination

Part 2, Strategy 2: Per-node Buffer

- Introduces a generic cost function s.t. cost of drop increases with hop count

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

subject to $\sum_{i=1}^{M} b_i = B$

and $b_i \geq 0, \forall\, i \in M$

where M is the number of nodes in the bottleneck collision domain

Part 2, Strategy 2: Per-node Buffer

- If cost of packet drop increases linearly with hop count, then:

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

$$b_1 : b_2 : \ldots : b_M = 1 : \sqrt{2} : \ldots : \sqrt{M}$$

Simulation Results

- Compare with:
  - Default ns-2 buffer size (50 packets)
  - TCP with adaptive pacing (TCP-AP)
    - Space packet transmission over a 4-hop propagation delay

K. Jamshaid, B. Shihada, L. Xia and P. Levis, "Buffer sizing in 802.11 Wireless Mesh Networks" *IEEE Mobile Adhoc and Sensor Systems (MASS), Valencia, Spain*, 2011.

Single Flow

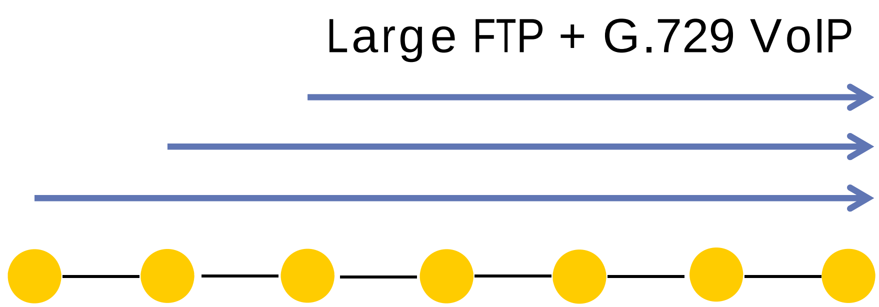
- Key observation: Collectively sizing buffers lead to small buffers at nodes

Scheme	Normalized goodput	Normalized RTT
Default TCP	1	20.3
TCP-AP	0.90	1
Neighborhood buffer sizing	0.96	2.2

10x improvement in delay while buffer is fixed to 50 pks

Performance statistics averaged over multiple topologies

Multi-Flows



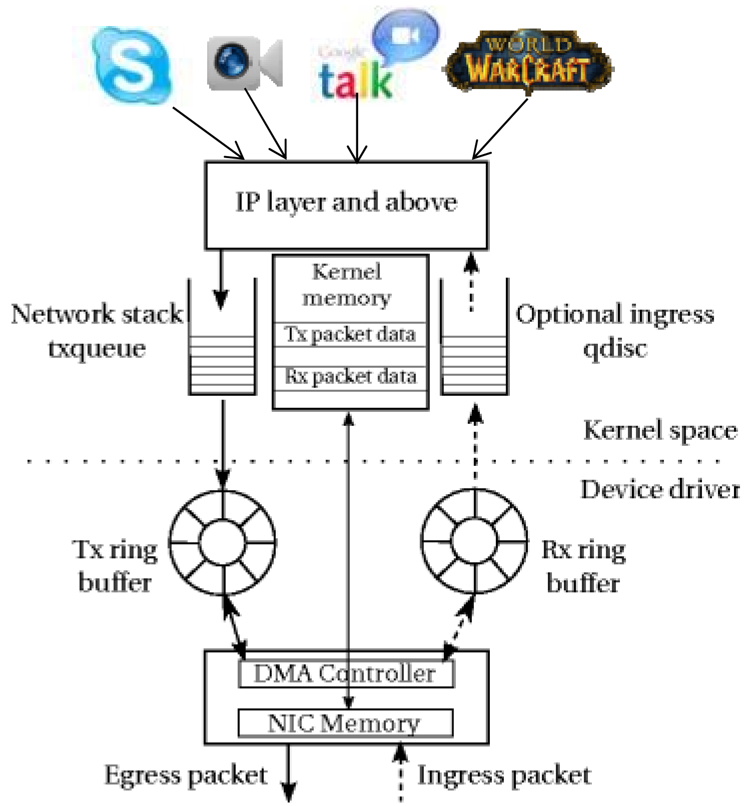
Scheme	FTP		VoIP	
	Goodput (Kb/s)	RTT (ms)	Goodput (Kb/s)	Delay (ms)
Default TCP	261	388	7.8	239
TCP-AP	240	54	8	37
Neighborhood buffer sizing	250	87	8	40

4% drop in throughput with 6x improvement in delay

Testbed Results

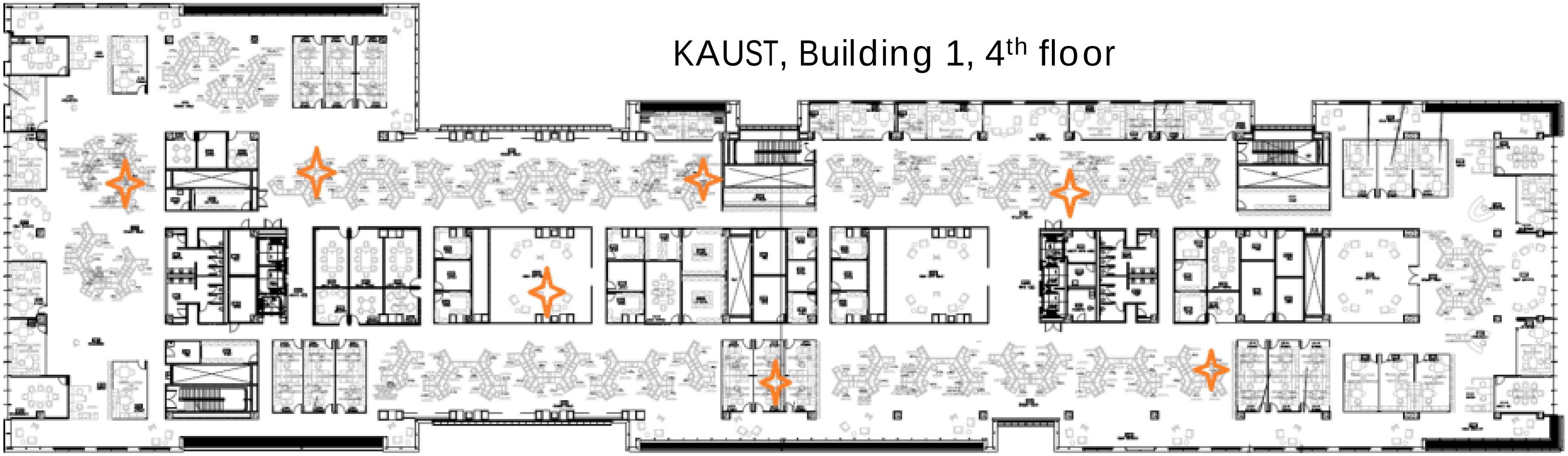
- Buffers exist at multiple layers in the stack
  - Application layer buffers
  - TCP socket buffers
  - Txqueue buffers
  - Device driver ring buffers
  - Hardware buffers

- Txqueue buffers (default 1000 packets) lead to the largest delays



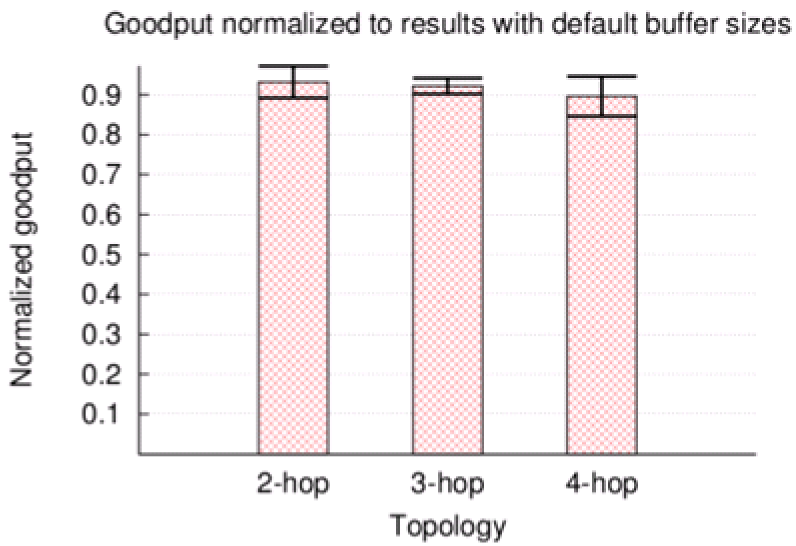
K. Jamshaid, B. Shihada, A. Showail, and P. Levis, "Deflating link buffers in Wireless Mesh Networks", *Elsevier Journal of Ad-Hoc Networks*, Minor Revision, 2013.

Testbed Topology

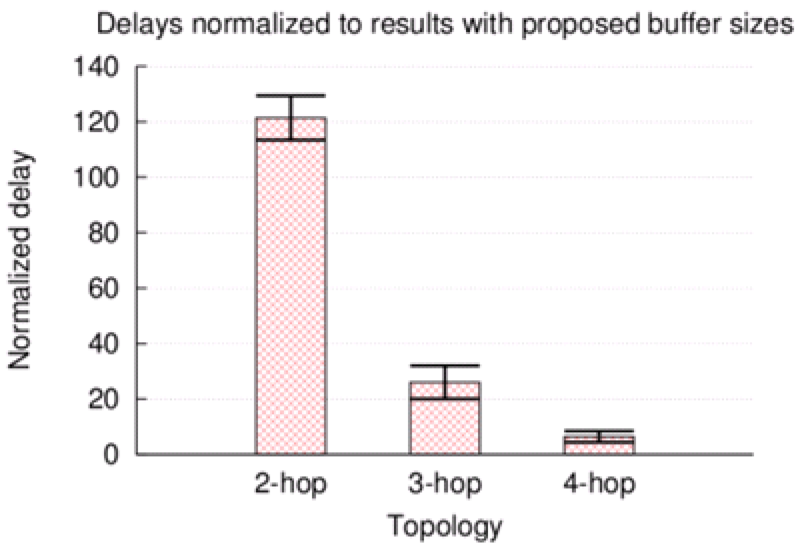


Node setup: 7 Distributed Nodes at Building 1, Level 4.
Network traffic setup: 1 file transfer in the background + real-time communication

Testbed Results



Flow goodput



RTT

Latency improvement of 6x (and more) with up to 10% drop in throughput

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

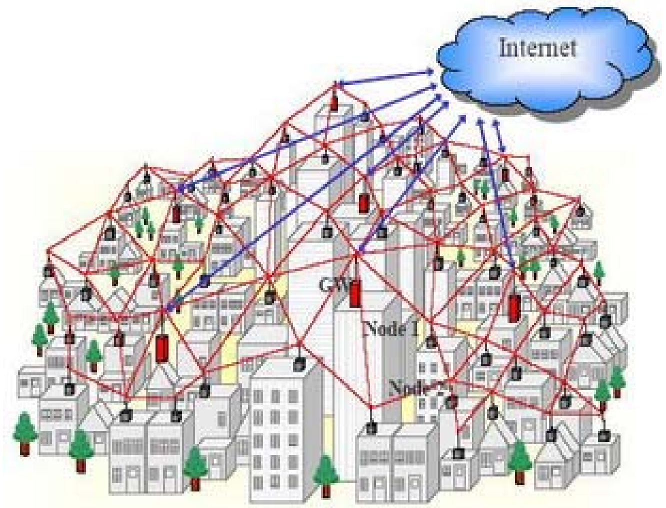
wired-network.mp3

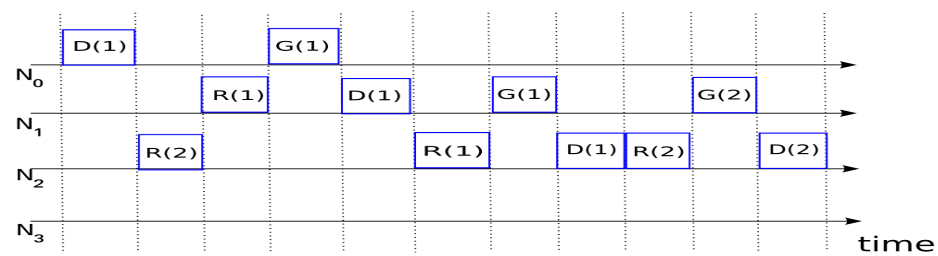
Video demo

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

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]





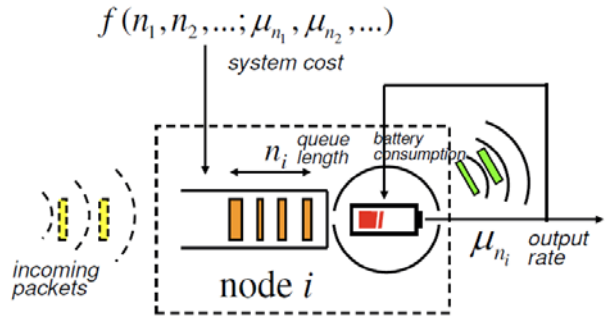
[1] F. Nawab, K. Jamshaid, B. Shihada, and P-H. Ho, "TMAC: Timestamp-ordered MAC for CSMA/CA Wireless Mesh Networks", In Proc. *IEEE ICCCN* 2011.

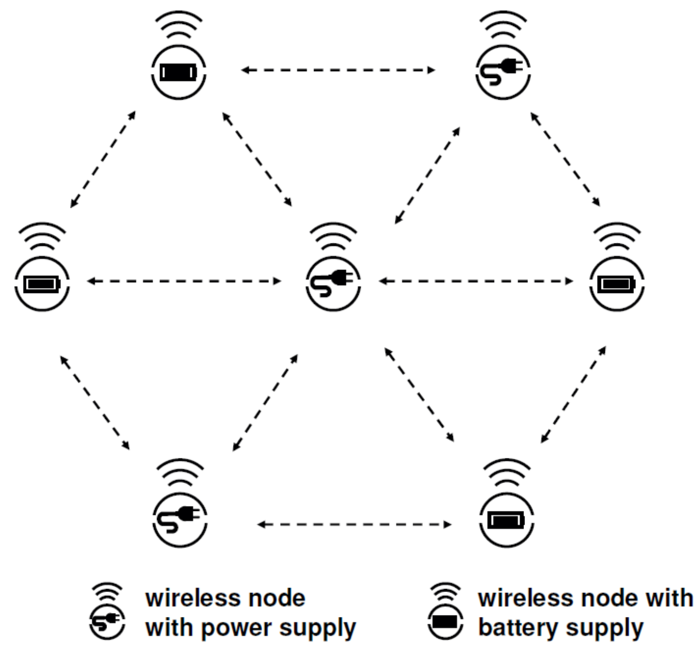
[2] F. Nawab, K. Jamshaid, B. Shihada, and P-H. Ho, "MAC-Layer Protocol for TCP Fairness in Wireless Mesh Networks", In Proc. *IEEE ICCC* 2012.

[3] F. Nawab, K. Jamshaid, B. Shihada, and P-H. Ho, " Fair Packet Scheduling in Wireless Mesh Networks", *Elsevier Journal of Ad-Hoc Networks*, 2013.

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].





[1] L. Xia and B. Shihada, "Decentralized Transmission Scheduling in Energy-Critical Multi-Hop Wireless Networks" *IEEE American Control Conference*, Accepted, 2013.
[2] L. Xia, 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] L. Xia, B. Shihada, and P-H. Ho, "Power and Delay Optimization for Multi-Hop Wireless Networks", *Elsevier Journal of Performance Evaluation*, Second Revision, 2012.

Conclusions and Remarks

- Shared wireless spectrum requires rethink of bottlenecks and buffers
- Mechanisms for sizing bottleneck buffers and distributing it among nodes
- Improvements in RTT by 6x - 10x over plain TCP with large buffers
- US patent granted
- Working on commercializing opportunities with KAUST Technology Transfer Office

Questions/Comments/Feedback

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