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Technische Universität Dresden

Practical Implementations of Network Coding

Frank Fitzek // Summer Semester 2019

Network Coding Use Cases

What is a good use case for network coding?

Let's find something where network coding shines !!!

Network Coding Use Cases:
Network Coding in the ISO/OSI Context

Where is network coding located?

Application Layer

Transport Layer

Network Layer

Data Link Layer

Physical Layer

http://www.youtube.com/watch?v=OnqGO7AWwxc

Where is network coding located?

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Transport Layer

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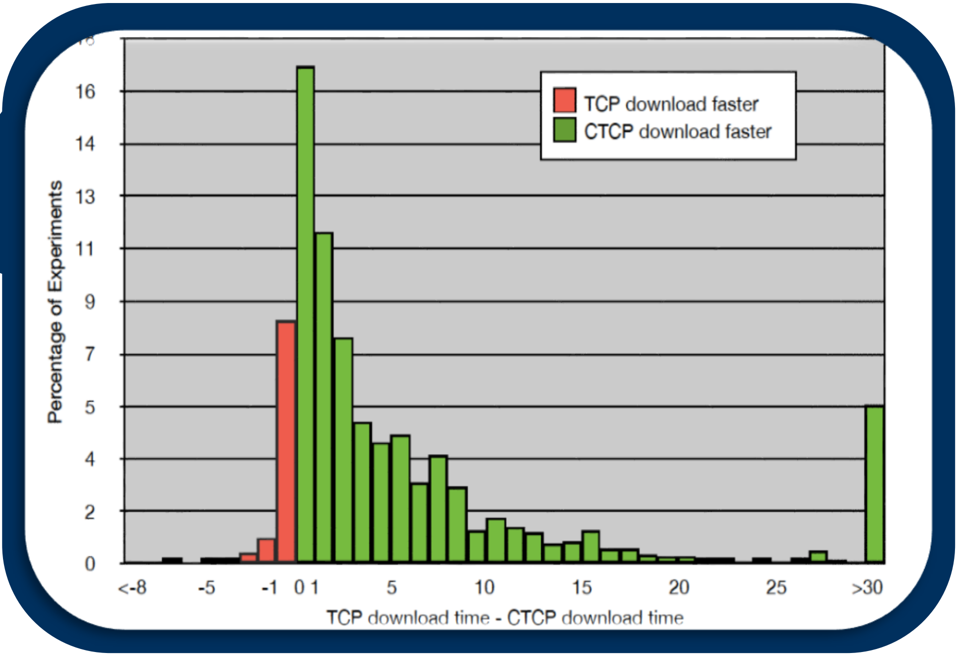
Data Link Layer

Physical Layer



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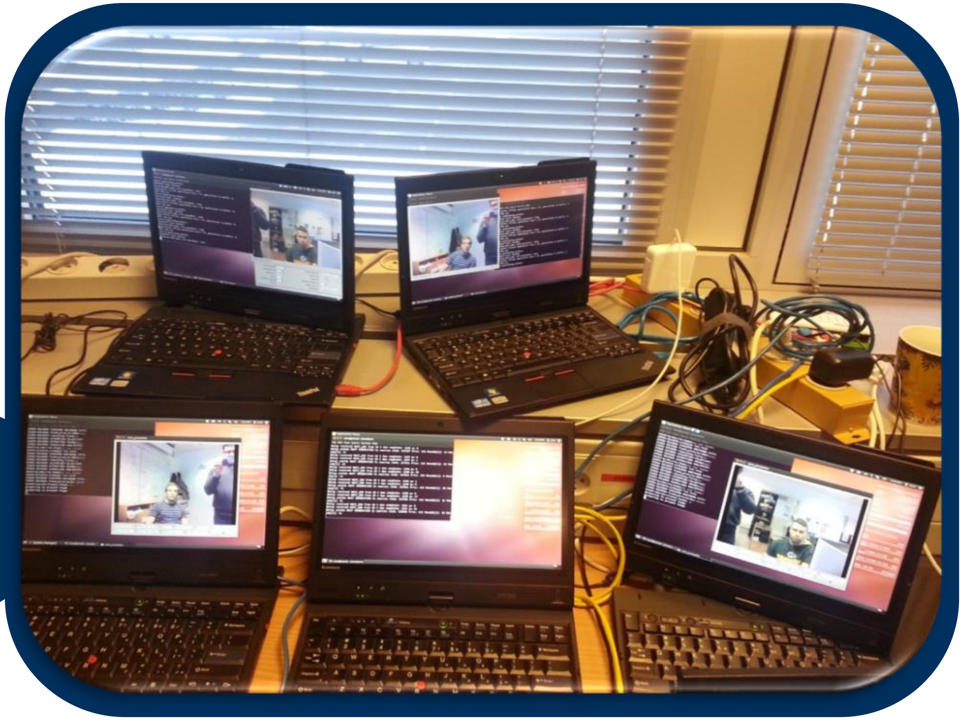

Where is network coding located?

Application Layer

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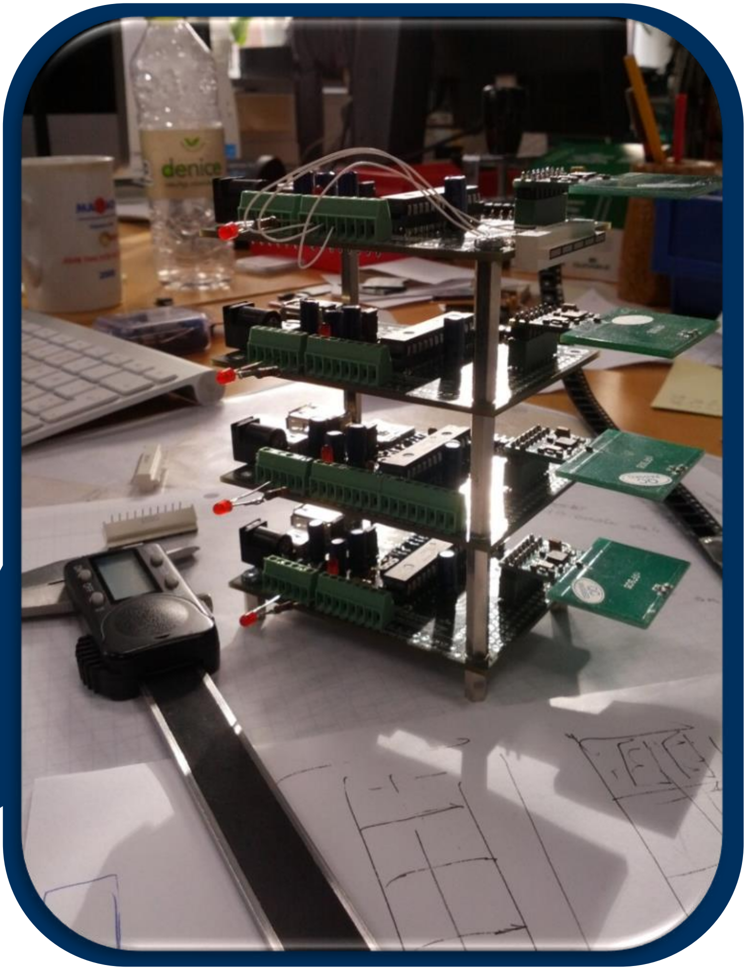


Conclusion

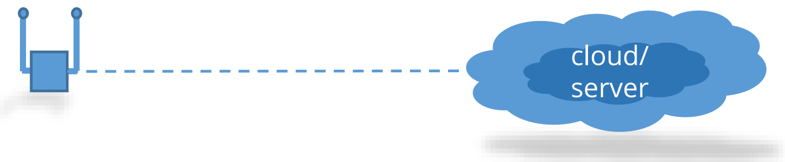
- Network coding is not limited to a single layer
- Network coding is not limited to the network layer
- Network coding can be applied at any layer

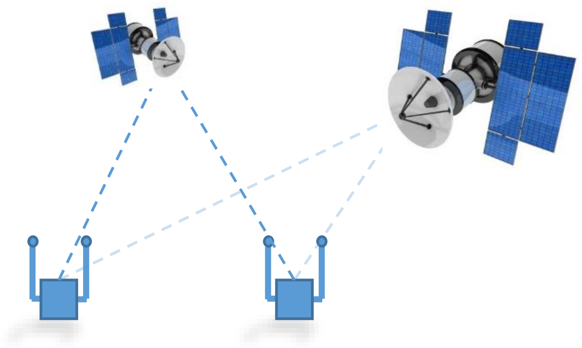
Network Coding Use Cases: Application Fields of Network Coding

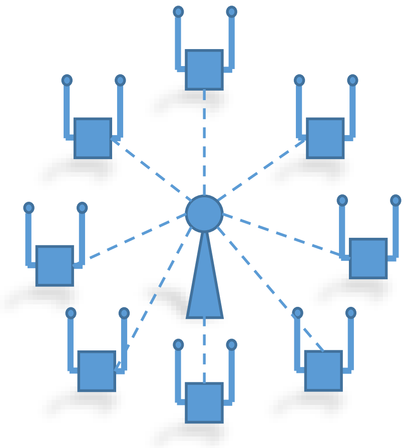
Application Fields of Network Coding

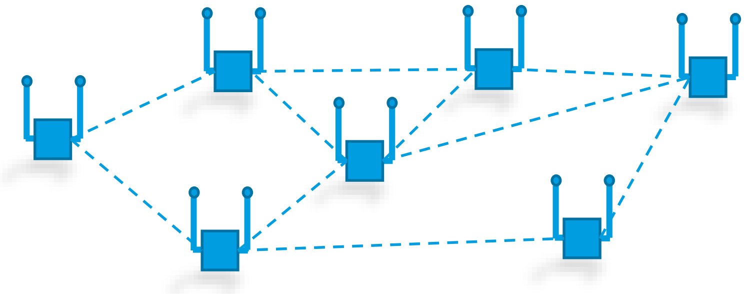
Network Coding Use Cases: Topologies

Architectures





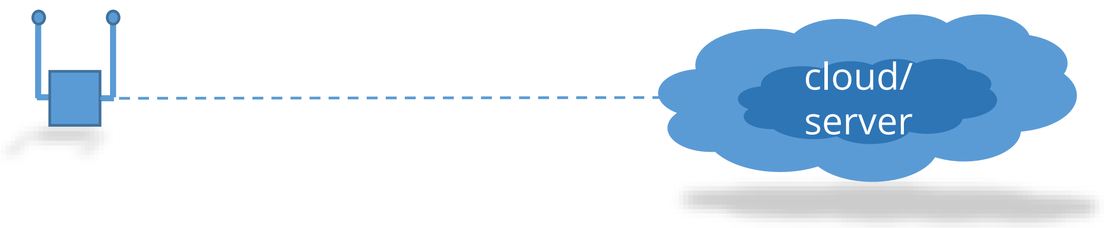




Network Coding Use Cases: Topologies | Point-to-Point

Point-to-Point (P2P) with RLNC

Application fields:
Substitute for traditional P2P. Better performance in: wireless (4G, VoLTE, small cell, back haul, satellite, WiFi), CDN, Ethernet, packet core, DSL, cable, PON, TCP, OTT, set-top box, cloud services, SDN, NFV, real time video streaming and any delay sensitive, lossy link.



Technology advantage:

- Sliding window
- On-the-fly coding
- Improved QoE
- Increased throughput
- Infrastructure savings

Improvement Metrics:

- Coded TCP (CTCP) has shown up to **10x** performance improvements[1]
- CTCP shows throughput improvements of **5x** at 3% losses in commercial public WiFi networks[2]
- CTCP eliminates video buffer overruns (interruptions) over a 25Mbps link even with 20% packet losses[2]
- RLNC yields **4-6x** goodput improvement and 5x download delay reductions over WiMAX links[3]
- RLNC was shown to yield a **2.5-7x** reduction in base station deployment for cellular access[4]

Coded TCP
Some pre-work

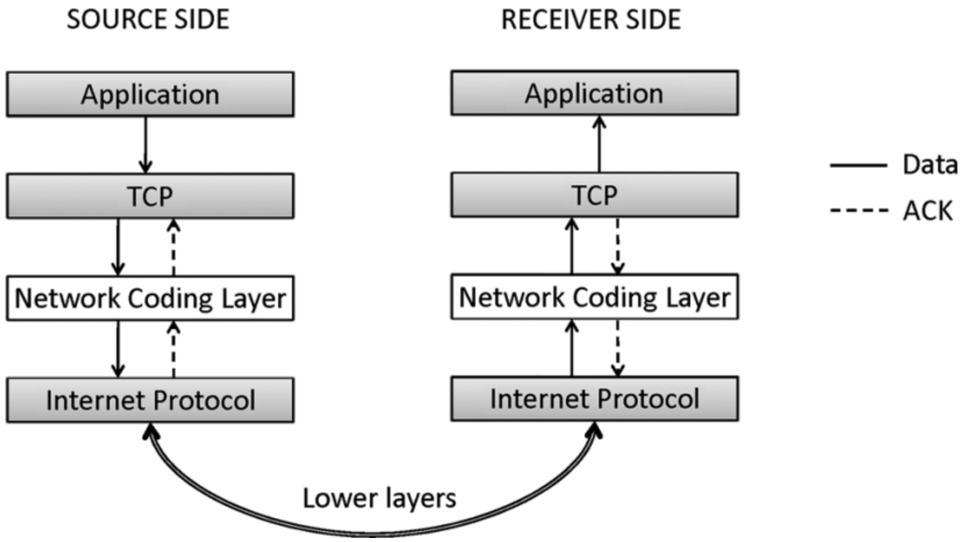
Jay Kumar Sundararajan, Devavrat Shah, Muriel Medard, Szymon Jakubczak, Michael Mitzenmacher, and Joao Barros

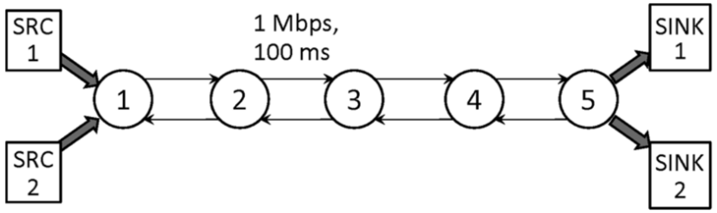
Network Coding Meets TCP: Theory and Implementation

http://ieeexplore.ieee.org/document/5688180/?anchor=references

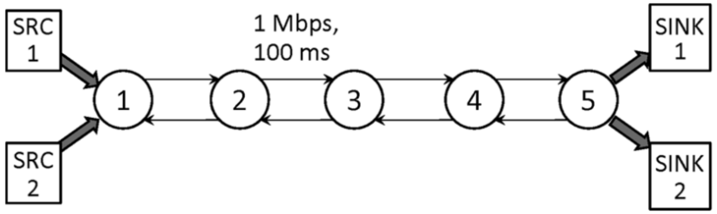
Coded TCP

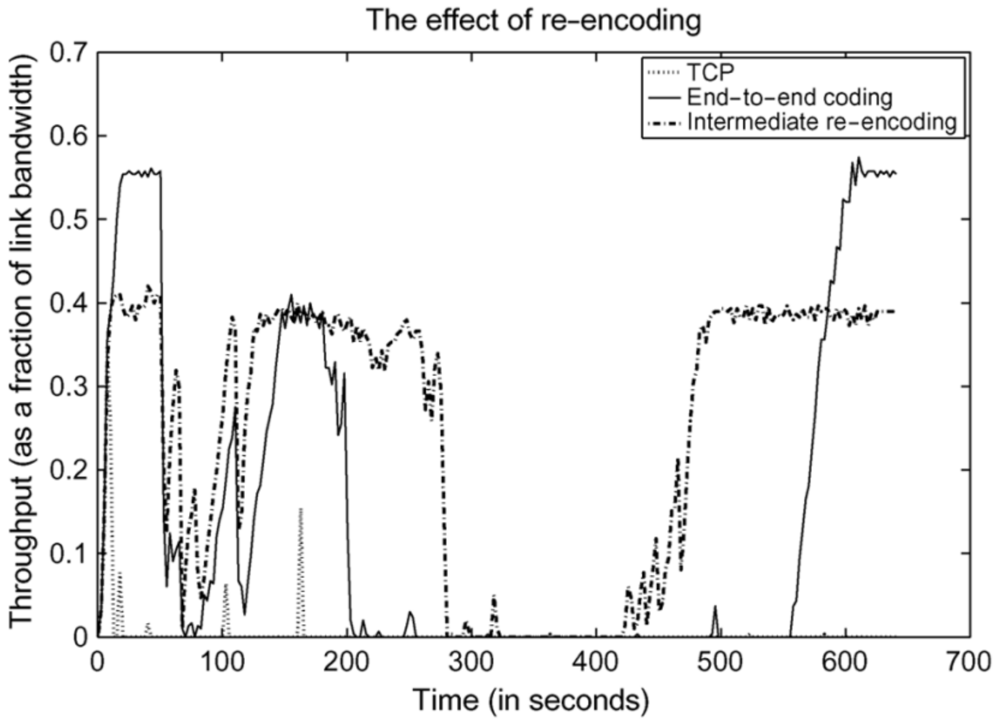
- Network Coding Layer:
  - UDP tunnel
  - Coded stream (Block / SW / etc.)
  - Congestion Control (fairness)





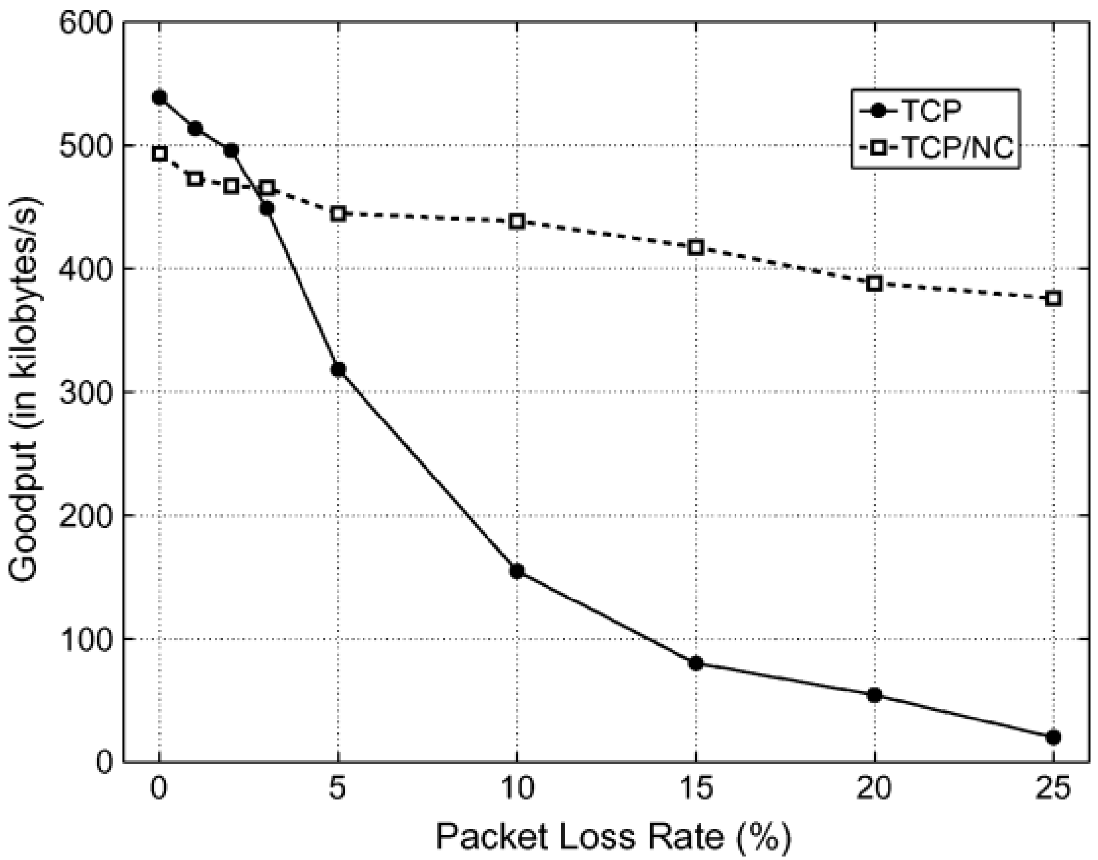
Coded TCP

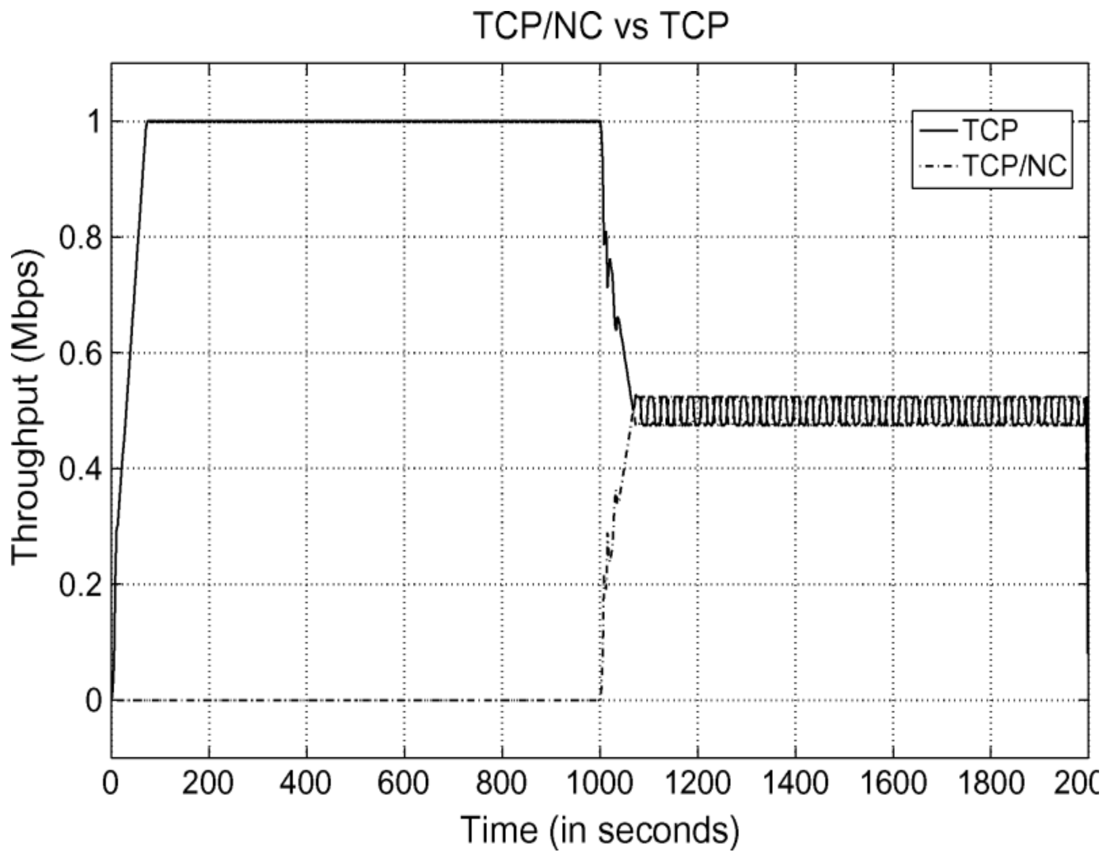




TCP	End-to-end coding	Re-encoding at node 3 only
0.0042 Mbps	0.1420 Mbps	0.2448 Mbps

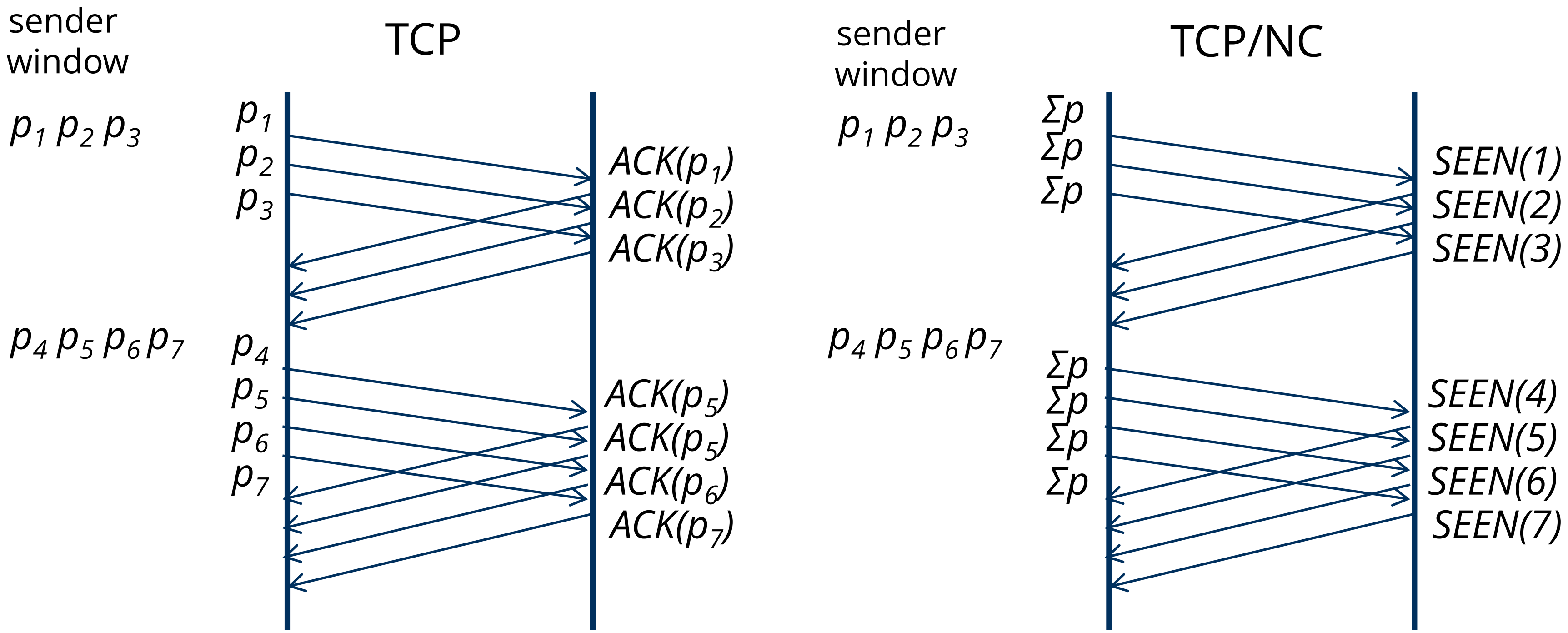
Experimental Results (Reno)





Coded TCP

Example: No Losses

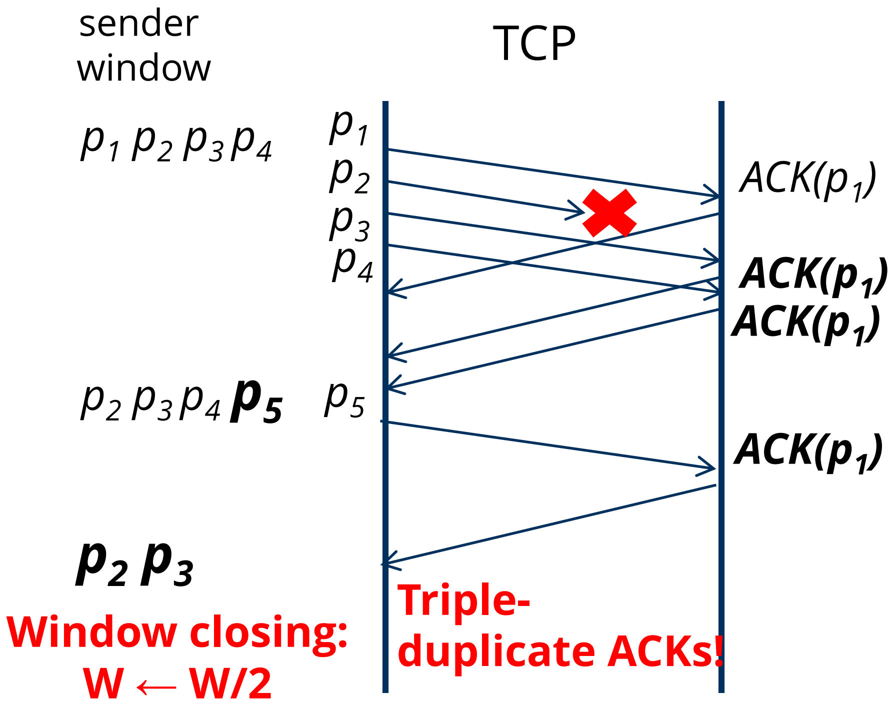


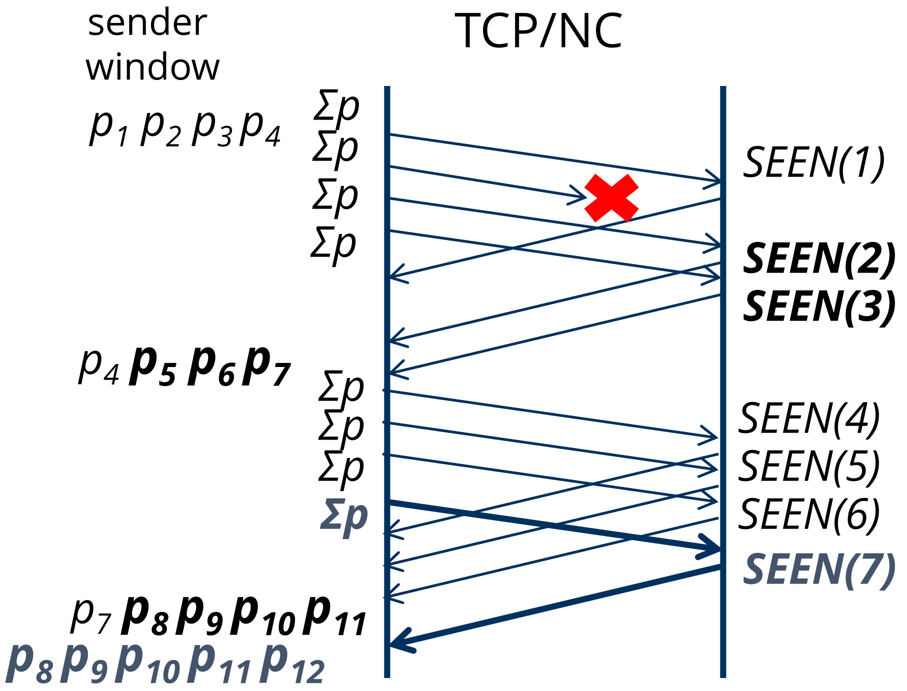
- Increment window by 1
- Sliding window

When no losses, network coding doesn't provide benefits (erasure correction)

Coded TCP

Example: Random Losses (Triple-Duplicate ACKs)





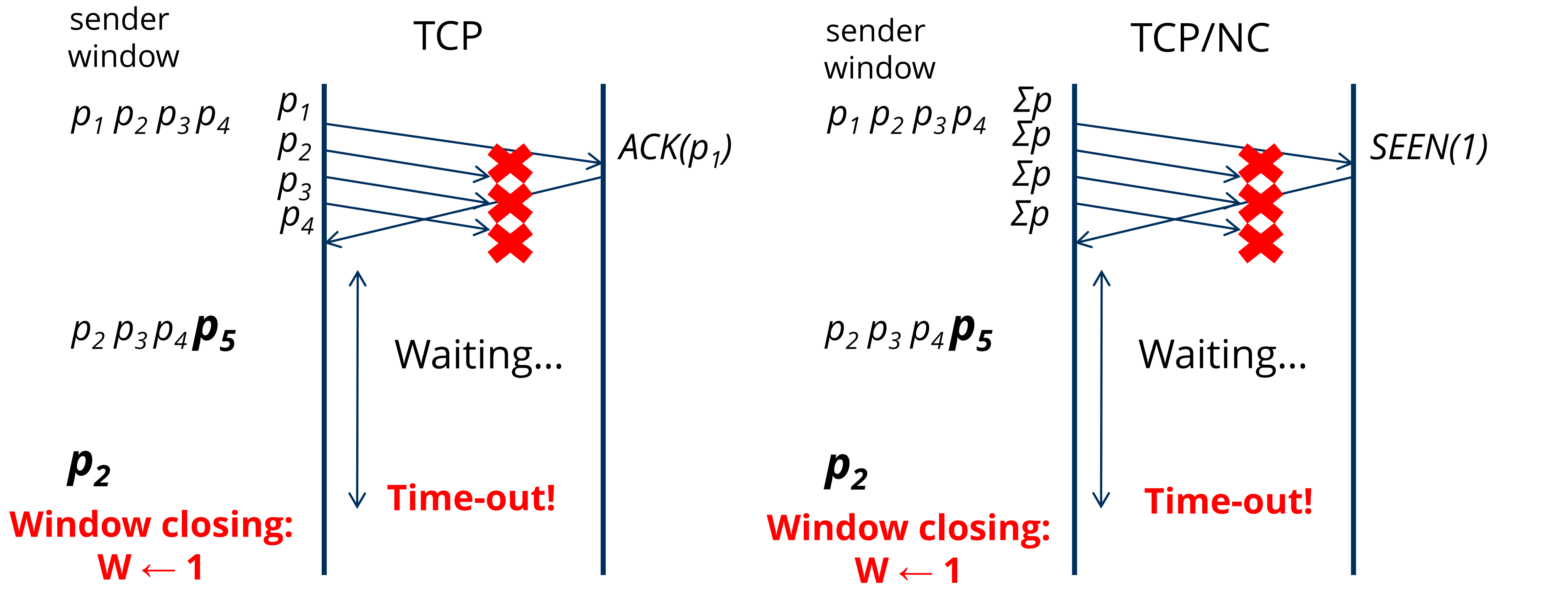
- Can't increment window by 1
- Partial sliding window

Prevents random losses being interpreted as congestion!

There is a lag in the "SEEN" acks: To avoid lag, introduce redundancy!

Coded TCP

Example: Random Losses (Triple-Duplicate ACKs)



Still allows congestion control while masking random losses!

Analysis and Simulations

Based on Padhye et al.'s model (correlated losses to model congestion).

$$\mathcal{T}_{tcp} = \min\left(\frac{W_{\max}}{RTT}, \frac{1-p}{p}\frac{1}{RTT\left(\frac{5}{3}+\sqrt{-\frac{1}{18}+\frac{2}{3}\frac{1-p}{p}}+P(\text{TO}|E[W])E[\text{duration of TO period}]\right)}\right)$$

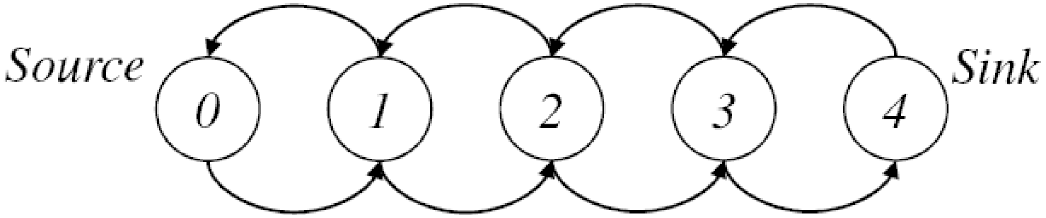
Simulation using NS-2

$$\mathcal{T}_{e2e} = \frac{1-p}{nR\cdot SRTT}\cdot f(p),$$

Proportional to *(1-p)*

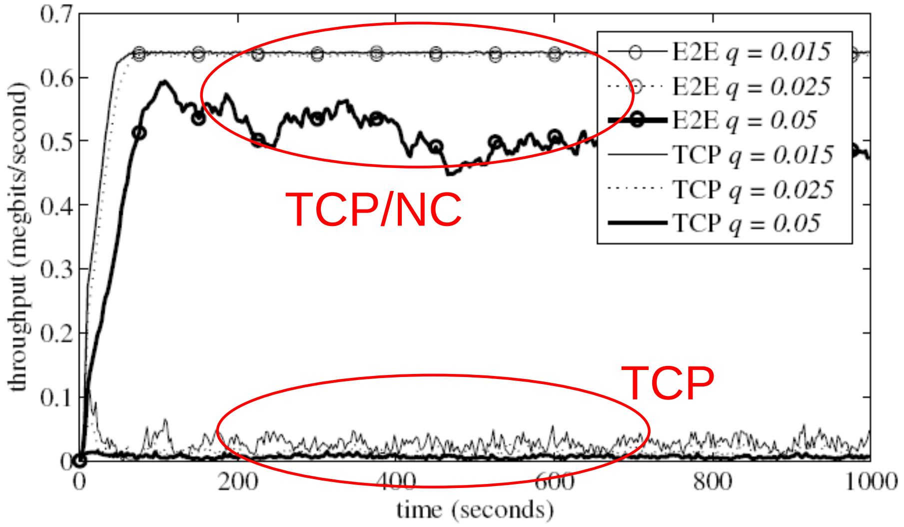
Does not degrade linearly

loss rate per link *q* End-to-end loss rate $1-p=(1-q)^4$



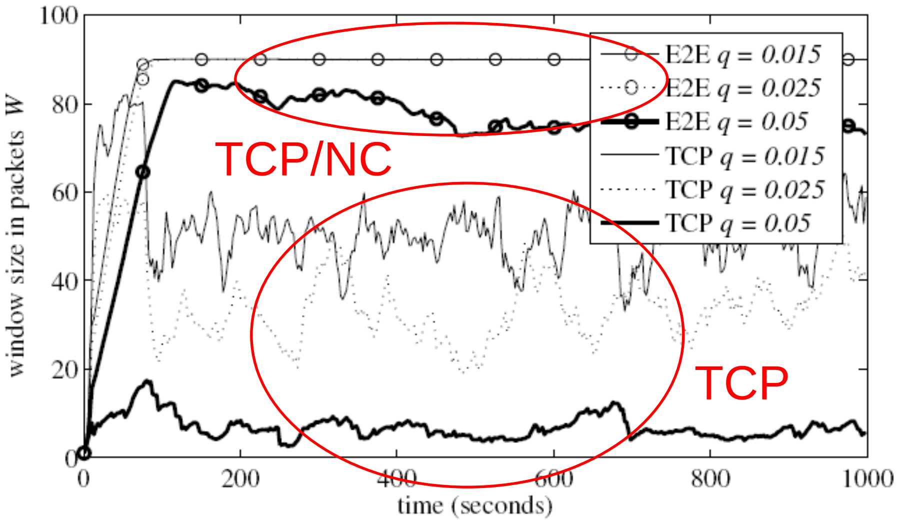
"Modelling TCP Throughput: A Simple Model and its Empirical Validation" by *Padhye*, *Firiou*, Towsley and Kurose (1998)

Throughput Gains Using TCP/NC



(a) Throughput

TCP/NC is able to grow its throughput and maintain high rate despite losses.



(b) Window size

TCP's window size is larger compared to its actual throughput – TCP sender is waiting for ACKs.

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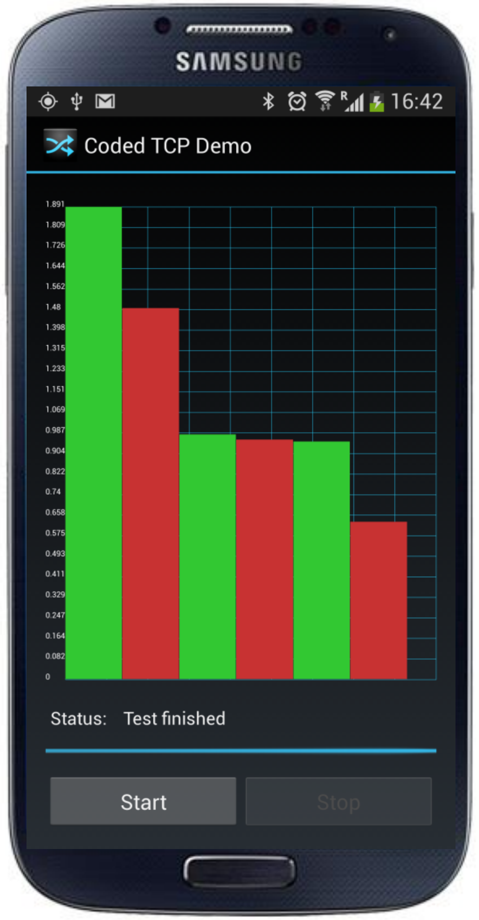
Coded TCP
Real implementation and measurements

Aalborg University, CodeOn, MIT

Coded TCP

- Experiments for amazon
- Four servers local spread
- Kindle reader
- Android
- Coded TCP vs. SoA TCP



Germany

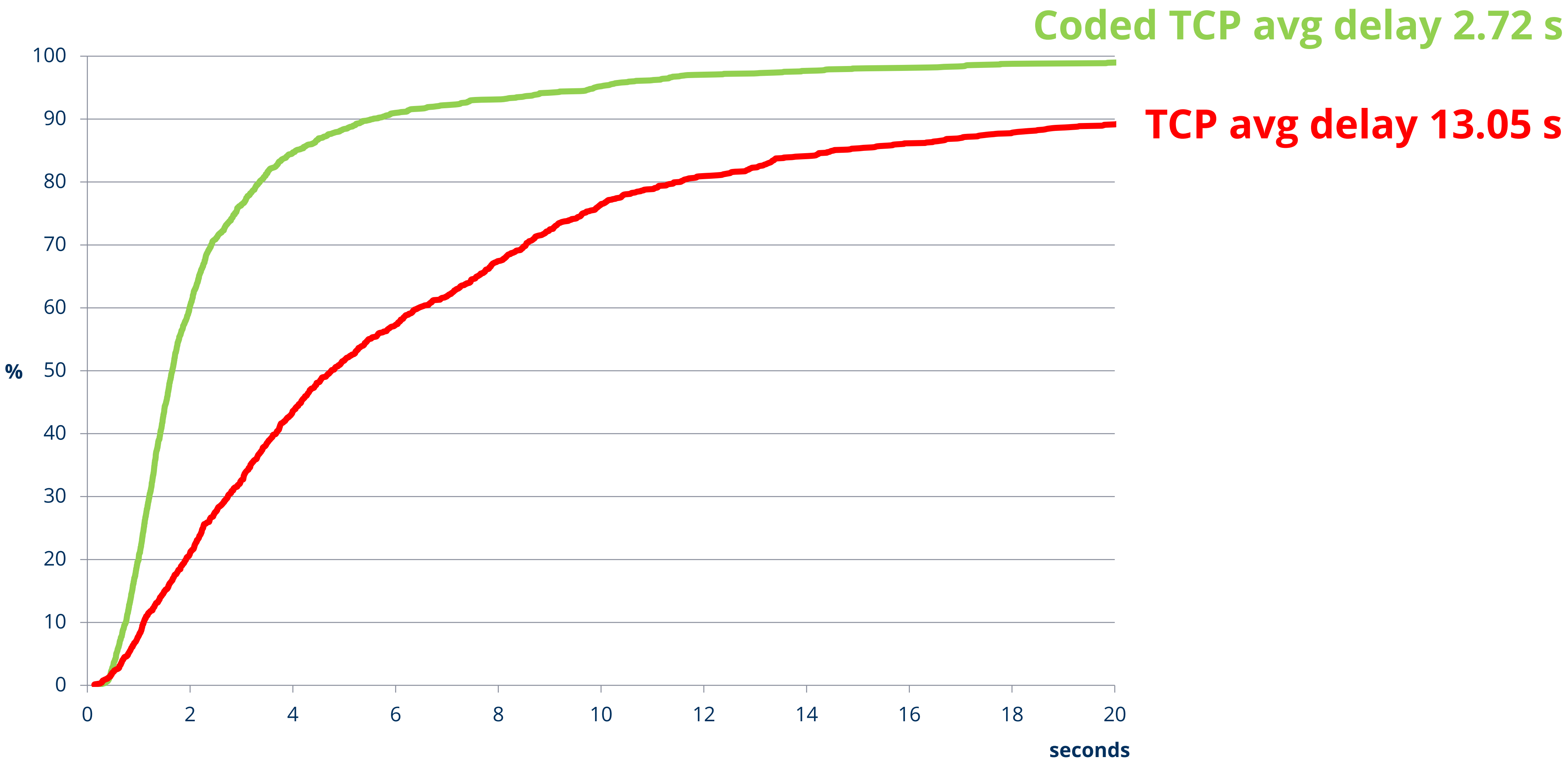
Irland

US East Coast

US West Coast

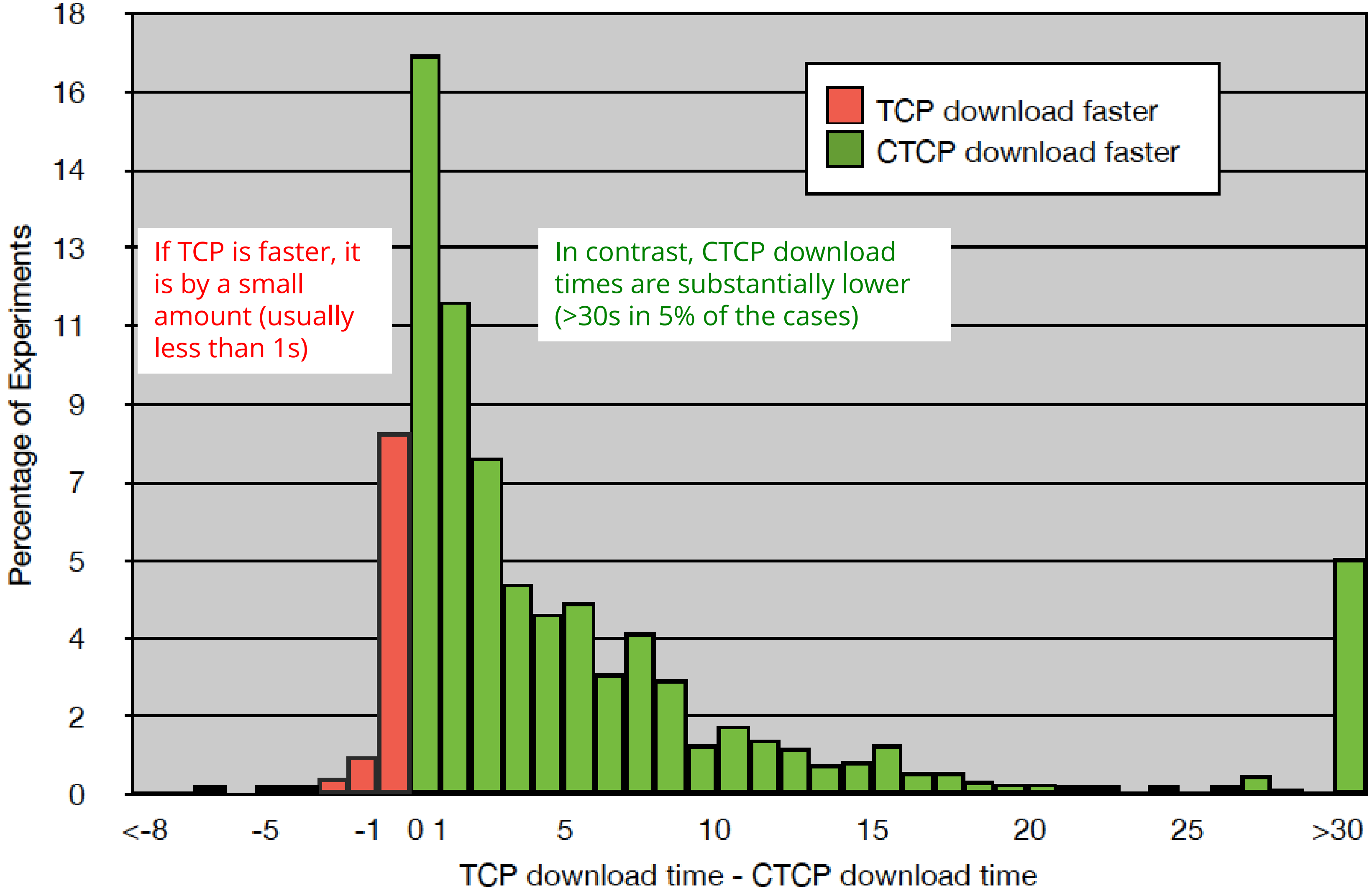
Coded TCP Results

Download Times on Mobile



Coded TCP Results

Histogram of CTCP-TCP Data Pairs



1354 data pairs

Pacific Island Testbed

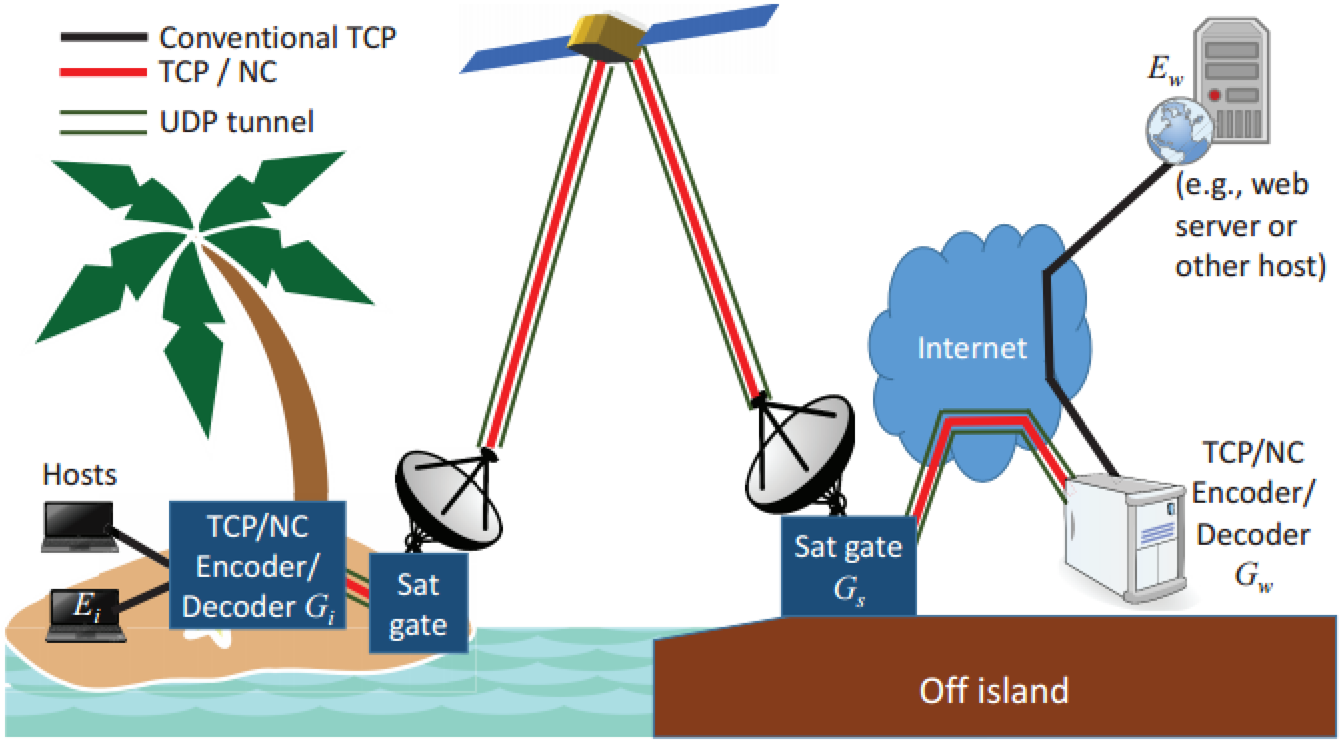
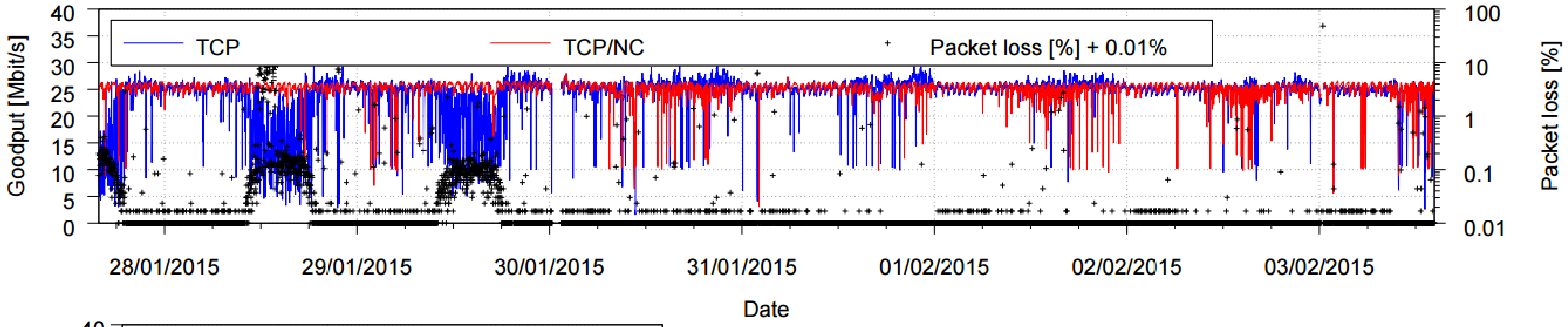
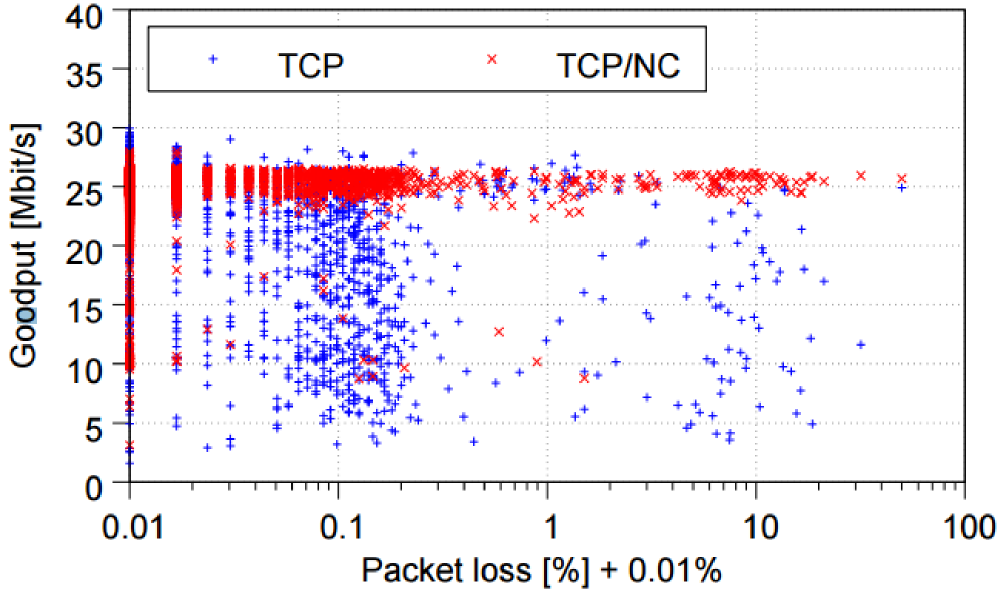


Fig. 1. TCP/NC network topology

http://arxiv.org/pdf/1506.01048v1.pdf

Pacific Island Testbed





… Morten happy

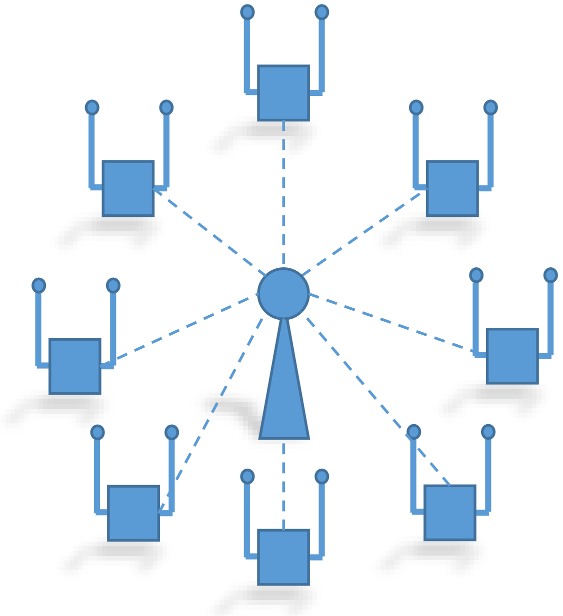
Network Coding Use Cases:
Topologies | Point-to-Multipoint

Wireless Broadcast Services

Application fields:

Substitute for all traditional point-to-multipoint applications.

Better performance in: multicast, broadcast, content distribution networks, IPTV, stadium wireless, DOCSIS, SDN, NFV, and others.



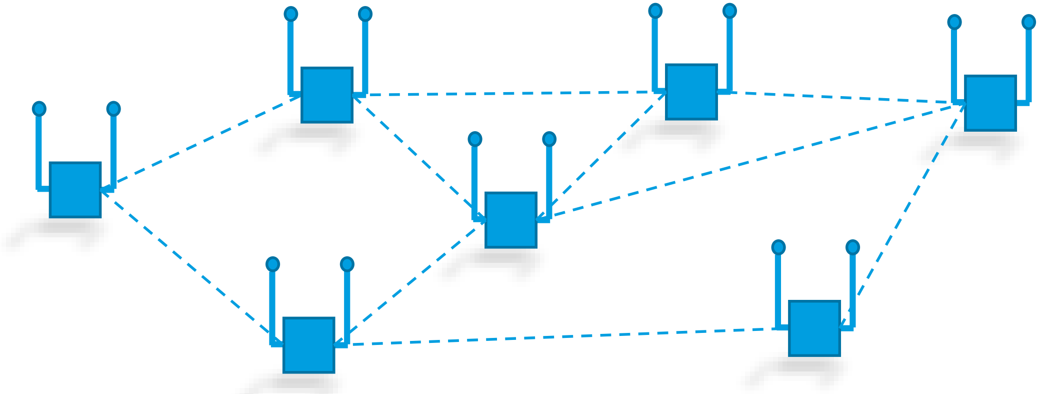
Technology advantage:
- Delay
- Energy reduction

Improvement Metrics:
- RLNC energy-per-bit savings reach factors of **2-3x** for mobile devices in WiFi[5]
- Energy-per-bit ratio for RLNC coding **2-3** orders of magnitude smaller than WiFi transmission[5]

Wireless Broadcast Services

Network Coding Use Cases: Topologies | Mesh

Wireless/Wired Mesh Networks



Application fields:
WiFi networks, small cell, smart grids, device-to-device in LTE-A, IoT, embedded systems (M2M, Internet of Things, RFID, vehicle2vehicle, SDN, NFV, sensor networks, home automation) and others.

Technology advantage:
Improved throughput
Smaller delay
Energy savings
QoE / range gains

Improvement Metrics:

Throughput gain

One relay network: 3dB gain [6]
Mobile mesh: 6dB gain [7]

Delay

Reduction by one order of magnitude for ping service [8], 3.6x decrease in delay for D2D [6],

Energy consumption

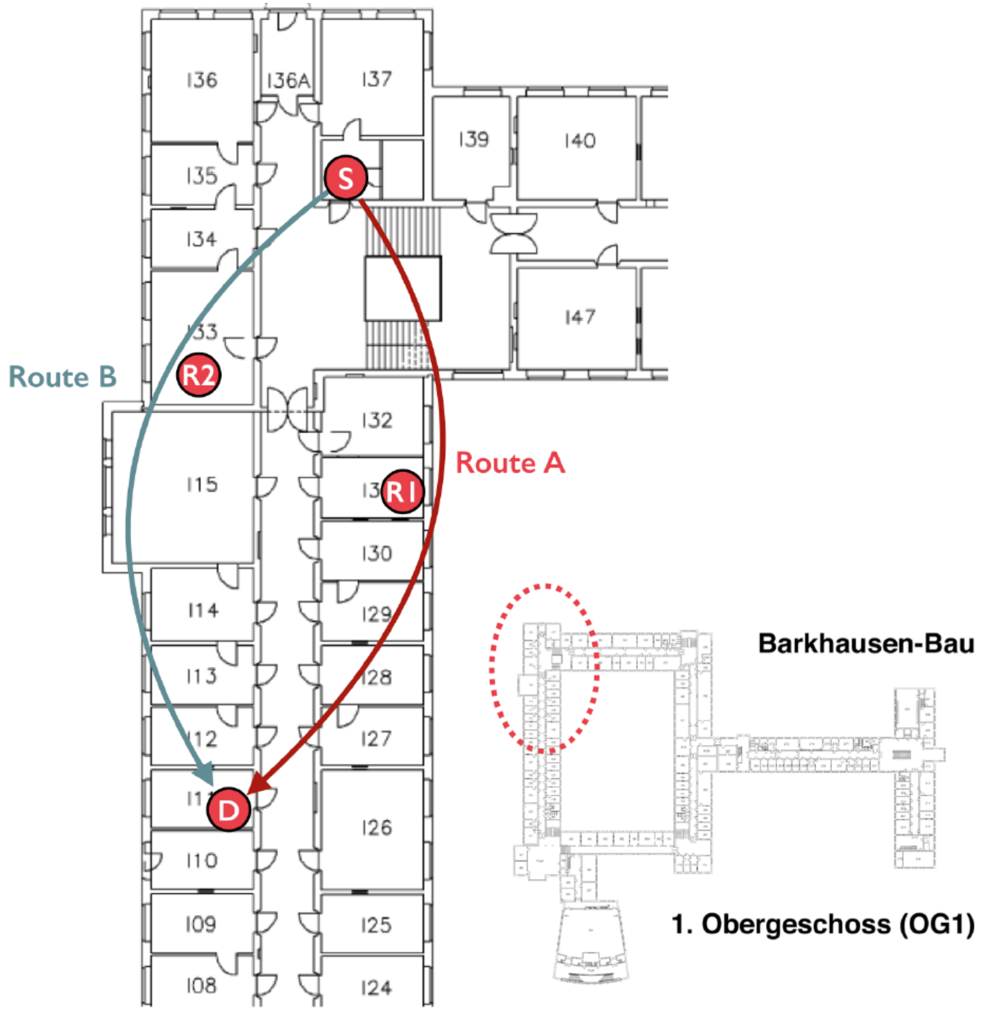
3.9x decrease in wireless mesh networks [7]

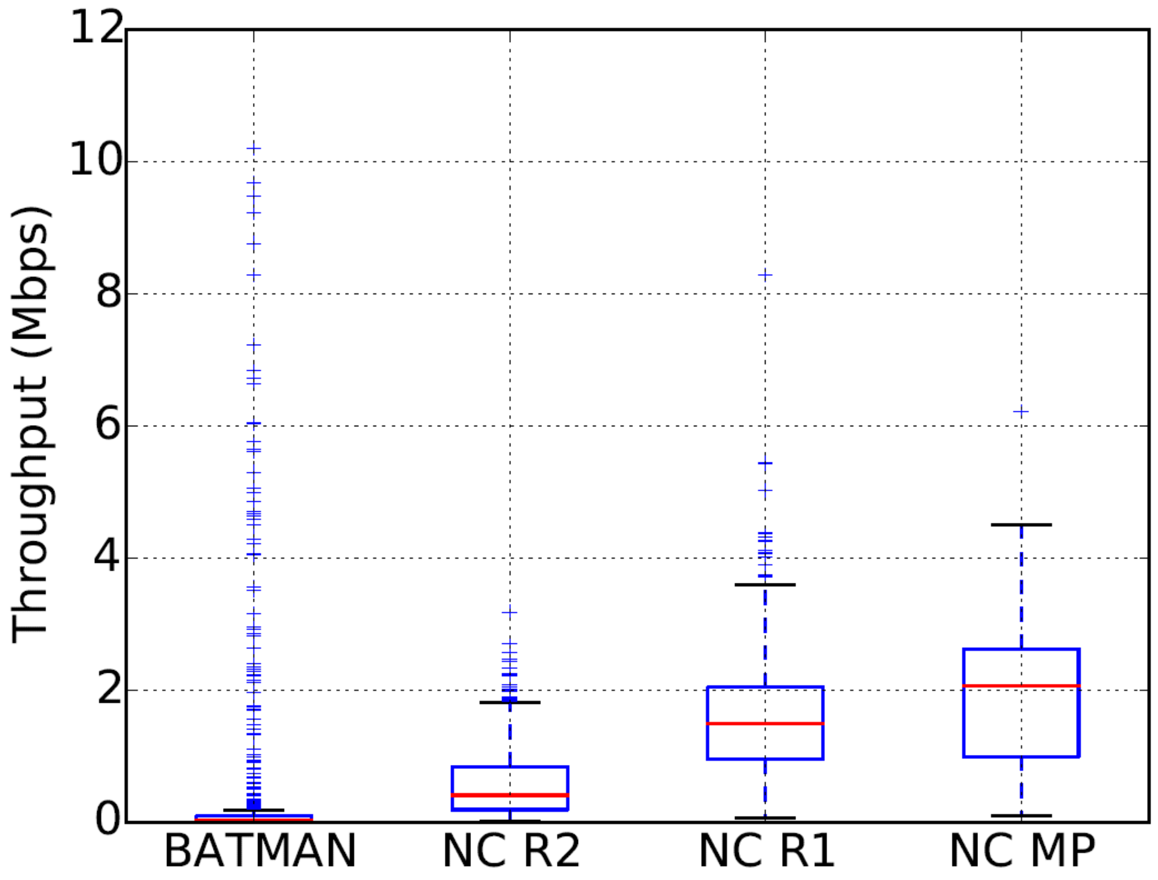
QoE / range

In multihop mesh networks the same QoE targets using 30% percent of the bandwidth 90% of the time and 10x improvement in network range [9]

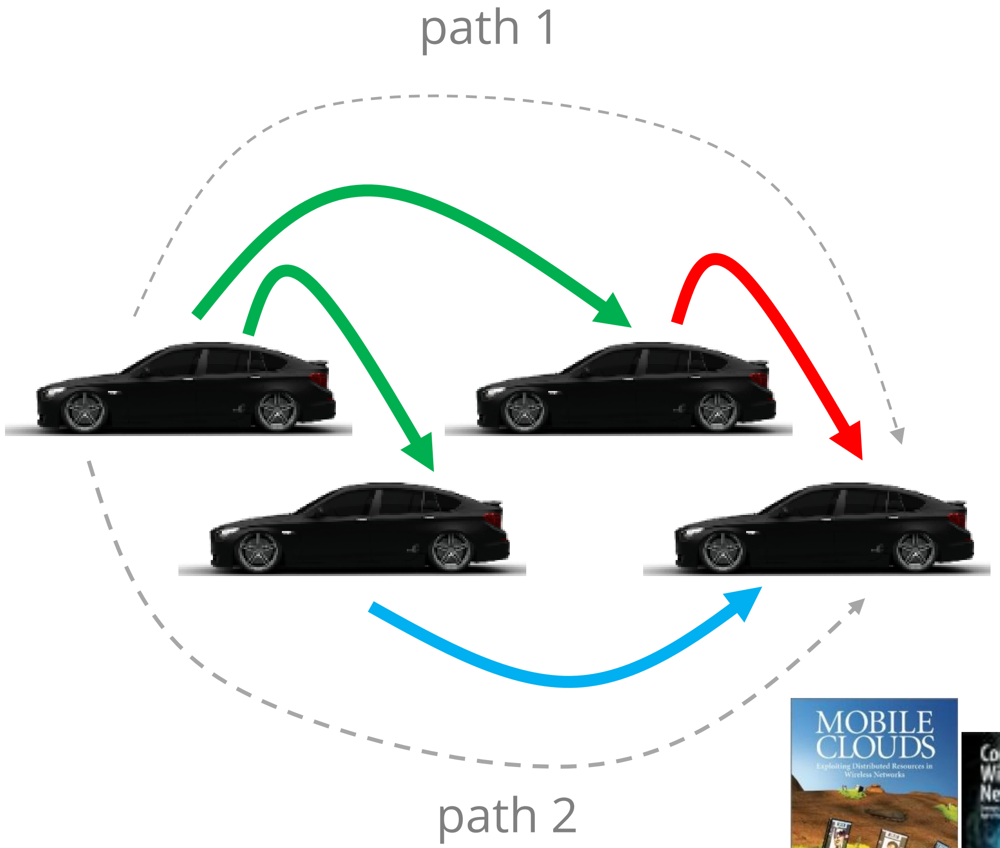
Wireless Mesh Networks

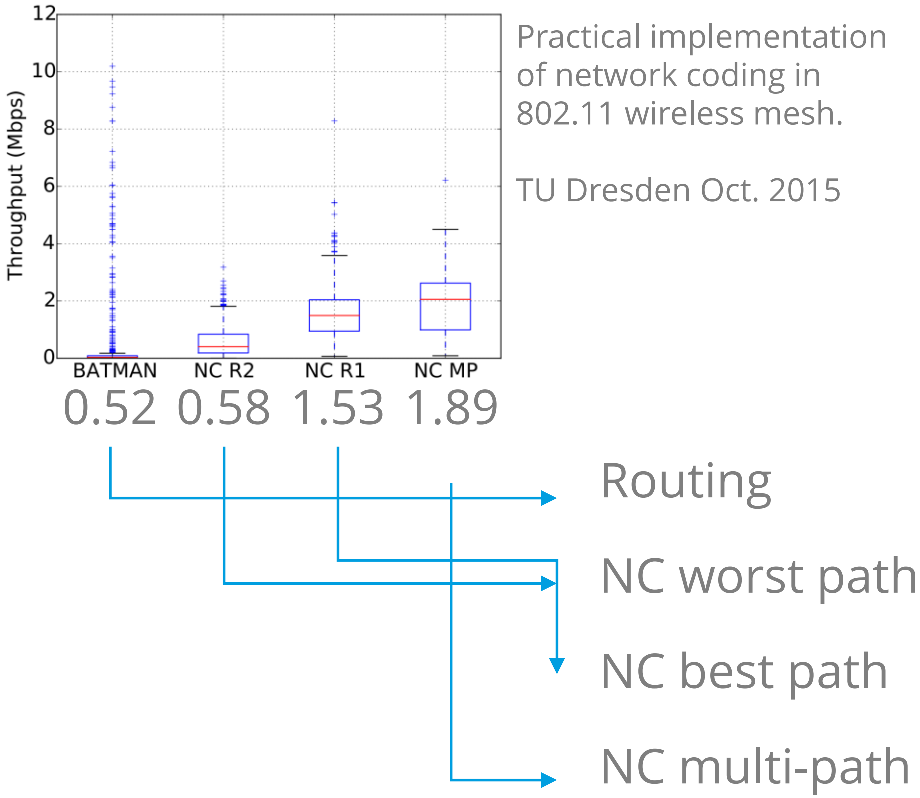
Wireless Mesh Networks





Wireless Mesh Networks





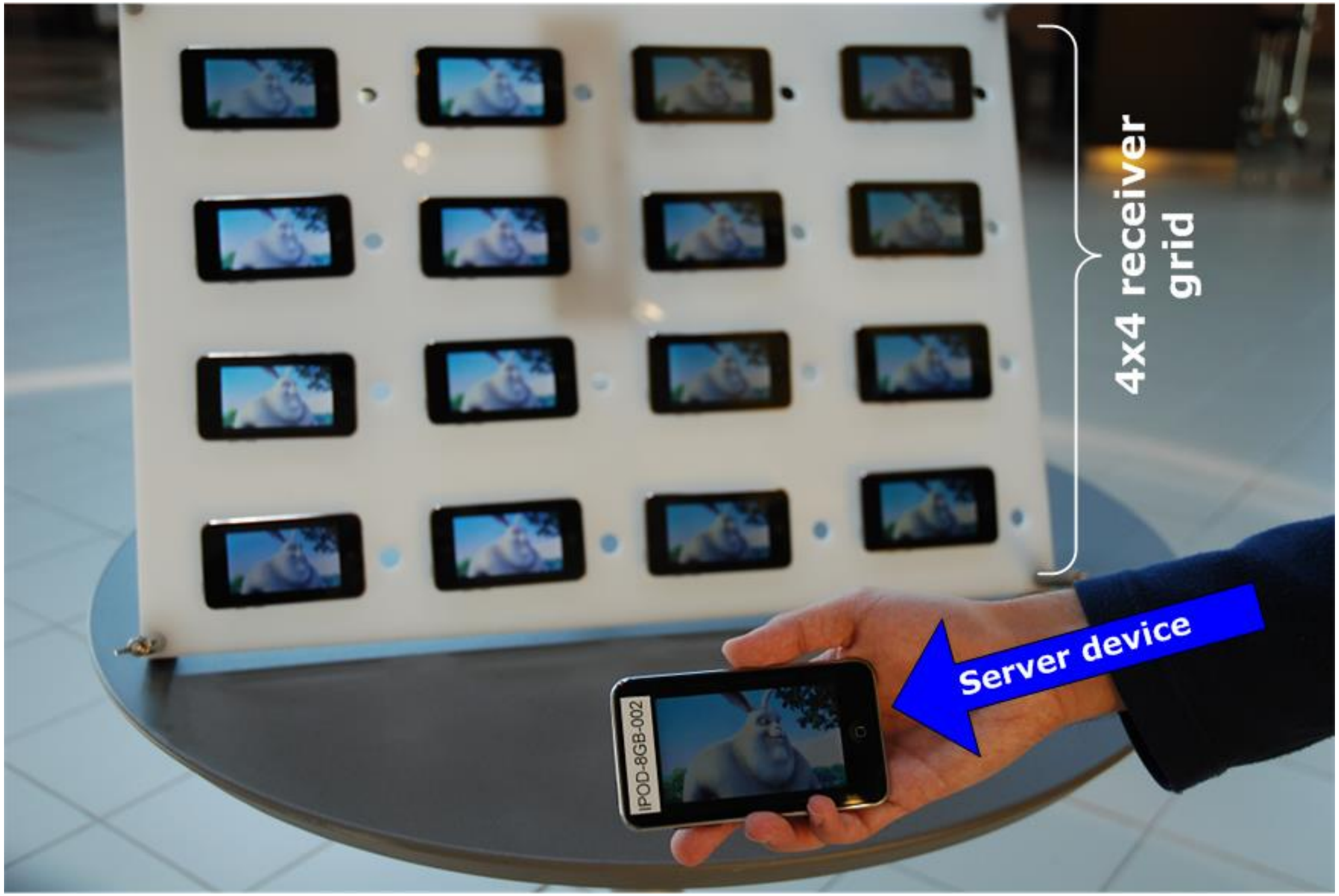
Practical implementation of network coding in 802.11 wireless mesh.

TU Dresden Oct. 2015

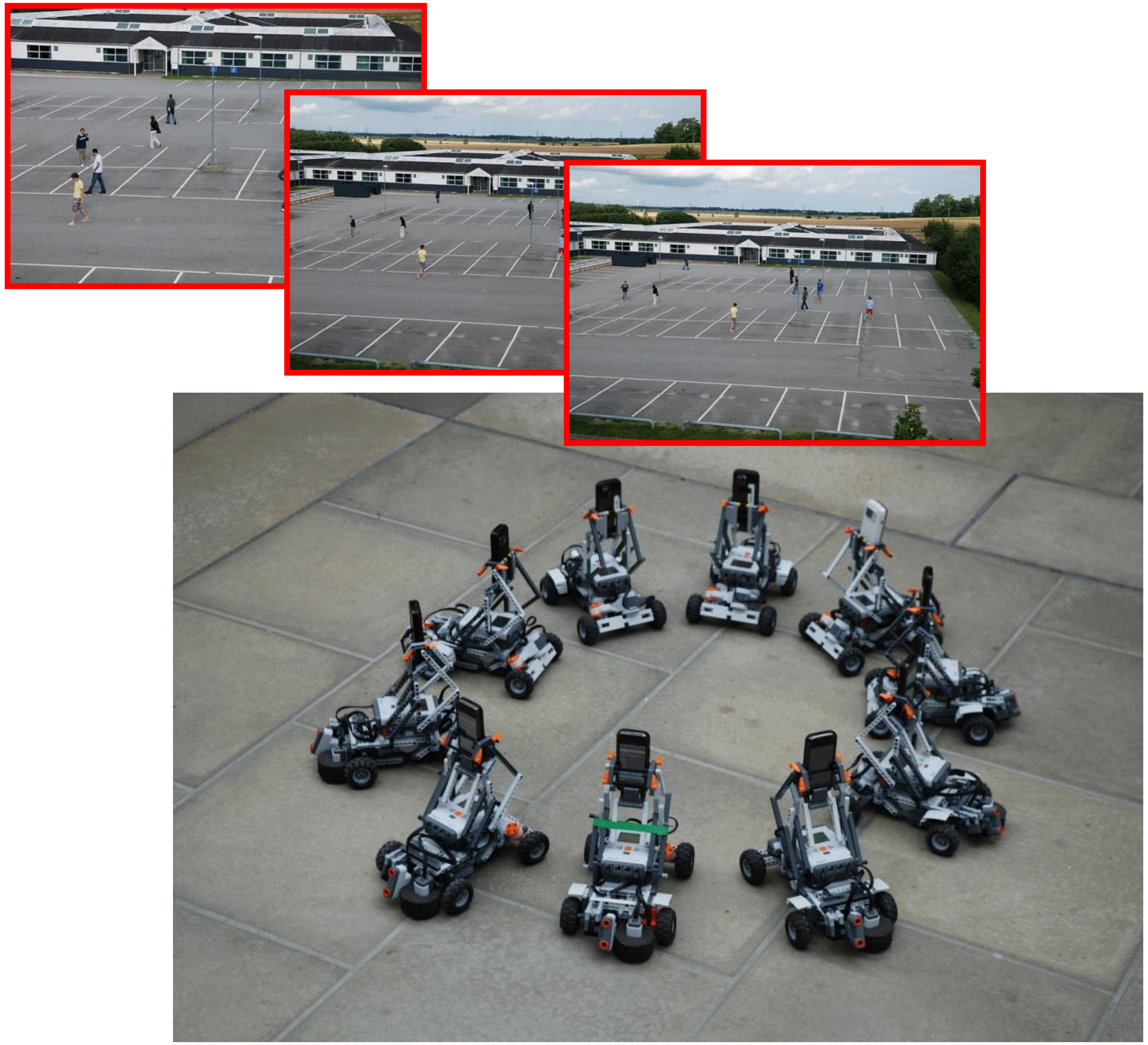
Reliable Multicast with D2D

Wireless Mesh (RLNC)

D2D



Mobile Testbed



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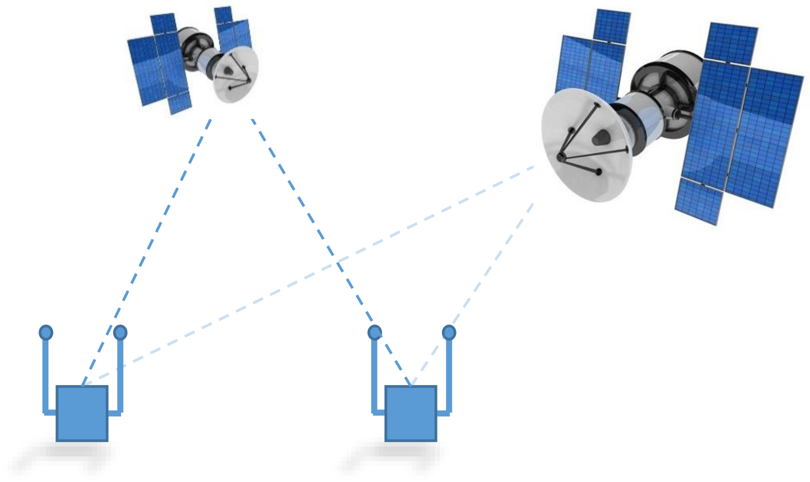
Network Coding Use Cases: Topologies | Satelitte

Satellite Communication



Application fields:

Satellite relaying and multi beam communications.

Applications include maritime communications, mid-air (airplane) internet connectivity, remote location internet access and others.

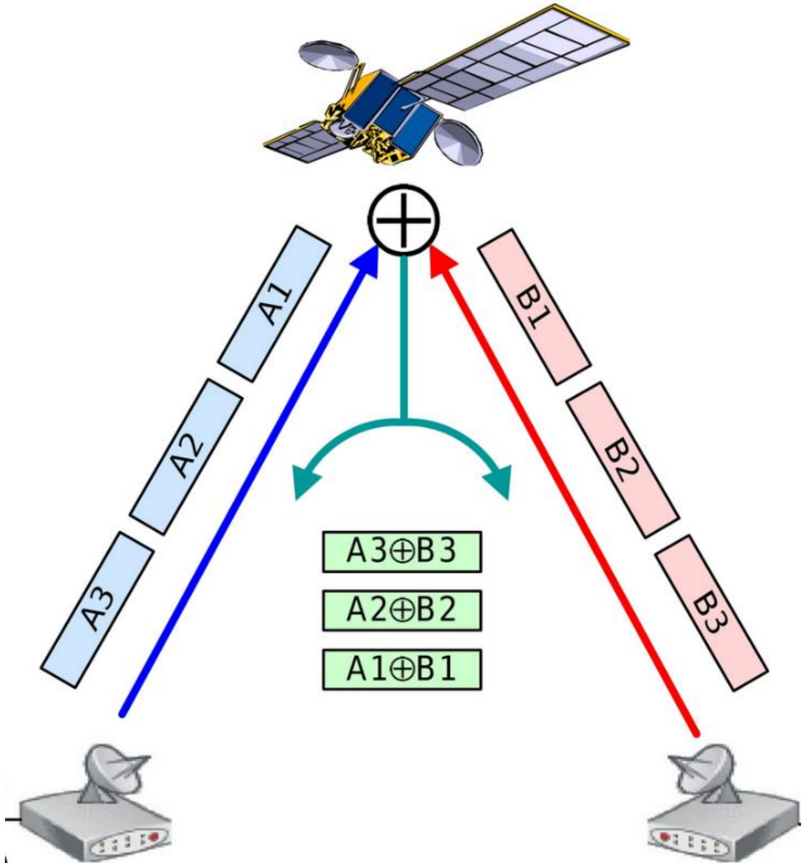
Technology advantage:

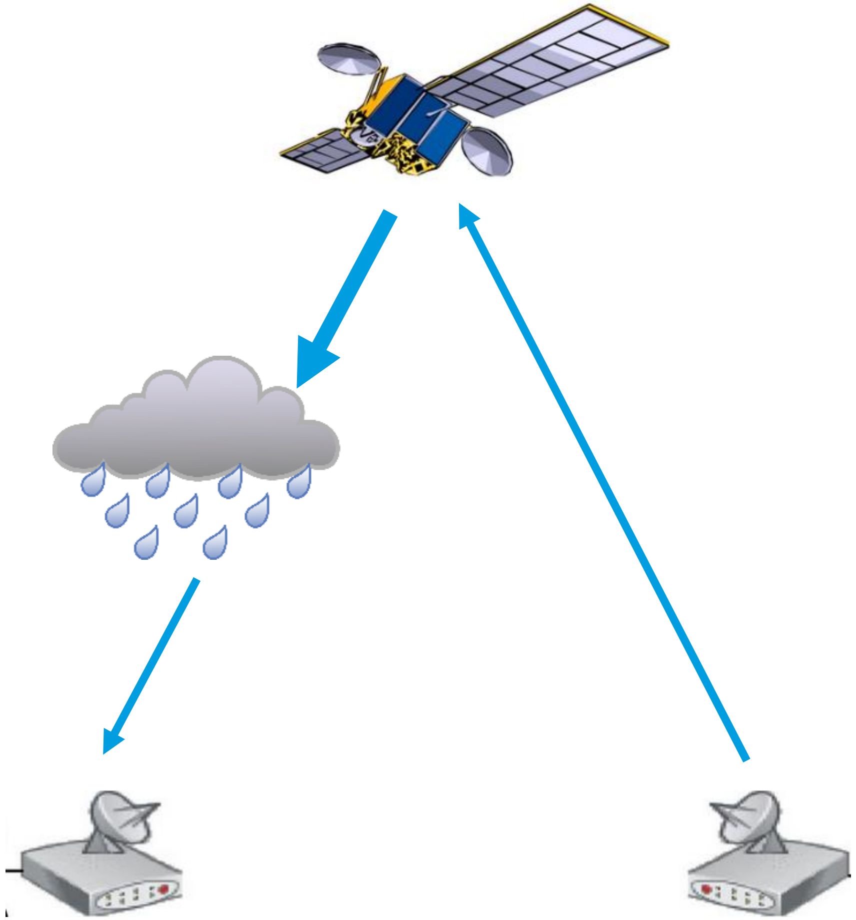
- Delay
- Flexibility
- Throughput potential

Improvement Metrics:

- Throughput increase by **2x**[10]
- CTCP throughput gains reach **20x** over lossy satellite links[11]
- RLNC-based protocols achieve **2x / 6x** the throughput of NACK-based protocols in satellite multicast networks with 100 receivers with 5% / 50% losses[12]

Network Coding for Satellites

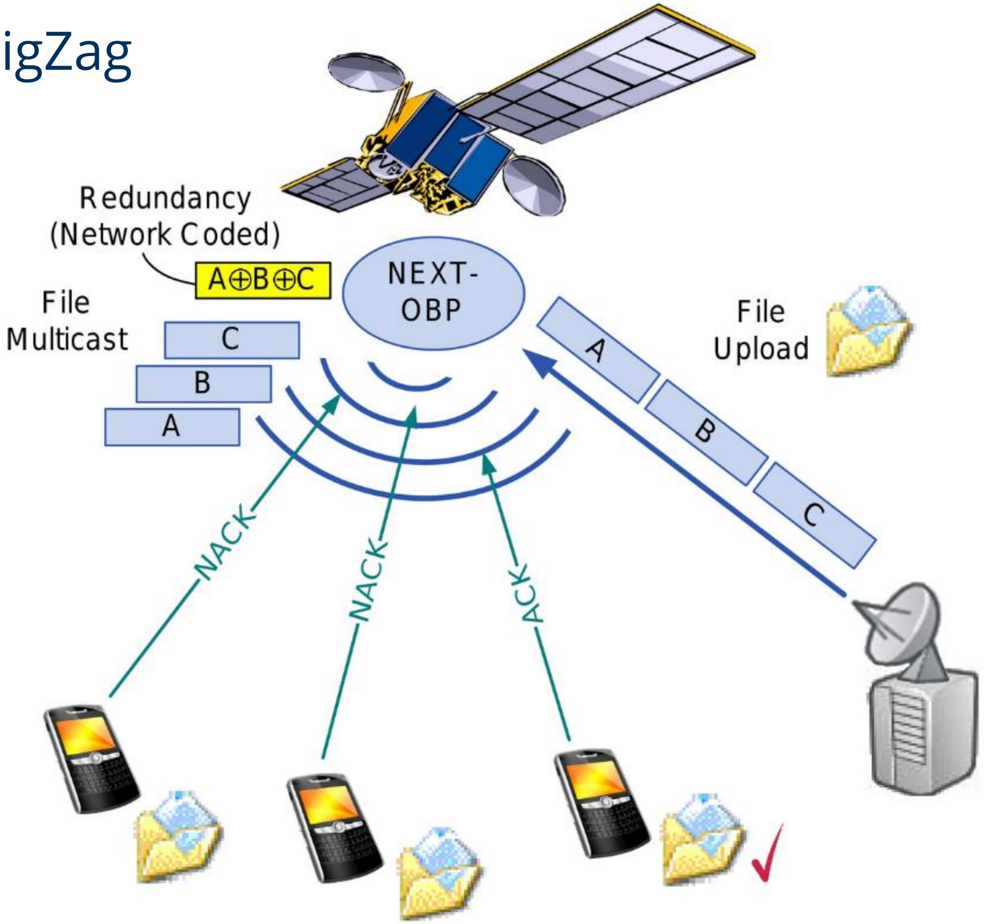




http://www.dlr.de/kn/Portaldata/27/Resources/images/projekte/NEXT-Network_coded_interconnection_of_computer_networks_via_satellite.jpg

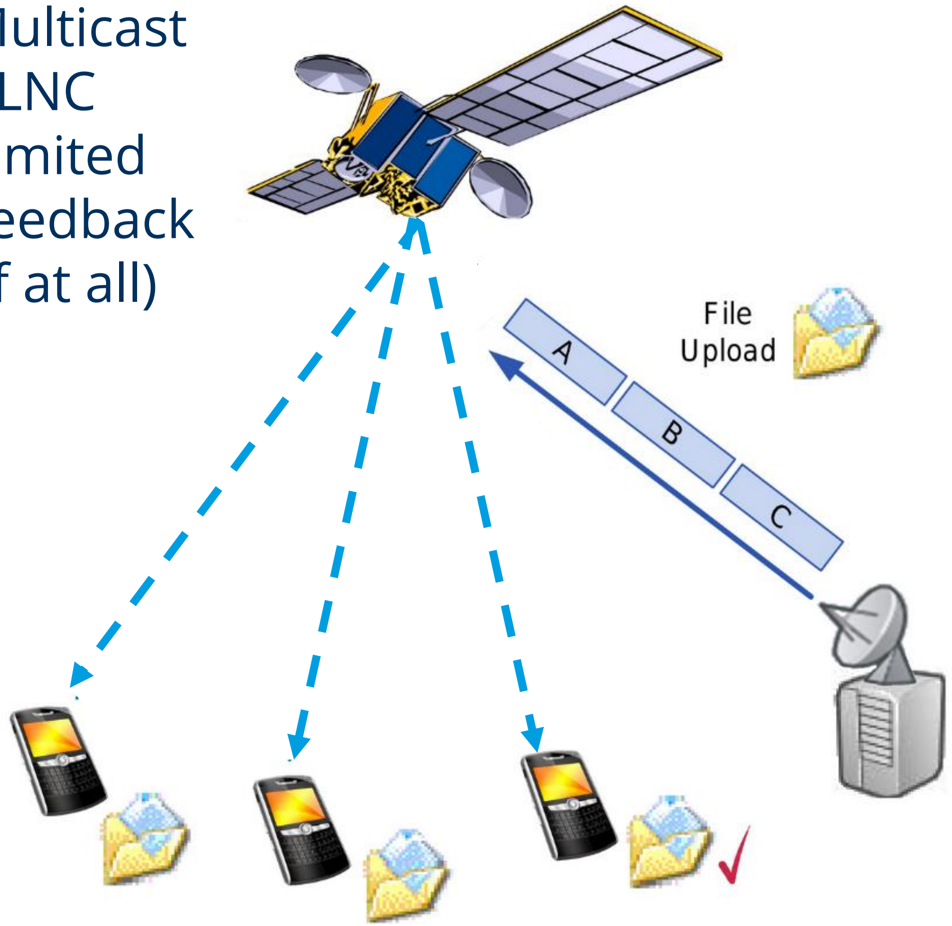
Network Coding for Satellites

ZigZag



http://www.dlr.de/kn/Portaldata/27/Resources/images/projekte/NEXT-Network_coded_reliable_multicast_via_satellite.jpg

Multicast
RLNC
Limited
*F*eedback
(if at all)



Network Coding Use Cases:
Topologies | Multi-Source Multi Destination

Multi-Source Multi Destination

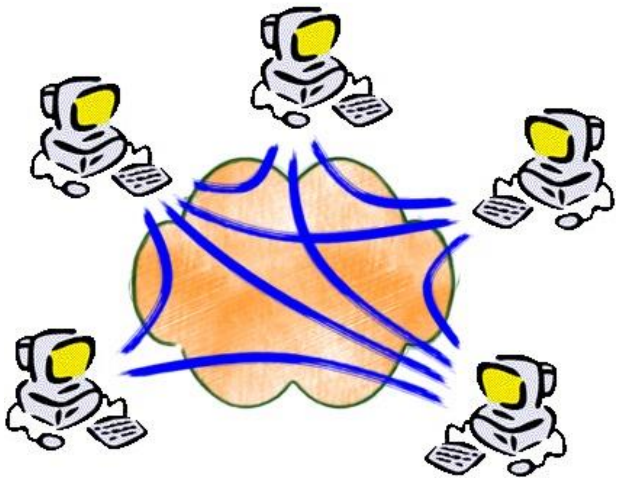
Application fields:
Peer to peer networks, WebRTC, SDN, distributed storage (drive, SAN, edge cache, peer-to-peer edge caching, multi-cloud, hybrid cloud), NFV, cloud services, cloud security, and others.

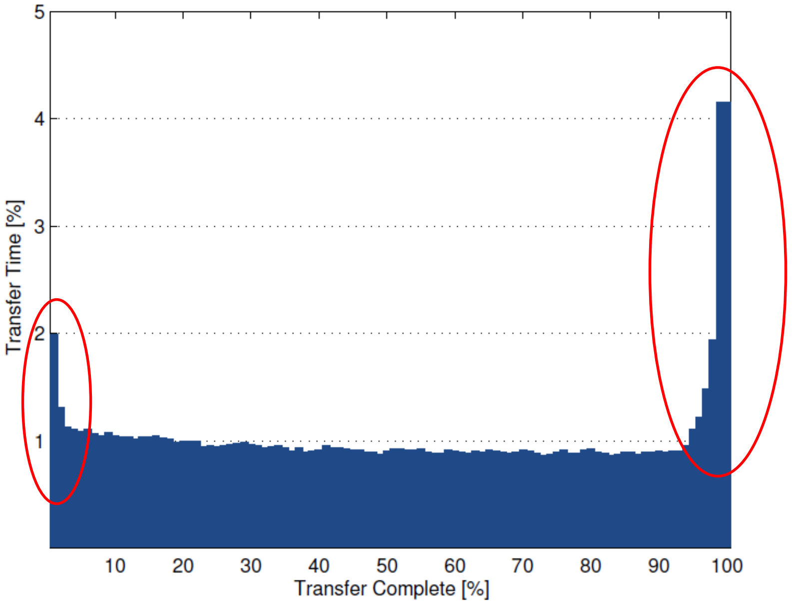
Technology advantage:
Throughput gains
Flexible tunable codes
Security
Dynamic network storage

Improvement Metrics:
RLNC-enabled minimum-cost multicast routing reduces bandwidth usage by up to 33% and energy consumption by up to 49% in a number of provider backbone networks [13]
Improves P2P reliability and security, reducing overhead over E2E coding by > 10x, starting at just 5% attack probability [14]

Peer2Peer

- File sharing
- Video streaming
- DOS if traffic is too large, P2P is vital solution
- Torrent based systems (collector's problem)
- WebRTC for video streaming





Cadami - Coded Caching for IFE/IFC

Cadami removes congestion from networks…

- Cache content in the network's quiet times

  like pumping up water at night when electricity is cheaper

- Reduce bandwidth usage by 50-80% when there is heavy demand

  caching + network coding to minimise network peak load

- Cadami is the market leader for **Coded Caching**
- Solution by Cadami & Steinwurf is deployed on 100+ aircraft
- game changer for future IFE/IFC systems

IFExpress on 2018 AIX highlights noted:

>> One tekkie vendor has developed a code based solution for installations in IFE systems that "reduces" the bandwidth required for streamed movies and the system prevents delays when all are watching movies.
The German start-up Cadami is one to watch. <<

Network Coding Use Cases: Topologies | Content Storage and Delivery

Content Storage and Delivery

Application fields:
Distributed storage (drive, SAN, edge caching, multi-cloud, hybrid cloud), peer-to-peer, IPTV, CDN, SDN, NFV, cloud services, cloud security, streaming video and others.

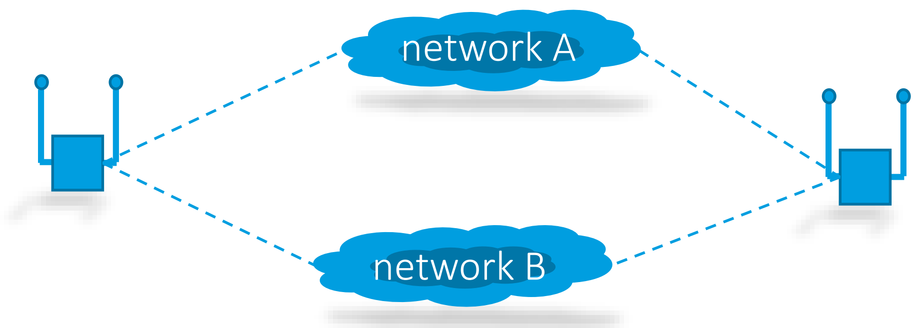
Technology advantage:
Download speeds
Increased availability
Security / data integrity
Reduced energy

Improvement Metrics:
Reducing the download time for distributed delivery by 2x using RLNC [15,16]
Cloud integrity can be assured for distributed storage with dynamic settings [17, 18]
Data availability gains from RLNC-based multi-resolution video schemes reach 80% for high traffic loads [18]
RLNC reduces data center energy consumption by 20% - 50% by reducing transaction times and required storage [19]

Network Coding Use Cases: Topologies | Multi-Path

Multi-path Communications

Application fields:
Heterogeneous network channel bundling for improved QoE (LTE + WiFi, DSL + DSL, MPLS + Internet, satellite + cellular), Multi-path TCP, SDN, NFV, CDN, cloud services, and others.



Technology advantage:
Improved throughput
Smaller delay
Robustness
Reduced administrative complexity

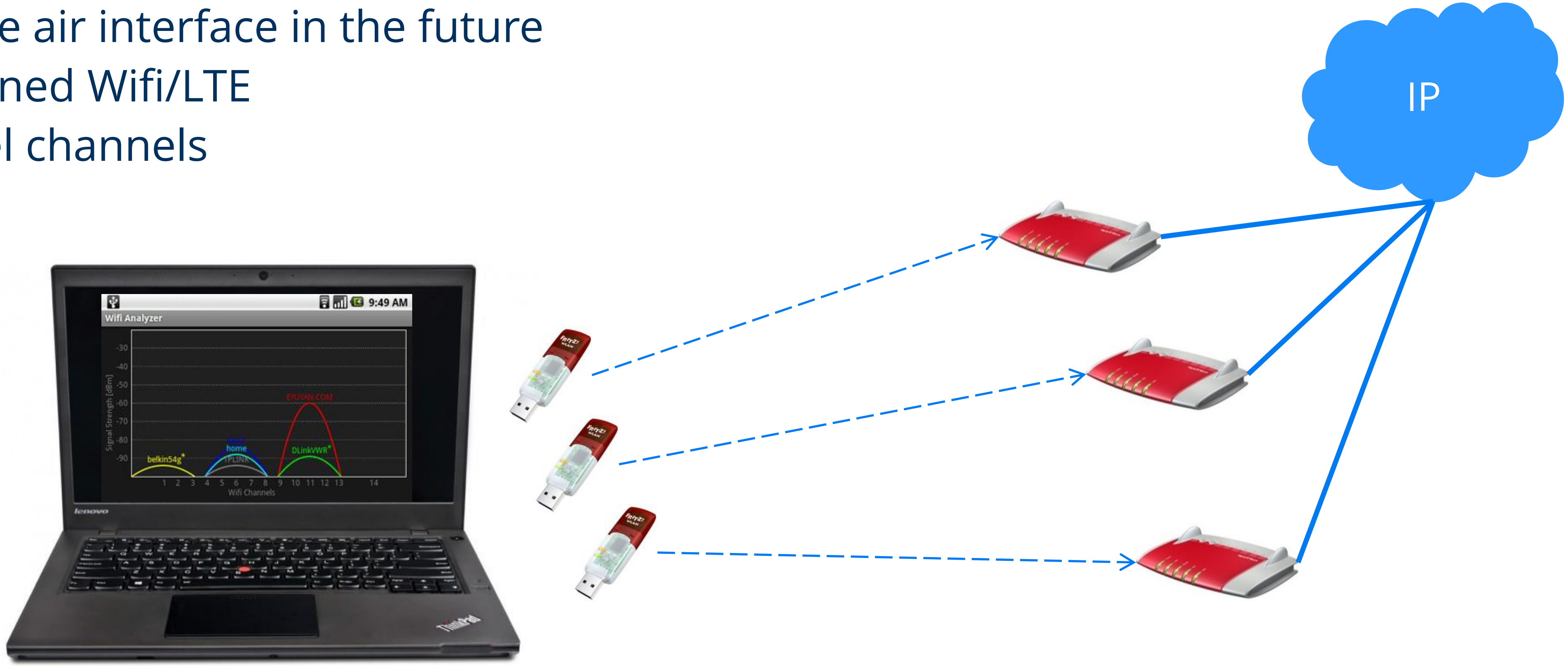
Improvement Metrics:
5x improvement on RTT (delay) [20]
Coded MPTCP in WLAN / cellular scenarios show a tenfold reduction of download delays and 8-15x goodput gains compared to uncoded MPTCP [21]
Improves uptime and improves throughput by up to 20x over uncoded MPTCP in combined cellular, WiFi and satellite networks [22]

Channel Bundling

- Single air interface (SoA)
- Mutliple air interface in the future
  - Combined Wifi/LTE
  - Parallel channels
- Network operators going for small cells or Femto cells

Channel Bundling

- Single air interface (SoA)
- Mutliple air interface in the future
  - — Combined Wifi/LTE
  - — Parallel channels



Supporting References

1. Customer field trials
2. M. Kim, J. Cloud, A. ParandehGheibi, L. Urbina, K. Fouli, D. Leith, M. Médard; Network Coded TCP (CTCP). arXiv: 1212.2291v
3. S. Teerapittayanon, K. Fouli, M. Médard, M.-J. Montpetit, X. Shi, I. Seskar, A. Gosain; Network Coding as a WIMAX Link Reliability Mechanism. MACOM 2012: 1-12
4. M. Kim, T. Klein, E. Soljanin, J. Barros, M. Médard; Trade-off between cost and goodput in wireless: Replacing transmitters with coding. MONAMI 2013
5. A. Paramanathan, M.V. Pedersen, D.E. Lucani, F.H.P. Fitzek, M. Katz; Lean and Mean: Network Coding for Commercial Devices; IEEE Wireless Communications Magazine, 2013
6. P. Pahlavani, D.E. Lucani, M.V. Pedersen, and F.H.P Fitzek, “PlayNCool: Opportunistic Network Coding for Local Optimization of Routing in Wireless Mesh Networks,” in GLOBECOM 2013, Dec. 2013.
7. P. Vingelmann, M.V. Pedersen, F.H.P. Fitzek, and J. Heide, “Data dissemination in the wild: A testbed for high-mobility manets,” in IEEE ICC, Jun. 2012.
8. Own testbed (customer)
9. V. Firoiu, G. Lauer, B. DeCleene, and S. Nanda; Experiences with Network Coding within MANET Field Experiments. MILCOM 2010

Supporting References

10.http://www.tvtechnology.com/article/research-at-mit-and-hamilton-institute-could-effectively-double-satellite-ip-bandwidth/222941#sthash.ZmbMInWZ

11. J. Cloud, D. Leith, and M. Médard. Network Coded TCP (CTCP) Performance over Satellite Networks SPACOMM 2014

12. F. Vieira and J. Barros. Network Coding Multicast in Satellite Networks. NGI '09 , July 2009.

13. D.S. Lun, N. Ratnakar, M. Médard, R. Koetter, D.R. Karger, T. Ho, E. Ahmed, F. Zhao. Minimum-Cost Multicast over Coded Packet Networks. *IEEE Transactions on Information Theory*, Vol. 52, Issue 6, pp. 2608-2623, June 2006.

14. M. Kim, L. Lima, F. Zhao, J. Barros, M. Médard, R. Koetter, T. Kalker, and K. Han. On Counteracting Byzantine Attacks in Network Coded Peer-to-Peer Network, *IEEE Journal on Selected Areas in Communications: Special Issue on Mission-Critical Infrastructure*, vol 28, Issue 5, May 2010, pp. 692-702

15.M. Wang and B. Li. R2: Random Push with Random Network Coding in Live Peer-to-Peer Streaming, , *IEEE Journal on Selected Areas in Communications,* Vol. 25, No. 9, December 2007

16.Sipos, M., Fitzek, F., Roetter, D. E. L. & Pedersen, M. V., Distributed Cloud Storage Using Network Coding, 2014 I : IEEE Consumer Communications and Networking Conference

Supporting References

17. Unpublished, own testbed

18. T. Wang, L. Zheng, and Médard, M., “Joint Design of Multi-resolution Codes and Intra/Inter-layer Network Coding”, *Asilomar Conference on Signals, Systems and Computers 2012*

19. U.J. Ferner, M. Médard, and E. Soljanin. Toward Sustainable Networking: Storage Area Networks with Network Coding. *Allerton Conference 2012*

20. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6261900

21. J. Cloud, F. du Pin Calmon, W. Zeng, and M. Médard. Multi-Path TCP with Network Coding for Heterogeneous Networks. Presented at Information Theory and Applications Workshop (ITA) 2012

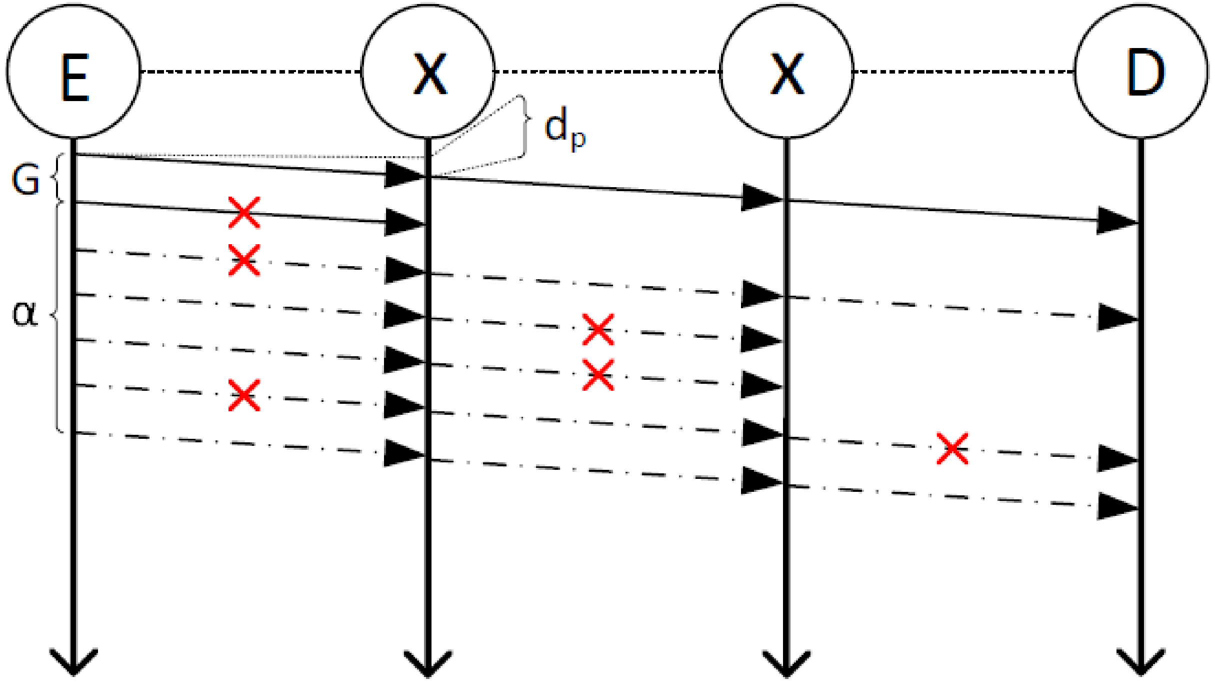
22. J. Cloud, F. du Pin Calmon, W. Zeng, G., Pau, L. Zeger, L., and M. Médard, “Multi-Path TCP with Network Coding for Mobile Devices in Heterogeneous Networks”, *VTC 2013*.

Enabler for Network Coding:
Software Defined Network (SDN)
Network Function Virtualization (NFV)

Software Defined Networks

End to End Coding Schemes: Store and Forward

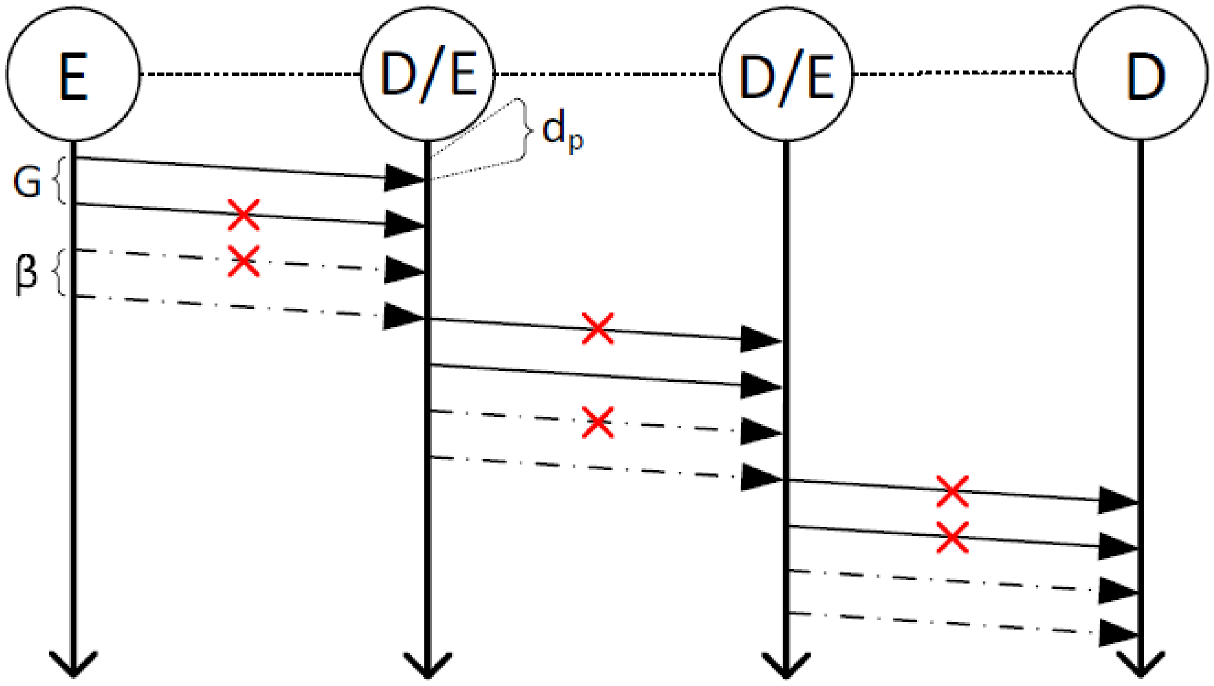
$$P_{E2E} = \sum_{h=1}^{H} G \cdot \left(\frac{1}{(1-\epsilon)^h} \right) \qquad D_{E2E} = \left(G \cdot \left(\frac{1}{(1-\epsilon)^H} \right) + (H-1) \right) \cdot d_p$$



Software Defined Networks

Hop by Hop Coding Scheme: Store and Forward

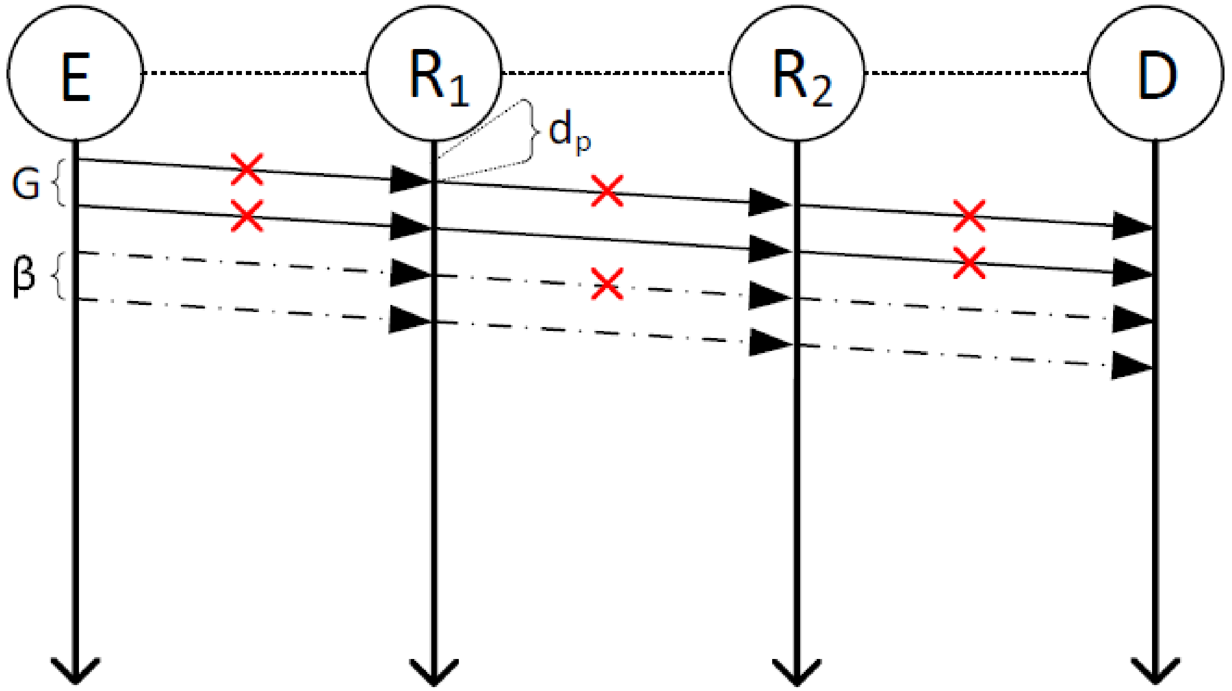
$$P_{HbH} = G \cdot H \cdot \left(\frac{1}{1-\epsilon}\right) \qquad D_{HbH} = G \cdot \left(\frac{1}{1-\epsilon}\right) \cdot H \cdot d_p$$



Software Defined Networks

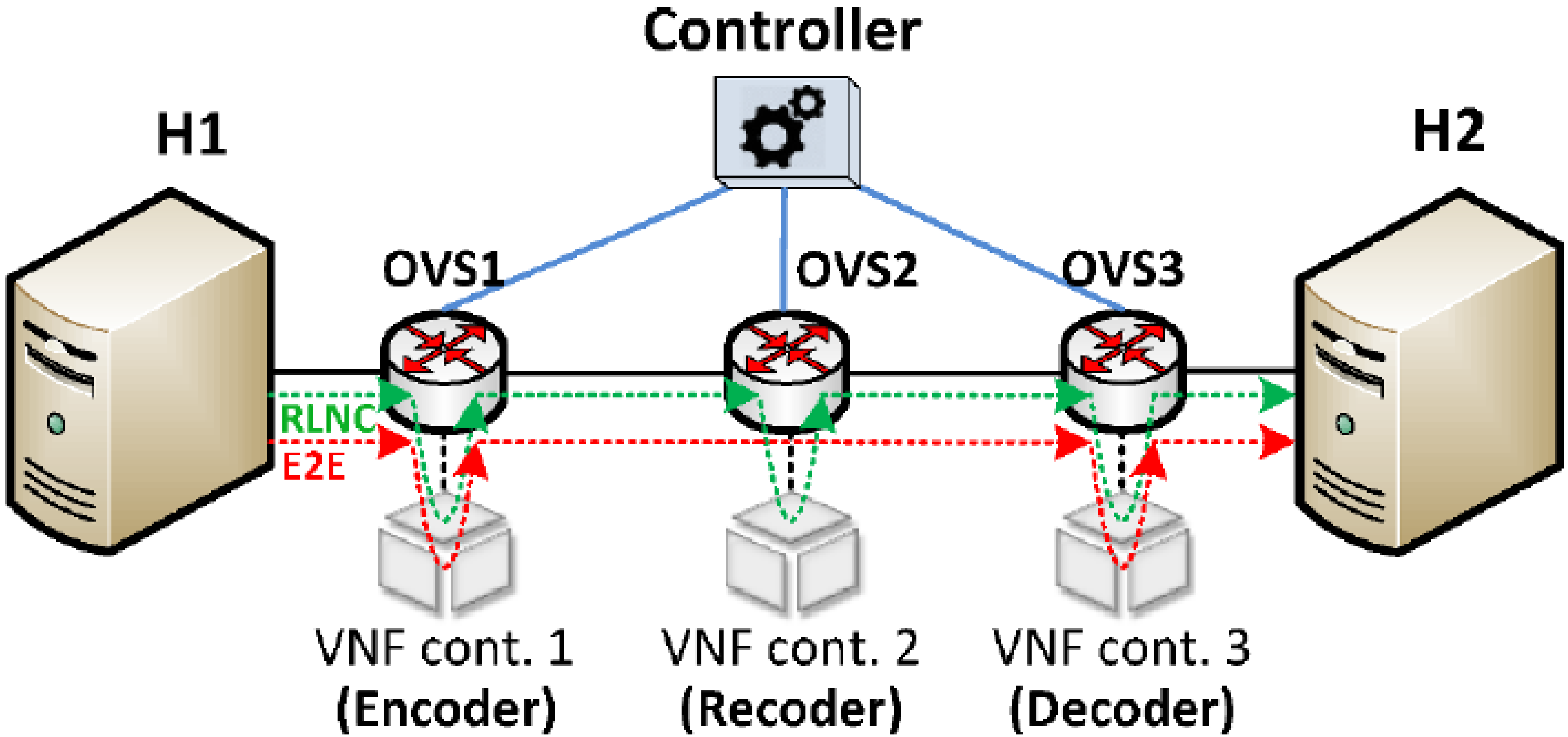
Network Coding Scheme: Compute and Forward

$$P_{RLNC} = G \cdot H \cdot \left(\frac{1}{1-\epsilon} \right) \qquad D_{RLNC} = (G \cdot \left(\frac{1}{1-\epsilon} \right) + (H-1)) \cdot d_p$$



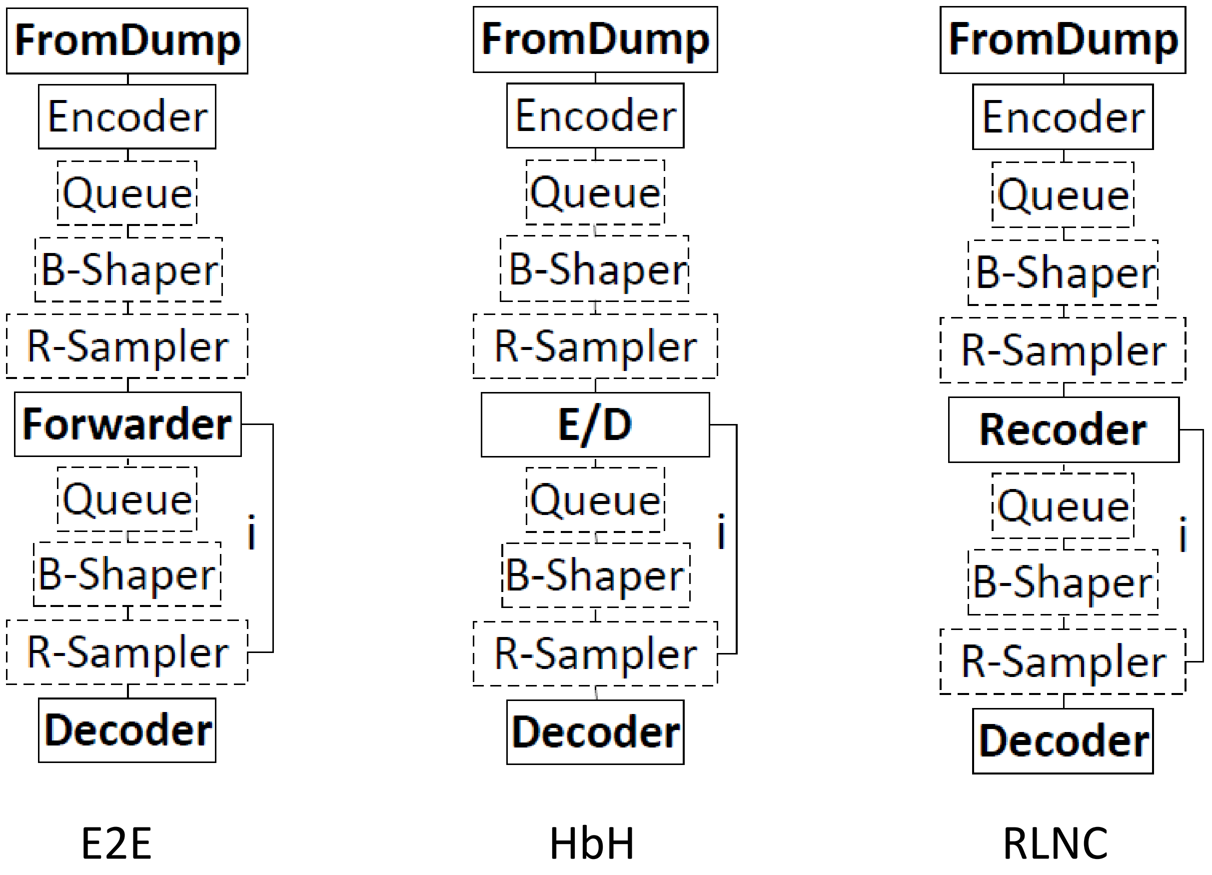
Software Defined Networks Testbed

Example with ESCAPE prototyping environment



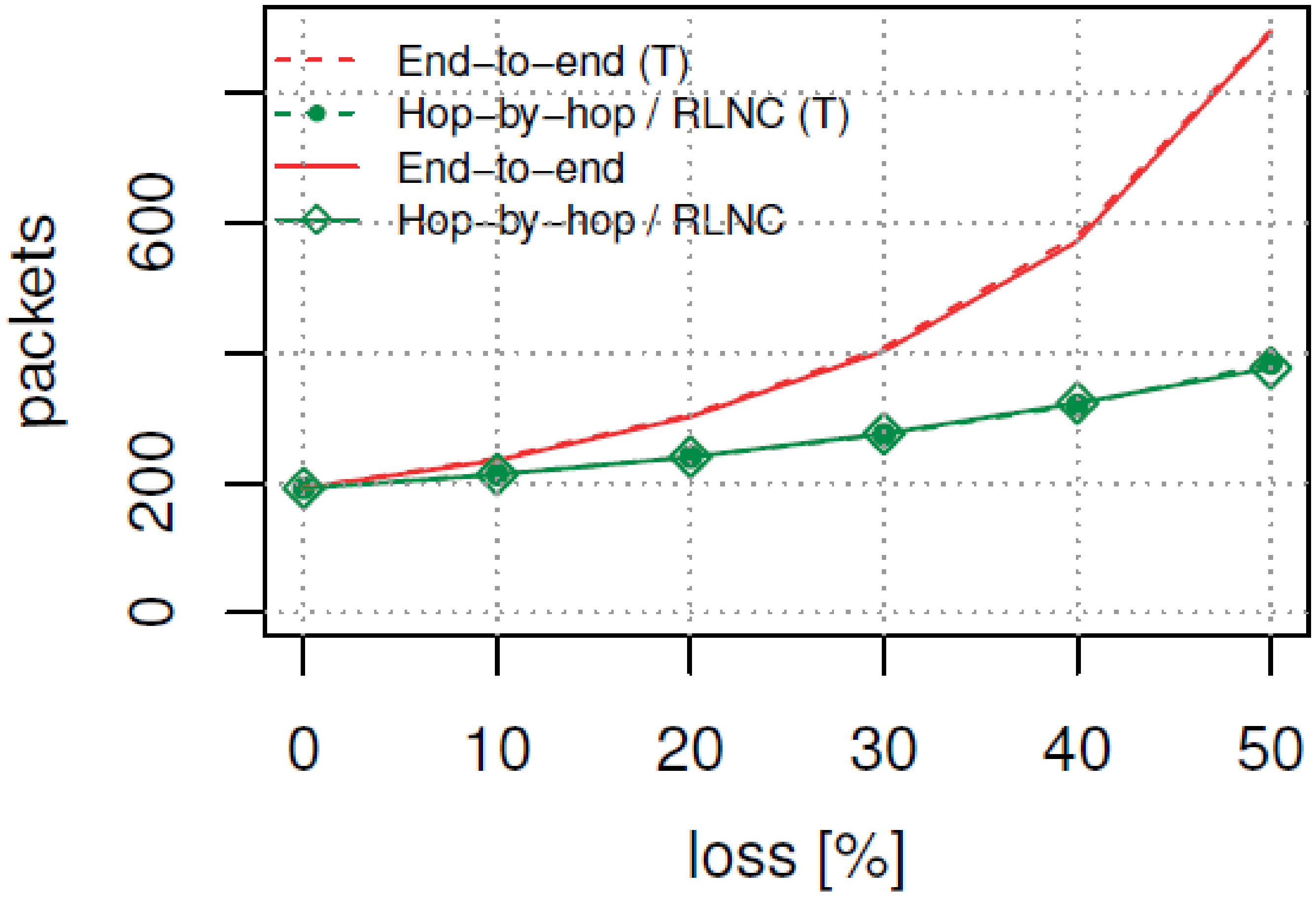
Software Defined Networks

Click configuration



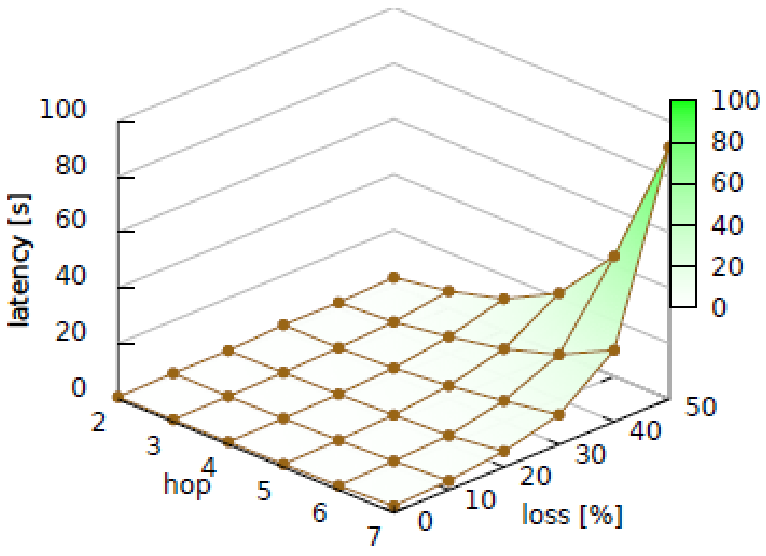
Software Defined Networks

Packets injected into network for the three approaches

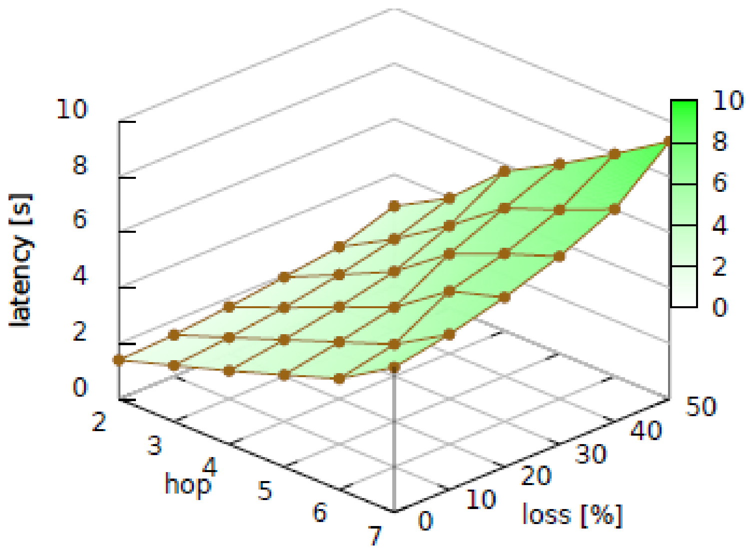


Software Defined Networks

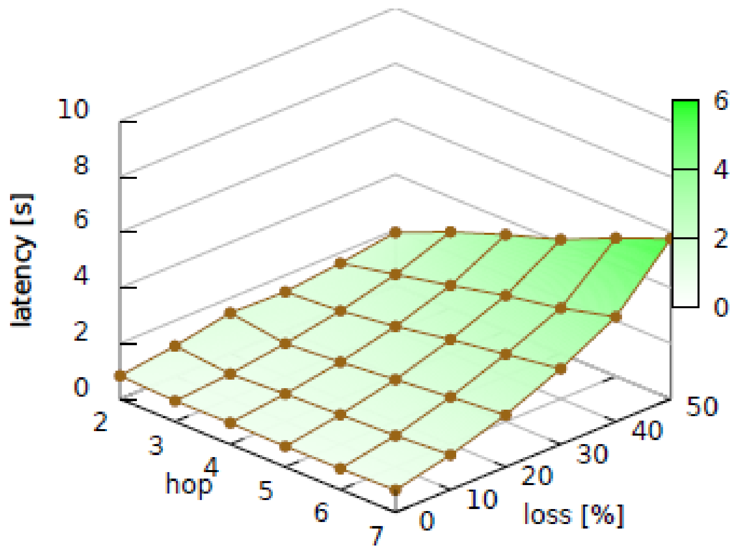
Packets 64 – Size 250 B – Bitrate 0.25 Mb/s



end-to-end



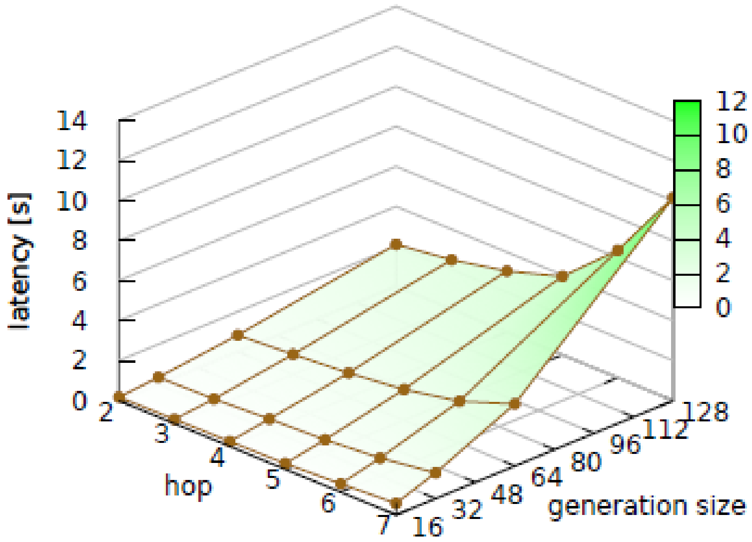
hop-by-hop



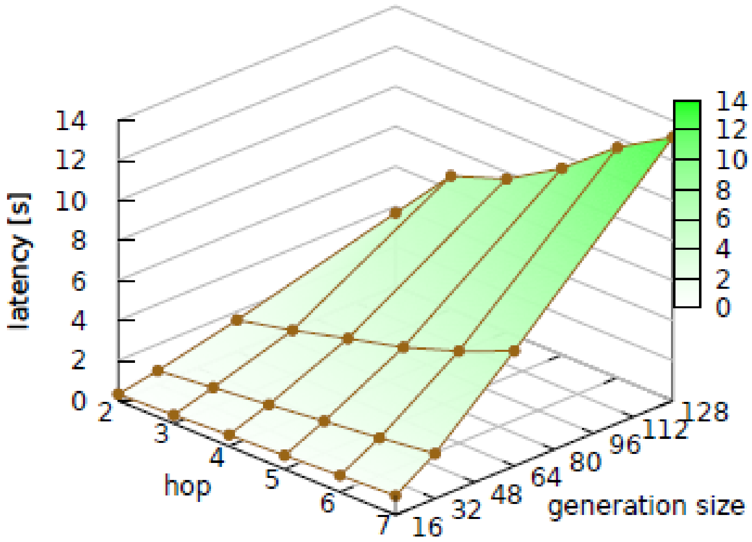
RLNC

Software Defined Networks

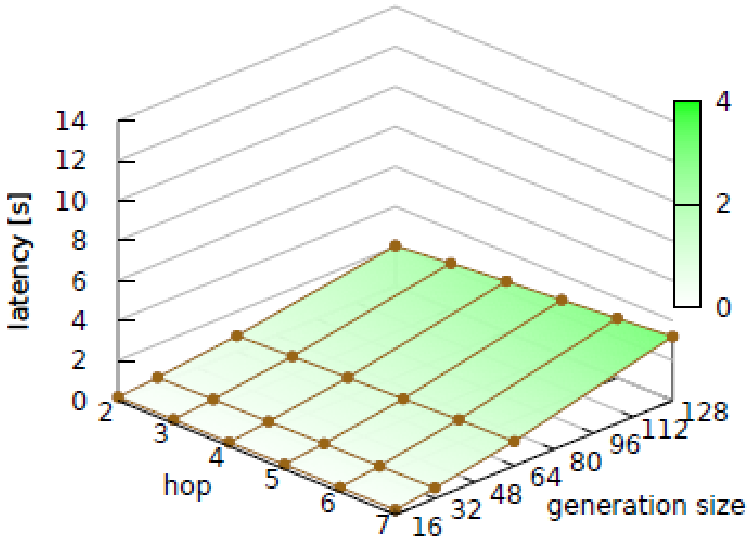
Size 250 B – Loss 10% – Bitrate 0.25 Mb/s



end-to-end



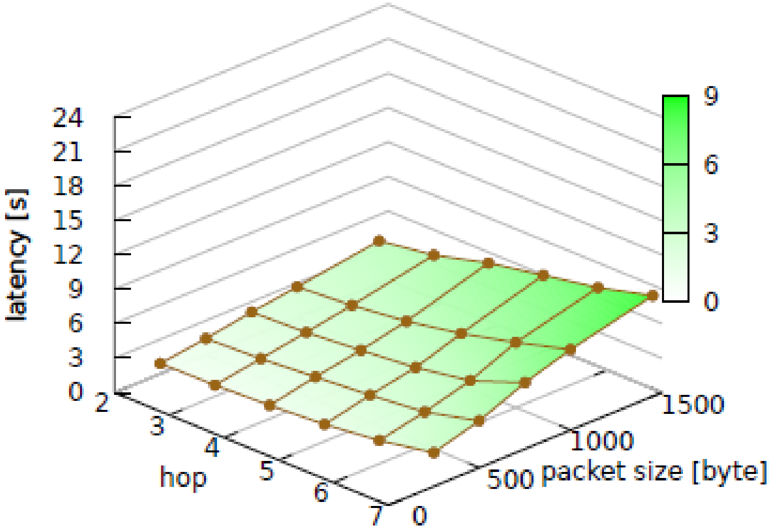
hop-by-hop



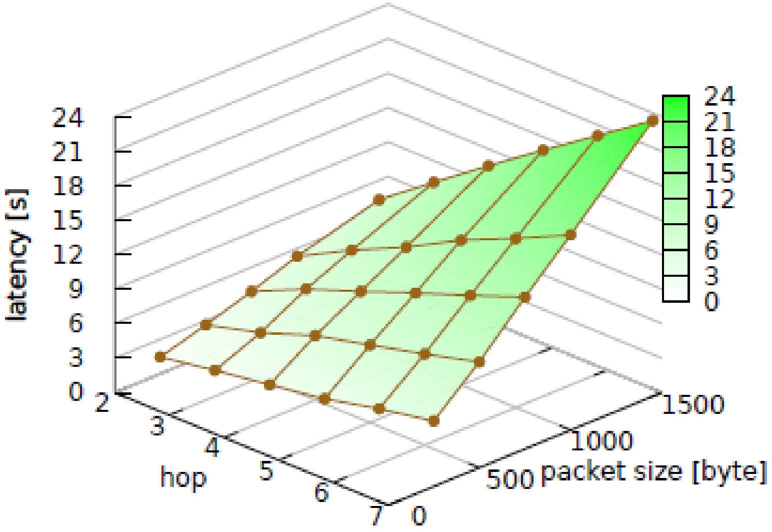
RLNC

Software Defined Networks

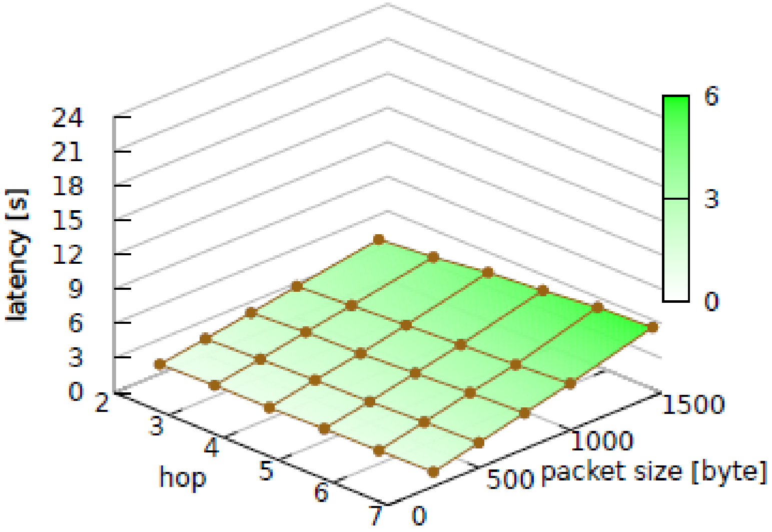
Packets 64 – Loss 10% – Bitrate 0.25 Mb/s



end-to-end



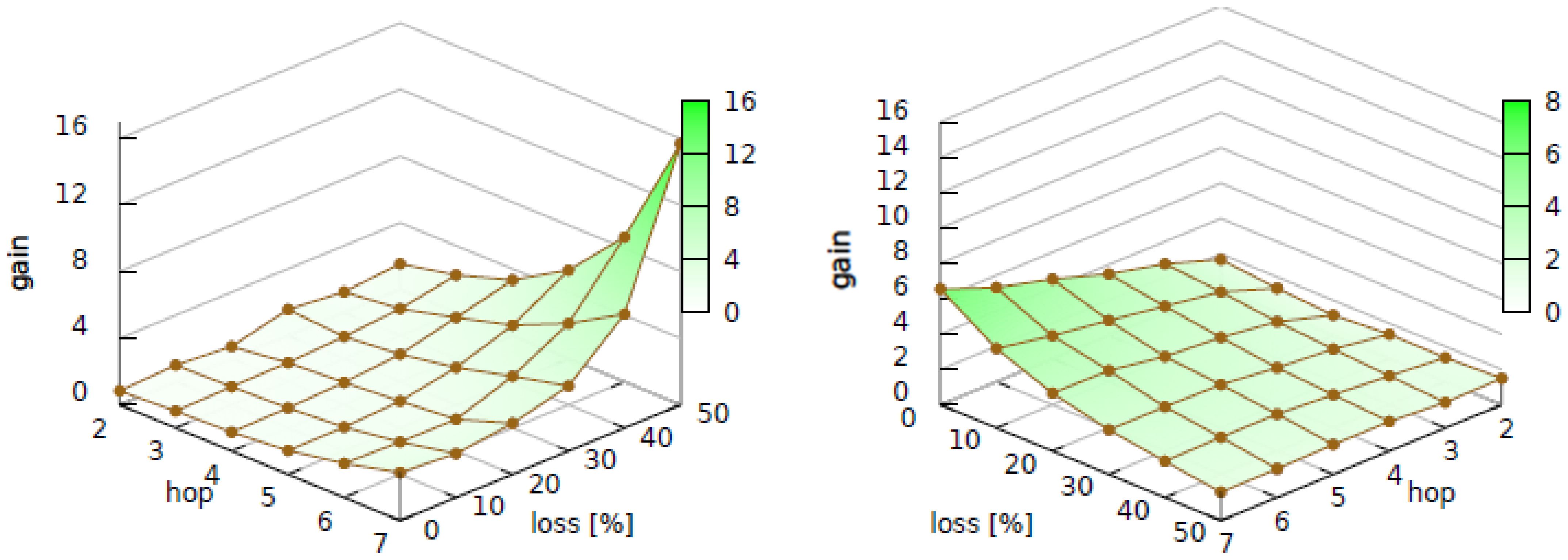
hop-by-hop



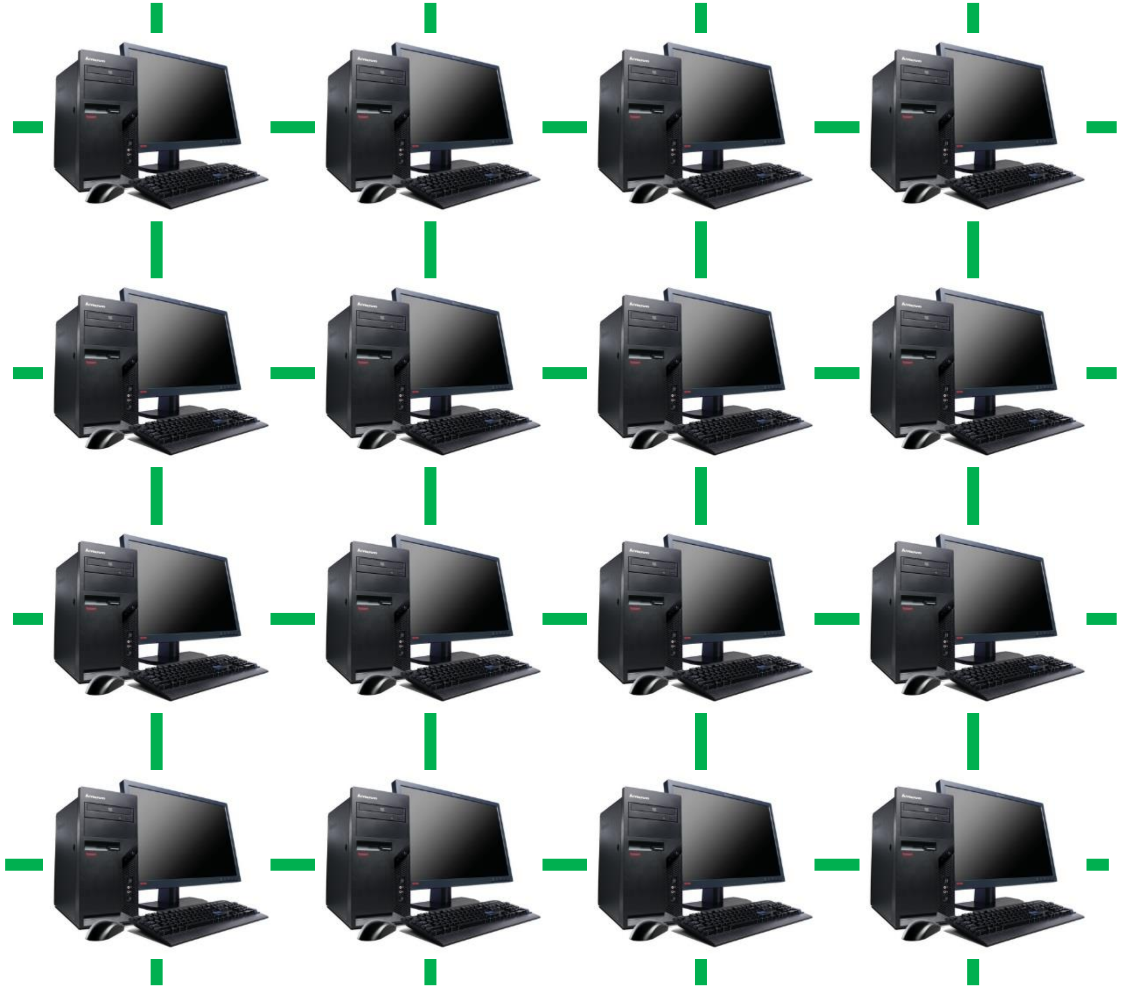
RLNC

Software Defined Networks

Latency gain of e2e vs RLNC (left) and hbh vs RLNC (right)



SDN Testbed Aalborg University



SDN Testbed Aalborg University

SOFTWARE DEFINED 5G NETWORKS FOR ANYTHING AS A SERVICE

Network Coded Software Defined Networking: Enabling 5G Transmission and Storage Networks

Jonas Hansen, Daniel E. Lucani, Jeppe Krigslund, Muriel Médard, and Frank H. P. Fitzek

SDN Testbed Aalborg University

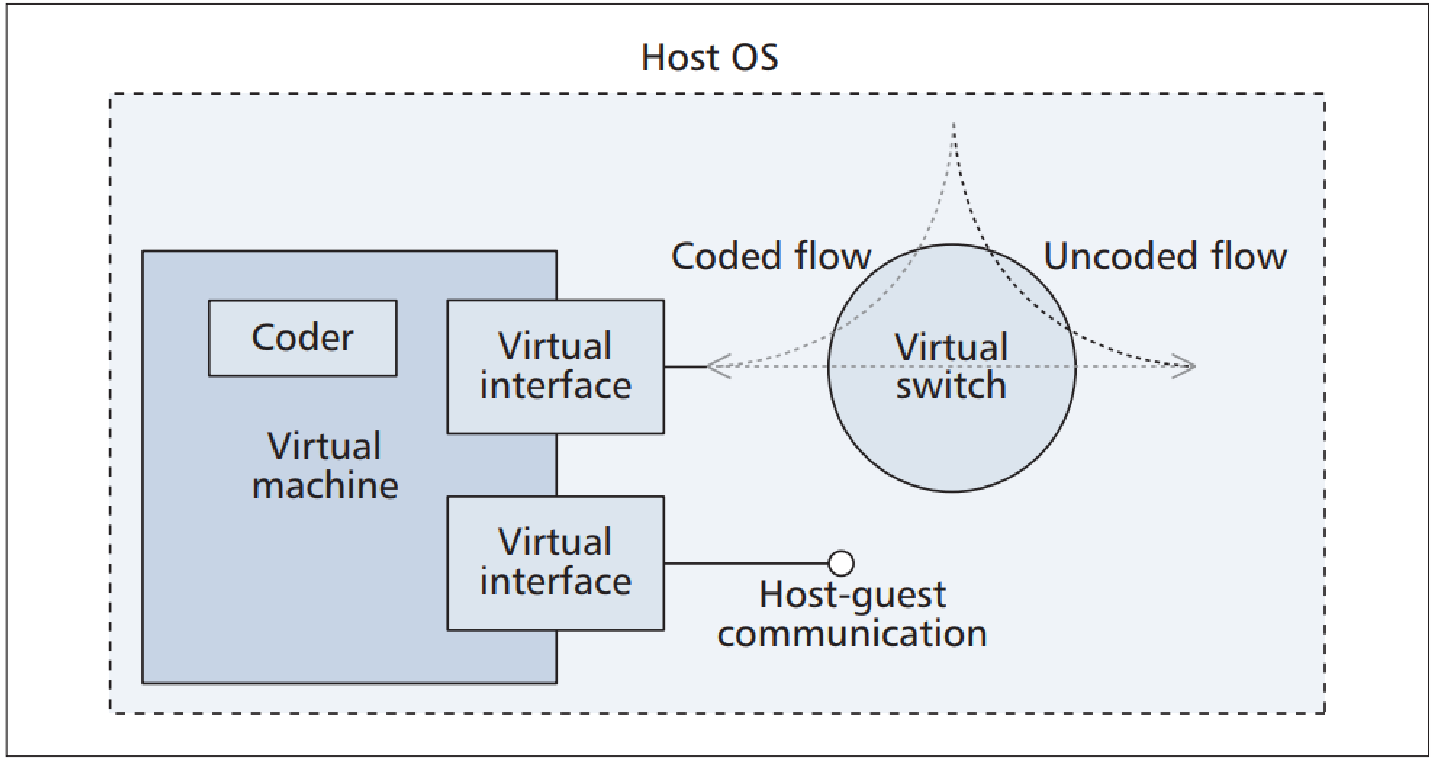
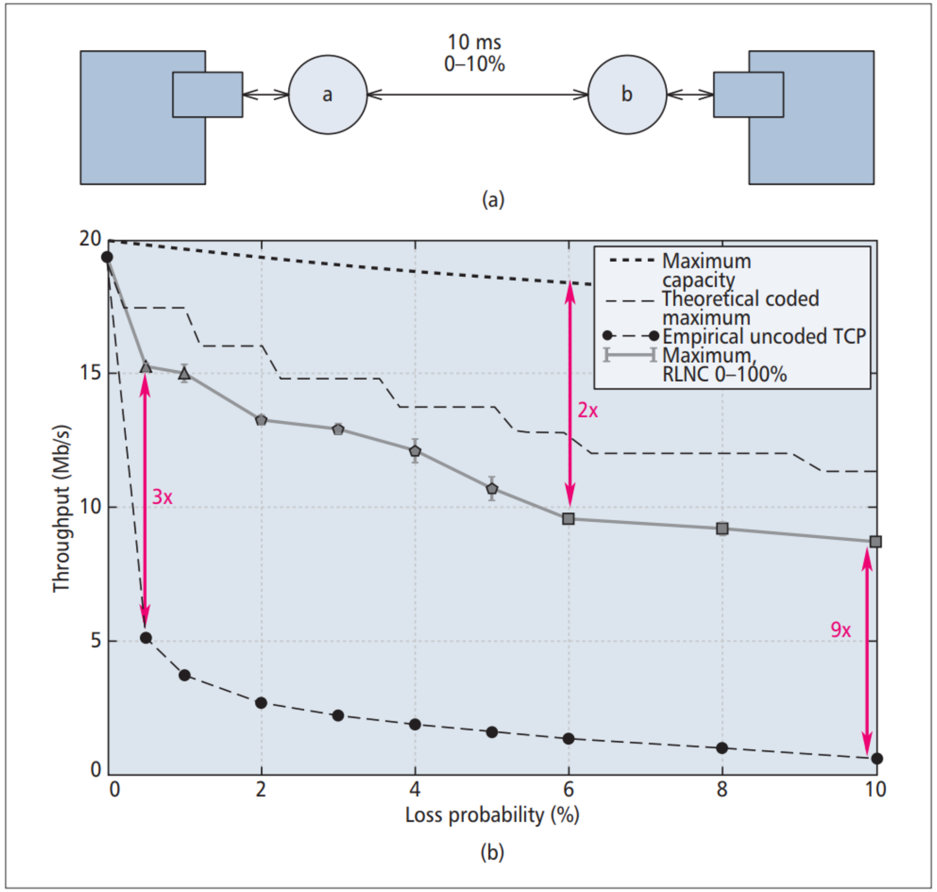


Figure 2. Integrating network coding into an Open vSwitch, showing the relation between coding software, virtual machine, and host OS. A data flow (the grey dashed line) is redirected through the coding device before it is forwarded onto the network. The flows that do not require coding follow the black dashed line straight through the switch.

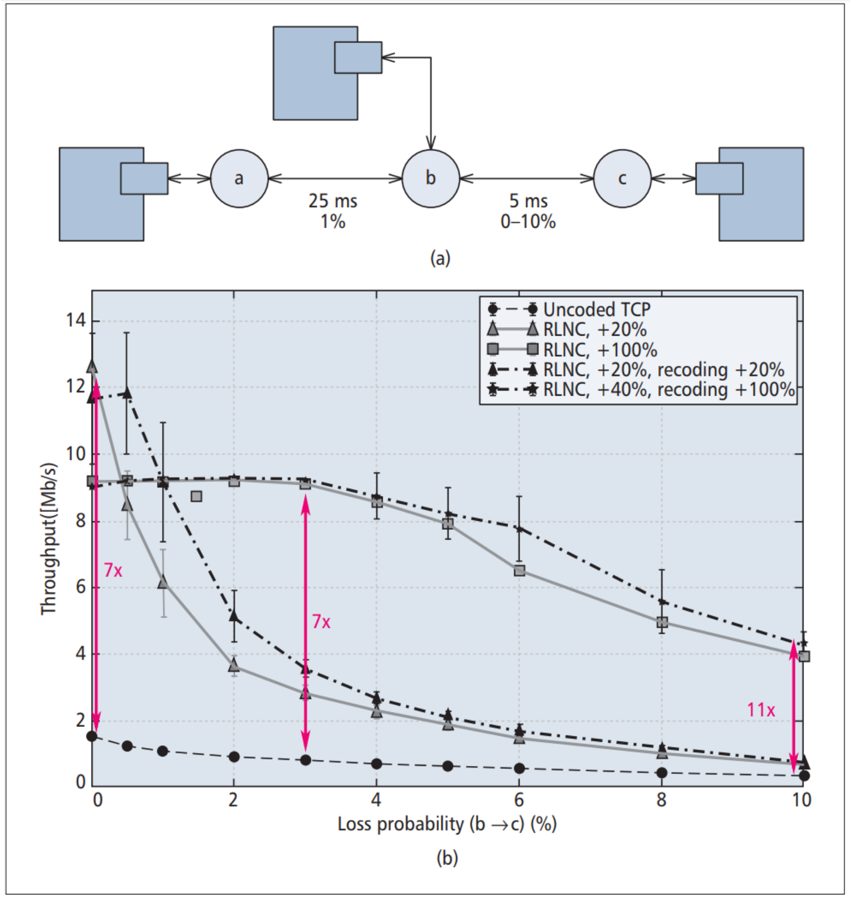
SDN Testbed Aalborg University – Point-to-Point

- Real SDN implementation
- Uncoded TCP vs E2E coded TCP
- TCP suffers by delay and losses (well known)
- Maximum = (1- loss probability)*Rate



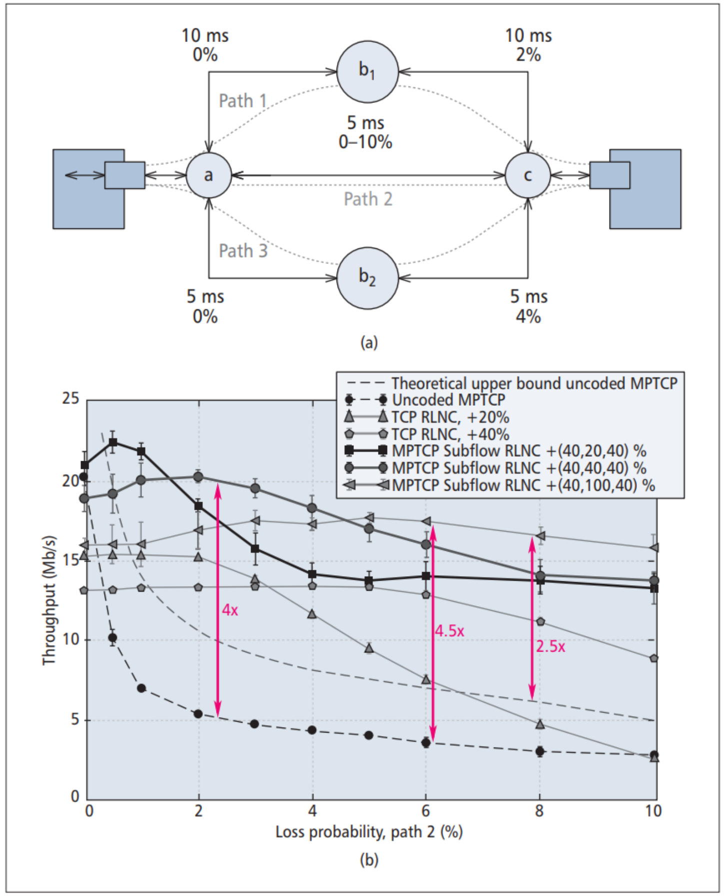
SDN Testbed Aalborg University – Multi-Hop

- Real SDN implementation
- Higher delay ~ 30ms
- Higher losses
- Lower redundancy level pays off for smaller losses
- Recoding always pays off



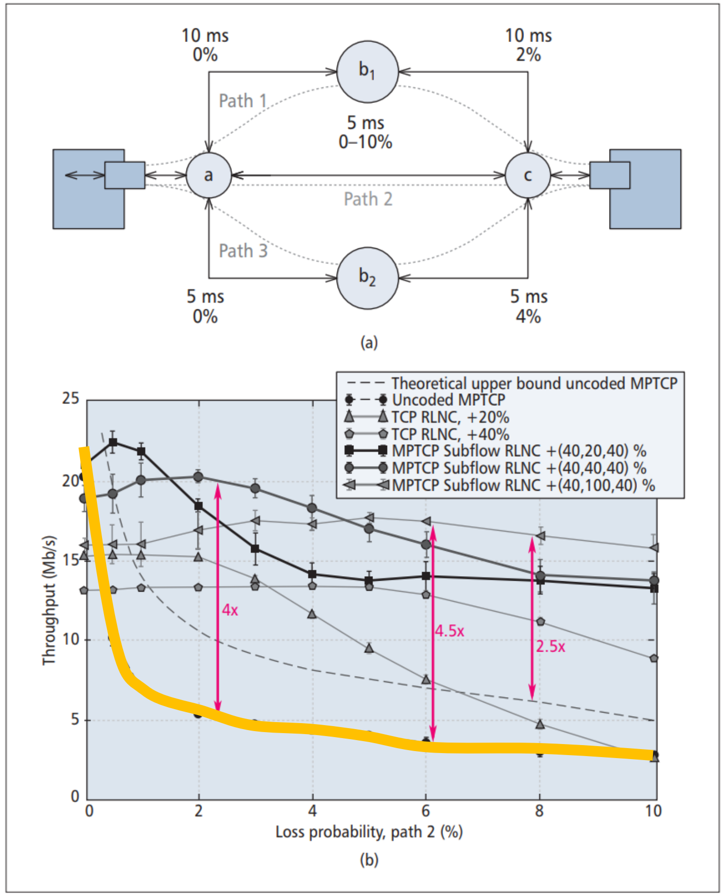
SDN Testbed Aalborg University - Multi-Path

- Real SDN implementation



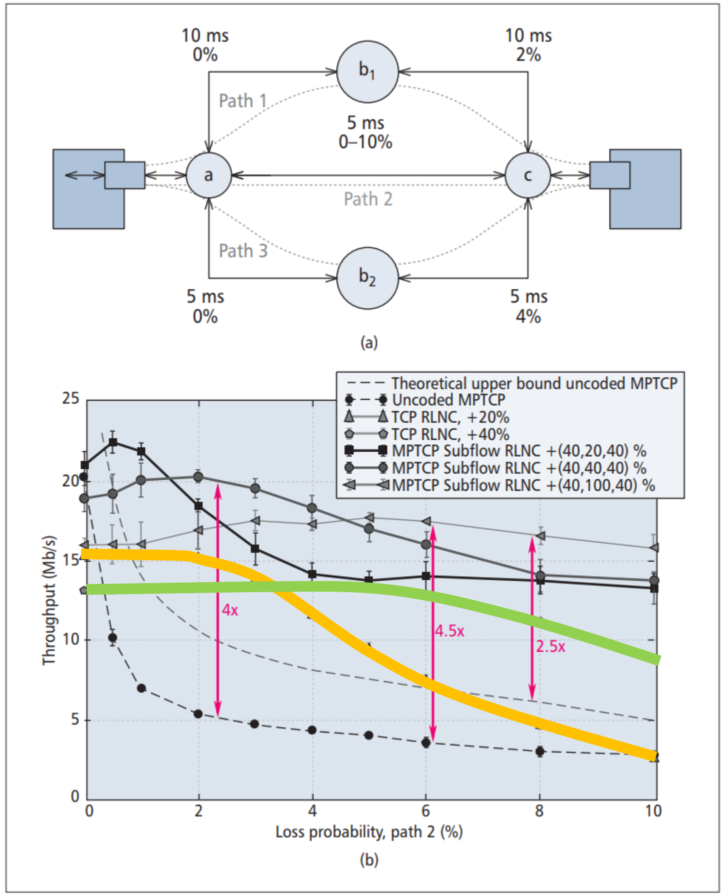
SDN Testbed Aalborg University - Multi-Path

- Real SDN implementation
- Uncoded is bad



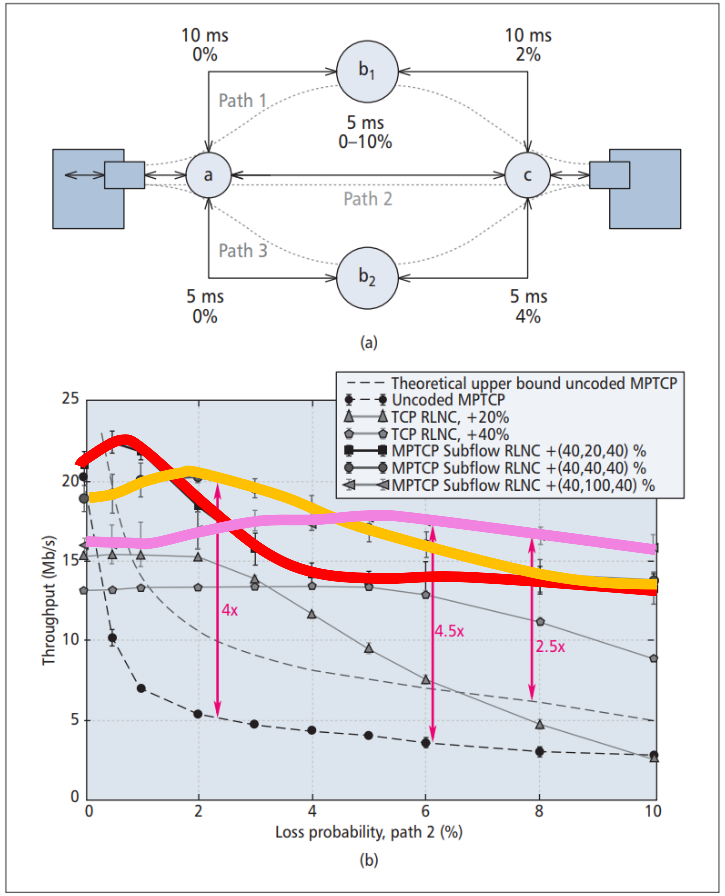
SDN Testbed Aalborg University - Multi-Path

- Real SDN implementation
- Uncoded is bad
- E2E Coding helps



SDN Testbed Aalborg University - Multi-Path

- Real SDN implementation
- Uncoded is bad
- E2E Coding helps
- Exploit multi-path



Implementation of Network Coding on SDN Basis

ComNets Chair at TUD hat retweetet

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