TECHNISCHE UNIVERSITÄT DRESDEN

ComNets Deutsche Telekom Chair of Communication Networks

Deutsche Telekom Chair of Communication Networks
Technische Universität Dresden

Practical Implementations of Network Coding

Frank Fitzek // Summer Semester 2019

Lecture / Exercise Dates - goo.gl/Lr7Xz4

- Here you find all the information for the lecture and the exercise can be found. Please check every week in case of changes (might happen)
- Slides
- Links

Main lecturer:
Professor Frank Fitzek

Co-lecturer:
M.Sc. Juan Cabrera

Co-lecturer:
Dipl.-Ing. Zuo Xiang

DATE	TYPE	ROOM	TOPIC
03.Apr.2019(FF)	L1	BAR/213/H	Organisation of the course; Motivation for NC and NC use cases (5G, IoT, Wireless Mesh); Butterfly example; min cut max flow. Inter Flow NC. Index Coding. Zick Zack Coding. CATWOMAN.
10.Apr.2019(FF)	L2	BAR/213/H	Alice Relay and Bob scenario under IEEE802.11 networks and asymmetric traffic. Analog Inter Flow NC.
17.Apr.2019	E1	FAL07/08	Analysis of the activity, throughput, power, and energy per bit of a system with the cross topology when using forwarding, network coding, and network coding with overhearing. Analysis of the processes of encoding and decoding in intra-session network coding, and analysis of the overhead due to linear dependencies of RLNC.
24.Apr.2019(FF)	L3	FAL07/08	Intra-flow network coding. Random Linear Network Coding (Basics)
25.Apr.2019(FF)	L4	FAL07/08	Random Linear Network Coding (Continuation)
08.May.2019(FF)	L5	FAL07/08	RLNC advanced 1 (systematic and sparse RLNC)
09.May.2019(FF)	L6	FAL07/08	RLNC advanced 2
15.May.2019(FF)	L7	FAL07/08	Network coding for storage.
22.May.2019	E2	FAL07/08	E1 continuation. Basic UDP transmissions over WIFI with Python. Example of Inter-Session Network coding: XORing packets
23.May.2019	E3	FAL07/08	Introduction to KODO. Lossless Encoding and Decoding
29.May.2019(FF)	L8	FAL07/08	Network coding use cases and applications.
05.Jun.2019(FF)	L9	FAL07/08	Novel research topics in network coding: Joint compressed sensing and network coding; PRAC (Packetized Rateless Algebraic Consistency).
06.Jun.2019(FF)	E4	FAL07/08	Code efficiency. Number of linear dependencies. Where does the linear dependencies occur? Multi-path and Multi-hop with NC

Aim of this lecture module

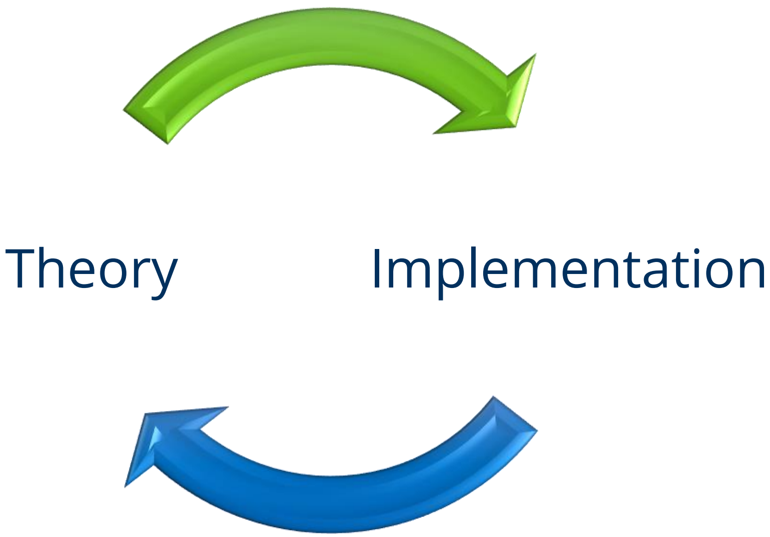
Explain network coding in theory and practice

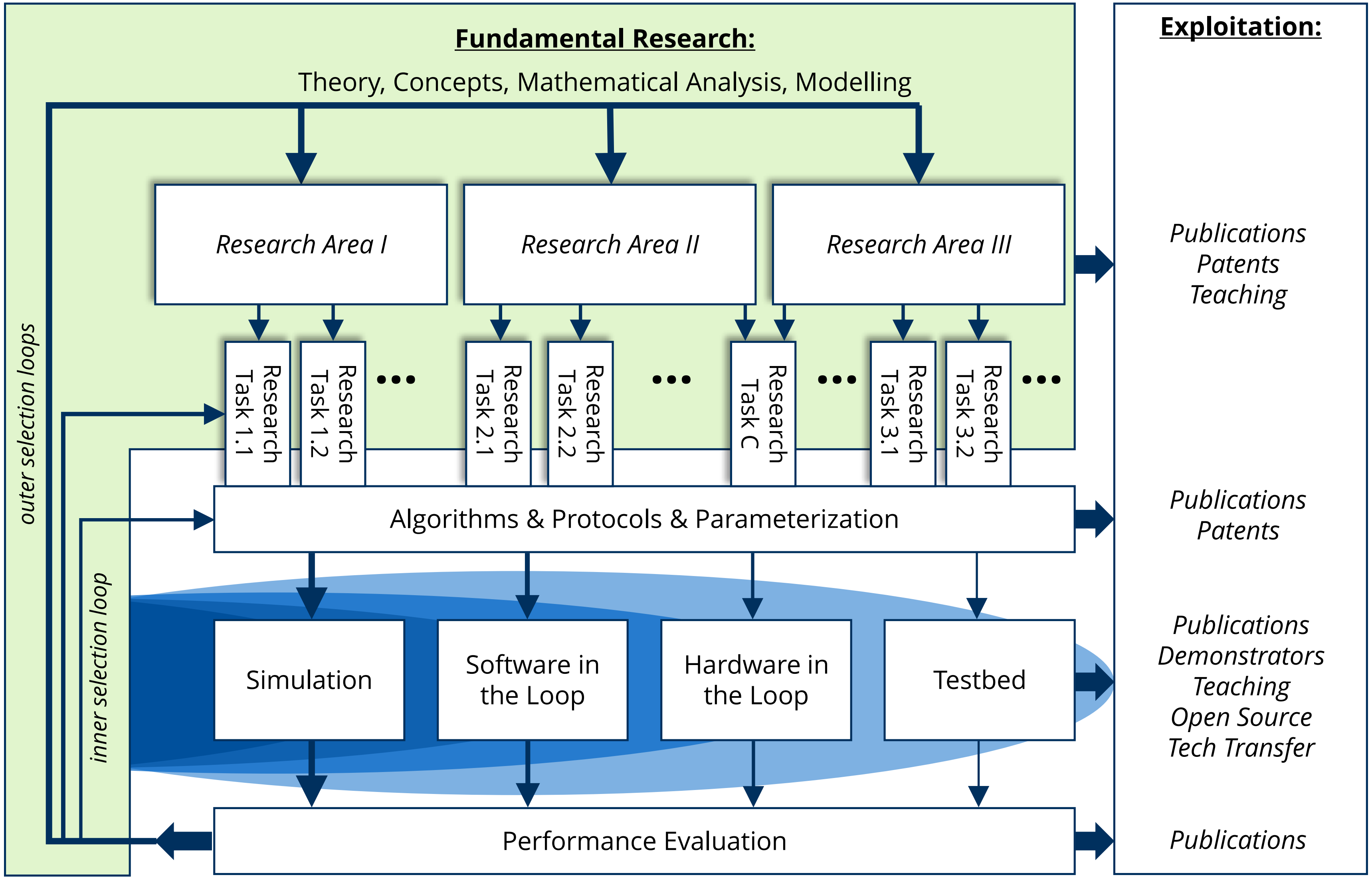
Explain the uniqueness of network coding

Describe a wide range of applications of NC in current and future communication systems
- 5G
- Storage as well as transportation

Important is the “hands on” parts aligned with the theory
- Please bring your laptop to all lectures and exercises
  - Preinstall software needed
  - Get KODO license from steinwurf.com/license

Research Methodology: Theory that matters!



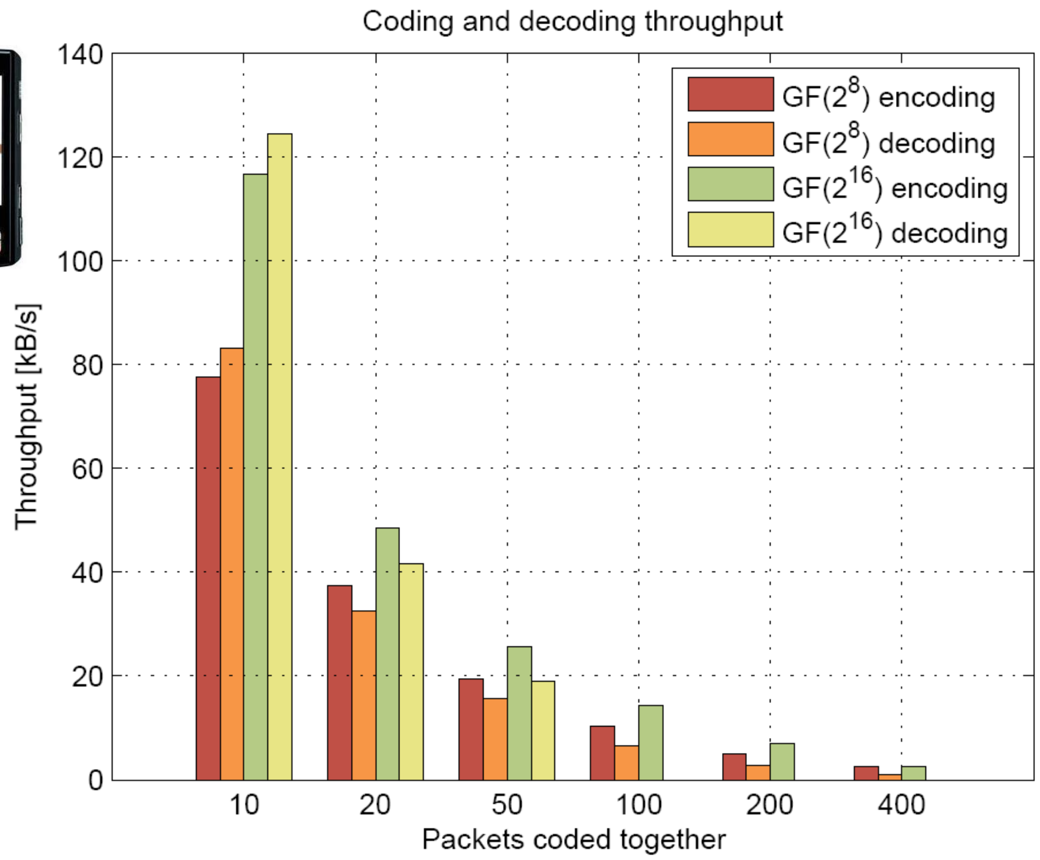


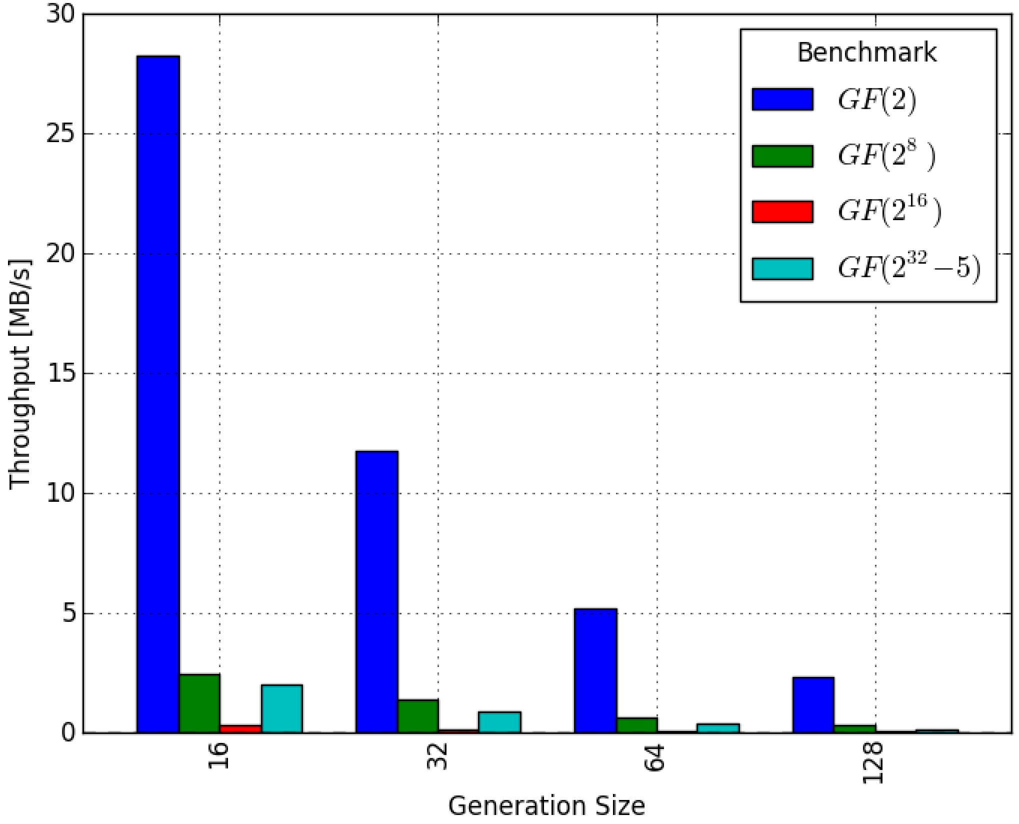
Research Methodology: Example

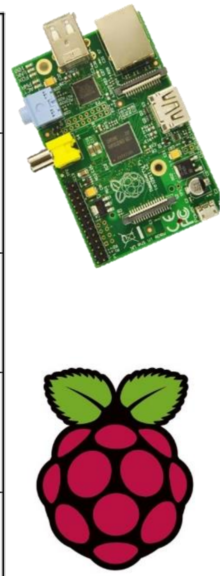
2007: 120kB/s

>200x

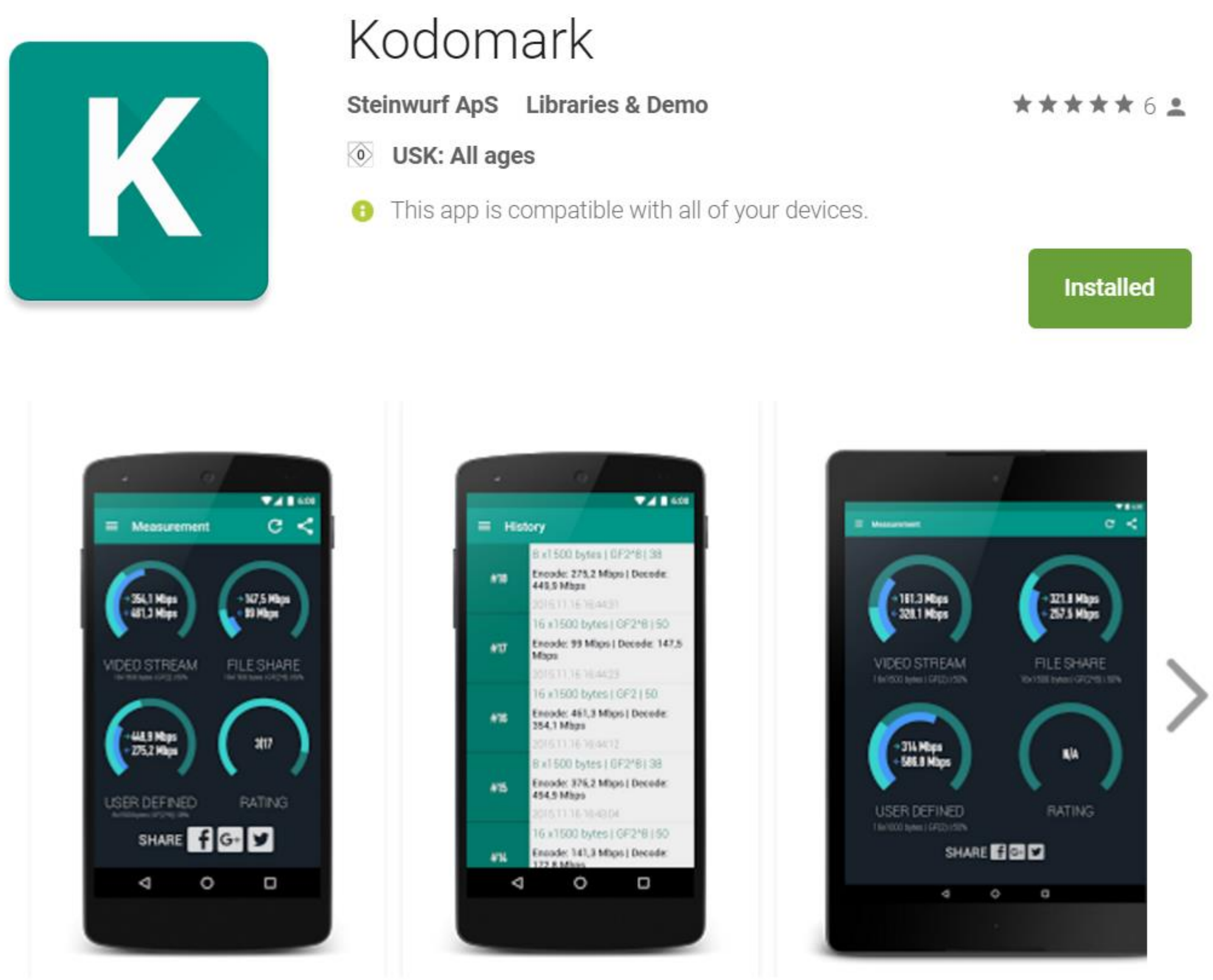
2012: 27 MB/s







How fast are we today?

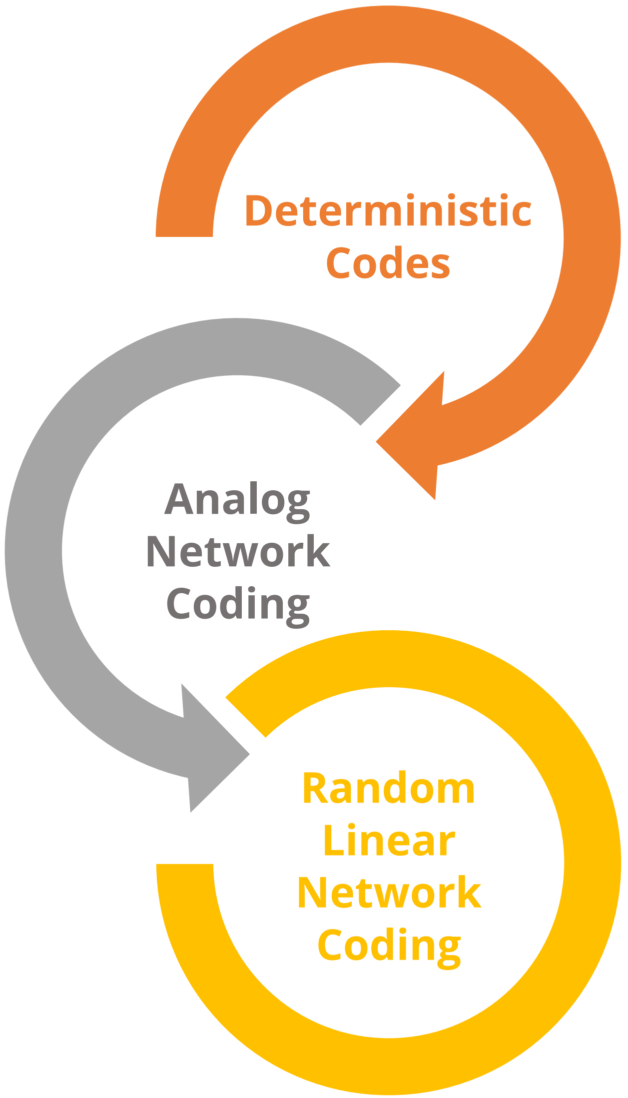


http://tinyurl.com/z7vsp4c

Please try it out and support our research! If you have an Android device simply install and press START! Change the parameters to learn about network coding.

How do we approach NC?

Extreme application of NC! In general the same ideas as before but more gains!

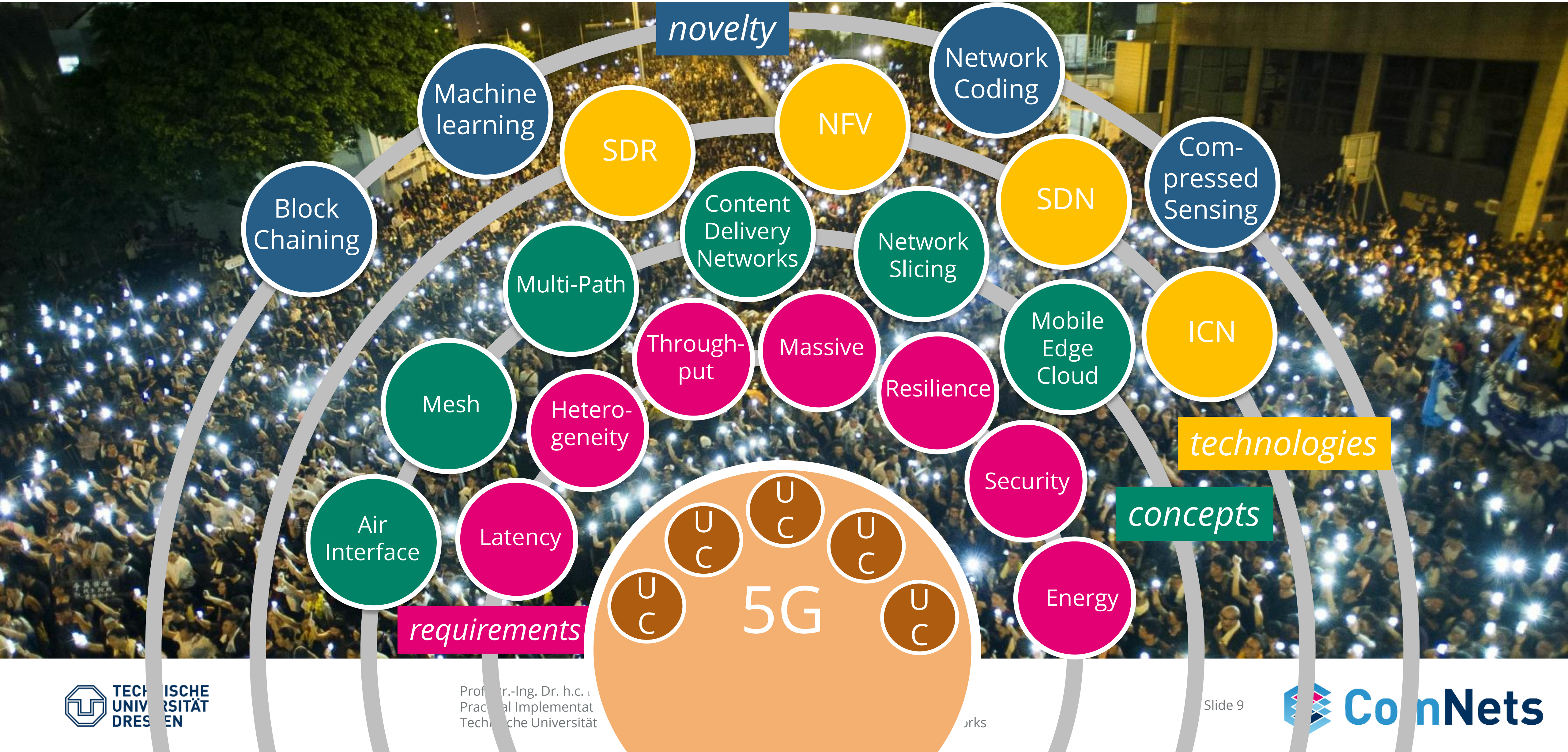


Let's have fun! We play around with some smart ideas!

The real deal! Versatile code for all application fields! Complex but powerful!

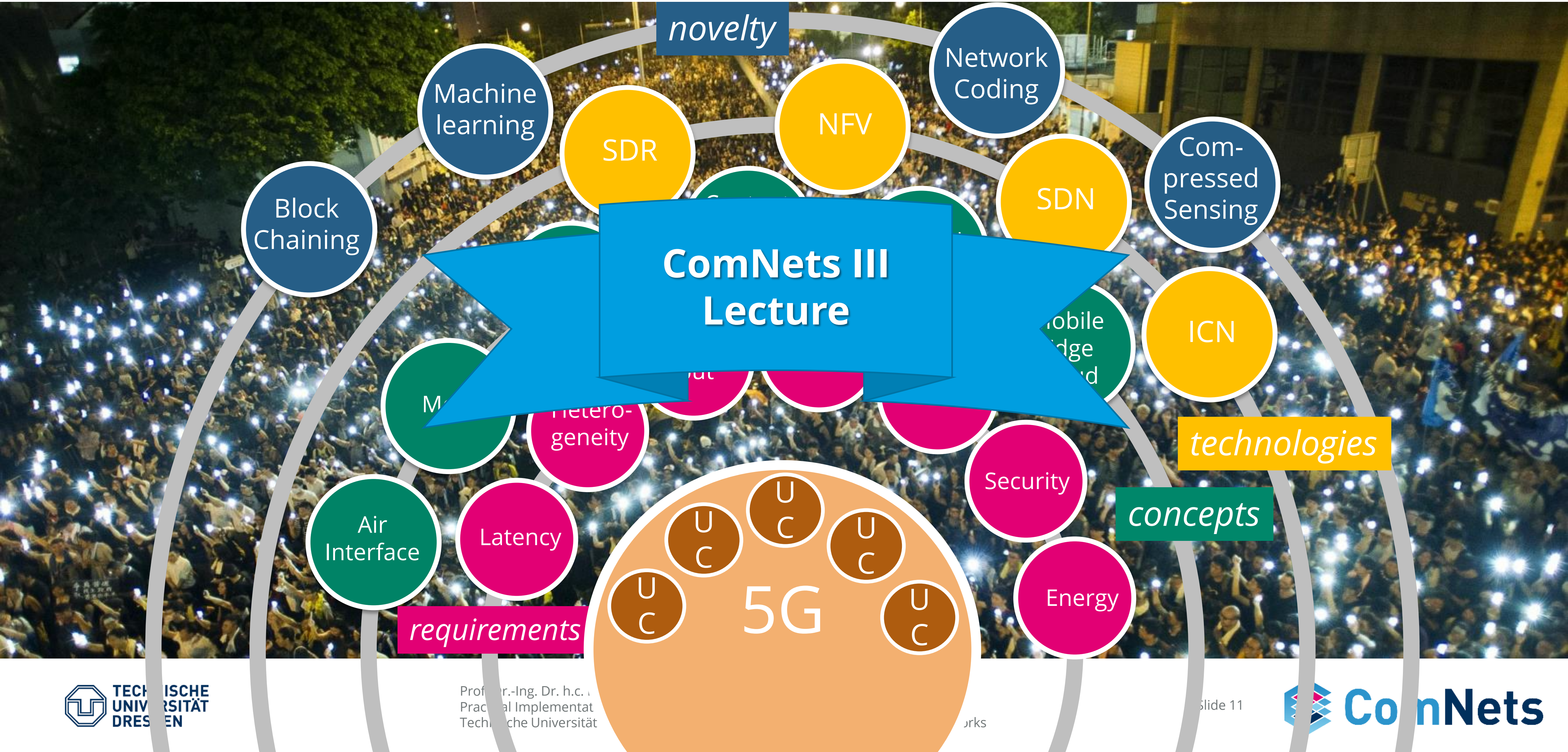
5G Motivation

5G atom definition



Mesh and Network Coding

5G atom definition



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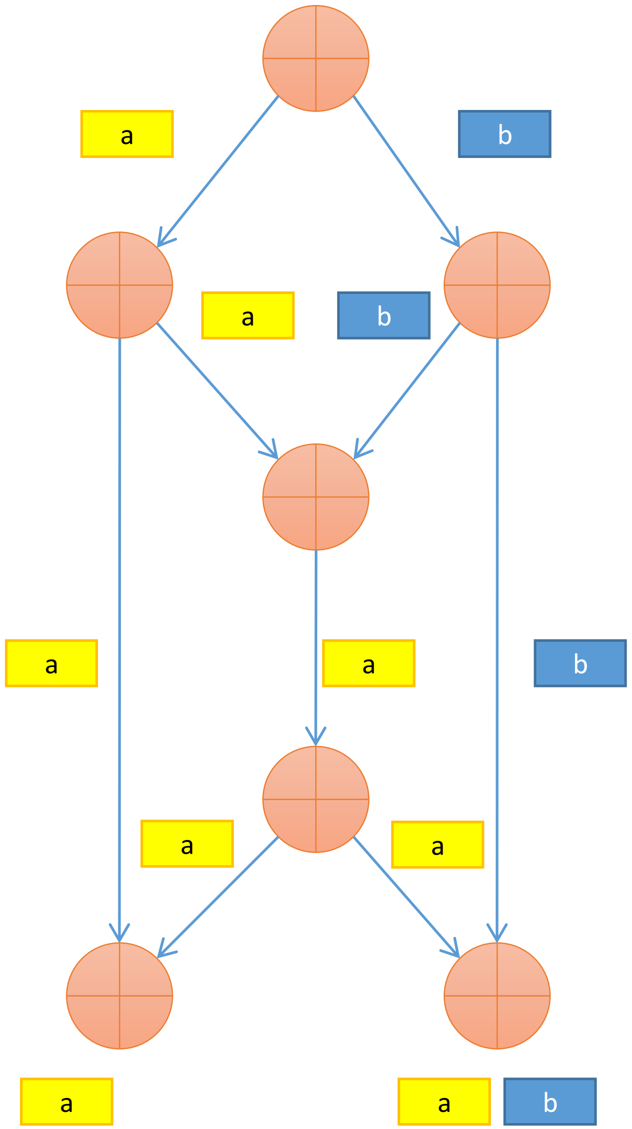
Digital Inter-Flow Network Coding: The Basics

Lecture 1

The Butterfly

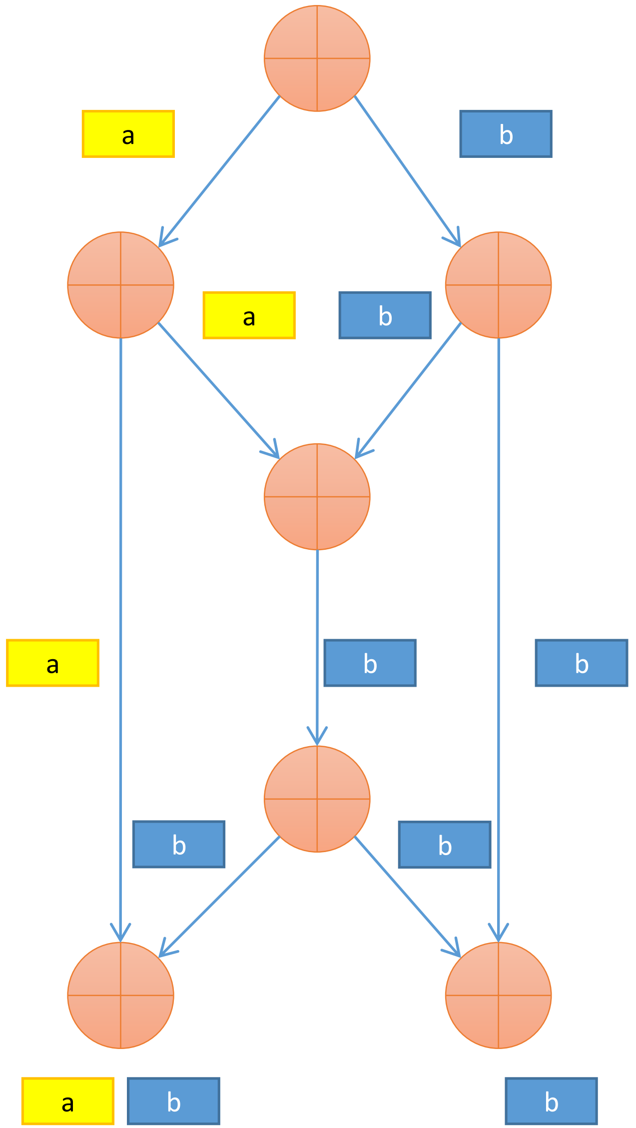
Network Coding: The Butterfly

- Two packets a and b must be conveyed to two destinations over a given network
- Assumption, capacity per link can handle one packet per time slot
- Bottleneck in the middle
- Either packet a or b will path the bottleneck
- One destination will receive one *unique* packet, the other two packets



Network Coding: The Butterfly

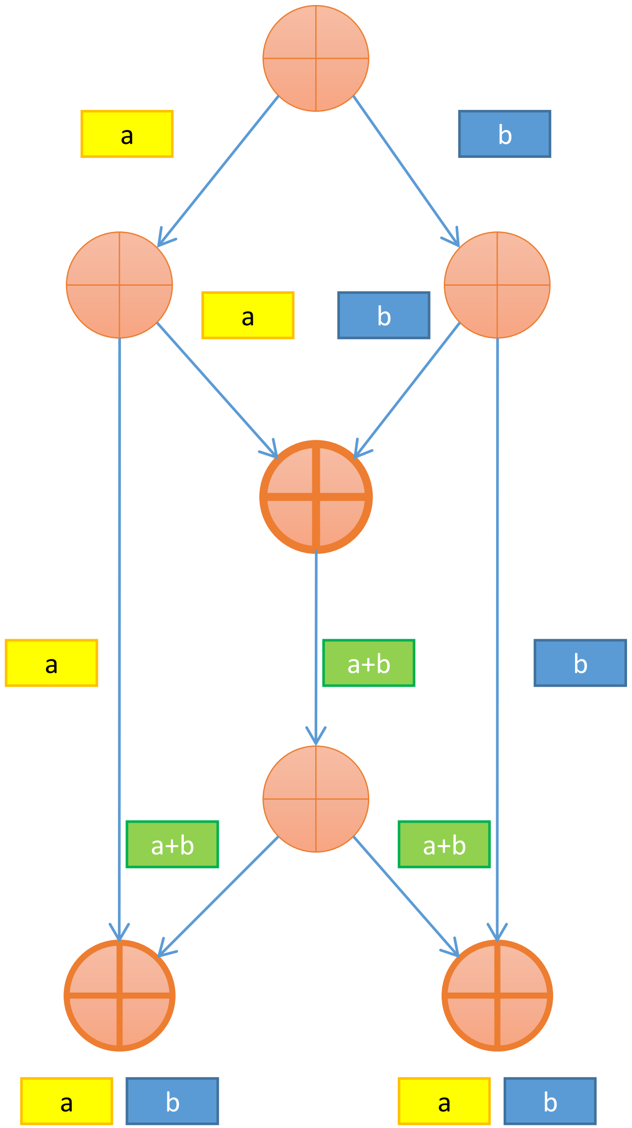
- Let‘s try b instead of a
- Same old problem



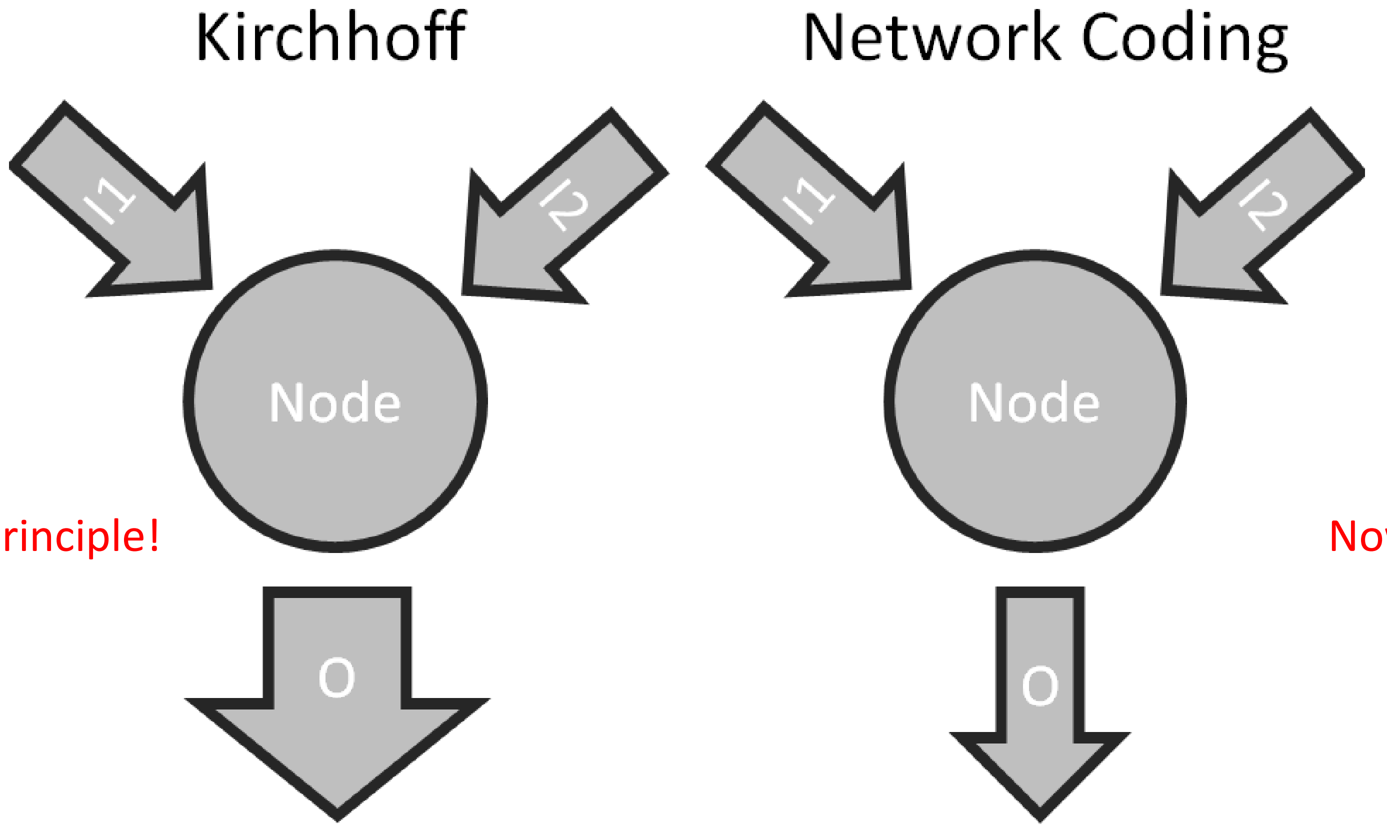
Network Coding: The Butterfly

- Ahlswede et. al. In 2000
- Coding the packet
- Other ideas were around
- Max-flow min-cut theorem

Ahlswede, Rudolf; N. Cai, Shuo-Yen Robert Li, and Raymond Wai-Ho Yeung (2000). "Network Information Flow". IEEE Transactions on Information Theory, IT-46 46 (4): 1204–1216.



Kirchhoff versus Network Coding



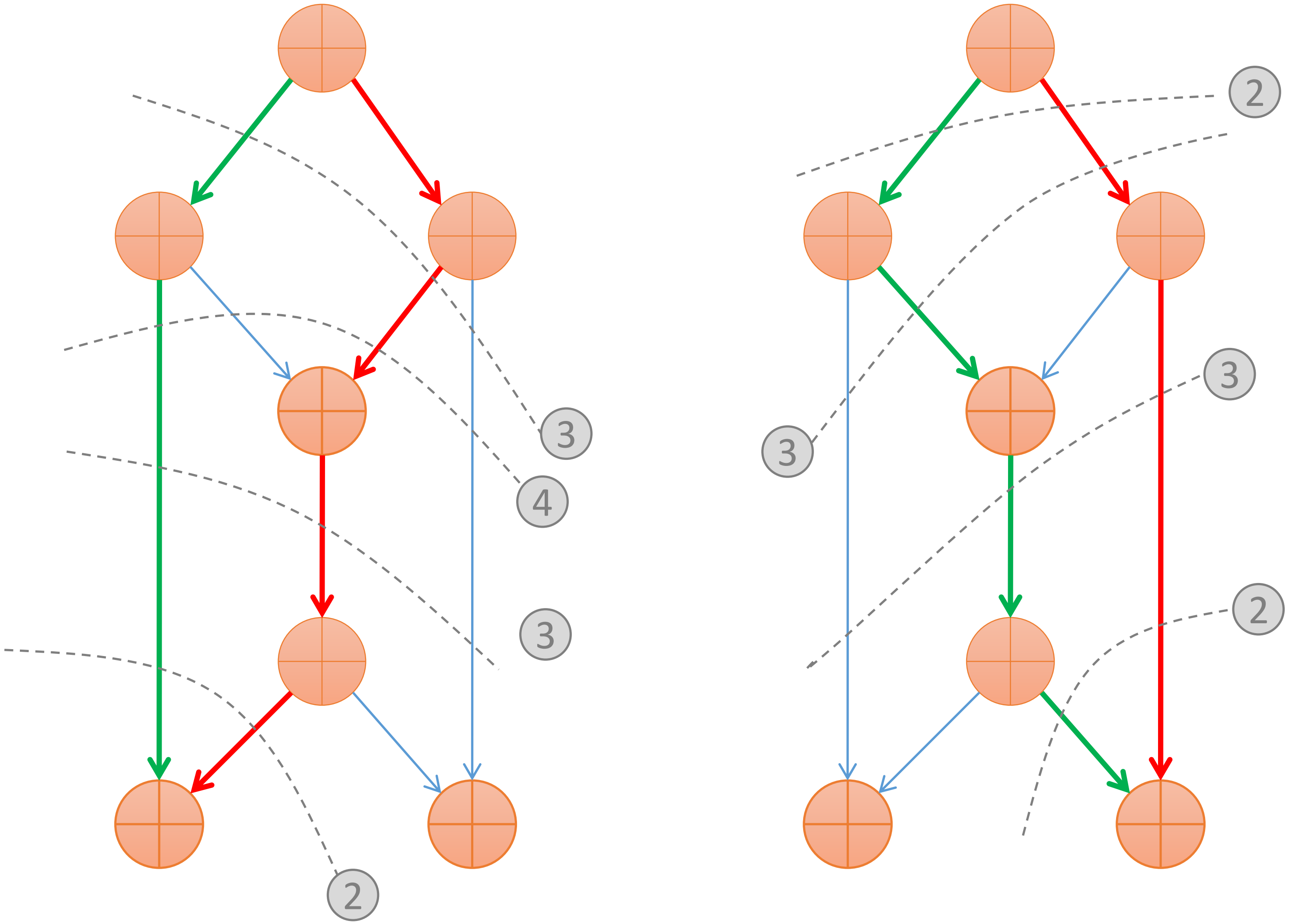
All engineers follow this principle!

Now we are alone ...!

O = I1 + I2

O = f(I1,I2)

Max-flow min-cut theorem



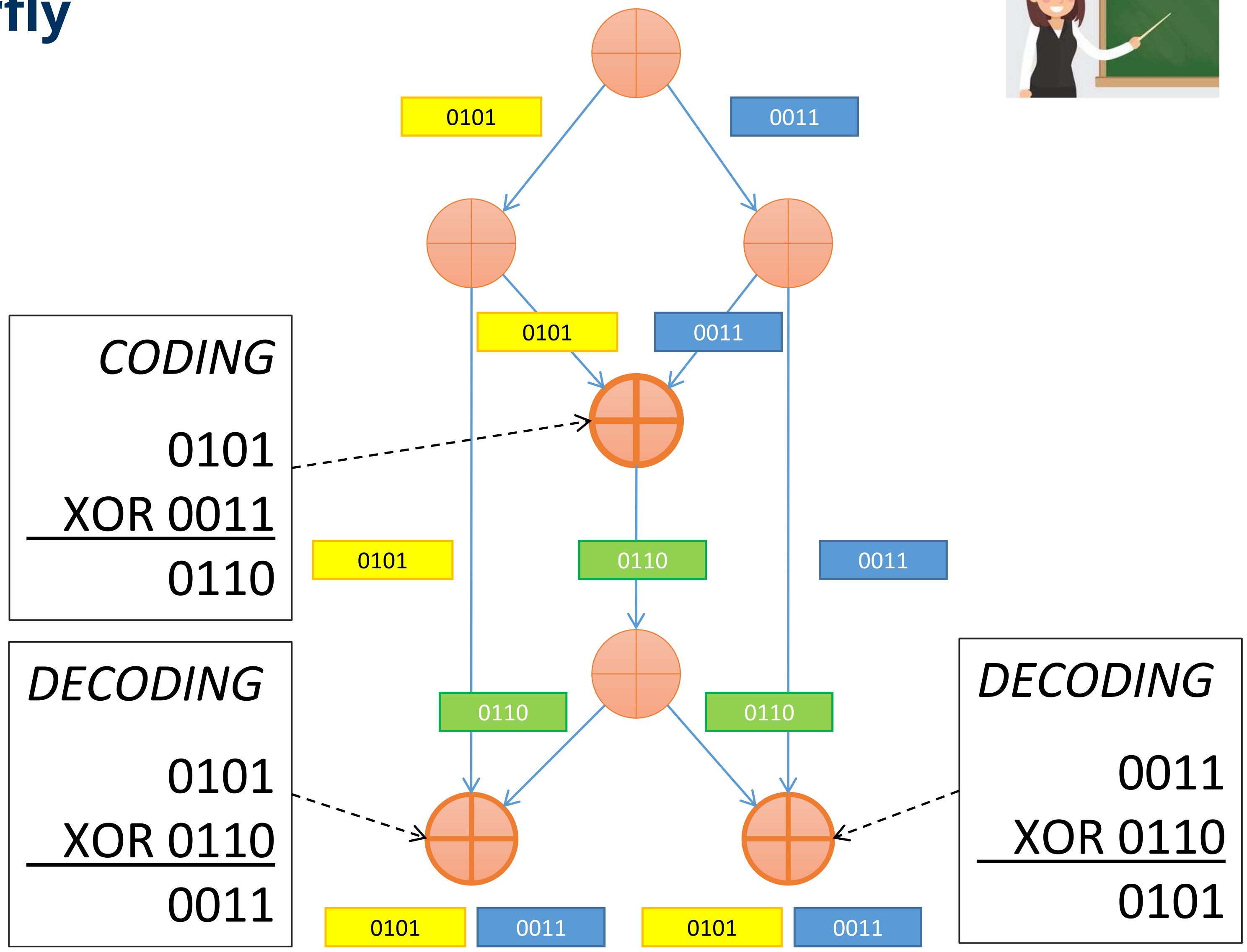
The existence of polynomial time algorithms is remarkable because the maximal rate without coding can be much smaller and finding the routing solution that achieves that maximum is NP-hard.

Jaggi-Sanders algorithm (2003): Polynomial Time Algorithms for Multicast Network Code Construction: S. Jaggi, P. Sanders, P. A. Chou, M. Effros, S. Egner, K. Jain, and L. M. G. M. Tolhuizen, “Polynomial time algorithms for multicast network code construction,” IEEE Trans. Inf. Theory, vol. 51, no. 6, pp. 1973–1982, Jun. 2005.

Network Coding: The Butterfly

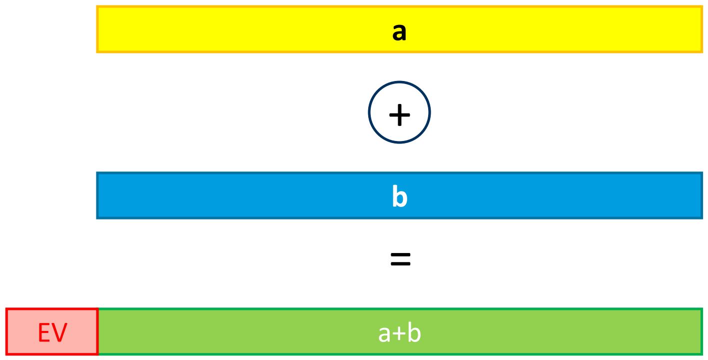
- XOR operation
- Bitwise operation
- Same bit value results in „0“
- Different bit value results in „1“

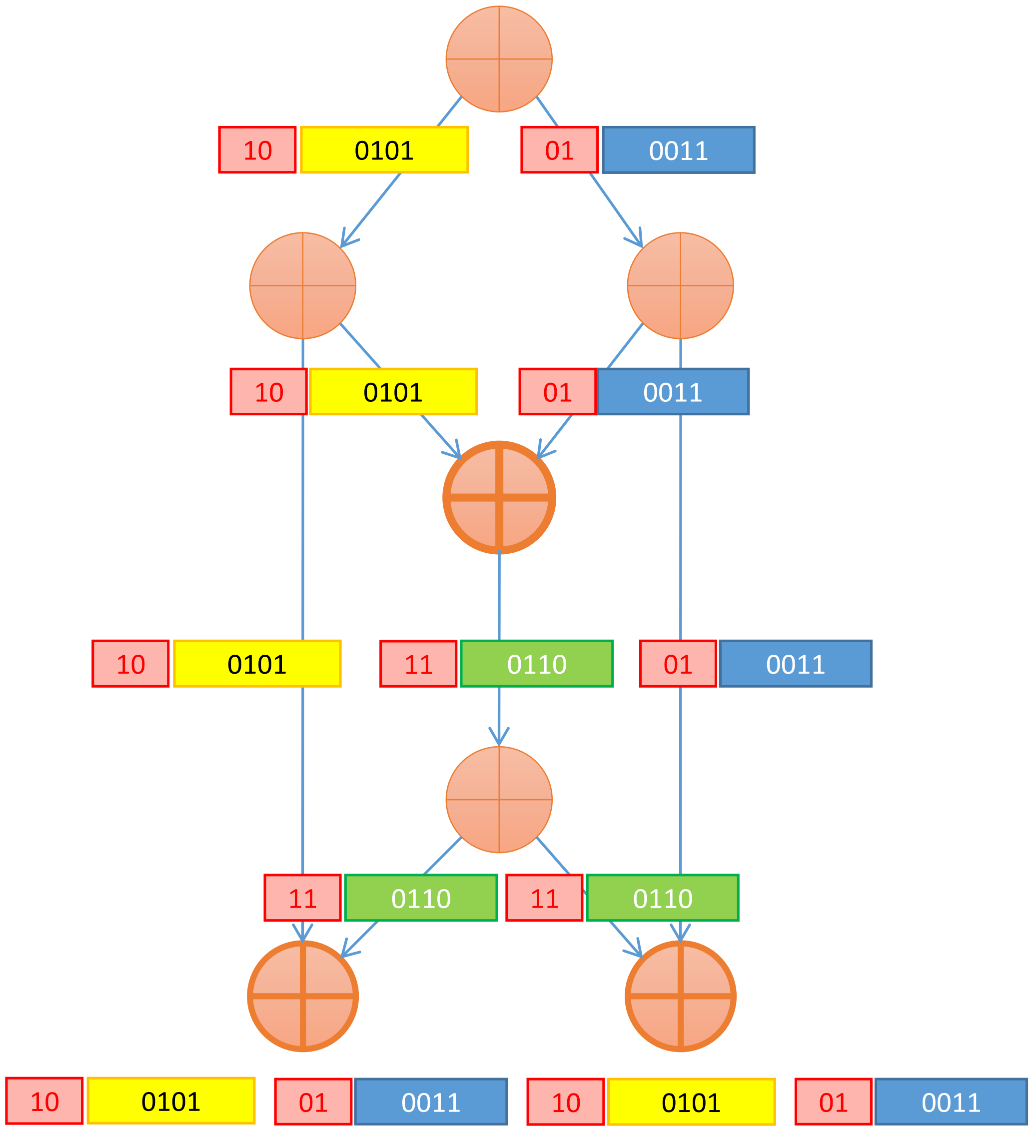
Input 1	0	1	0	1
Input 2	0	0	1	1
Result	**0**	**1**	**1**	**0**



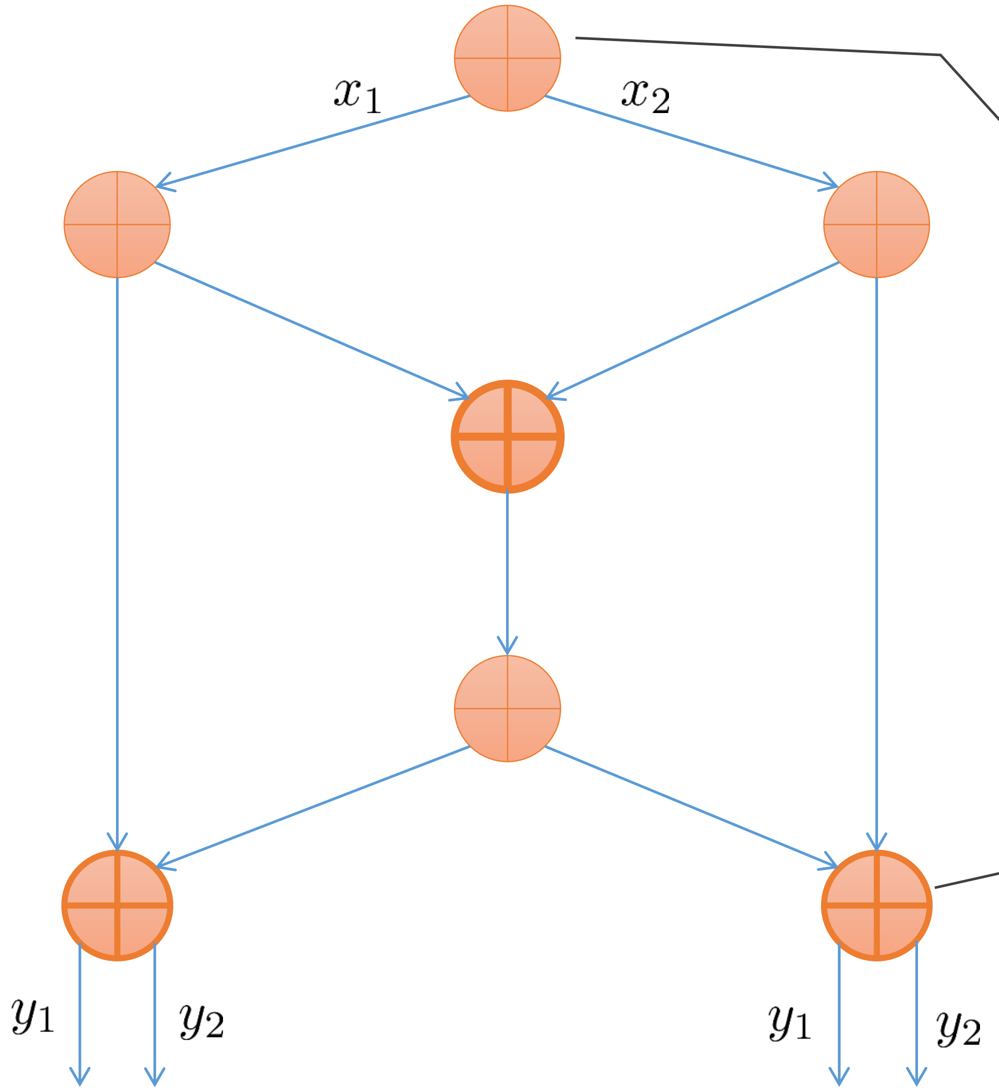
Network Coding: The Butterfly

- Adding complexity at some nodes of the network
- Adding overhead in order to know what was coded together (encoding vector)





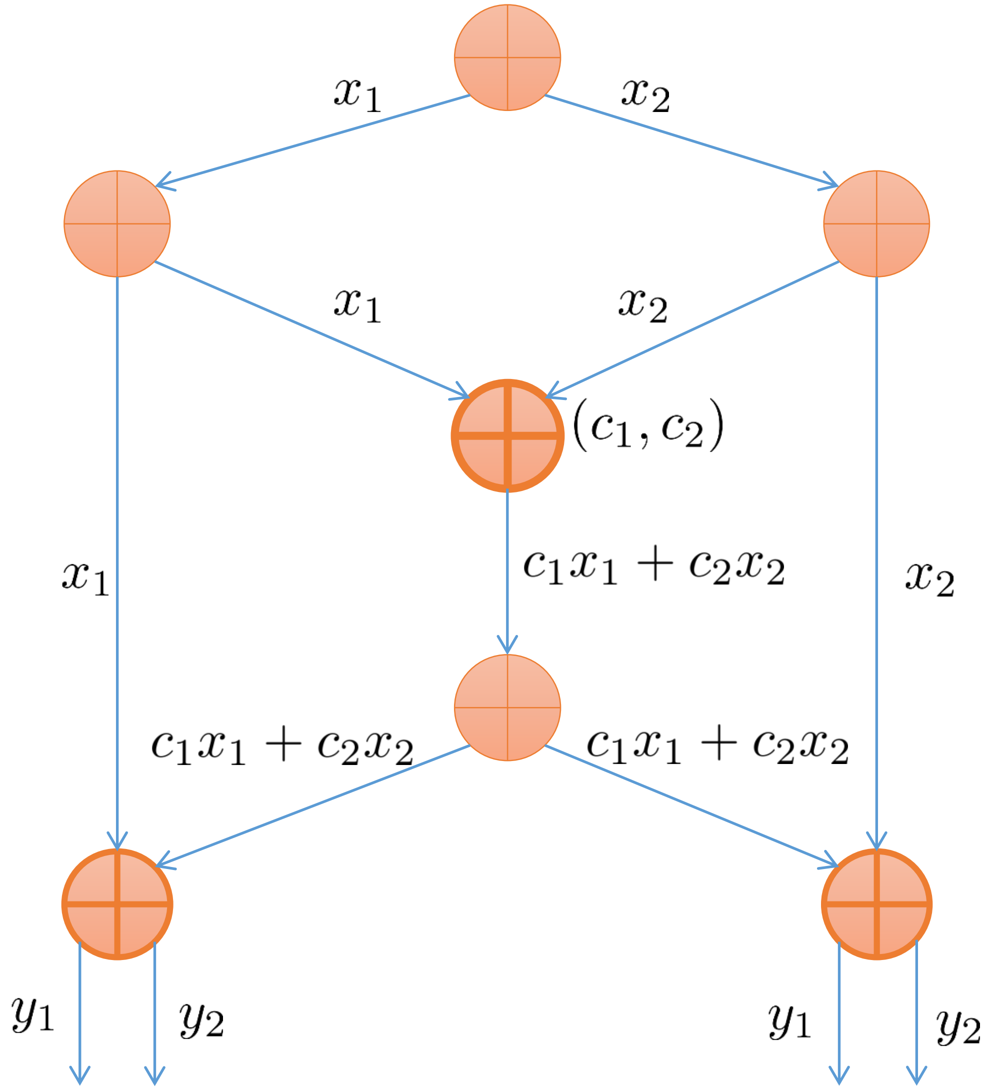
Network Coding: The Butterfly



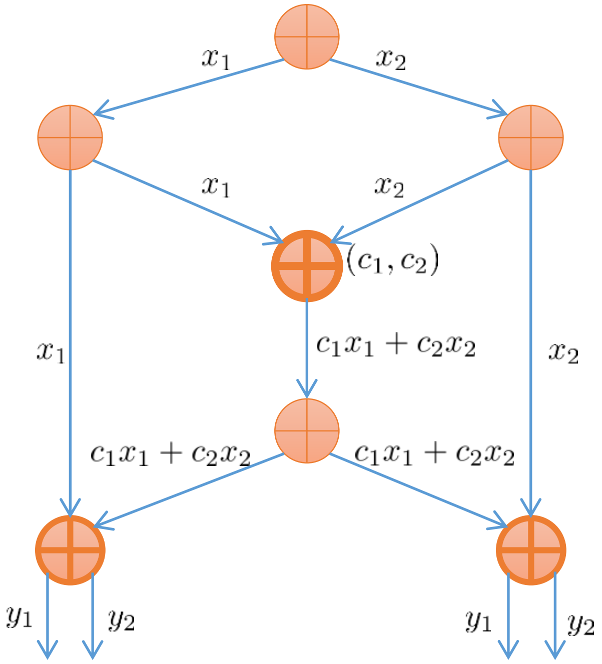
Source: transmitting two information entities

Receiver: receiving two <u>coded</u> information entities

Network Coding: The Butterfly



Network Coding: The Butterfly



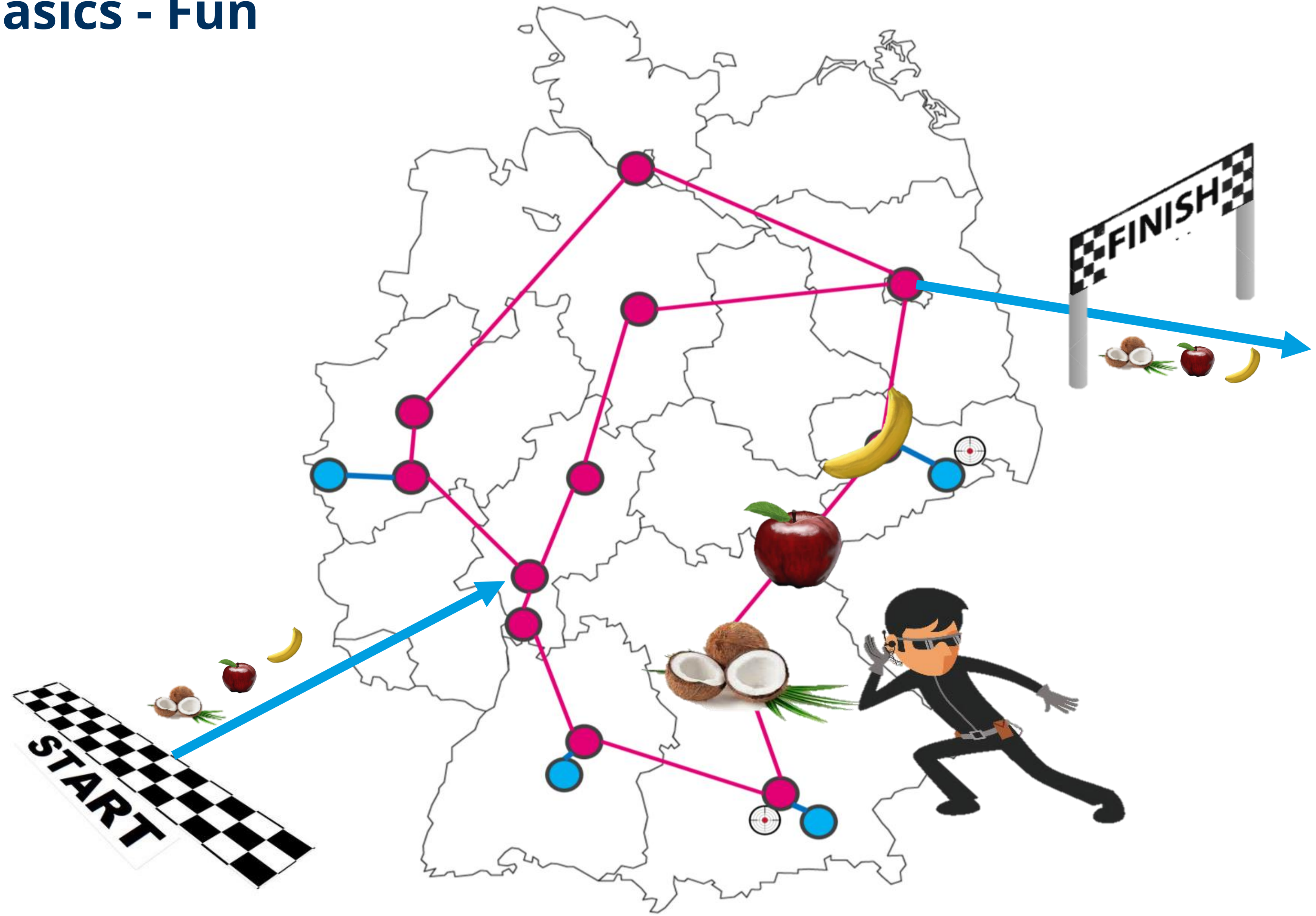
$$\begin{aligned} y_1 &= x_1 \\ y_2 &= c_1x_1 + c_2x_2 \end{aligned}$$

$$\begin{aligned} y_1 &= c_1x_1 + c_2x_2 \\ y_2 &= x_2 \end{aligned}$$

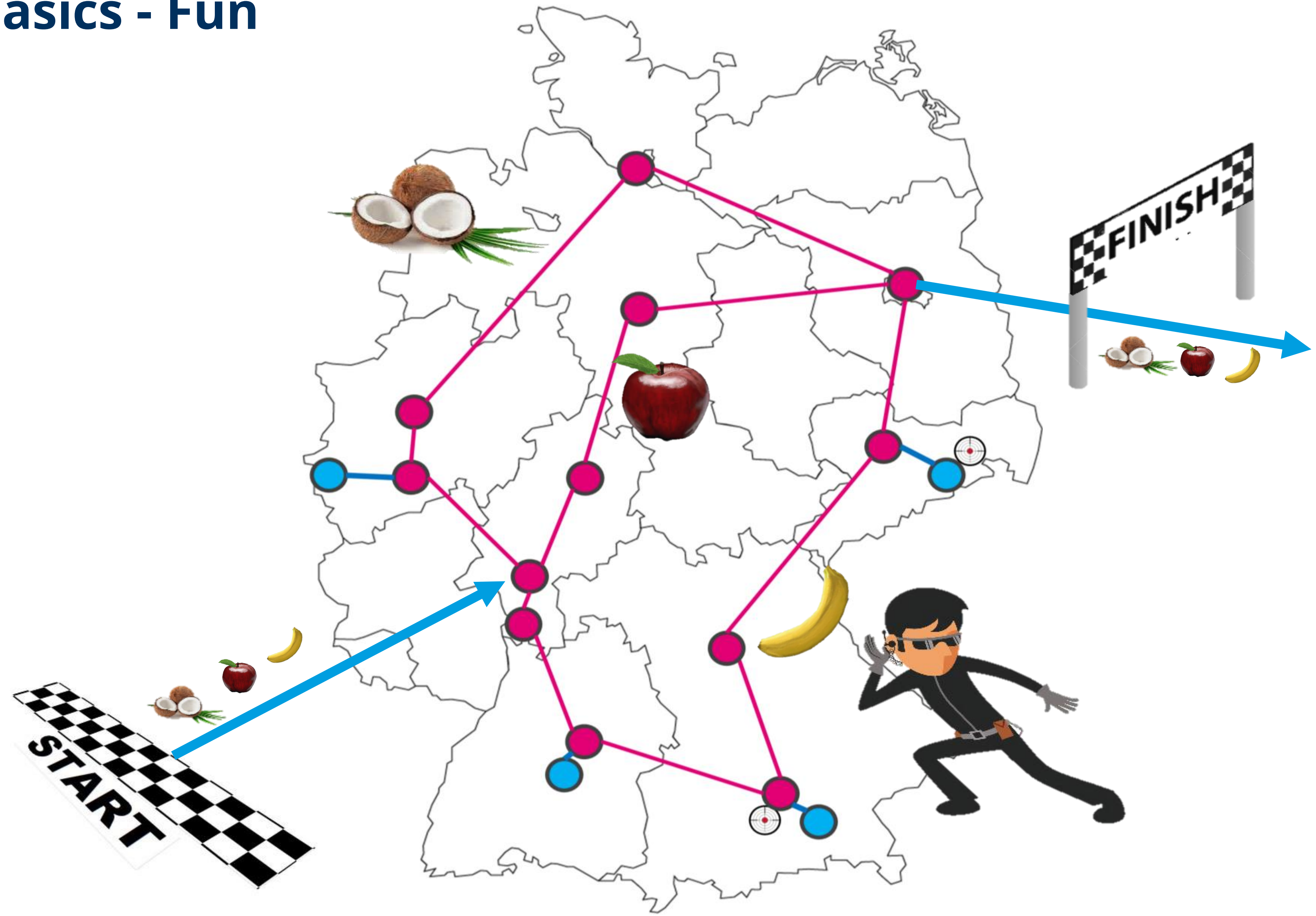
$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ c_1 & c_2 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} c_1 & c_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

Network Coding Basics - Fun



Network Coding Basics - Fun



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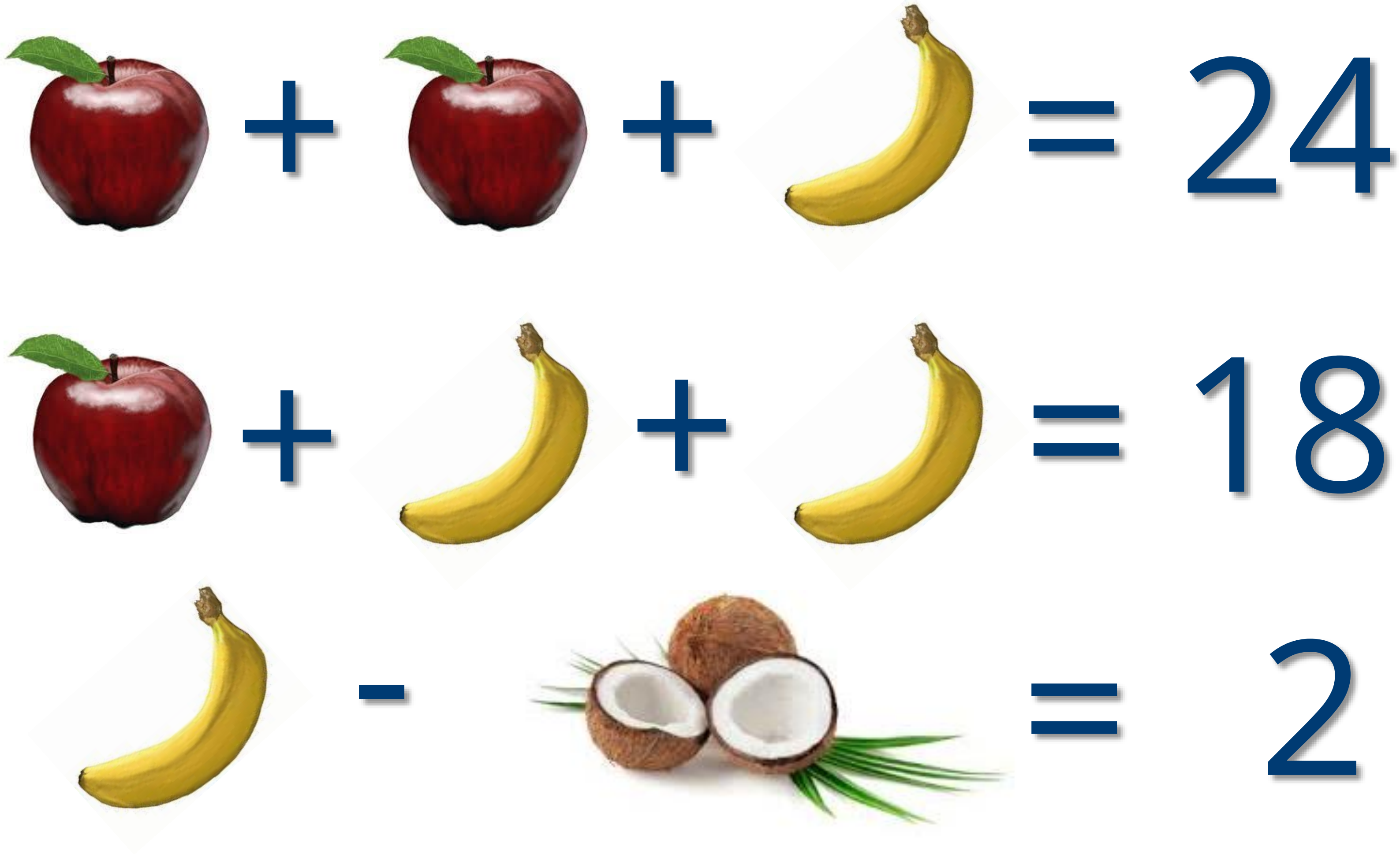

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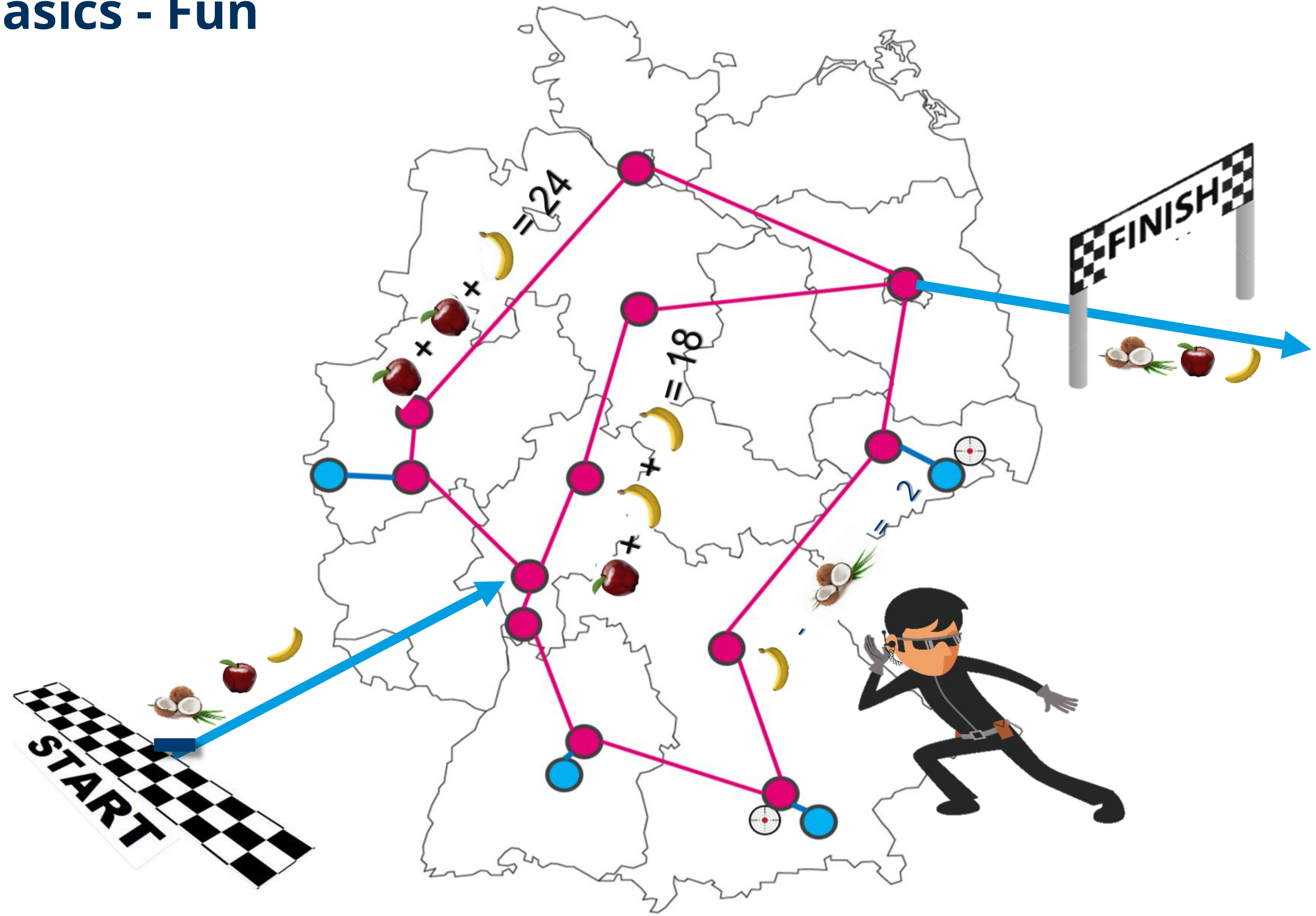
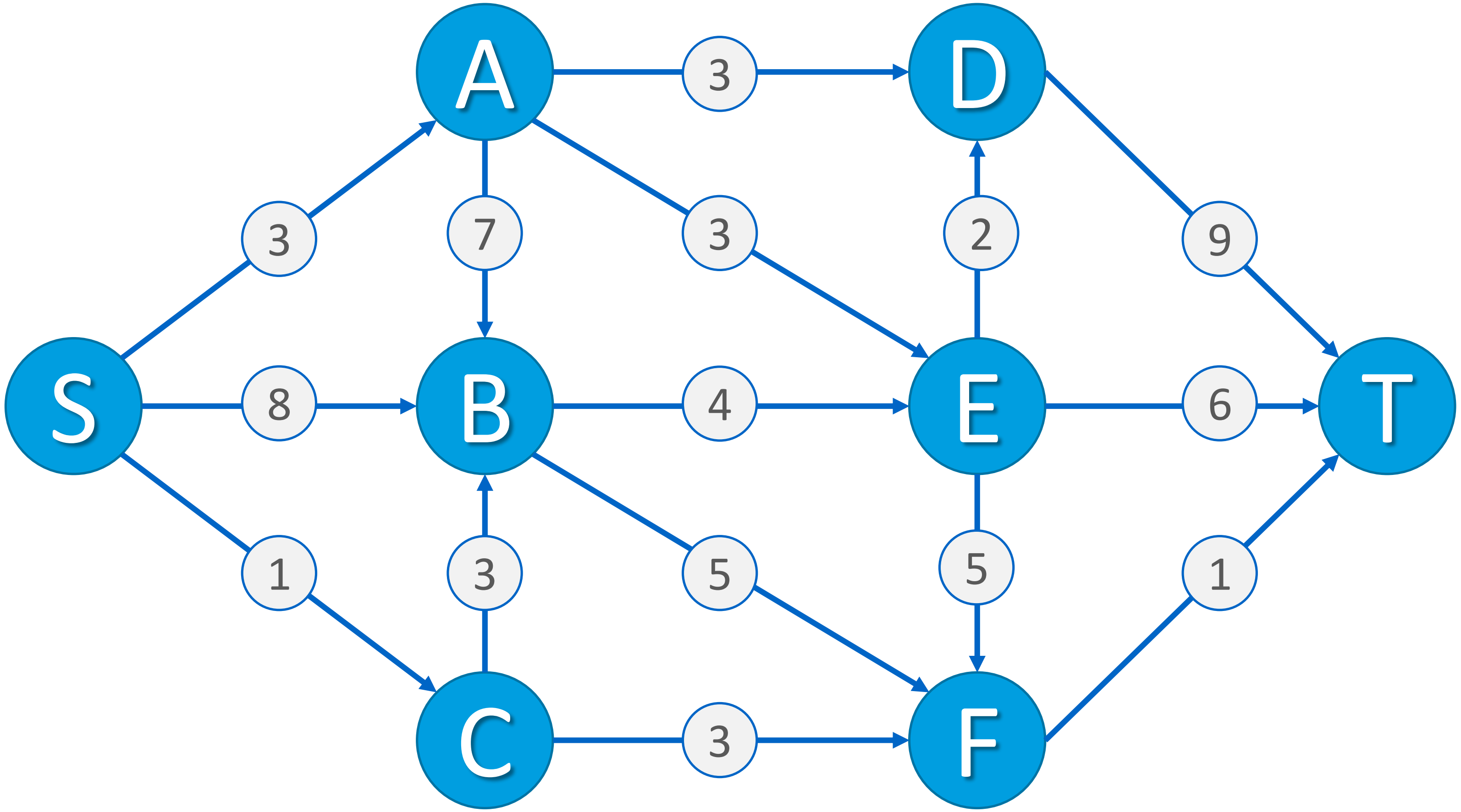
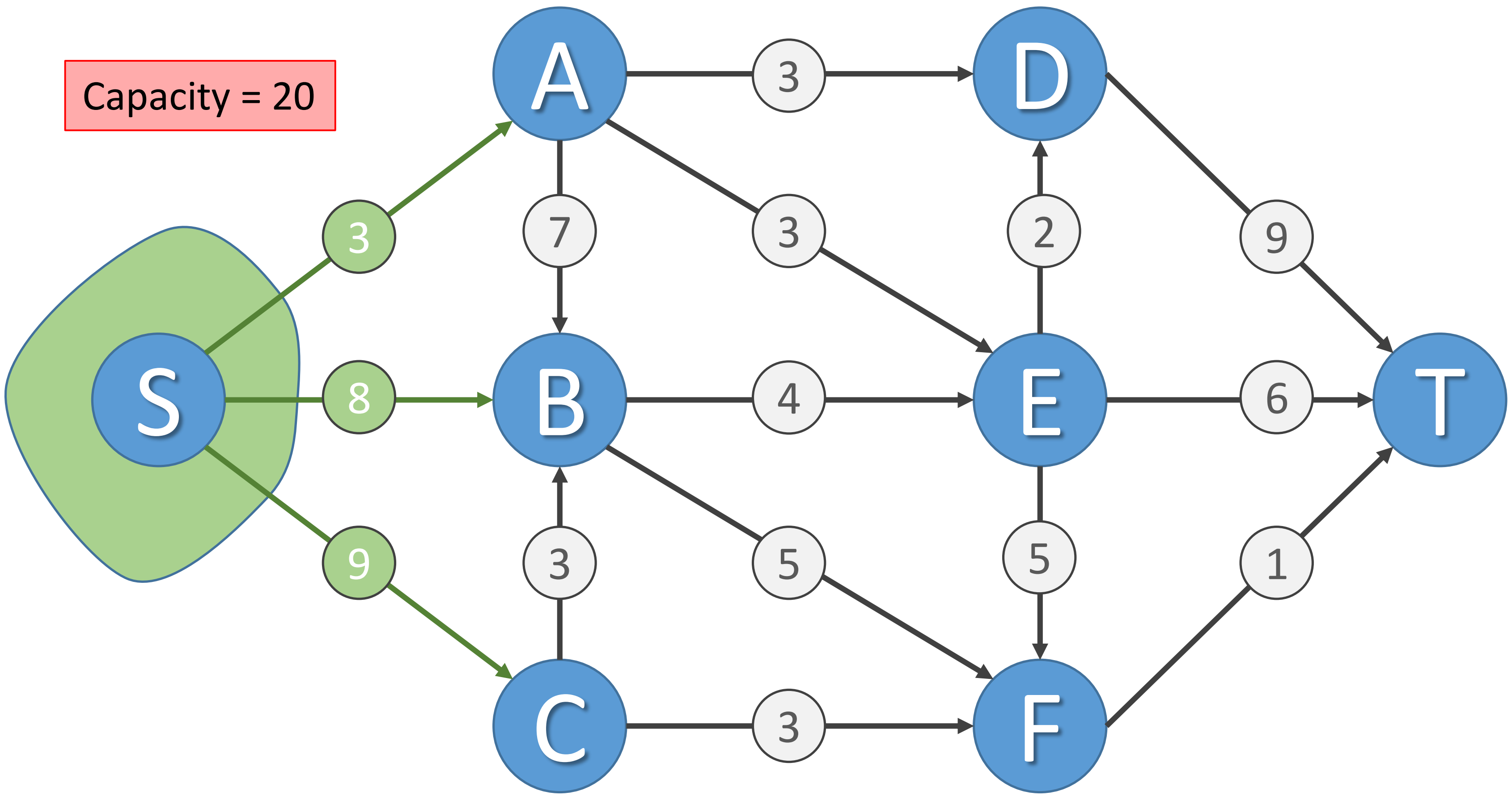


Min-Cut

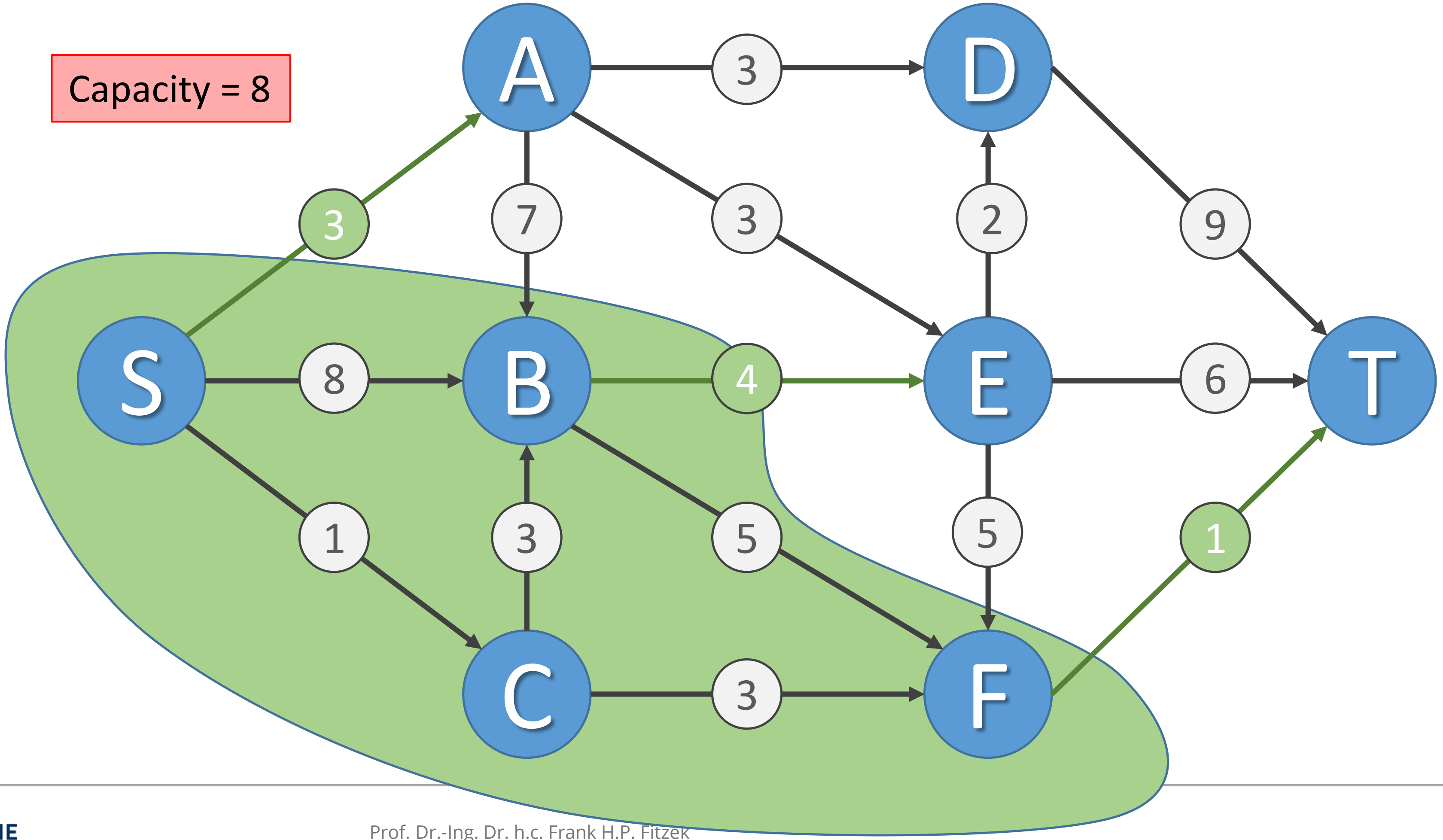
Cuts of Flow Networks



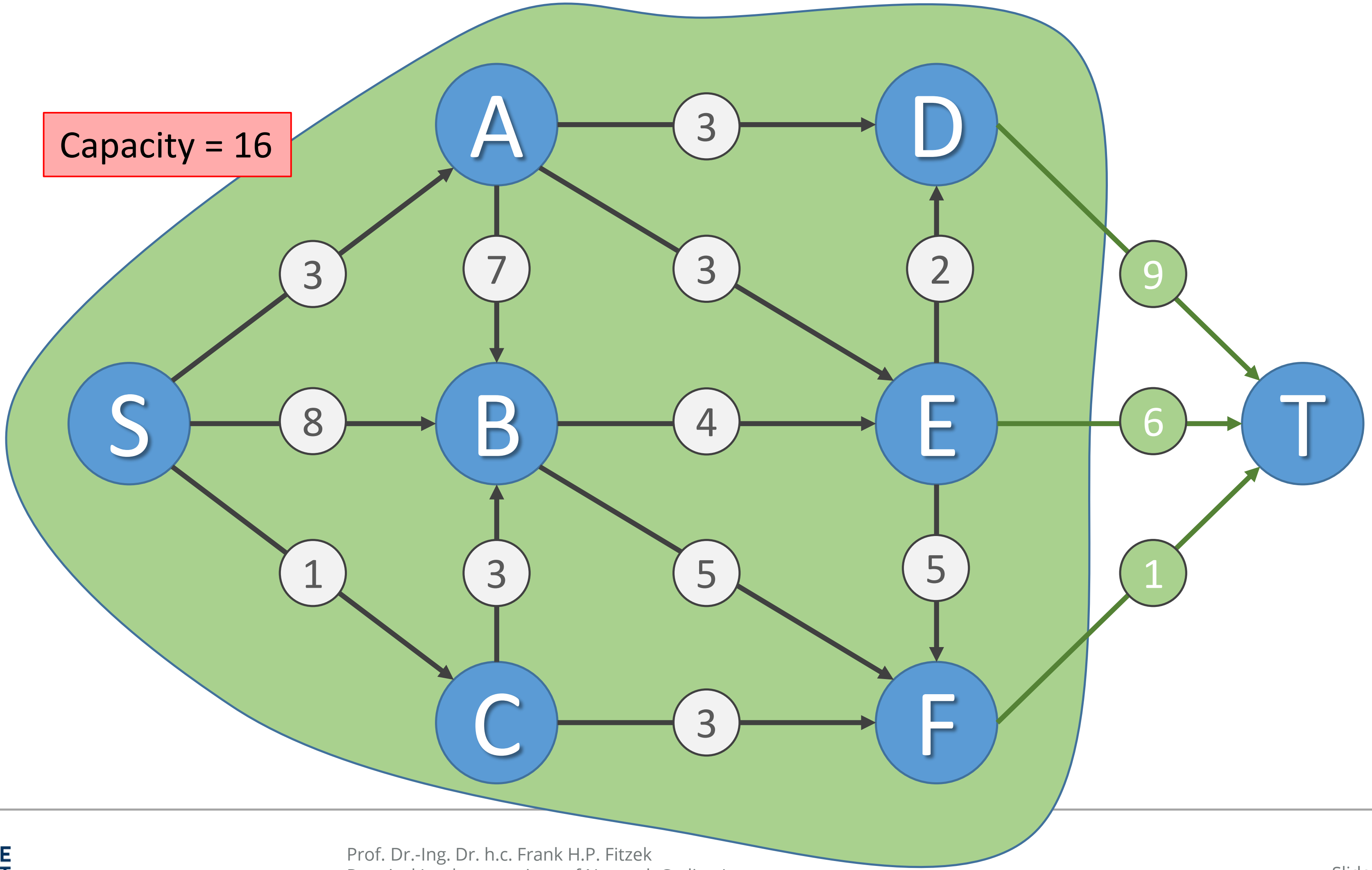
Cuts of Flow Networks



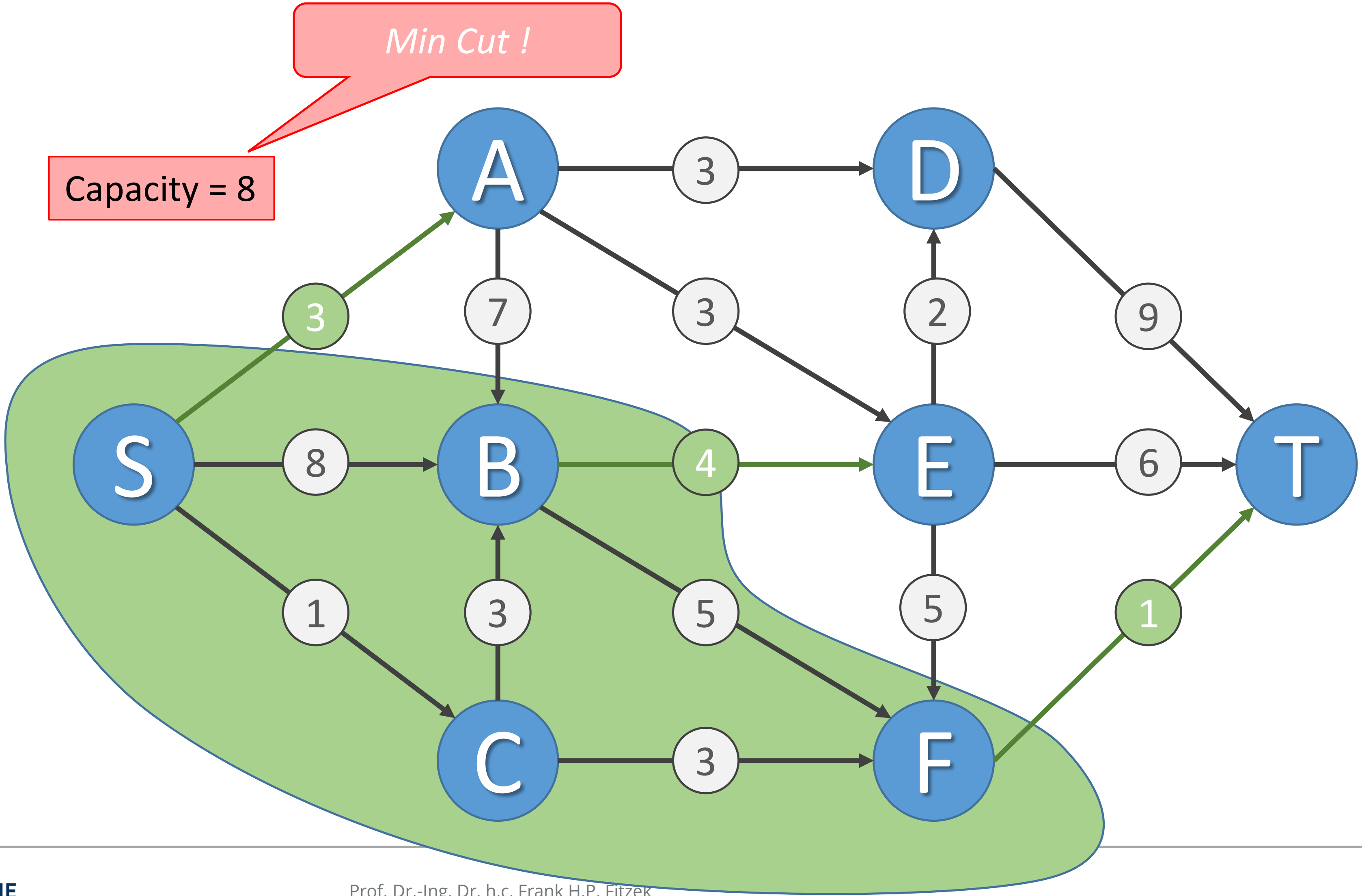
Cuts of Flow Networks



Cuts of Flow Networks

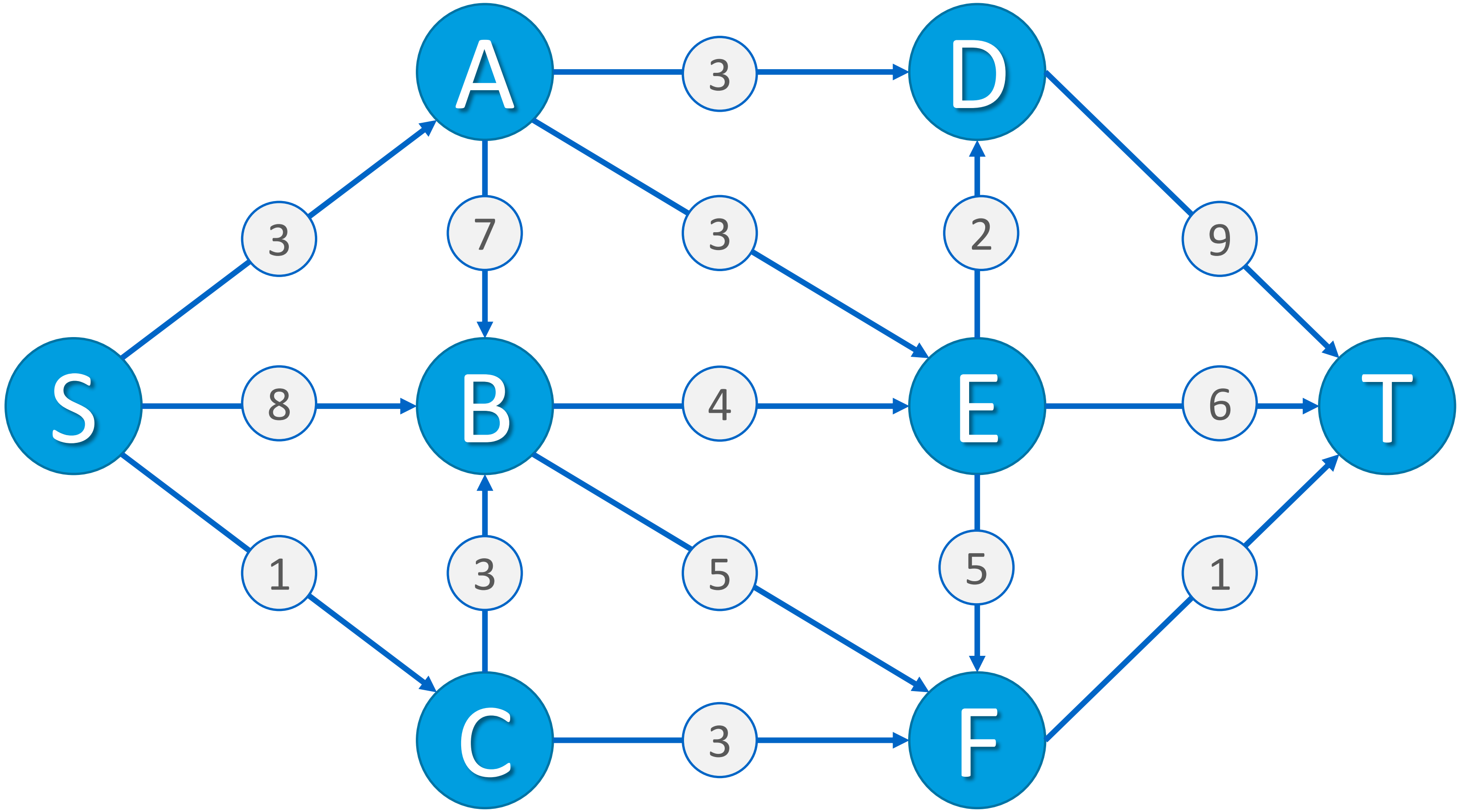


Cuts of Flow Networks

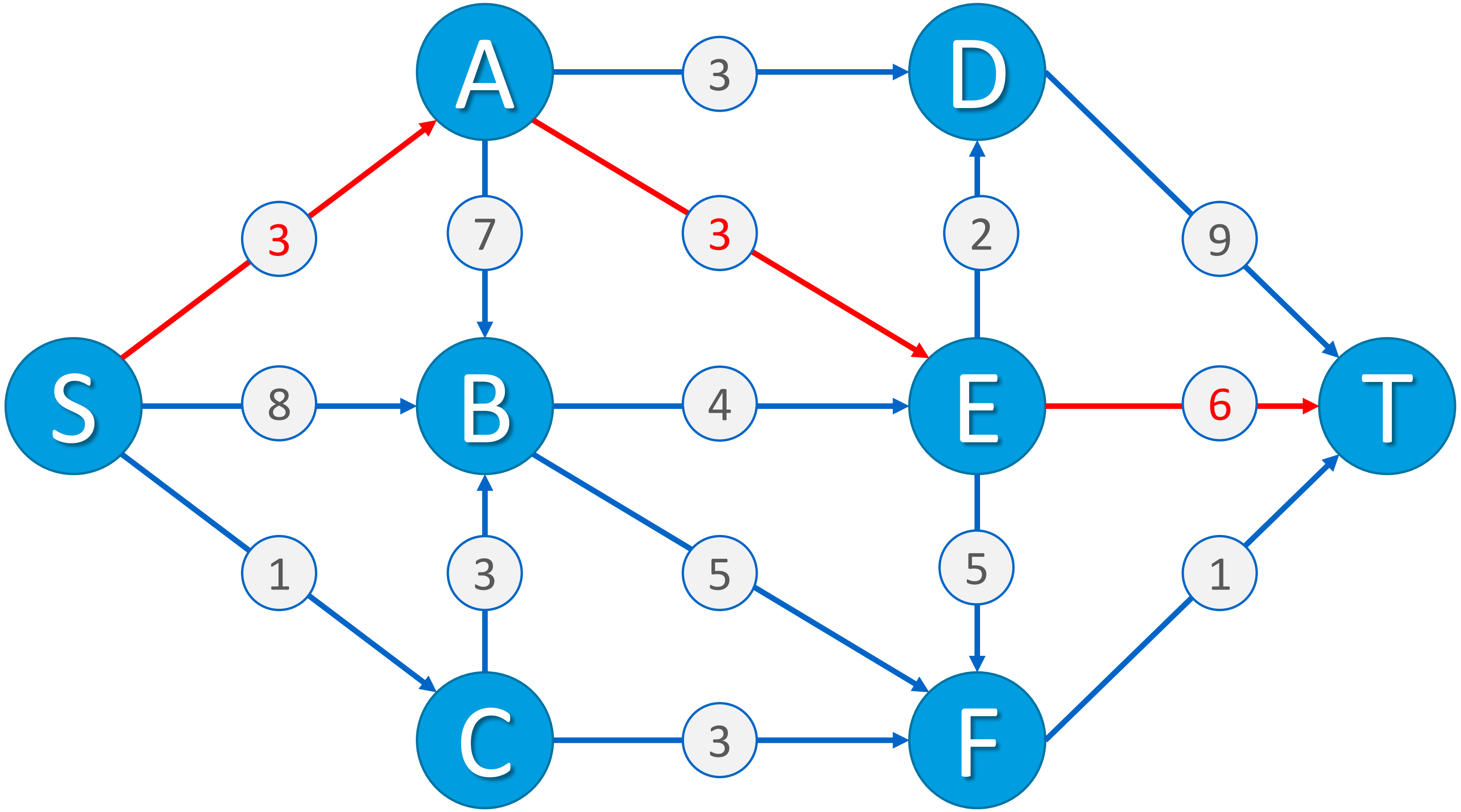


Ford-Fulkerson

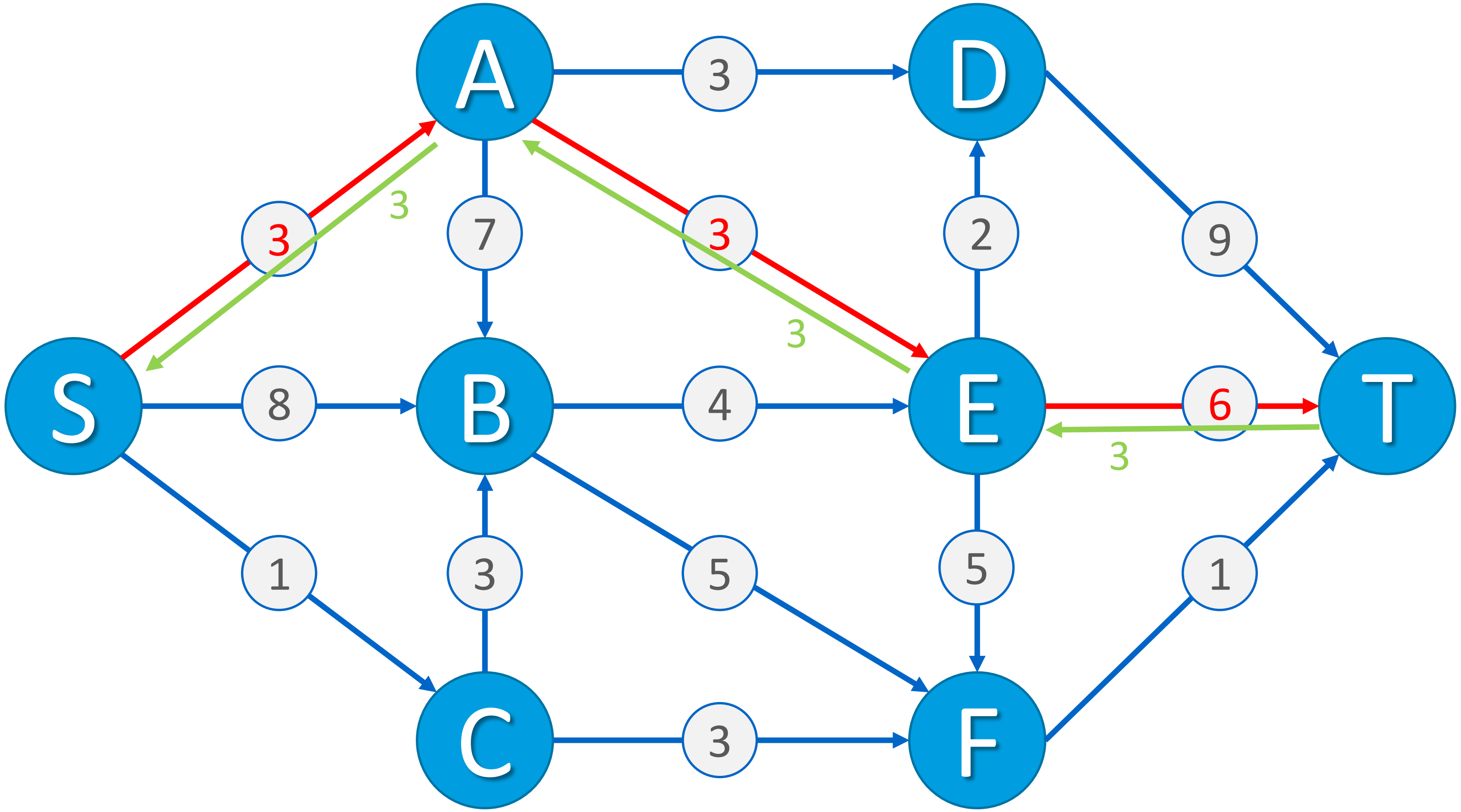
Ford-Fulkerson Max Flow



Ford-Fulkerson Max Flow



Ford-Fulkerson Max Flow



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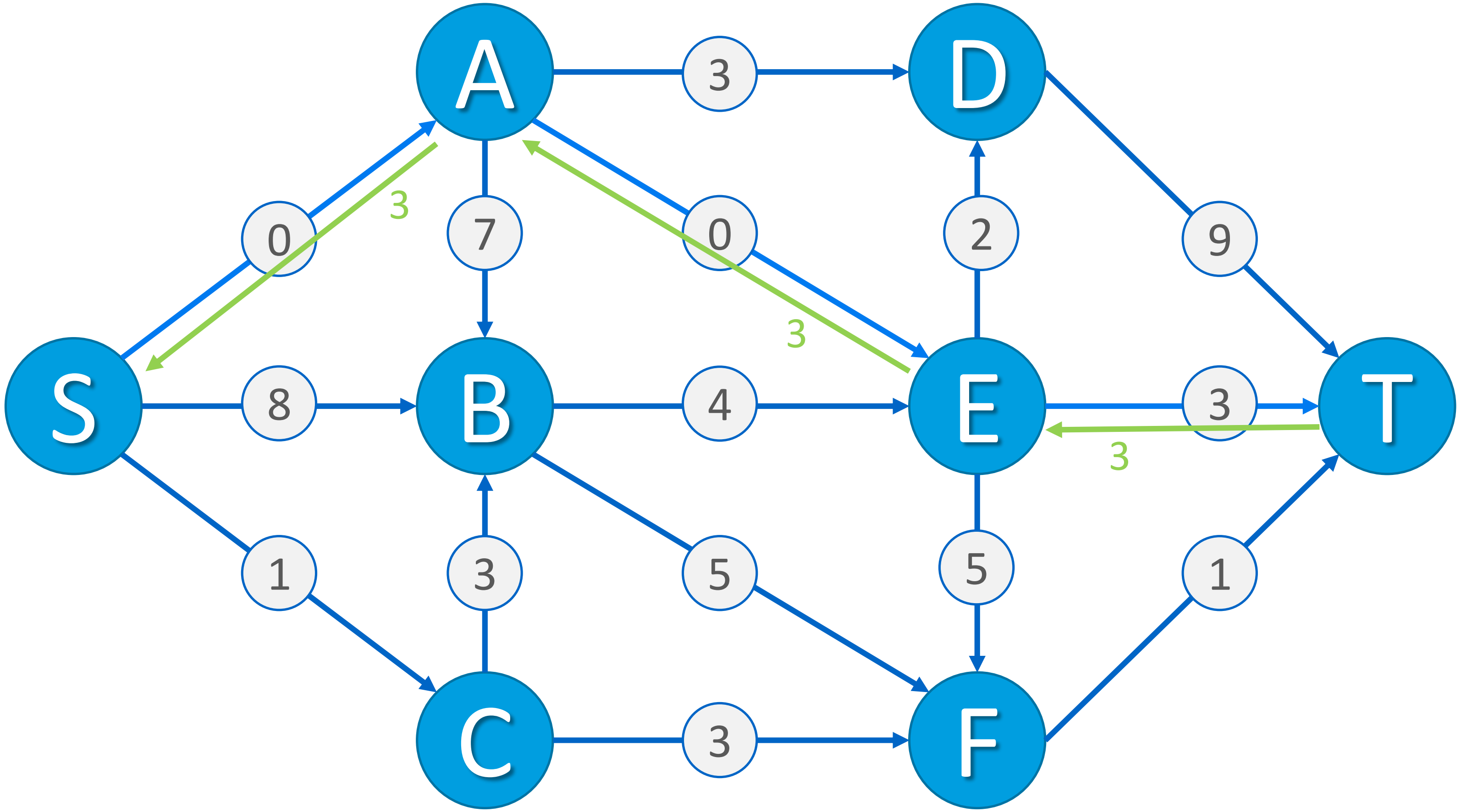

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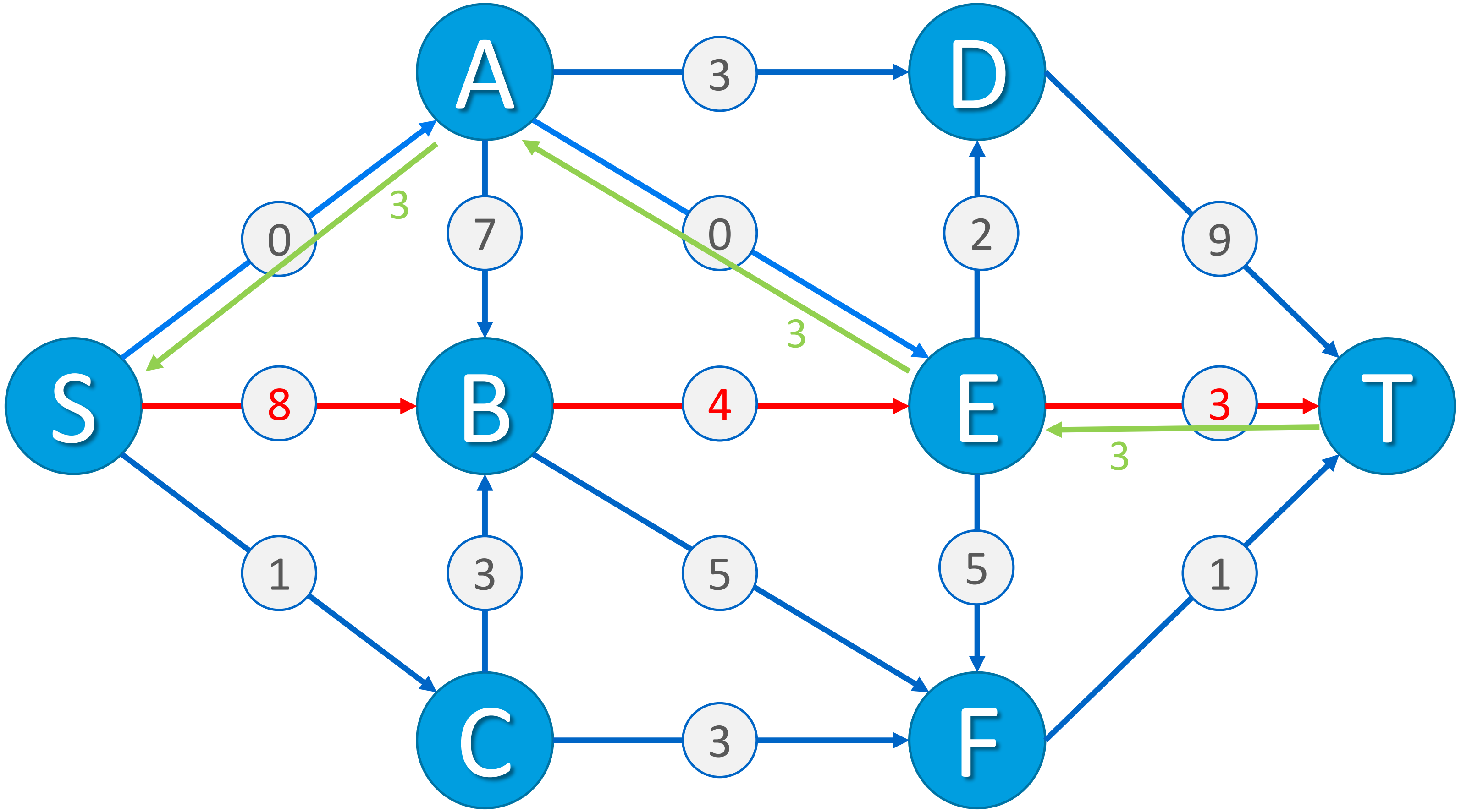

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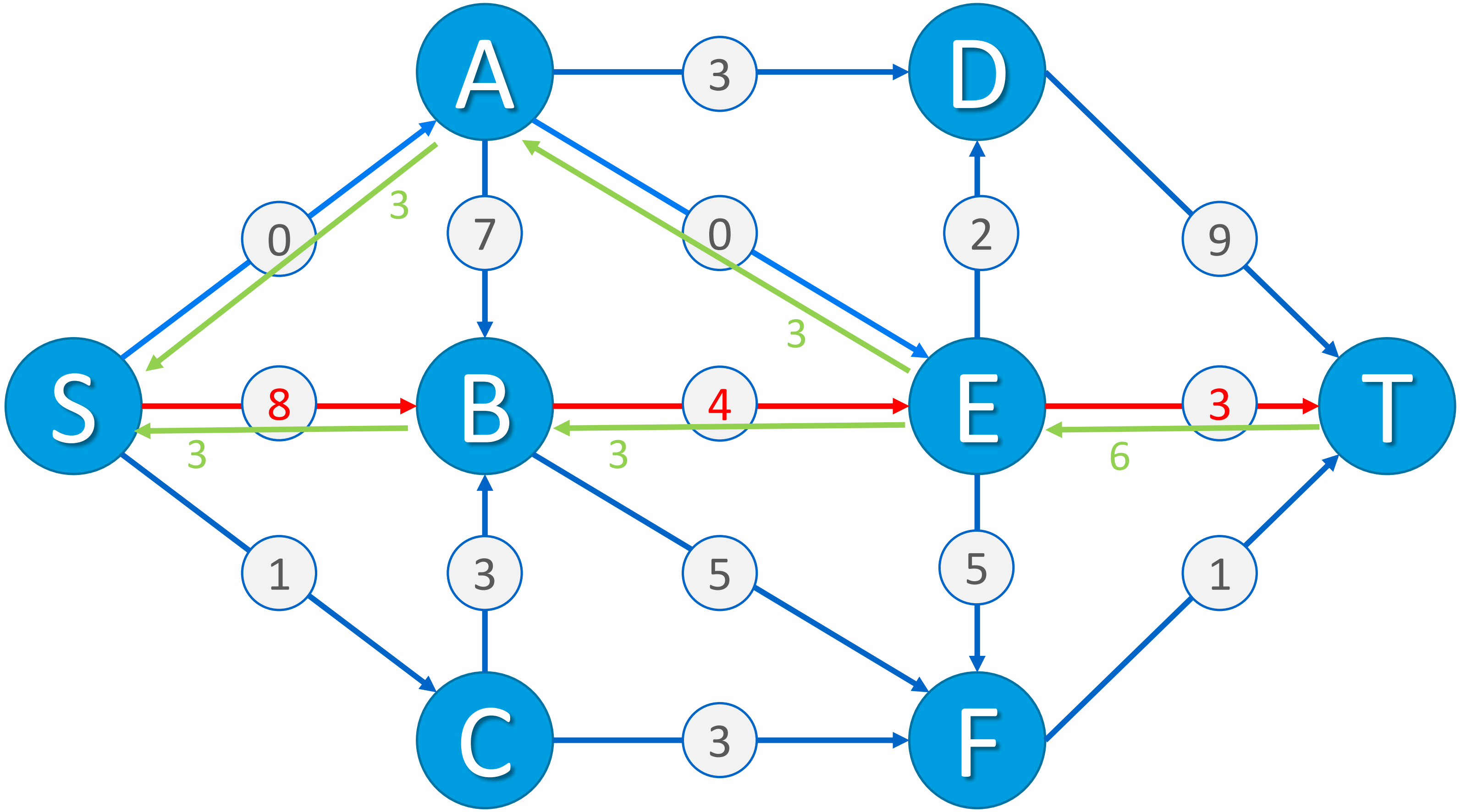

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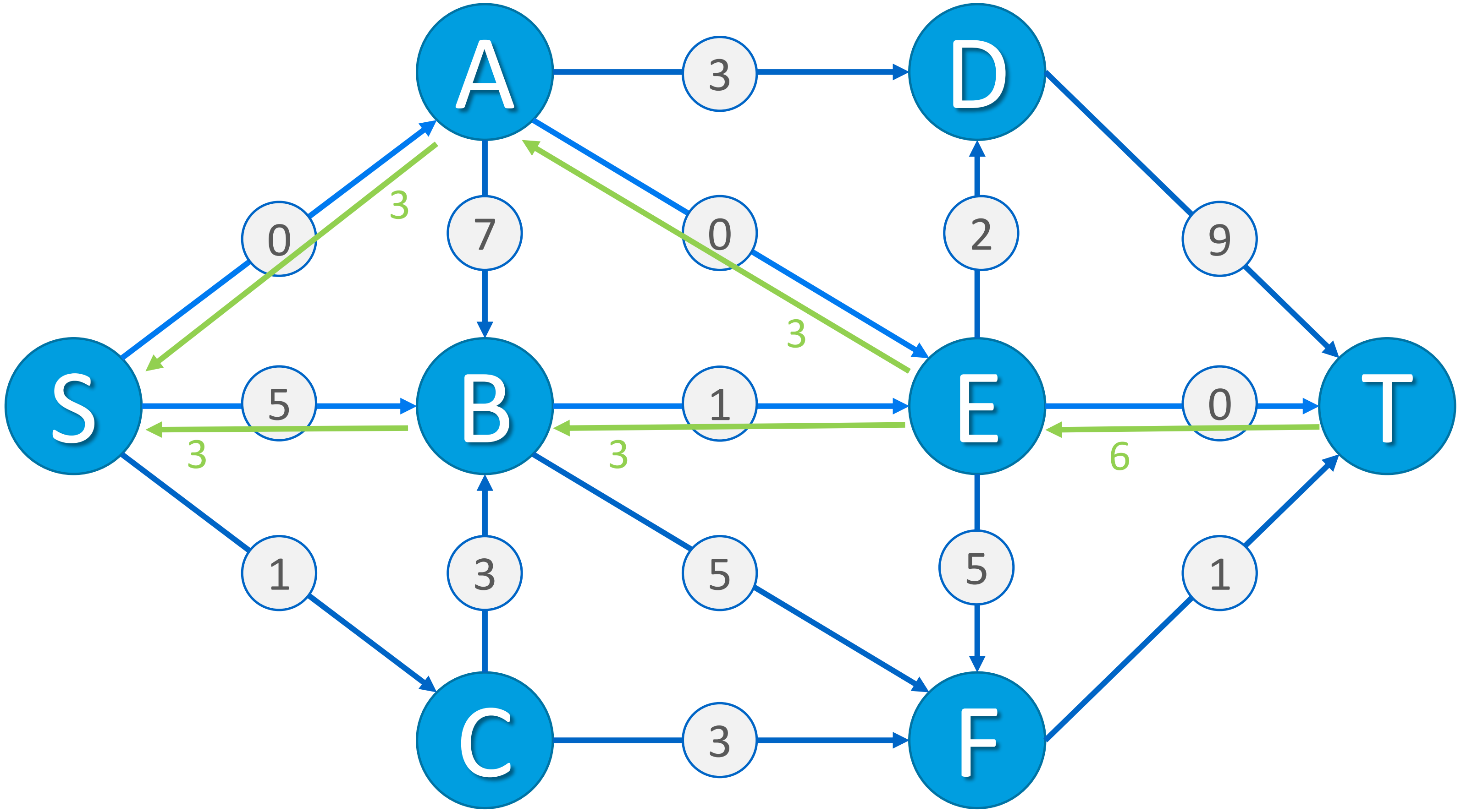

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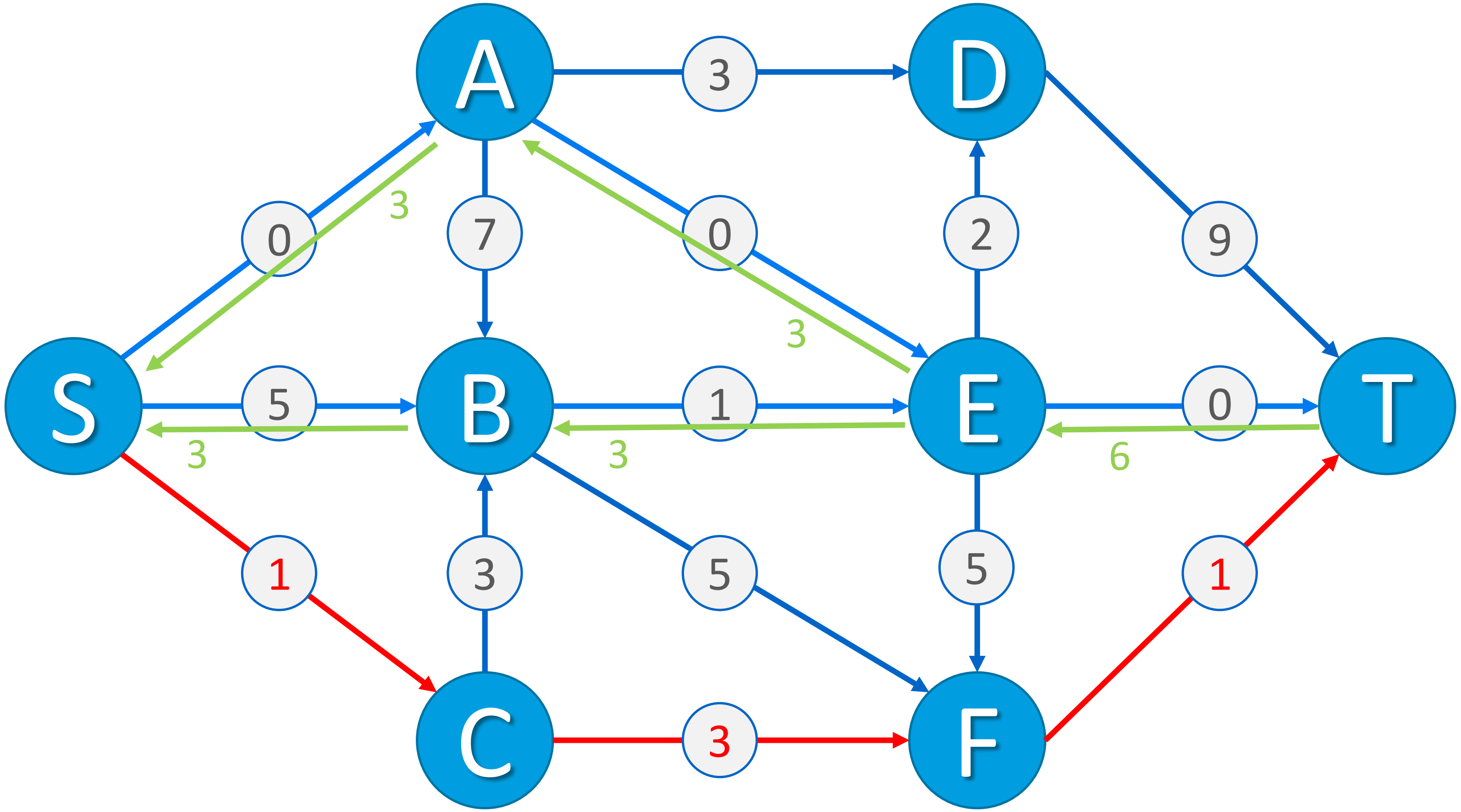

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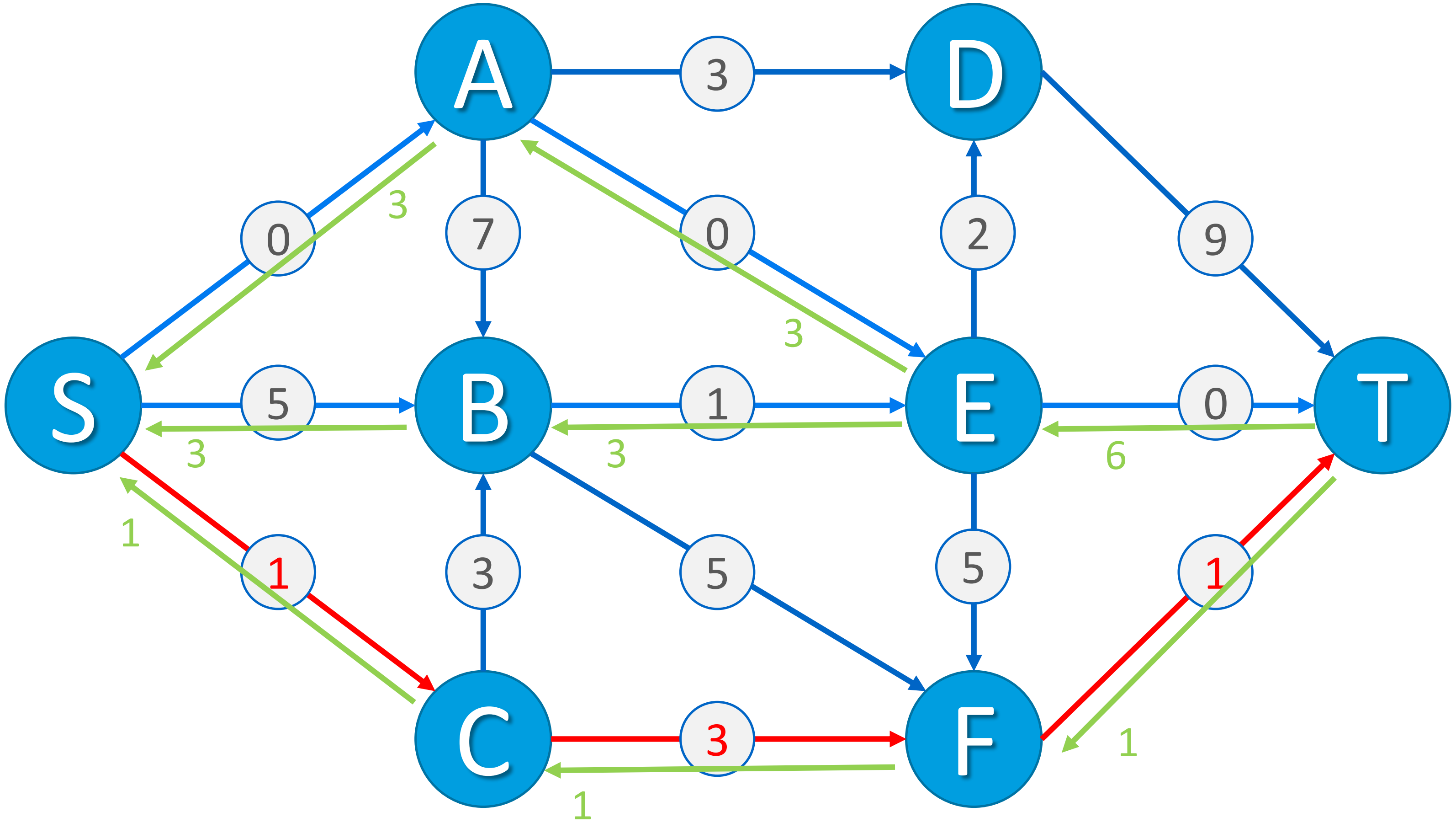
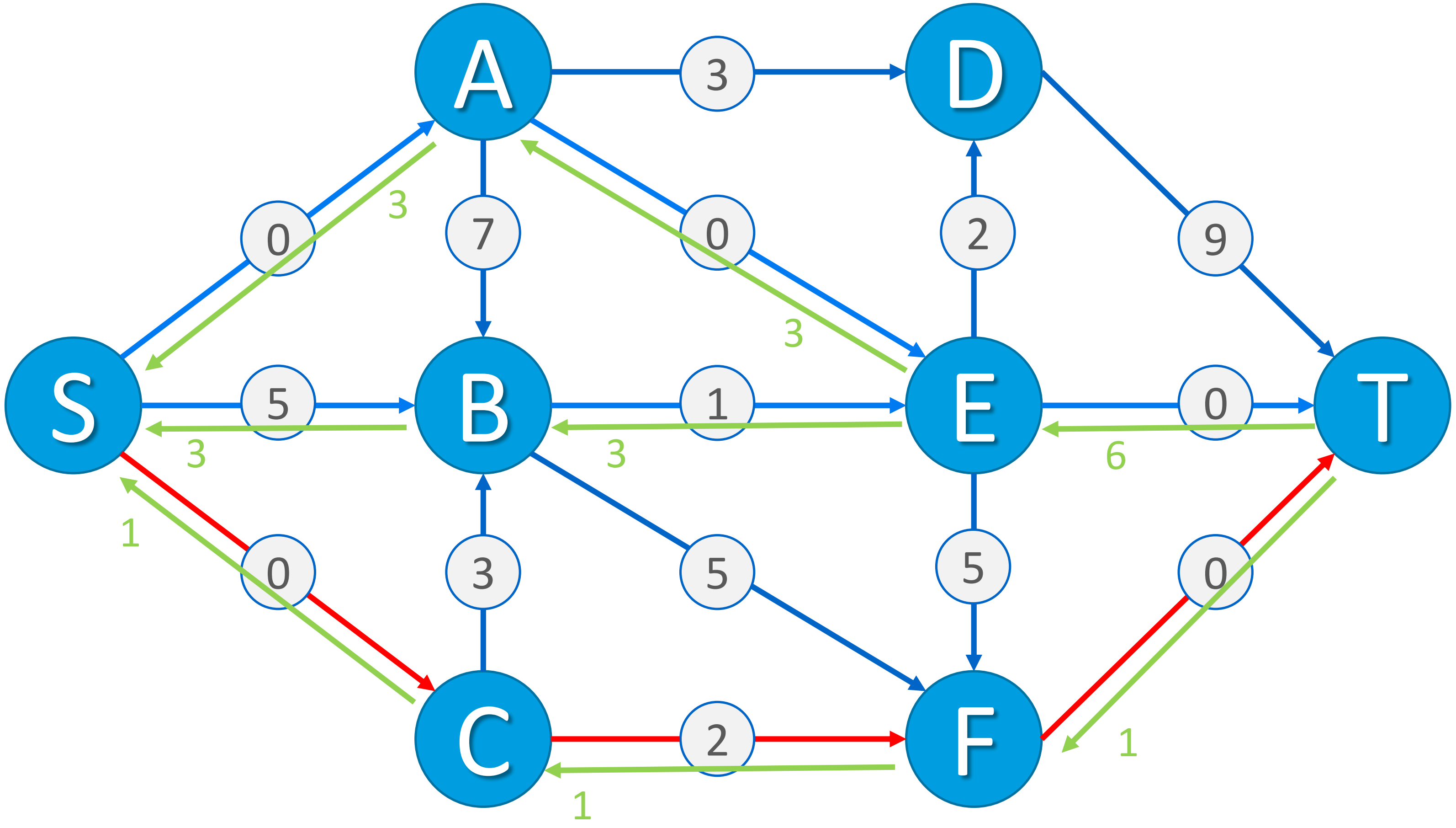
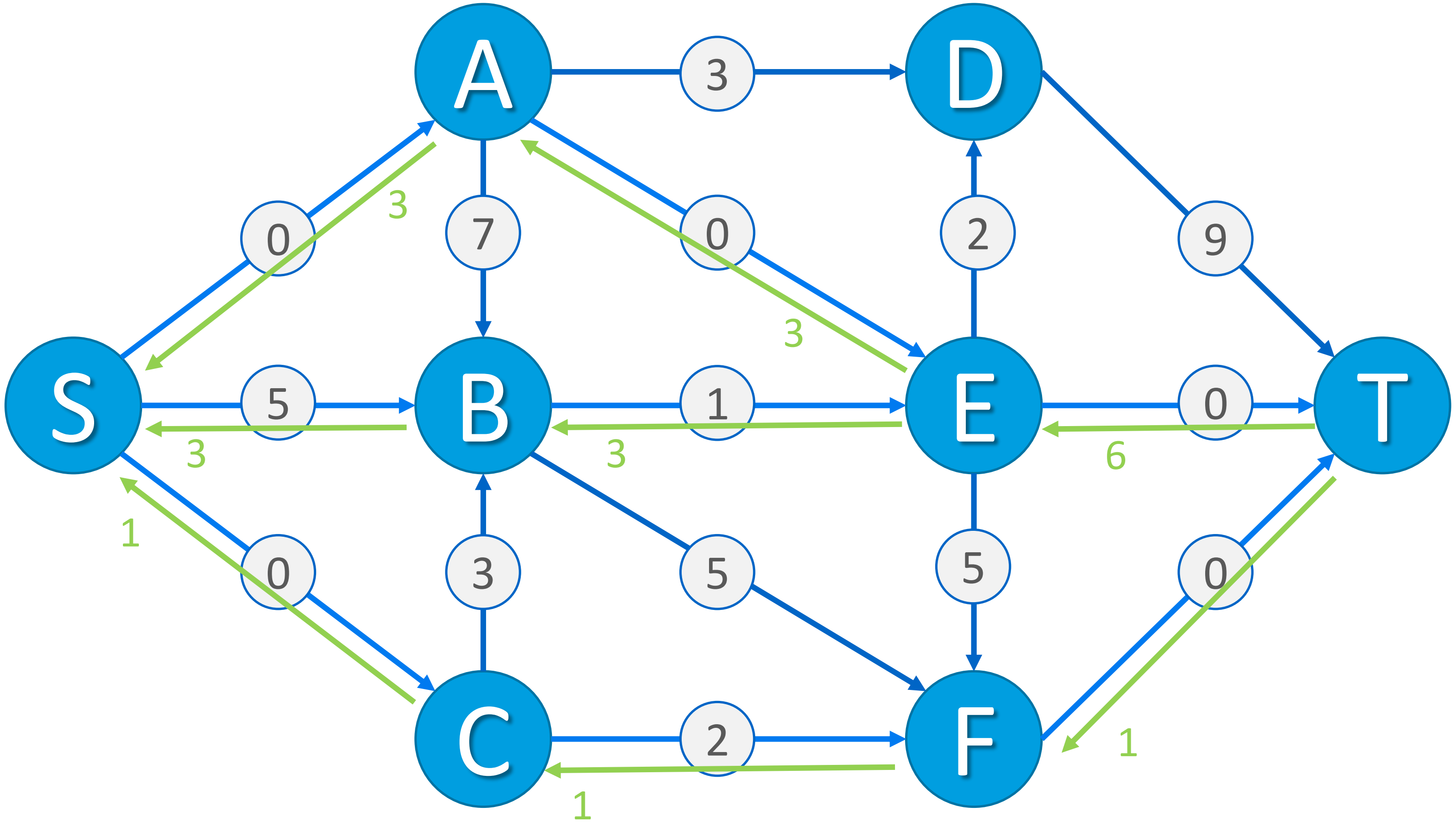


Ford-Fulkerson Max Flow



Ford-Fulkerson Max Flow



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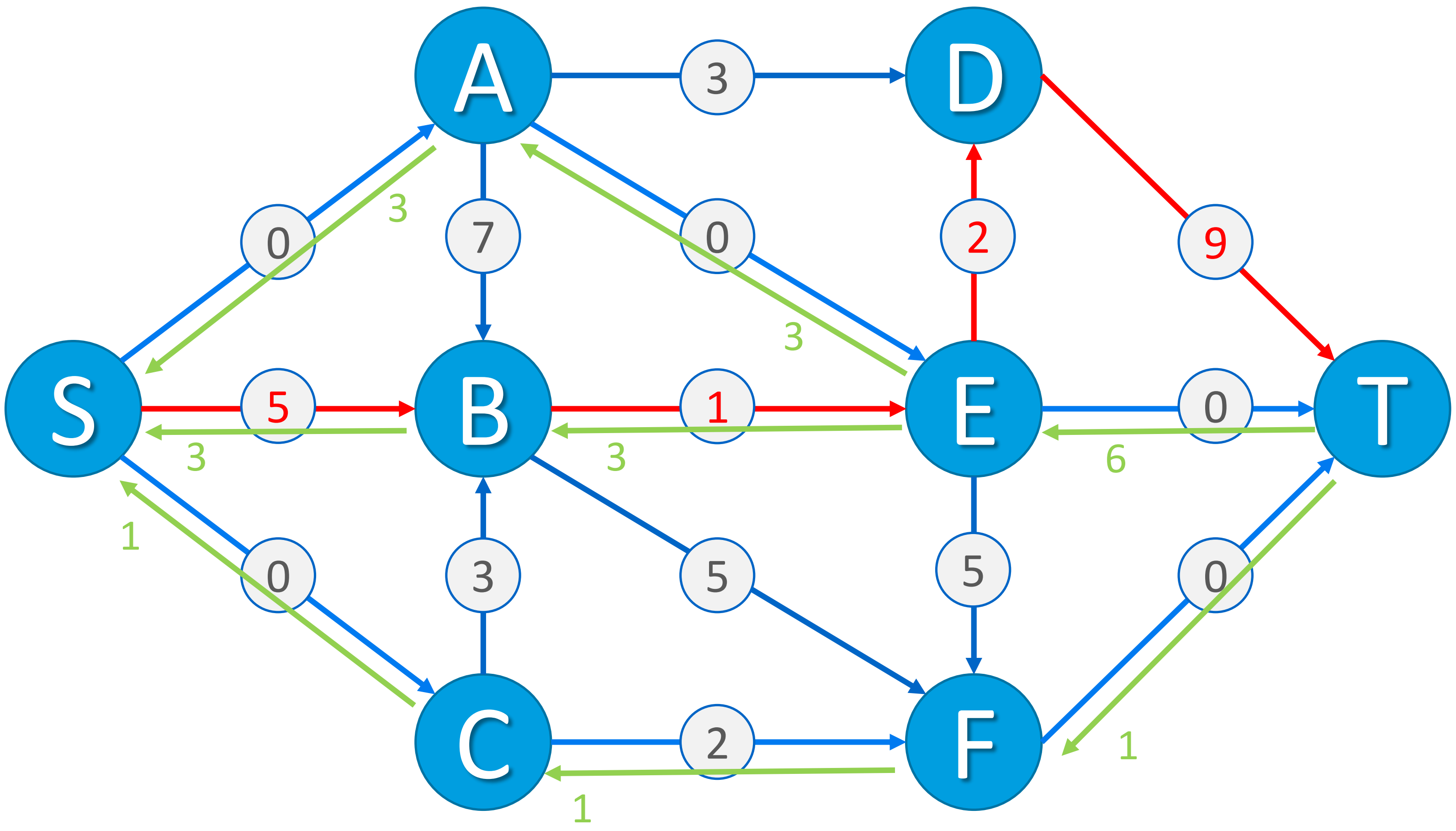
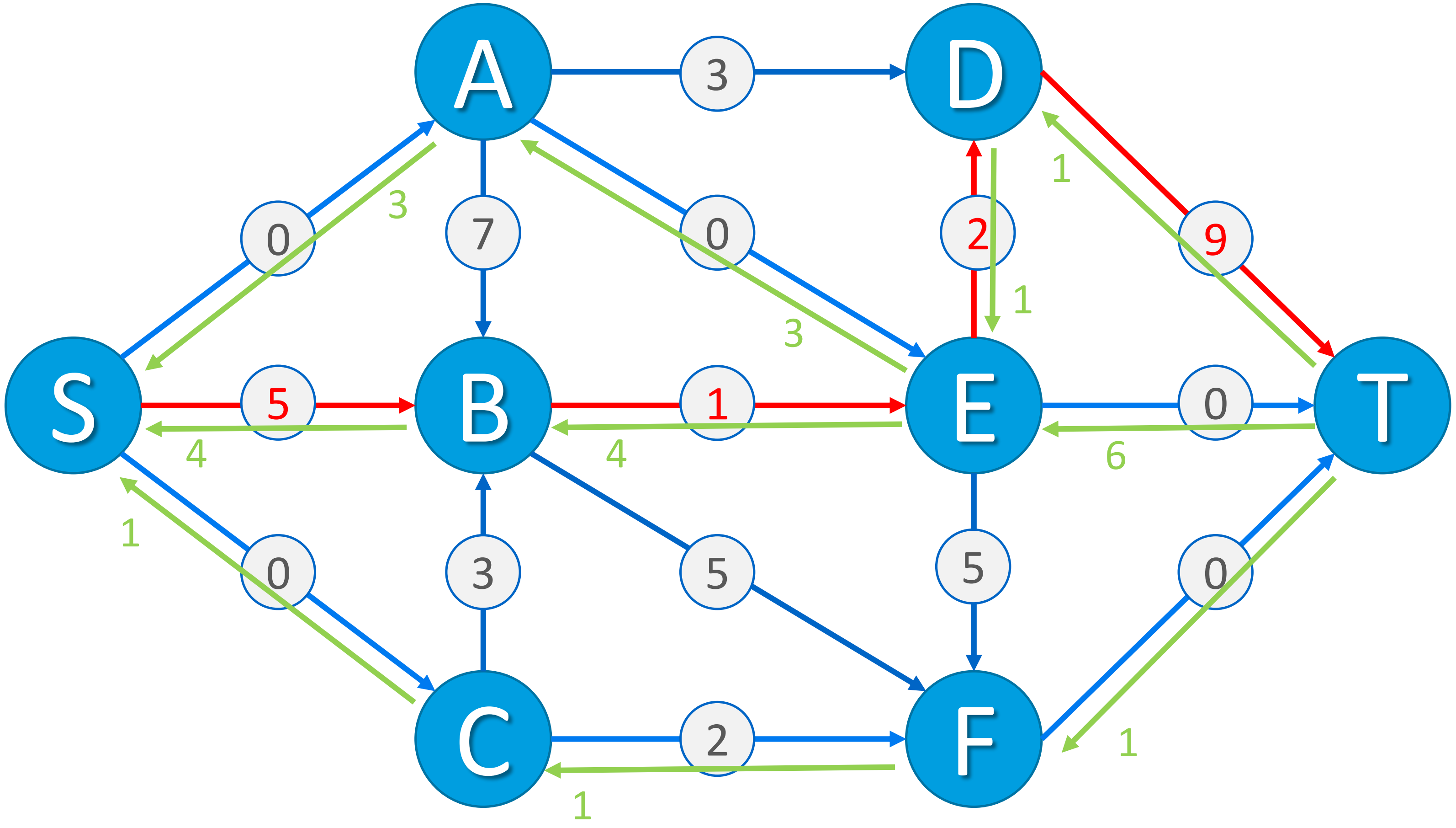
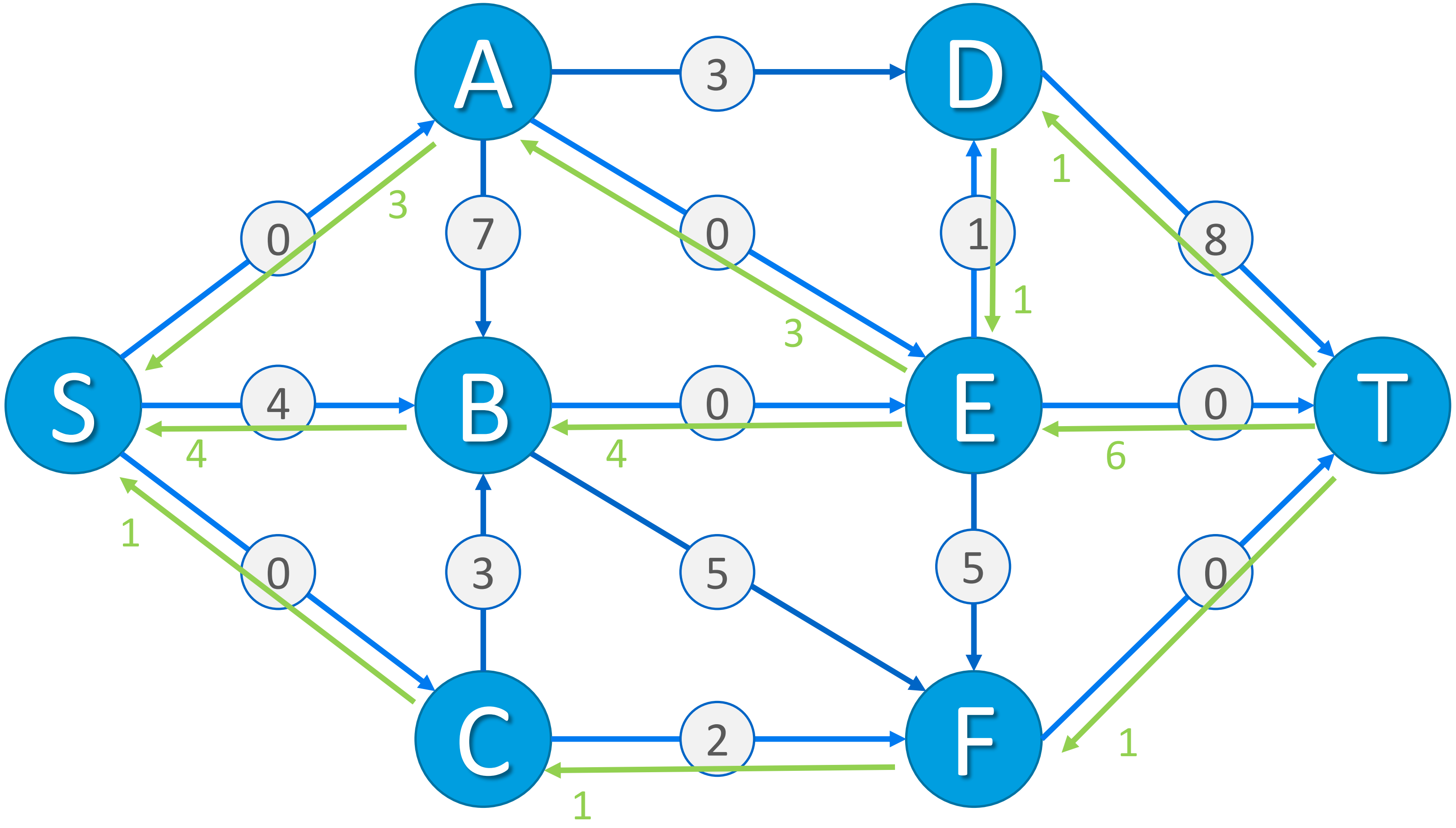


Ford-Fulkerson Max Flow



Ford-Fulkerson Max Flow



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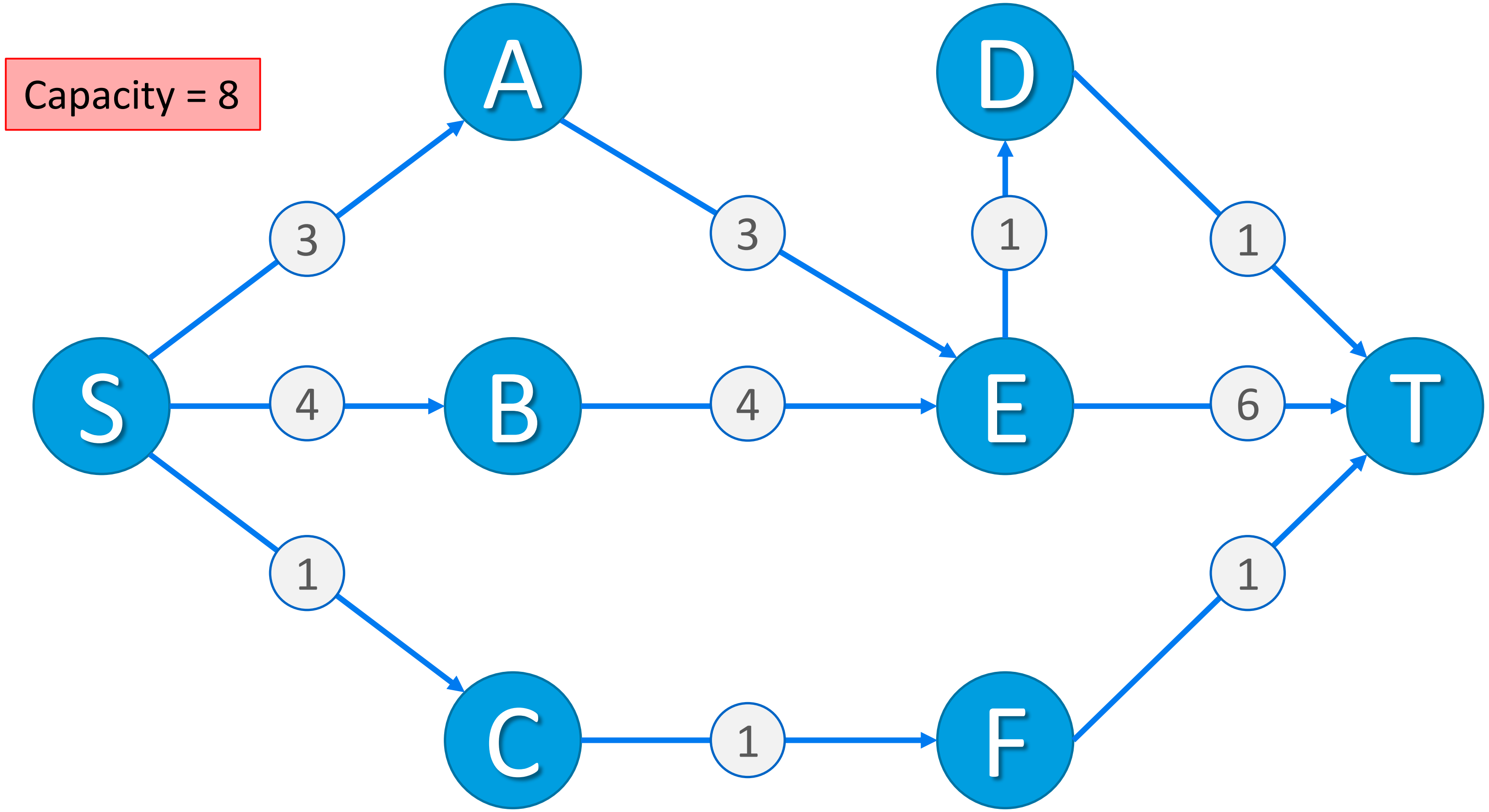

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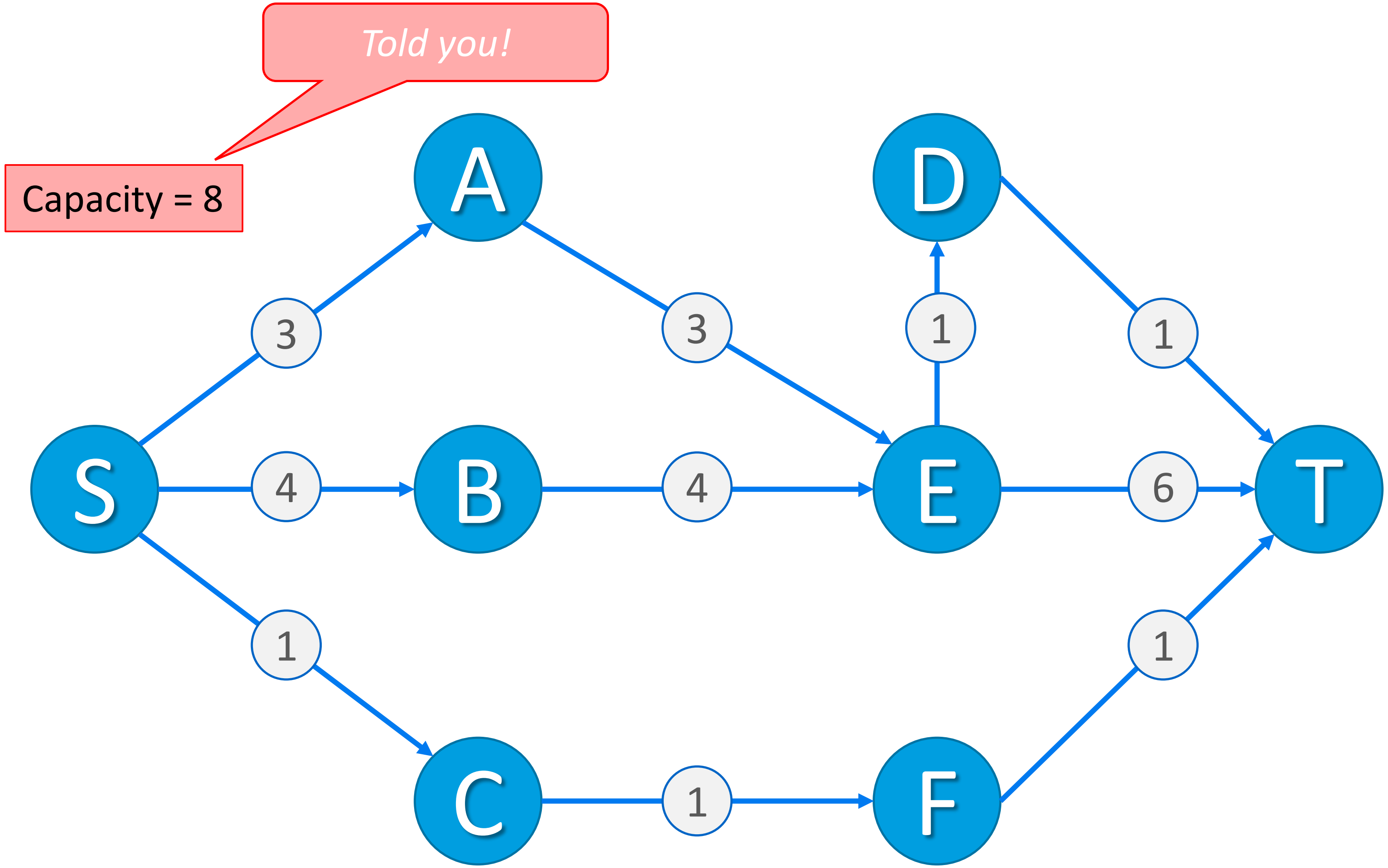
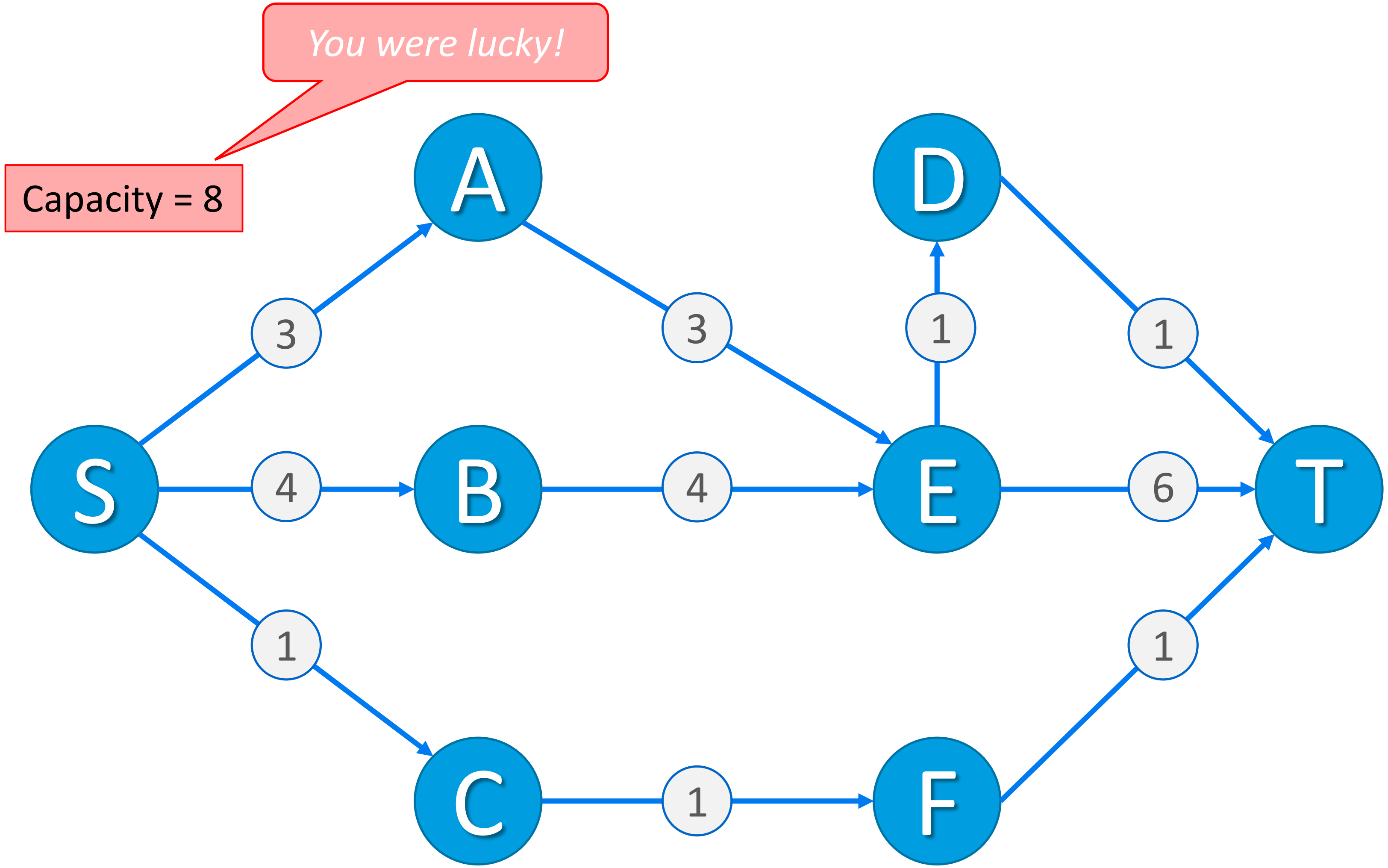
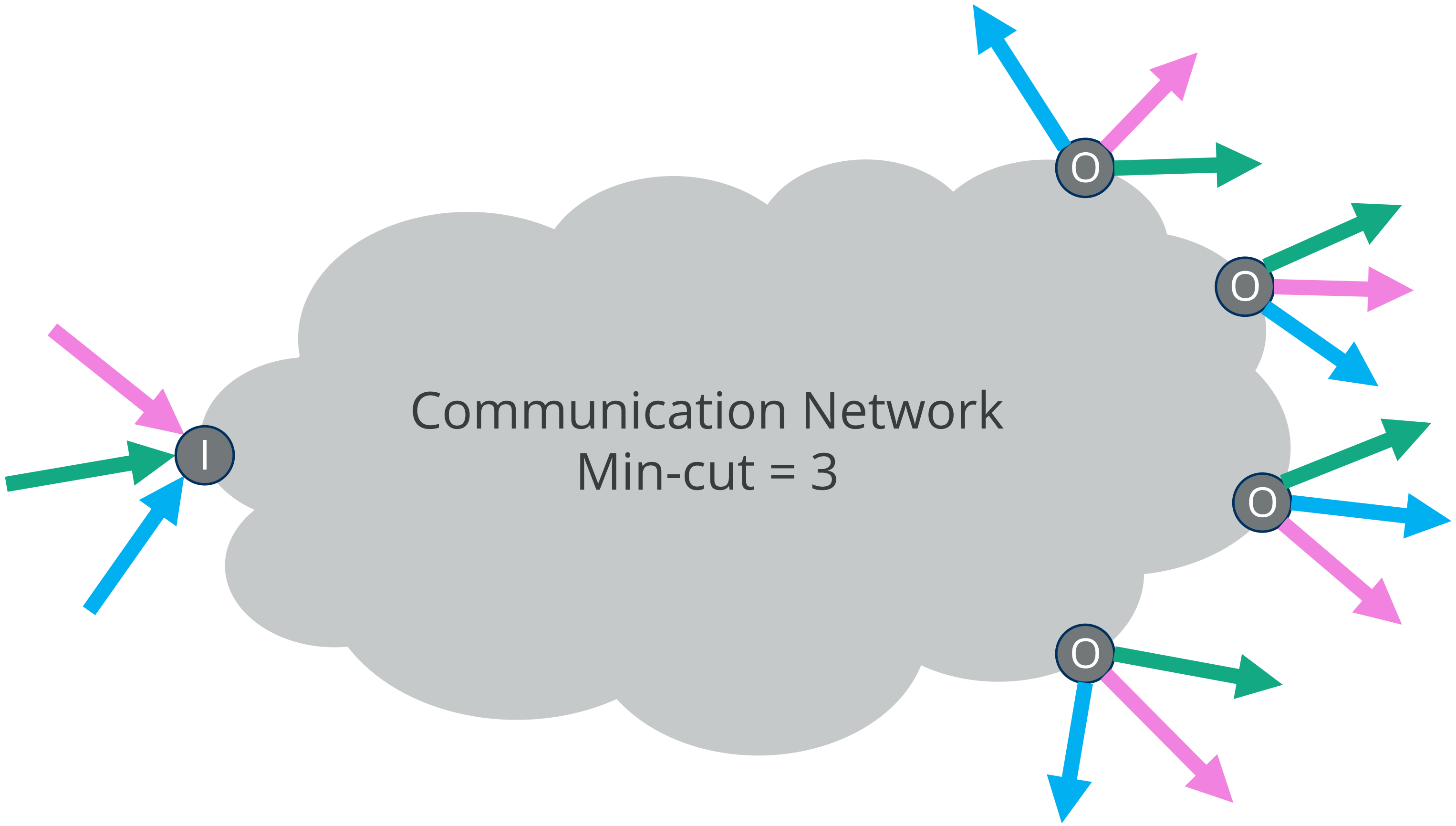


Ford-Fulkerson Max Flow



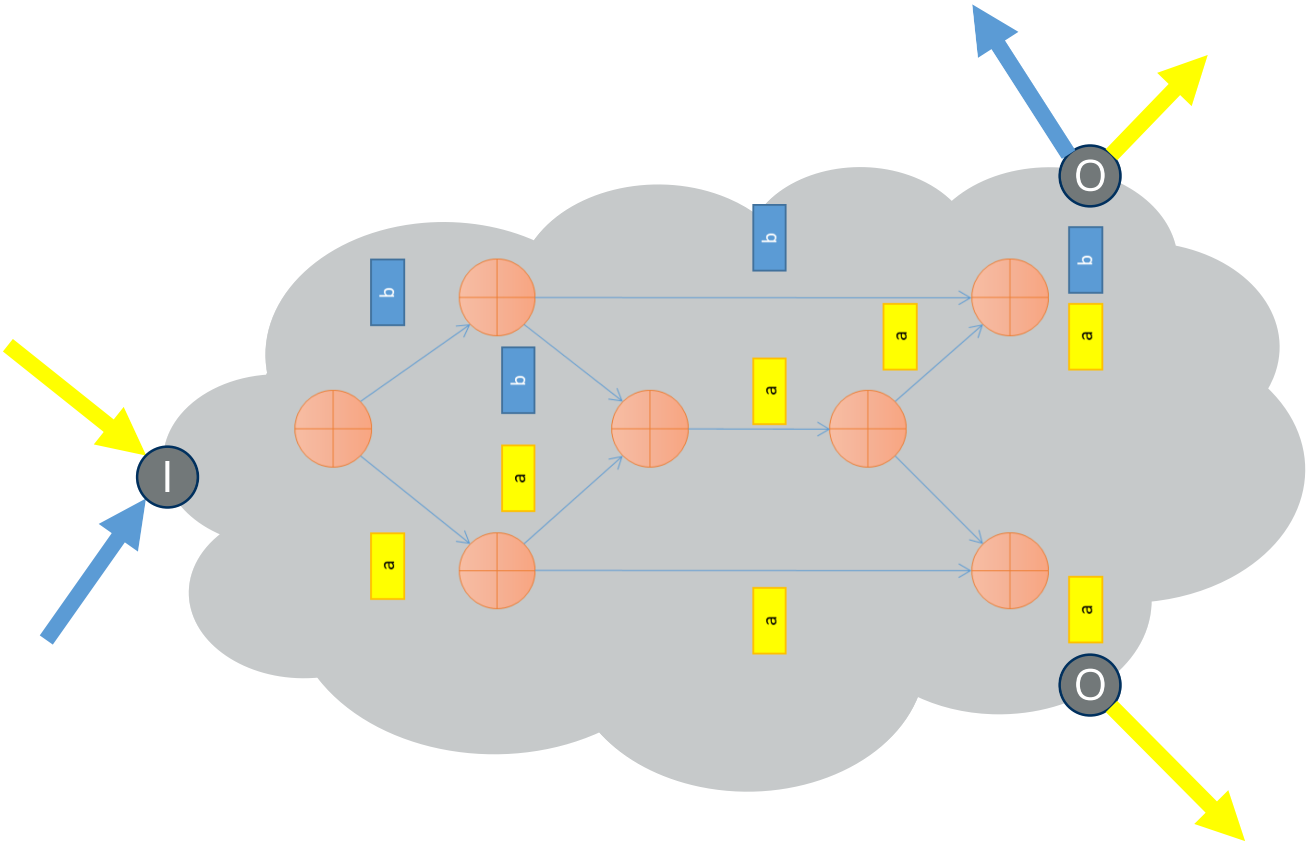
Multi-Cast Example

Multi-Cast Example



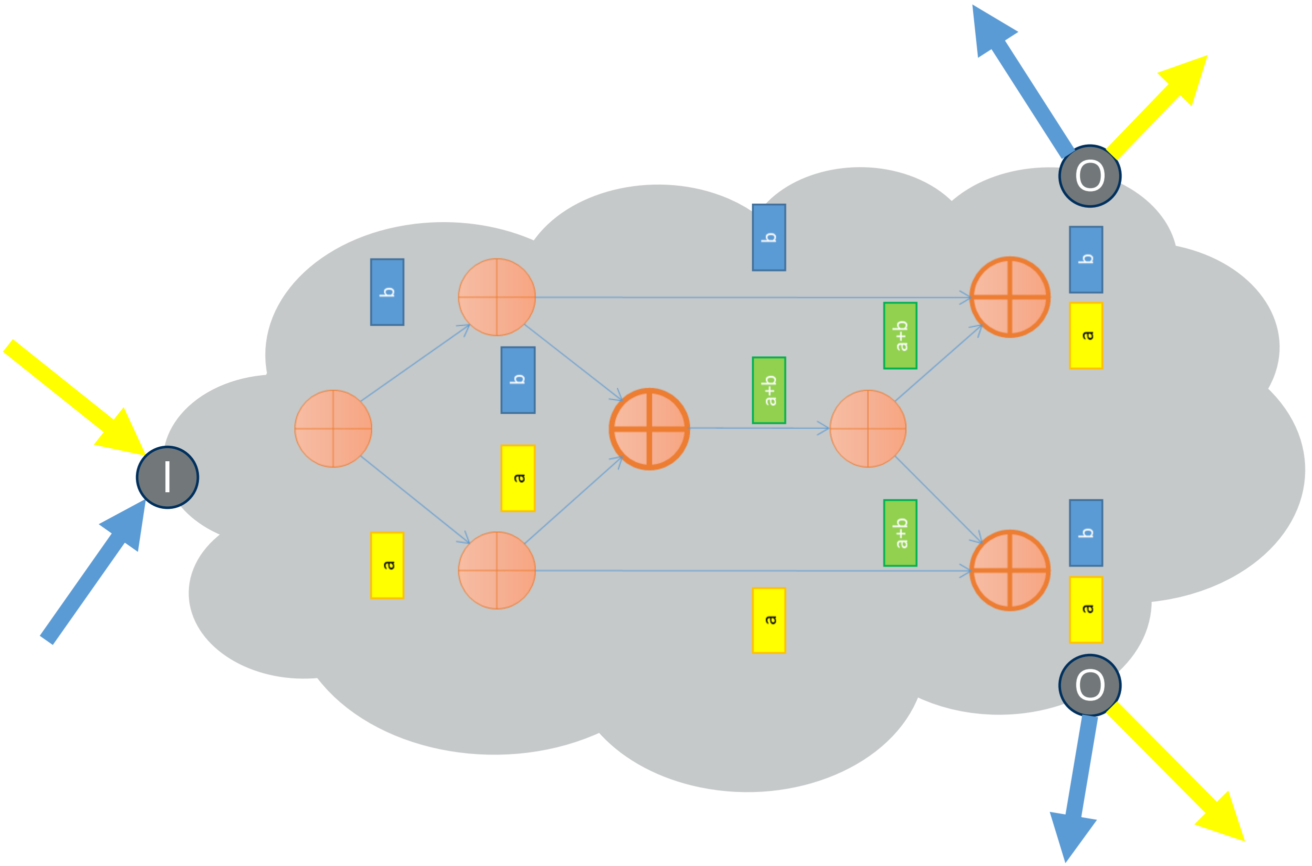
Compare Routing with Network Coding

Multi-Cast Example



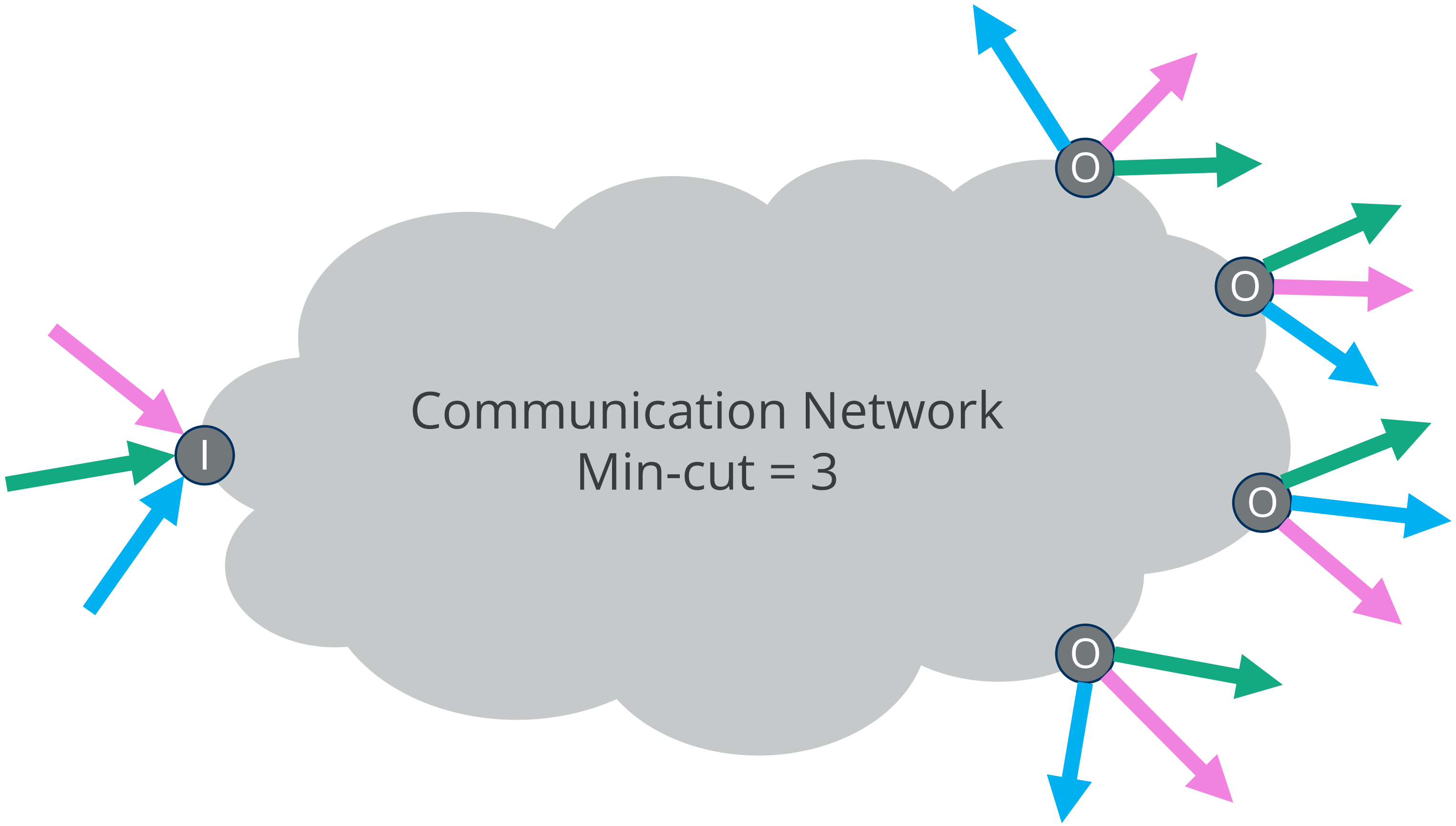
Compare Routing with Network Coding
Routing: np-hard; not optimal with respect to capacity

Multi-Cast Example



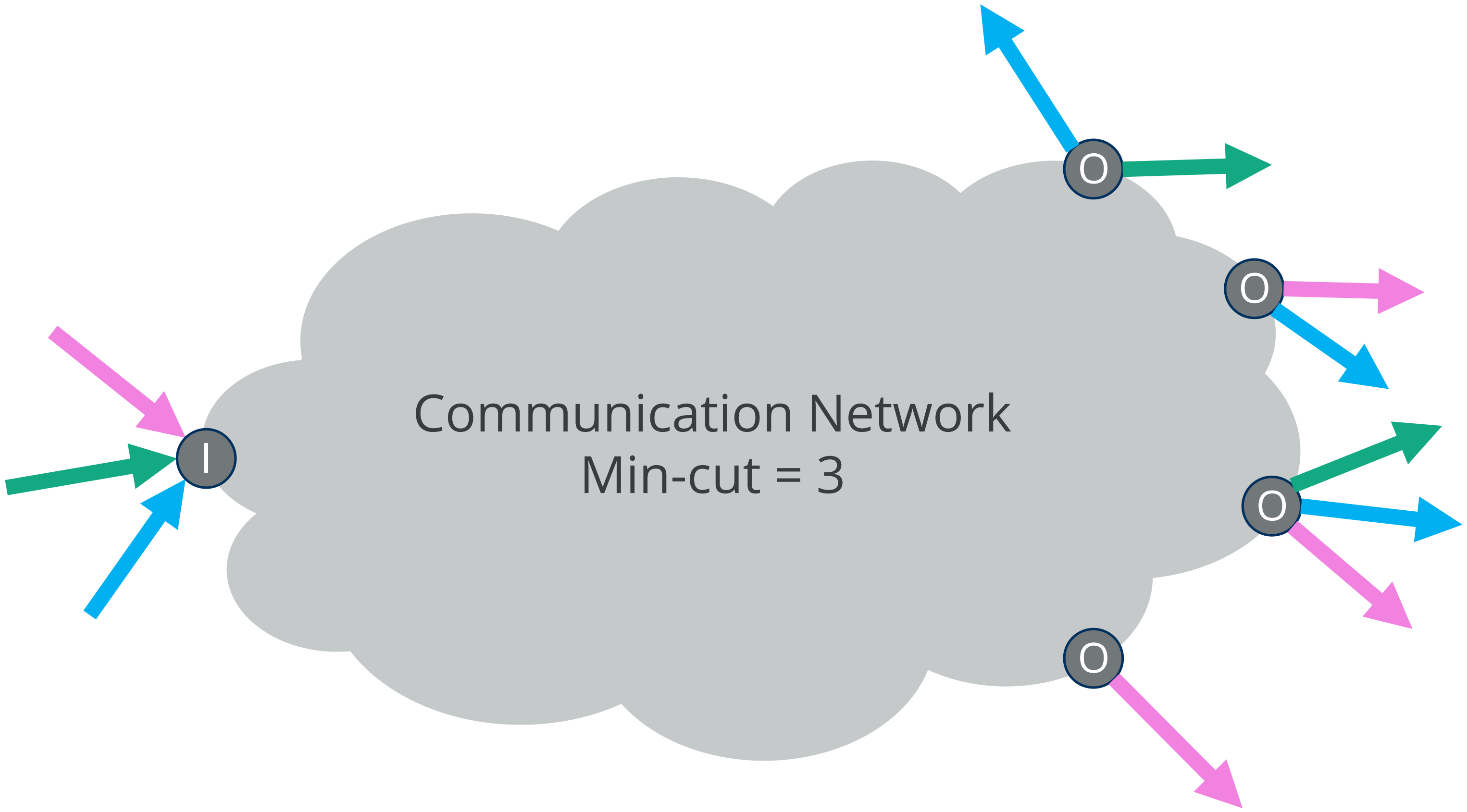
Compare Routing with Network Coding
Network Coding: optimal solution can be found and can be found fast

Multi-Cast Example



Compare Routing with Network Coding

Multi-Cast Example

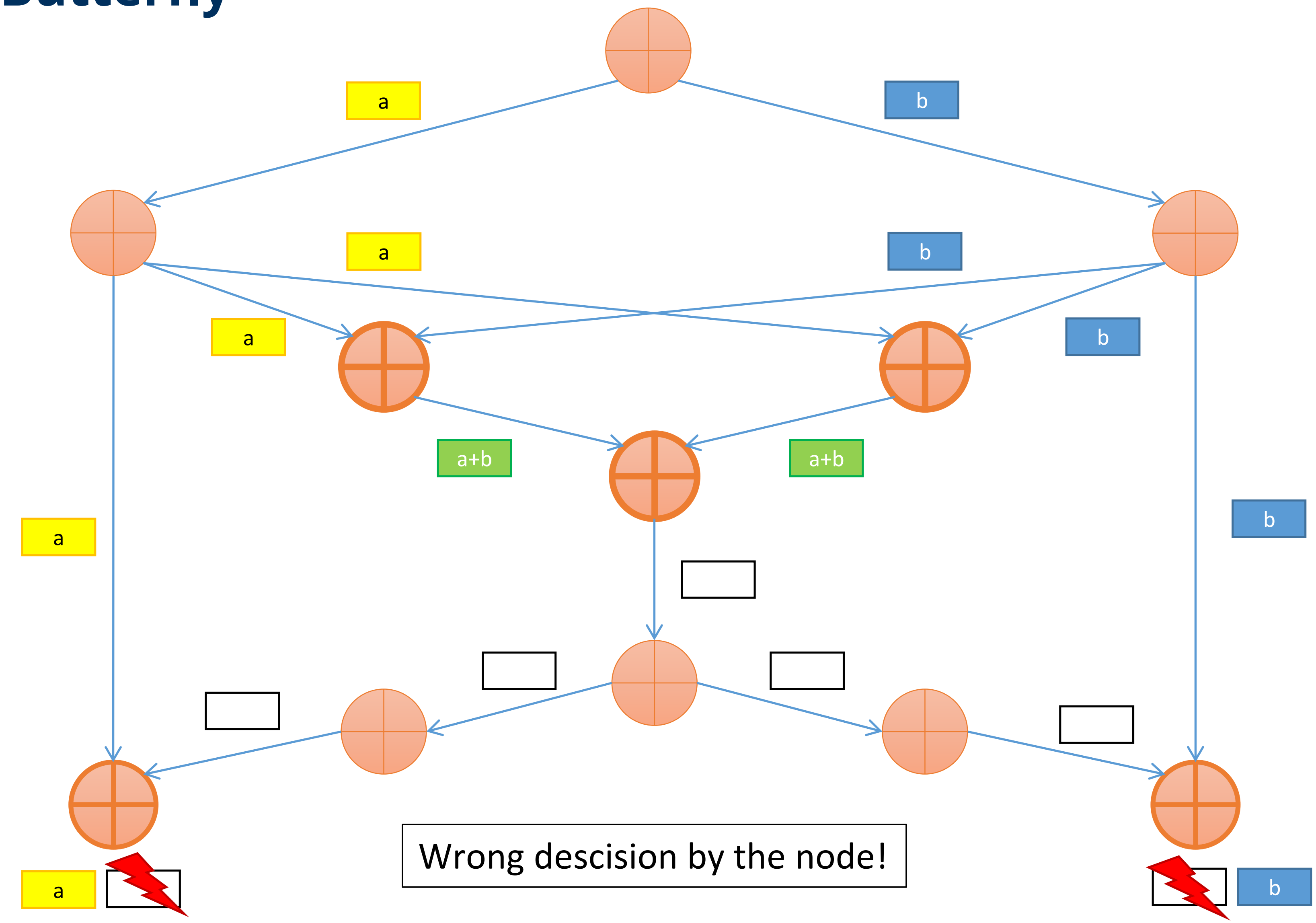


Compare Routing with Network Coding

The Butterfly++

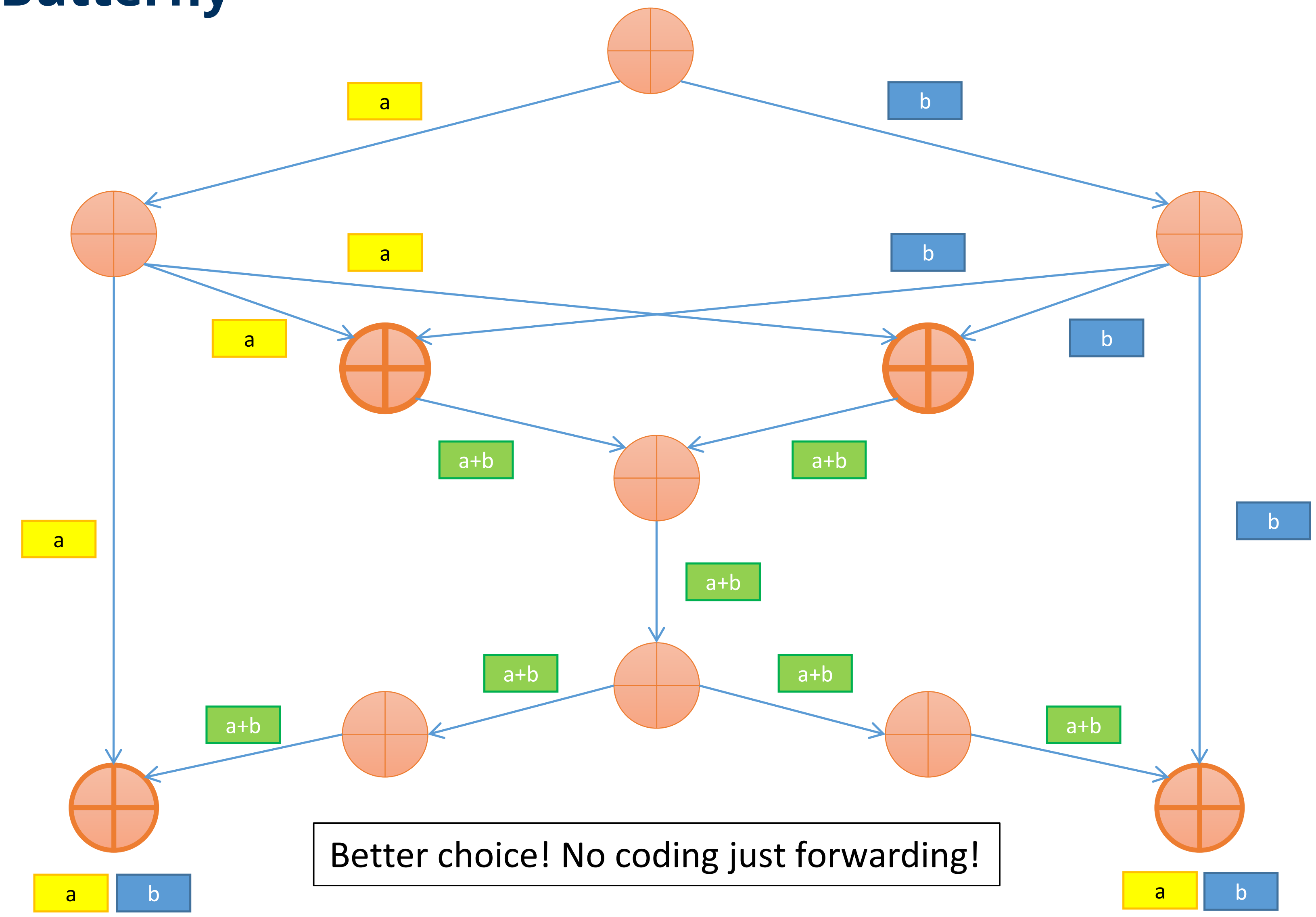
Network Coding: The Butterfly++

Let's code all
incoming packets
.... mmmh



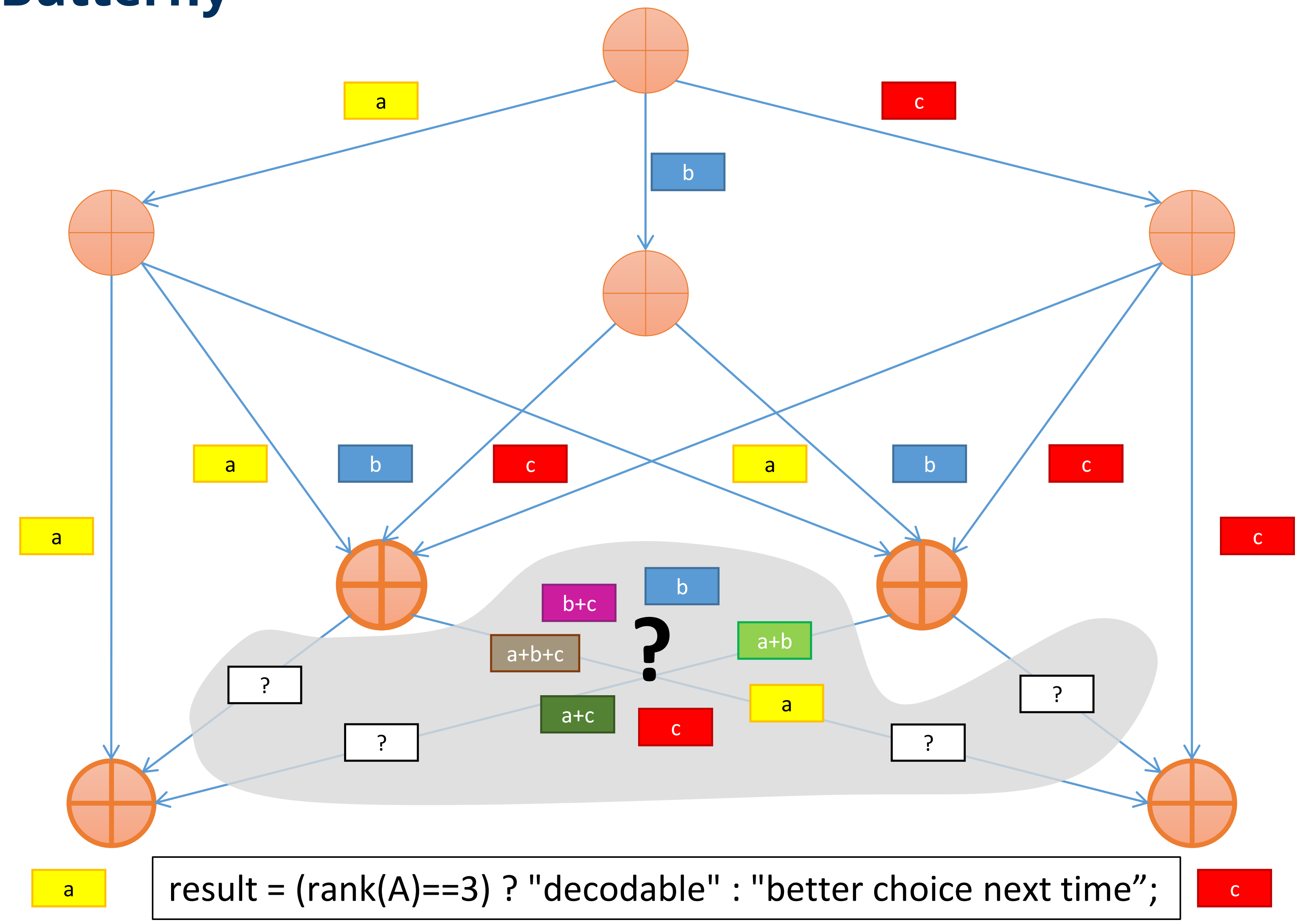
Wrong descision by the node!

Network Coding: The Butterfly++



Better choice! No coding just forwarding!

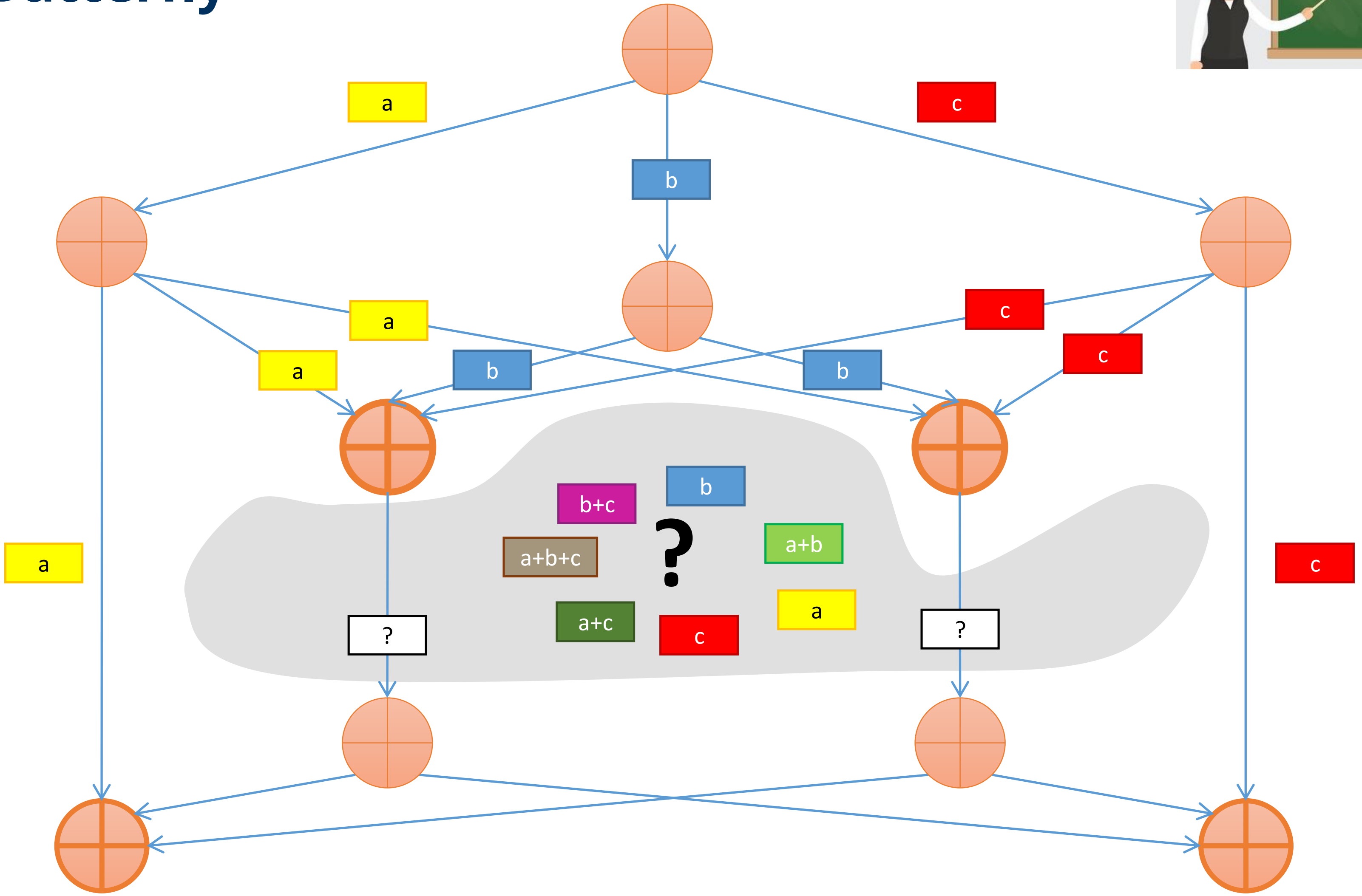
Network Coding: The Butterfly++



Network Coding: The Butterfly++

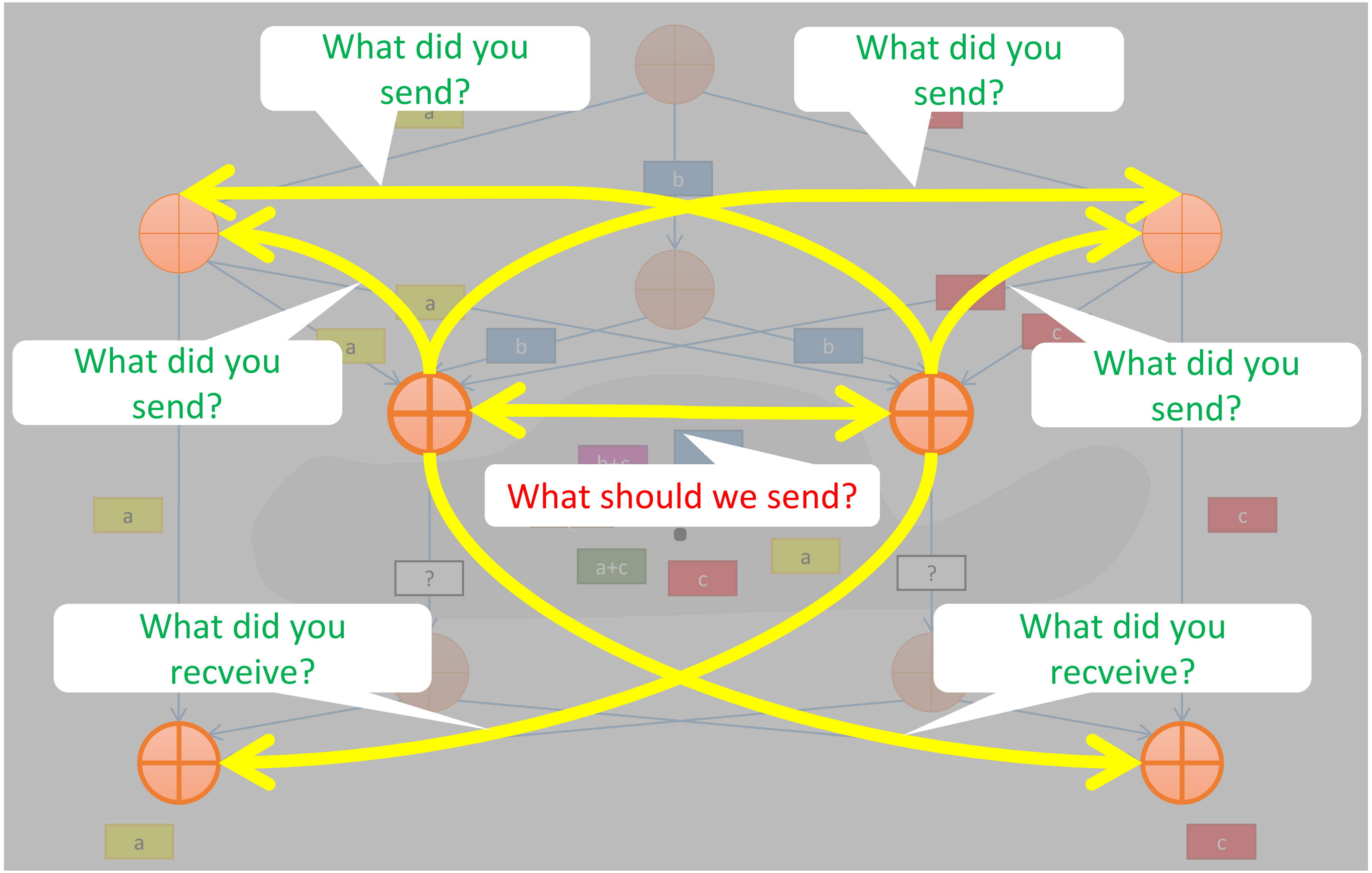
$$\begin{pmatrix} 1 & 0 & 0 \\ c_4 & c_5 & c_6 \\ c_1 & c_2 & c_3 \end{pmatrix}$$

$$\begin{pmatrix} c_1 & c_2 & c_3 \\ c_4 & c_5 & c_6 \\ 0 & 0 & 1 \end{pmatrix}$$



result = (rank(A)==3) ? "decodable" : "better choice next time”;

Network Coding: The Butterfly++



Deterministic Network Coding

Deterministic Network Coding refers to a specific method for network code design. I.e. exactly specifying how in-put data is mapped to output data for all nodes in a network. This is in contrast to Random Network Coding.

Advantages

- Coding coefficients are known and therefore not required to be explicitly communicated.

Drawbacks

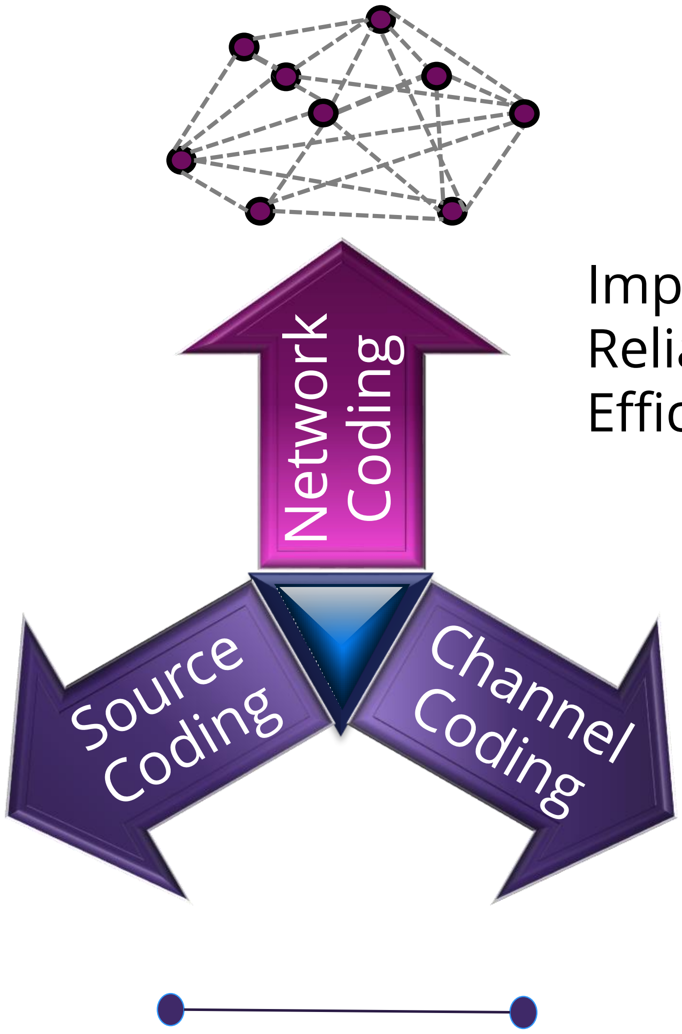
- Algorithms often require that the exact and full topology as input. → SDN
- Dynamic networks will require frequent updates, to reflect current state of the network.

Digital Inter-Flow Network Coding: The Basics

Lecture 2

Channel & Source Coding vs. Network Coding

Comparison of Coding Approaches

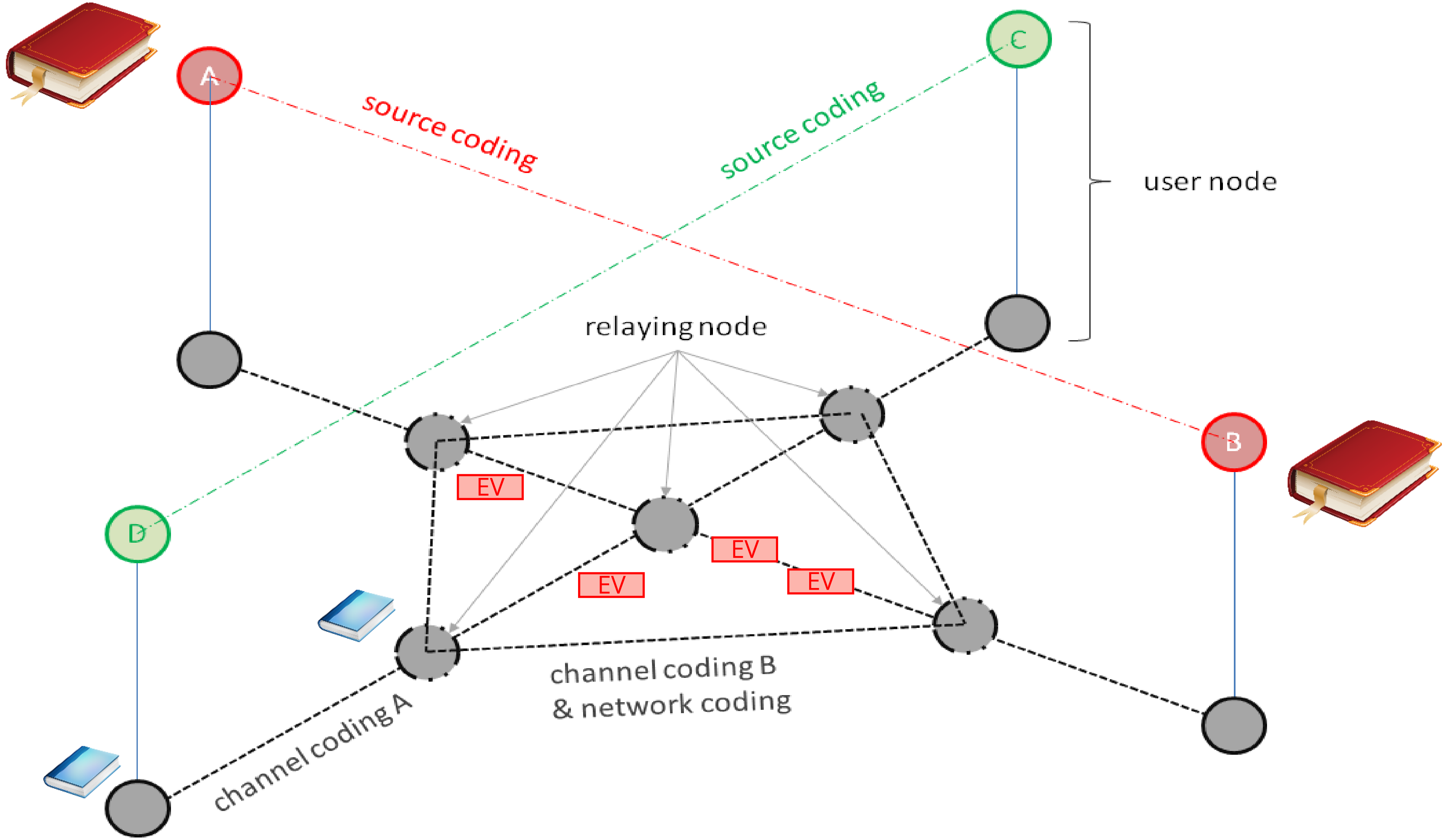


Improves ***Network*** Reliability, Security, and Efficiency

Removes Redundancy for Efficiency

Introduces Redundancy for Reliability

Comparison of Coding Approaches



Wireless Network Examples

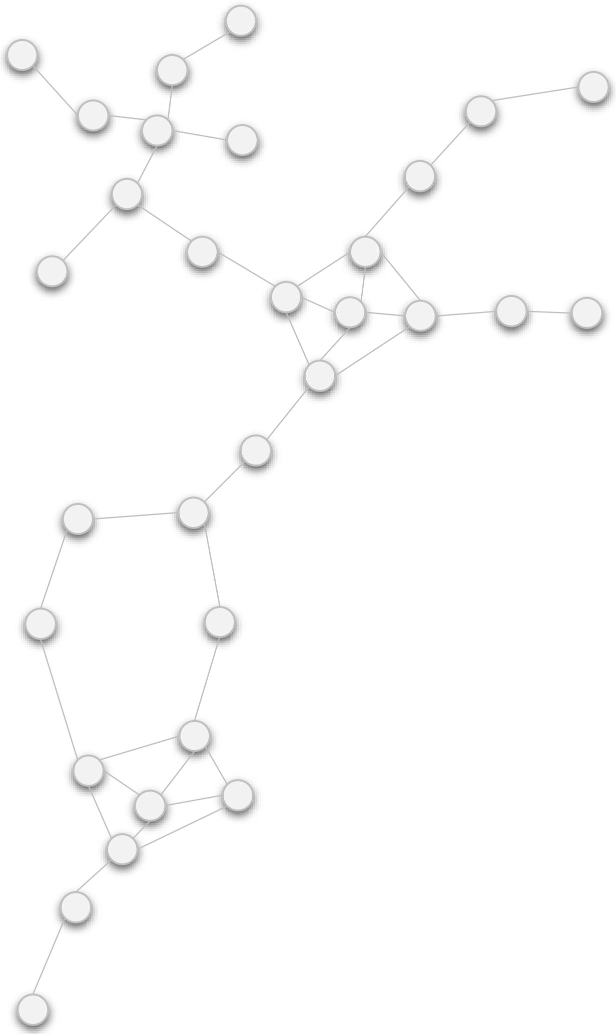
Exploiting the broadcast nature of the wireless medium

It is not about butterflies …

M. Medard and F.H.P. Fitzek and M.J. Montpetit and C. Rosenberg. Network coding mythbusting: why it is not about butterflies anymore. 2014. IEEE Communications Magazine, 52(7):177-183.

General Network Topologies and Sub-Nets

- Two way relay (Alice and Bob)
- Chain
- X- Topology
- Cross
- Cross with Overhearing



General Network Topologies and Sub-Nets

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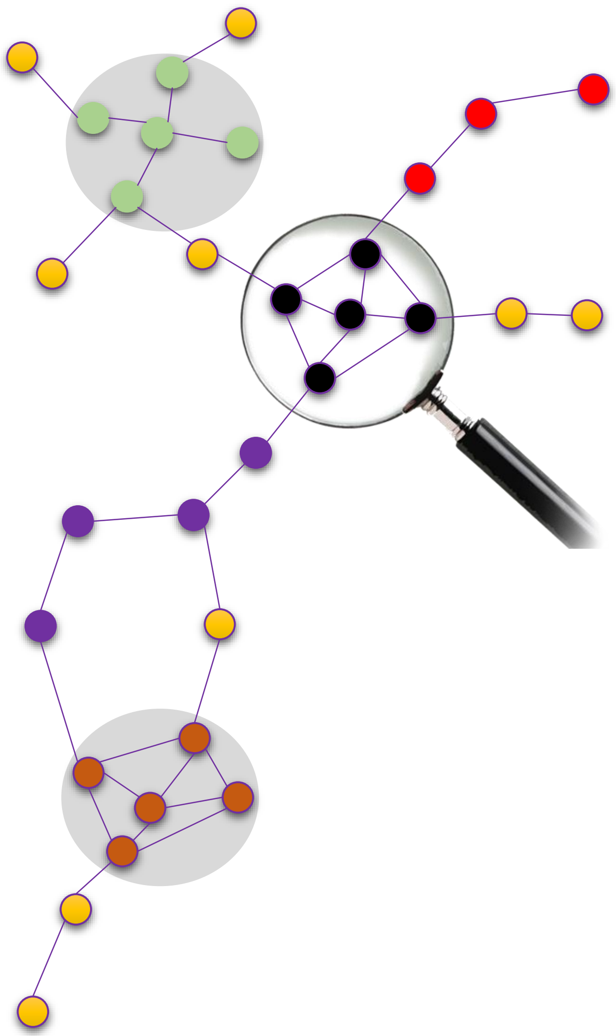
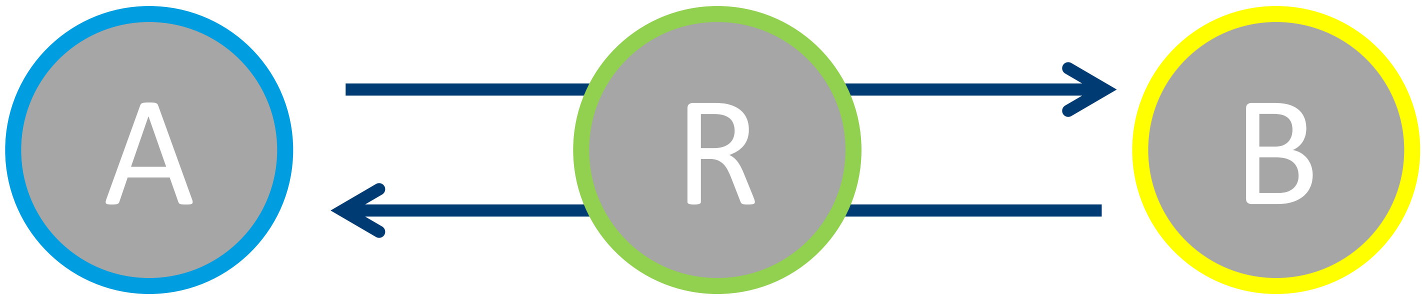


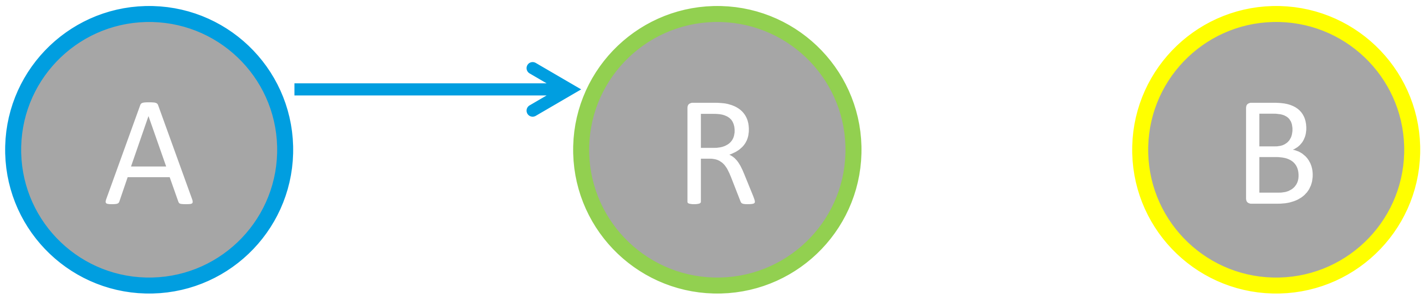
Alice and Bob –The two way relay

Early VTC paper by Ericsson

Alice and Bob



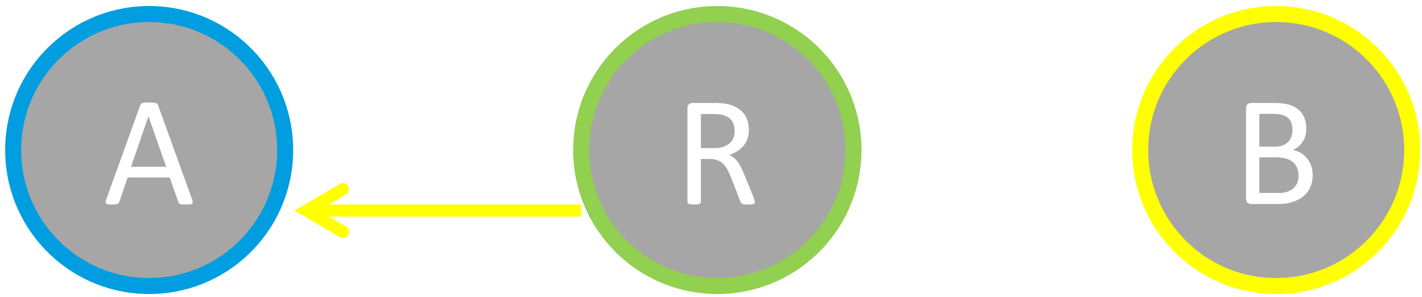
Alice and Bob: Forwarding



Alice and Bob: Forwarding

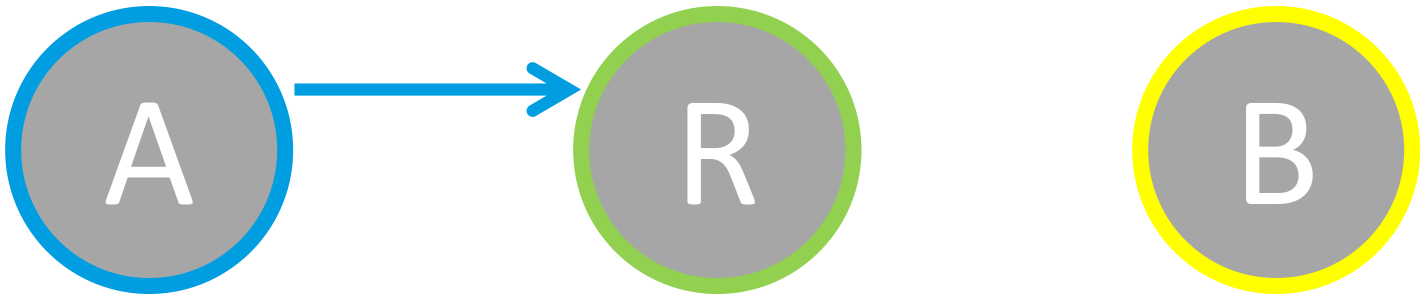
Alice and Bob: Forwarding

Alice and Bob: Forwarding



4 time slots for exchange

Alice and Bob: Network Coding



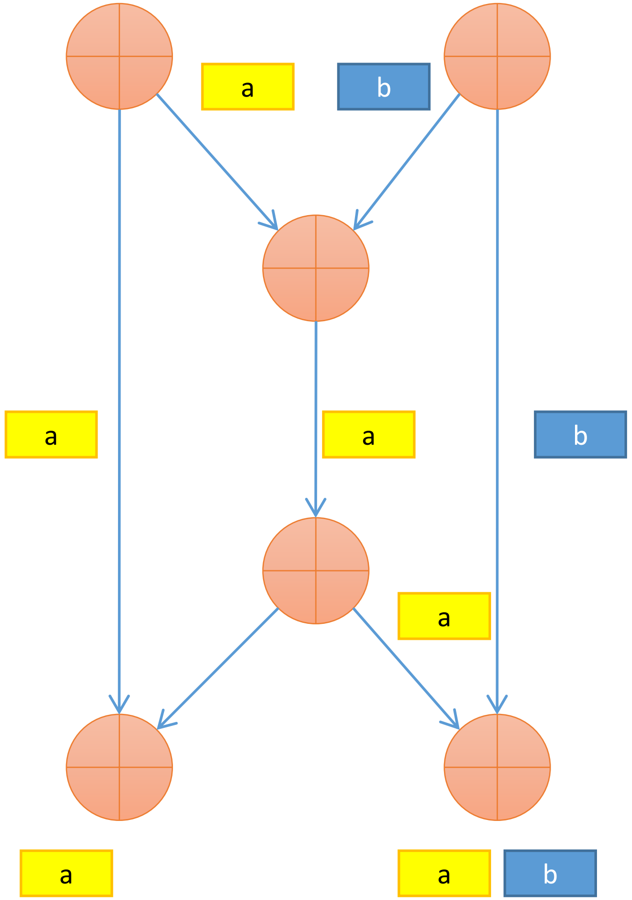
Alice and Bob: Network Coding

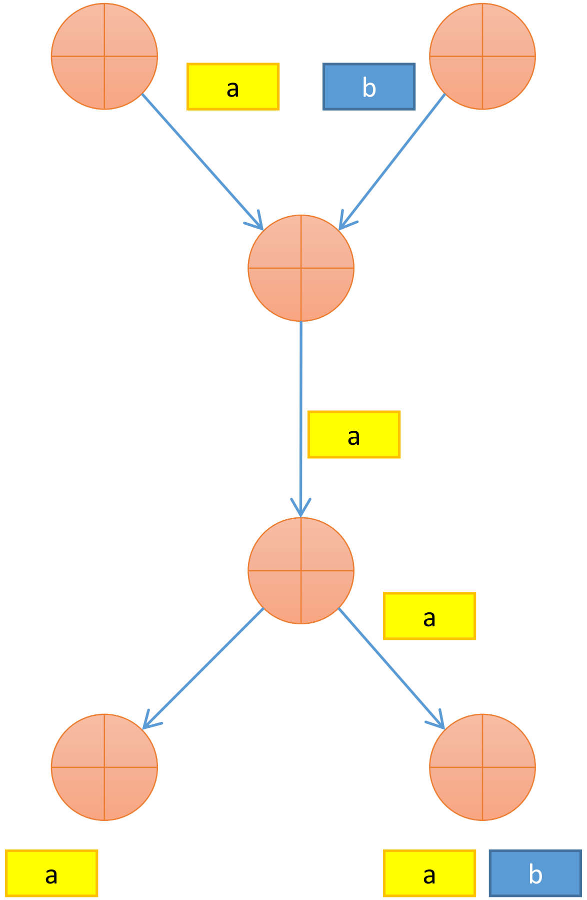
Alice and Bob: Network Coding

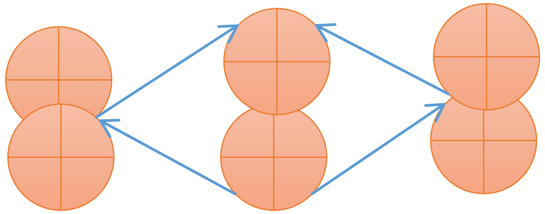
3 time slots for exchange

Gain = 33%

Two-Way Relay (Alice and Bob) vs. Butterfly







Network Coding: Magic XOR

M.V. Pedersen and F.H.P. Fitzek and T. Larsen. **Implementation and Performance Evaluation of Network Coding for Cooperative Mobile Devices.** 2008. in *IEEE International Conference on Communications (ICC 2008) - CoCoNet Workshop*.

Alice and Bob: Symbian60

Our starting point

Simple scenario

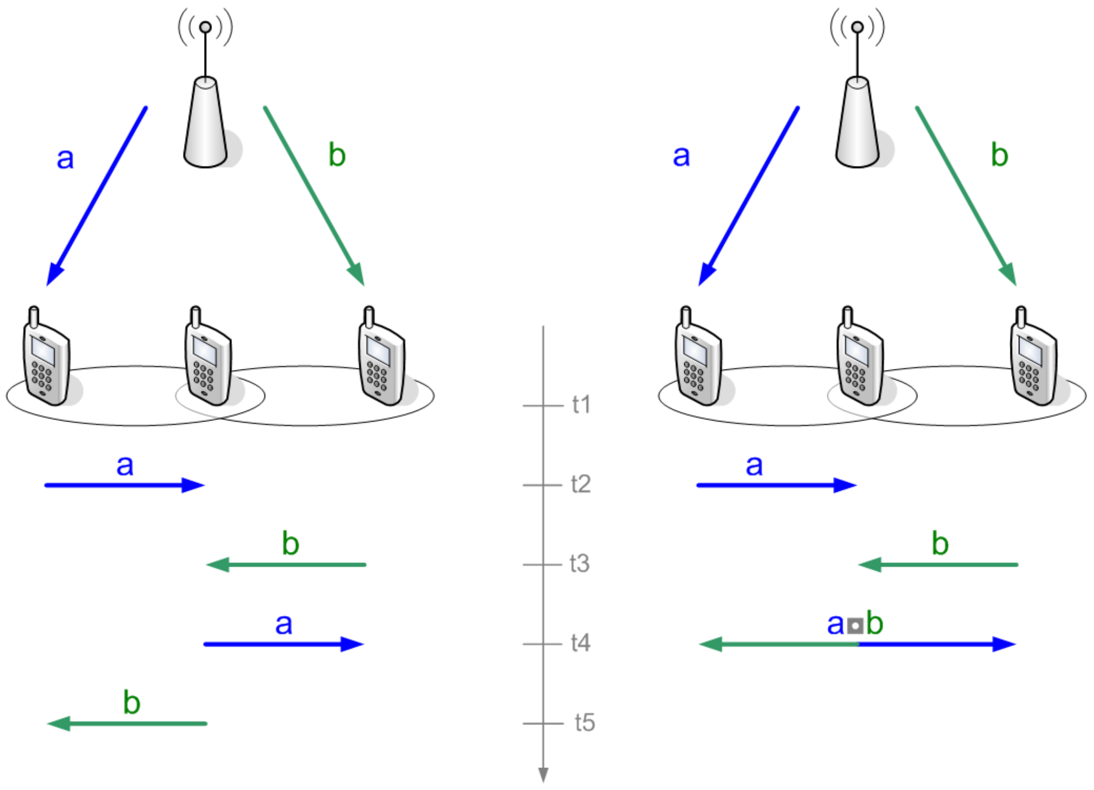
Seeding of packet a and b is crucial

- Fairness
- Performance

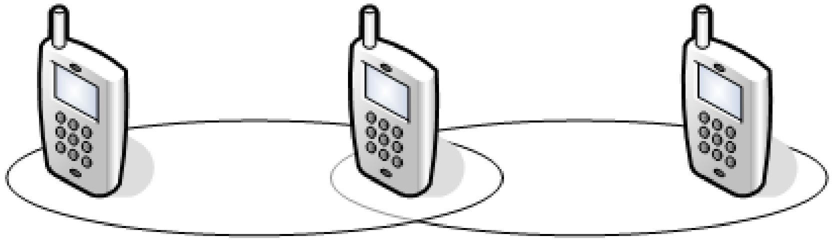
Forms of NC

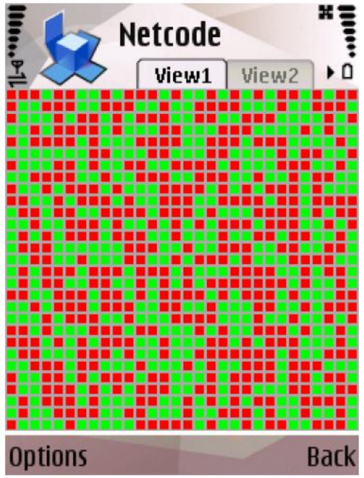
- XOR in the air (COPE)

Implementation on S60

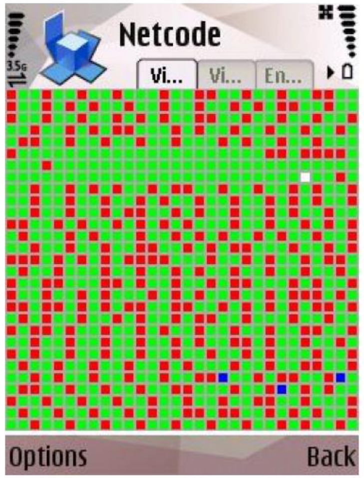


Alice and Bob: Symbian60



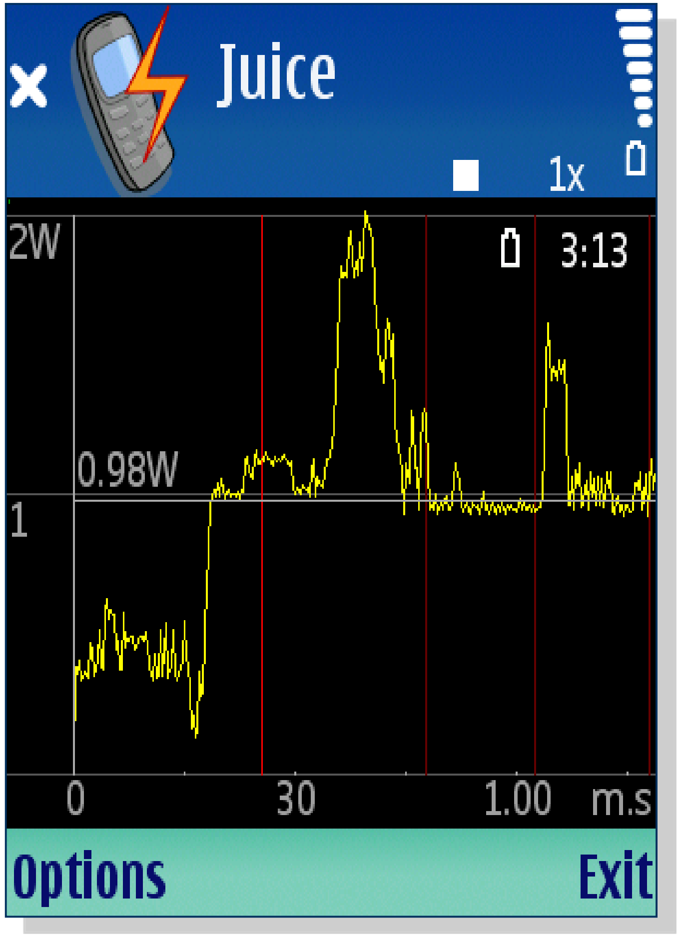


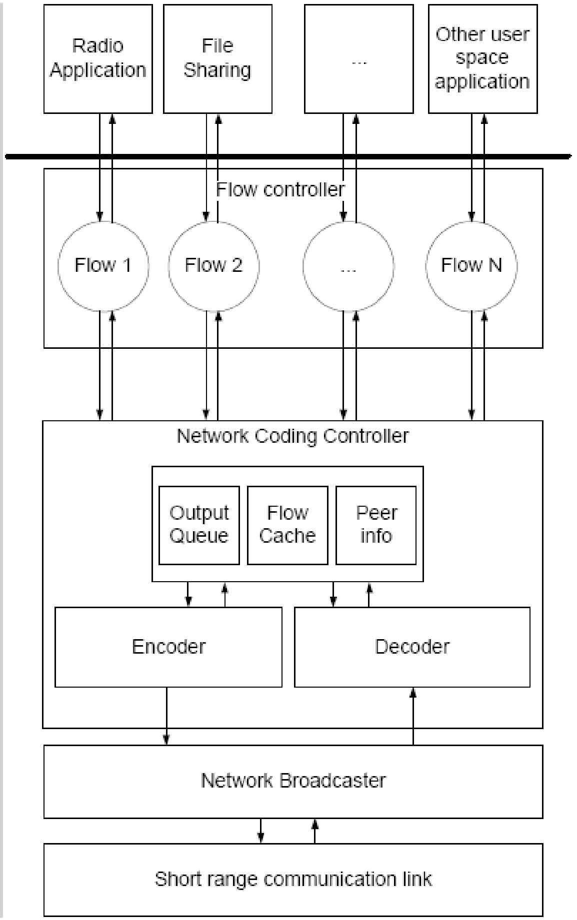
(a)



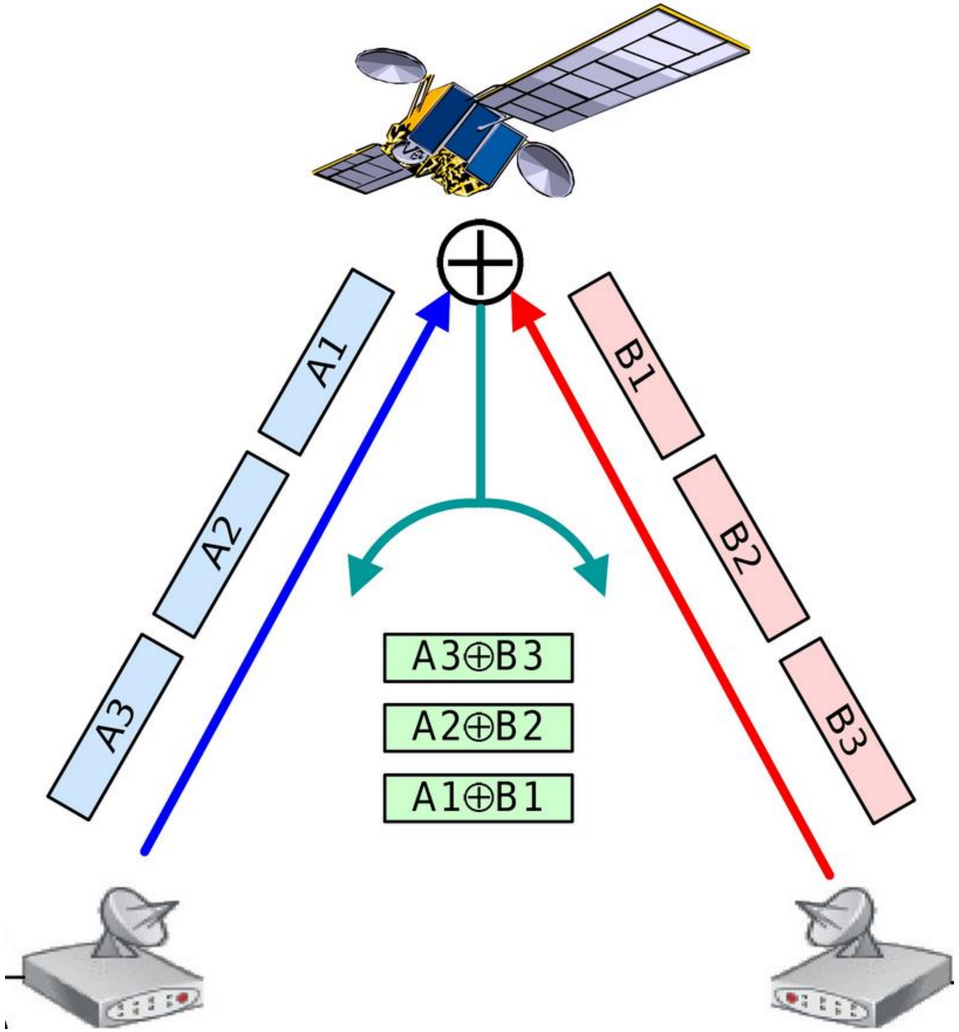
(b)

Lessons learned: It is important to create coding potential!





Alice and Bob: Satellite Communication



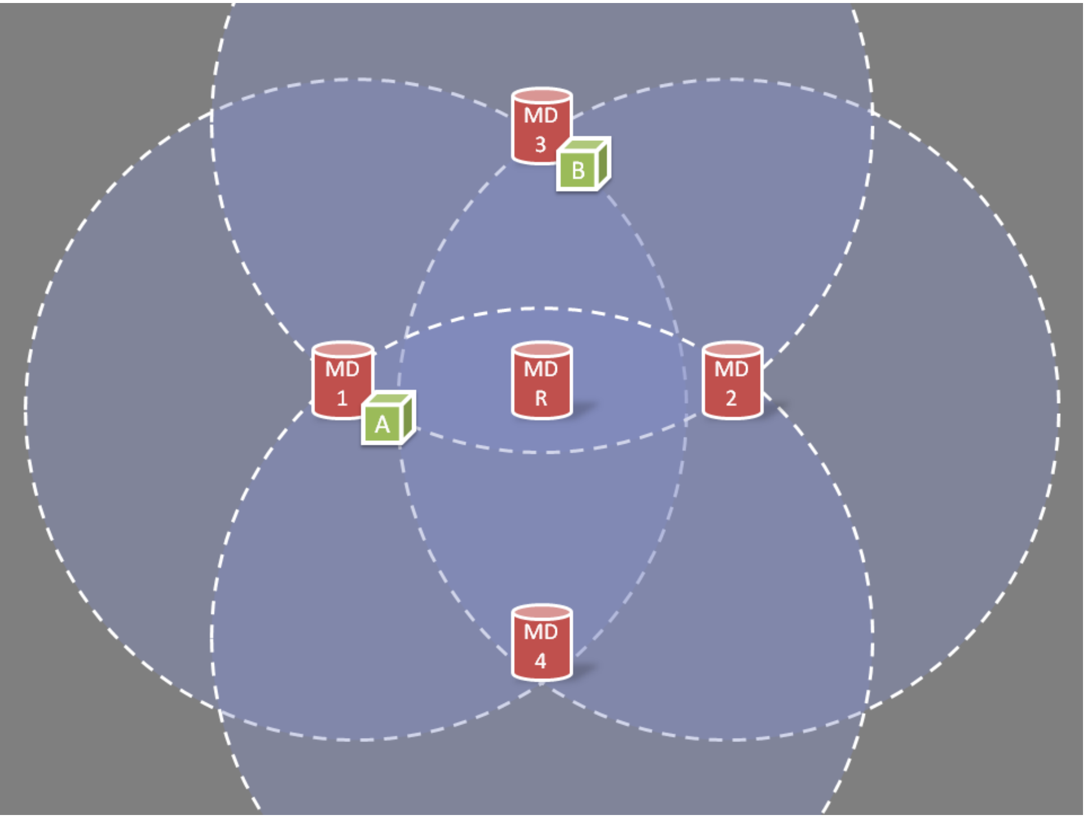
http://www.dlr.de/kn/Portaldata/27/Resources/images/projekte/NEXT-Network_coded_interconnection_of_computer_networks_via_satellite.jpg

The X-Topology

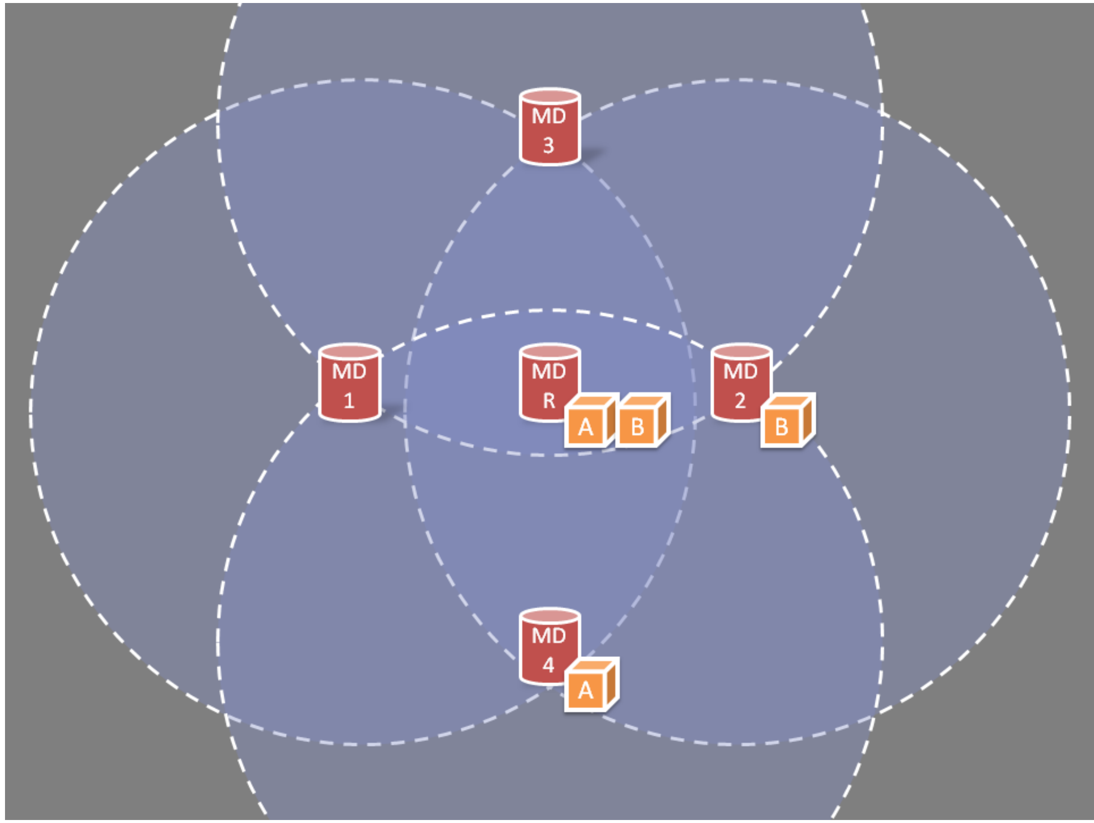
Introducing the concept of overhearing

X Topology with Overhearing

Start

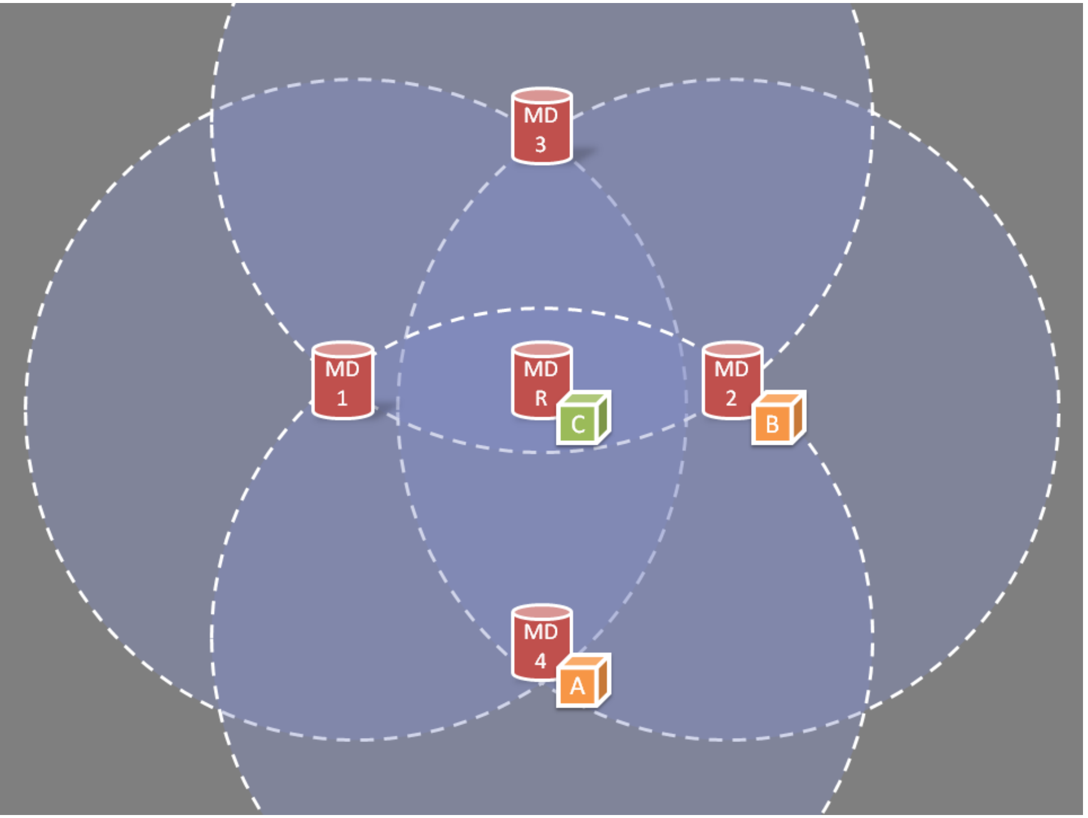


Broadcast

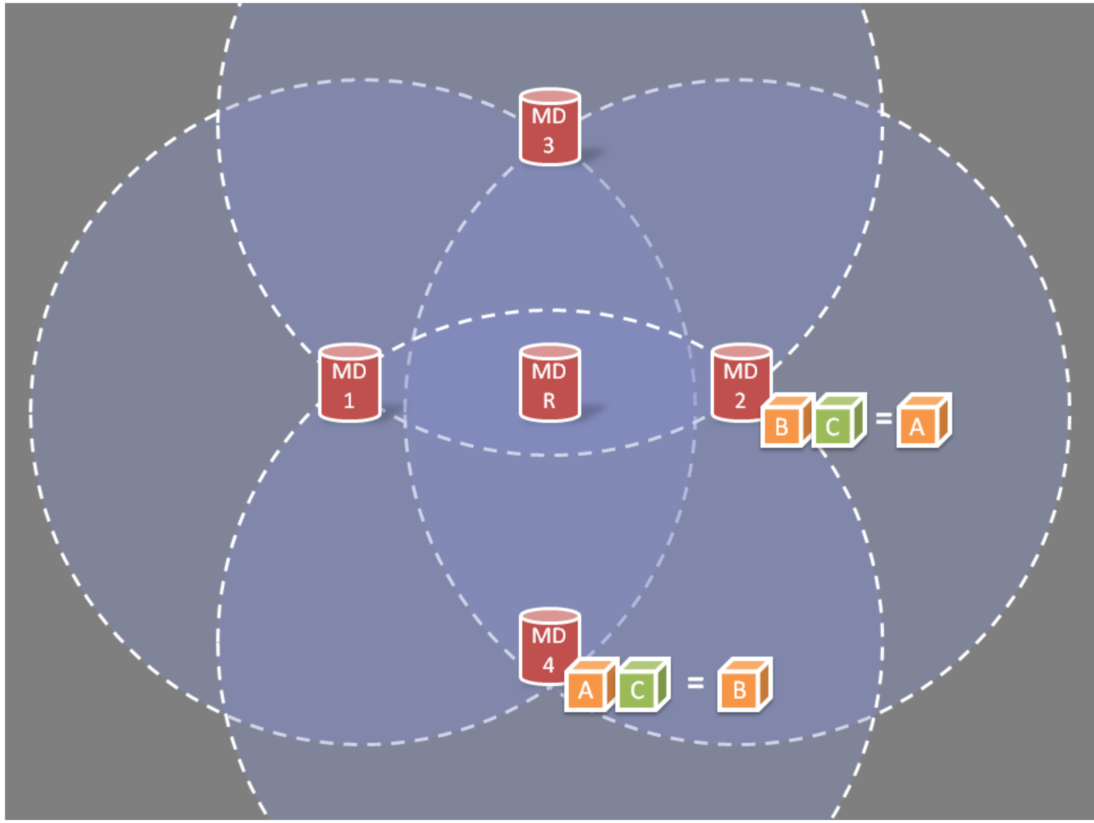


X Topology with Overhearing

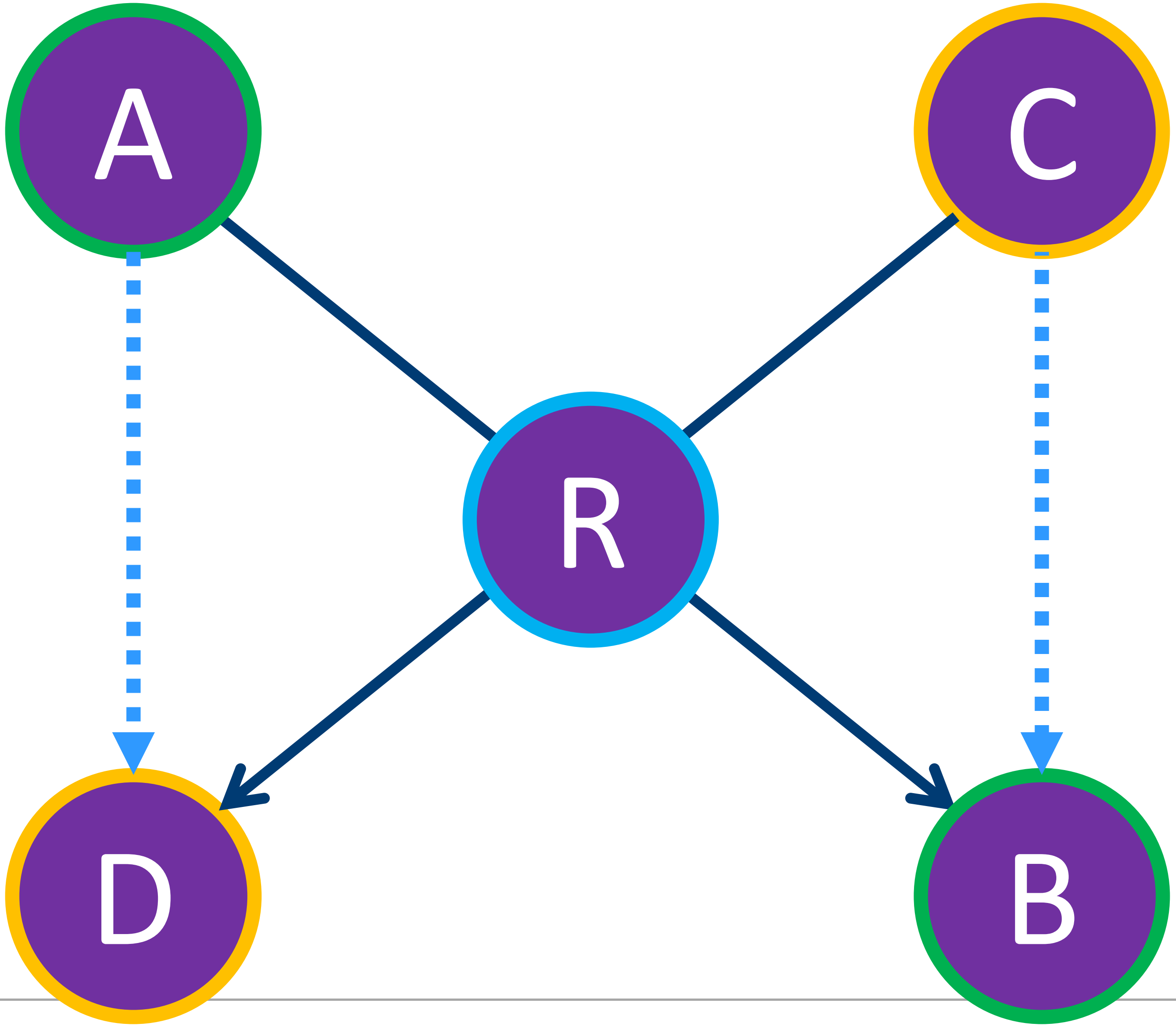
Coding @ relay



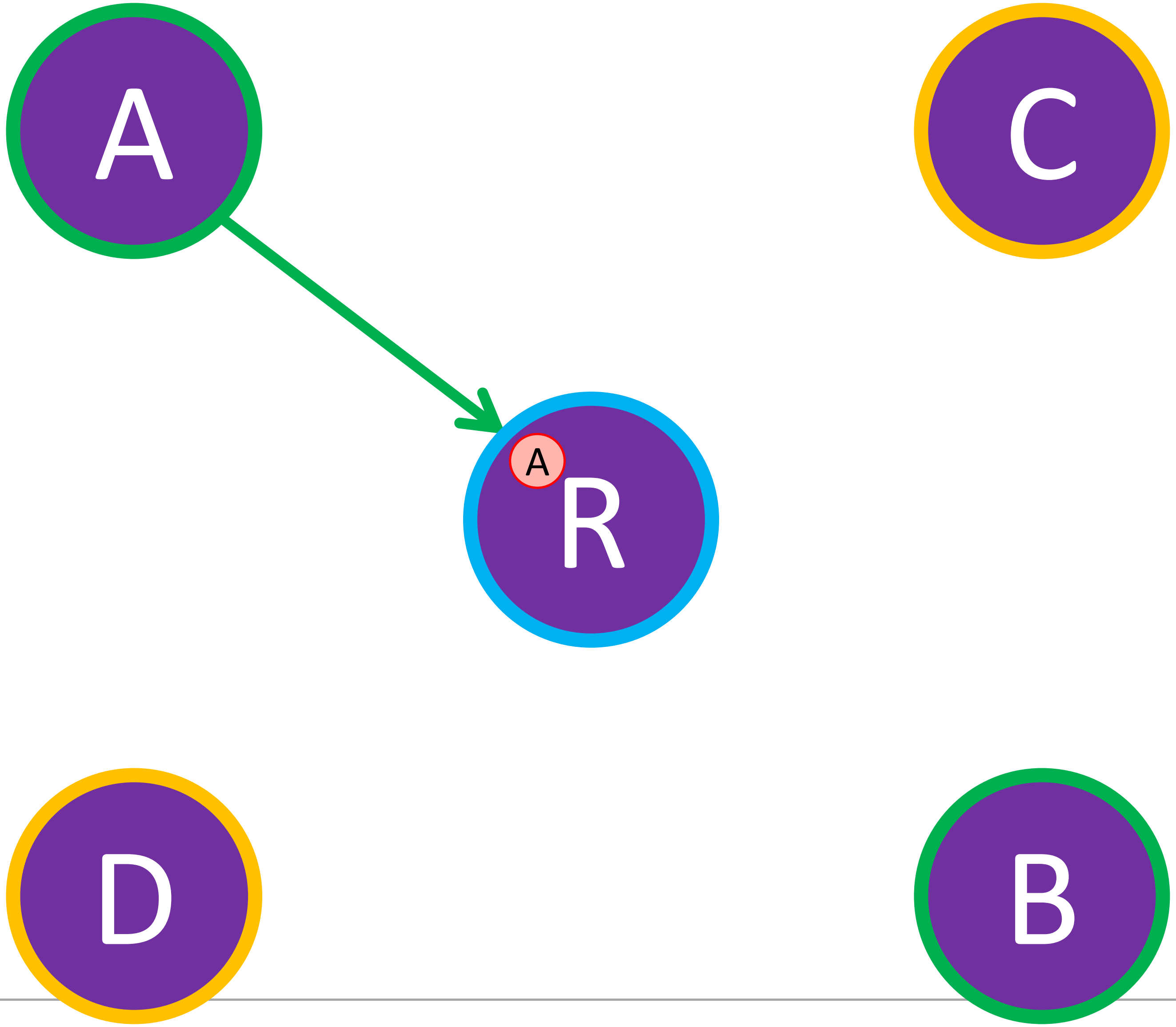
Decoding at receiver



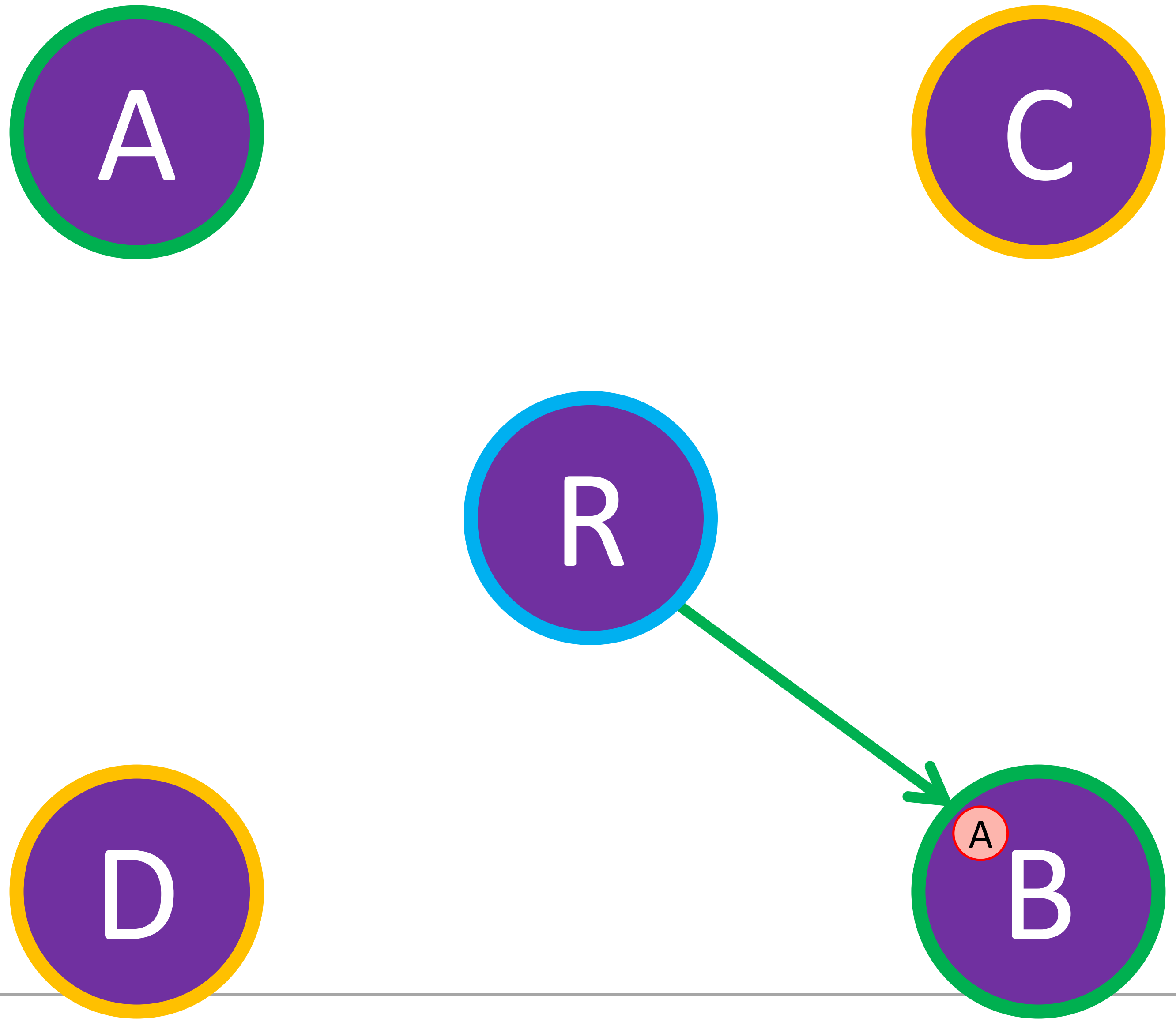
X Topology with Overhearing



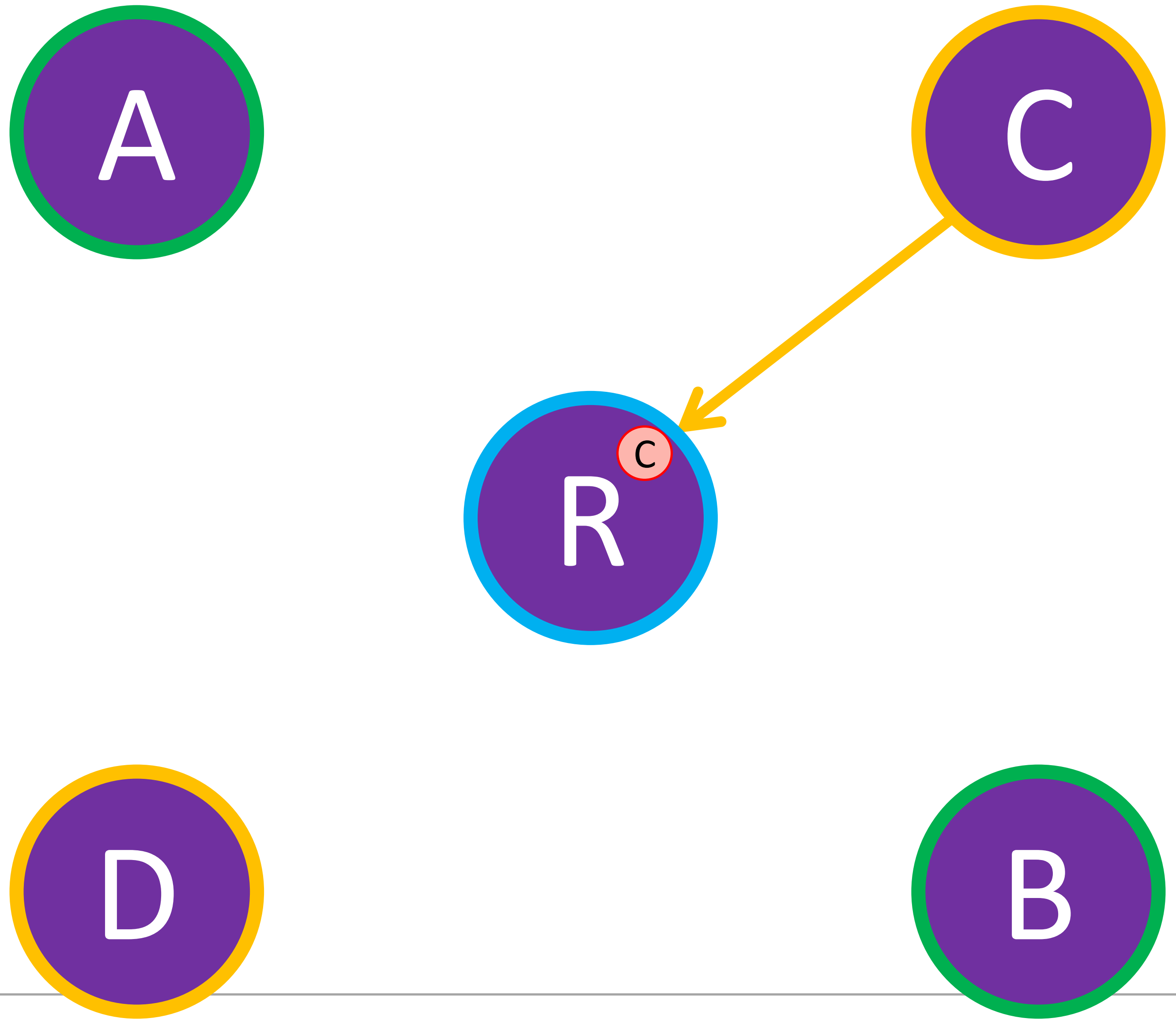
X Topology: SoA



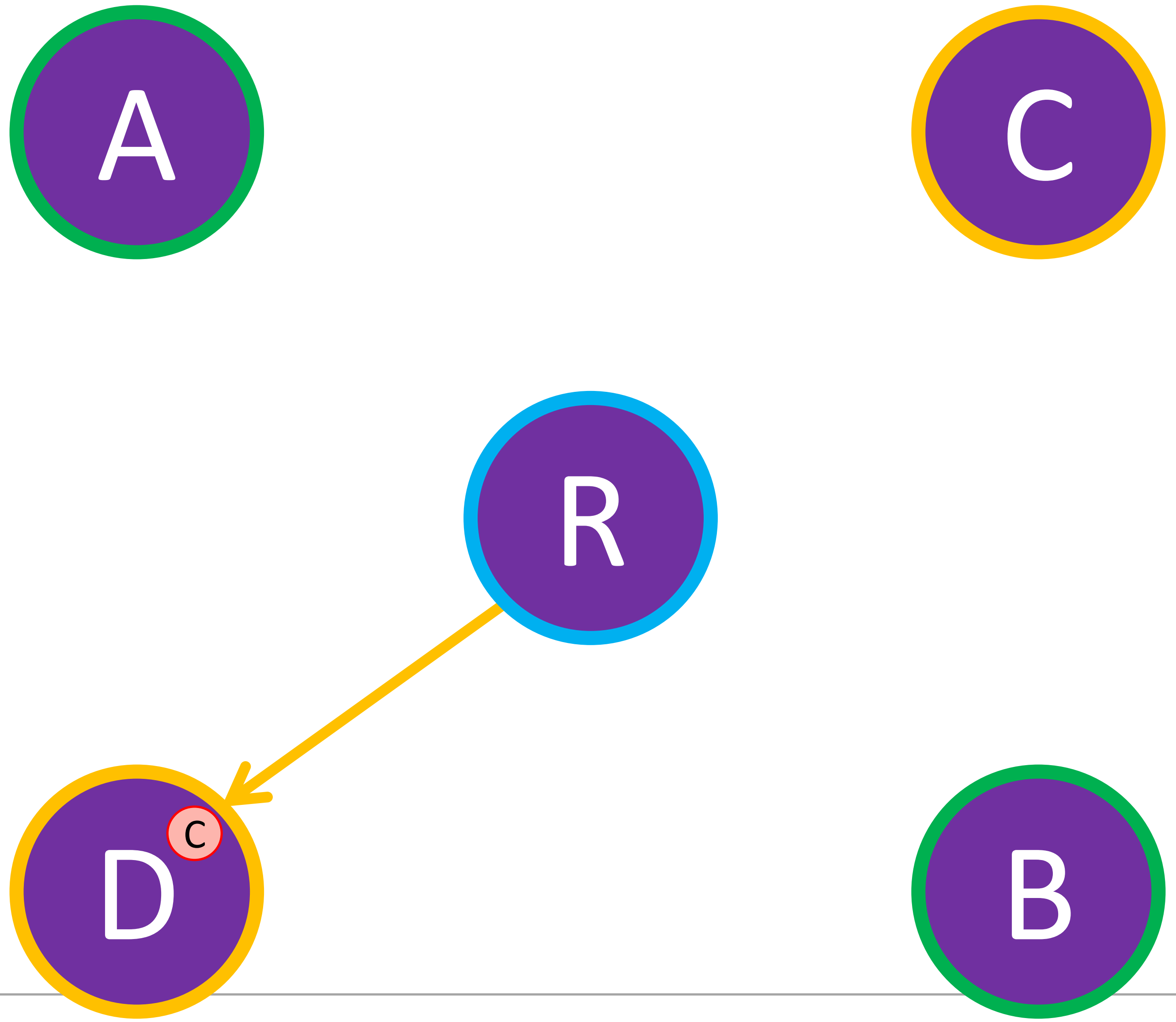
X Topology: SoA



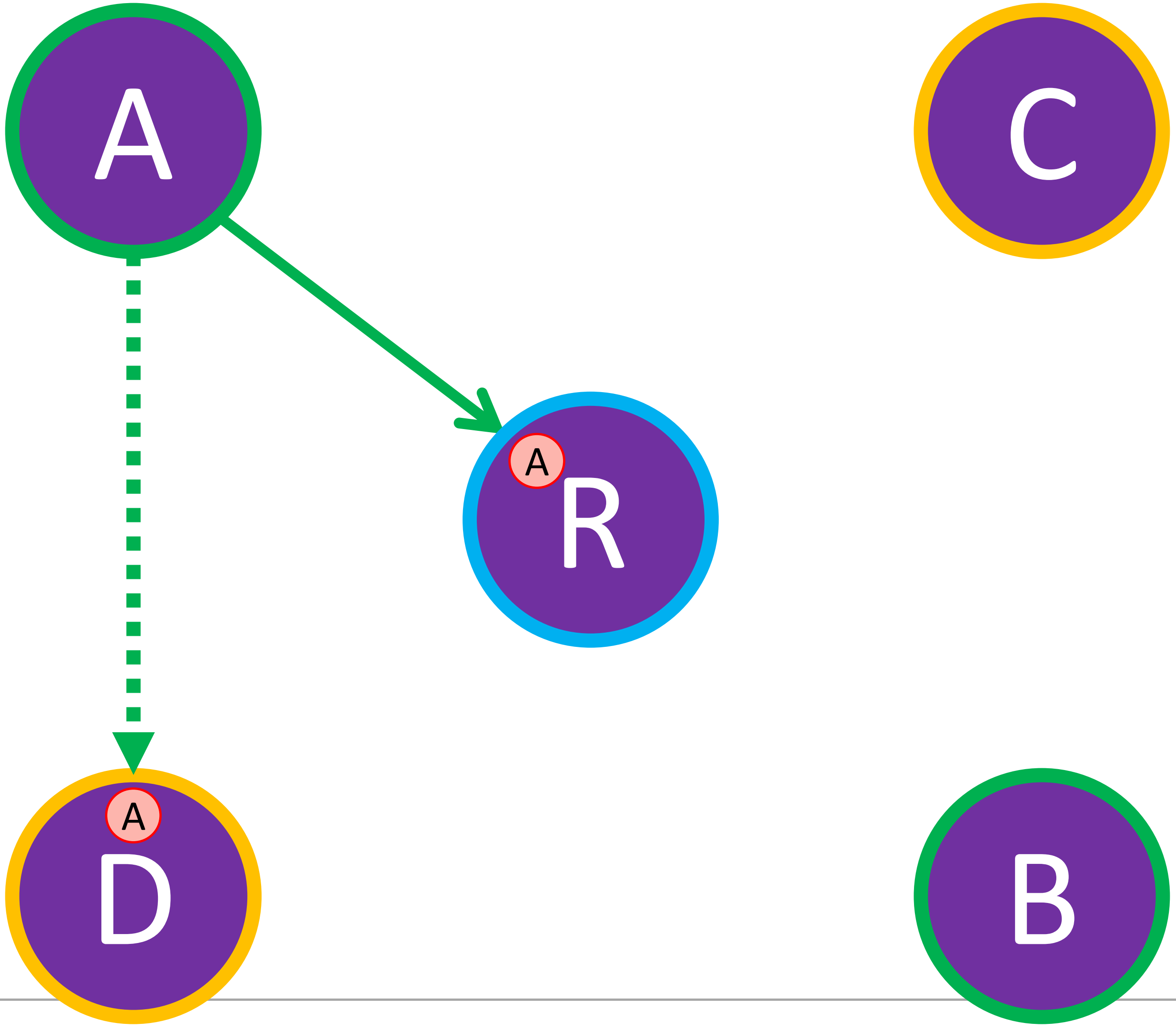
X Topology: SoA



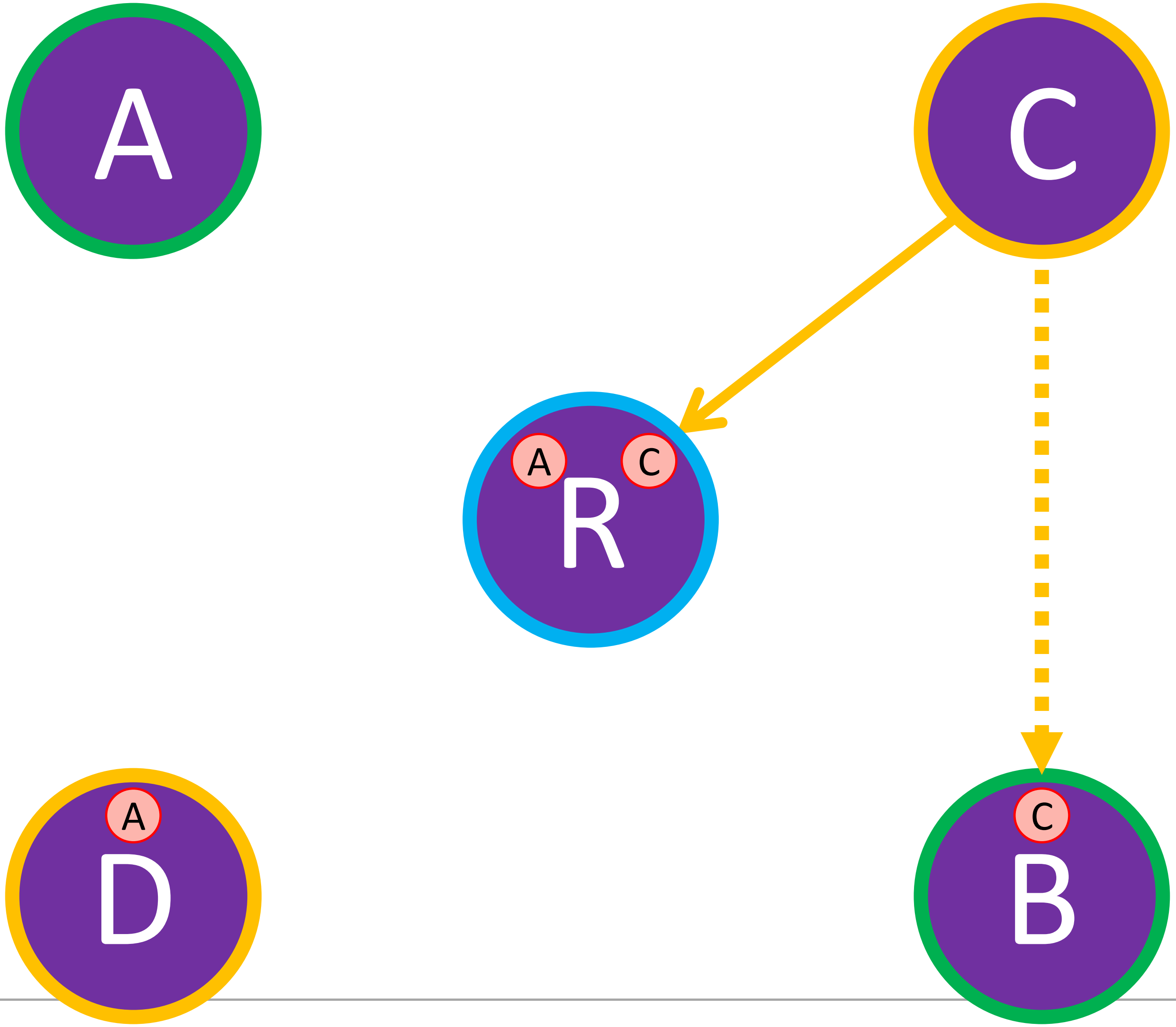
X Topology: SoA



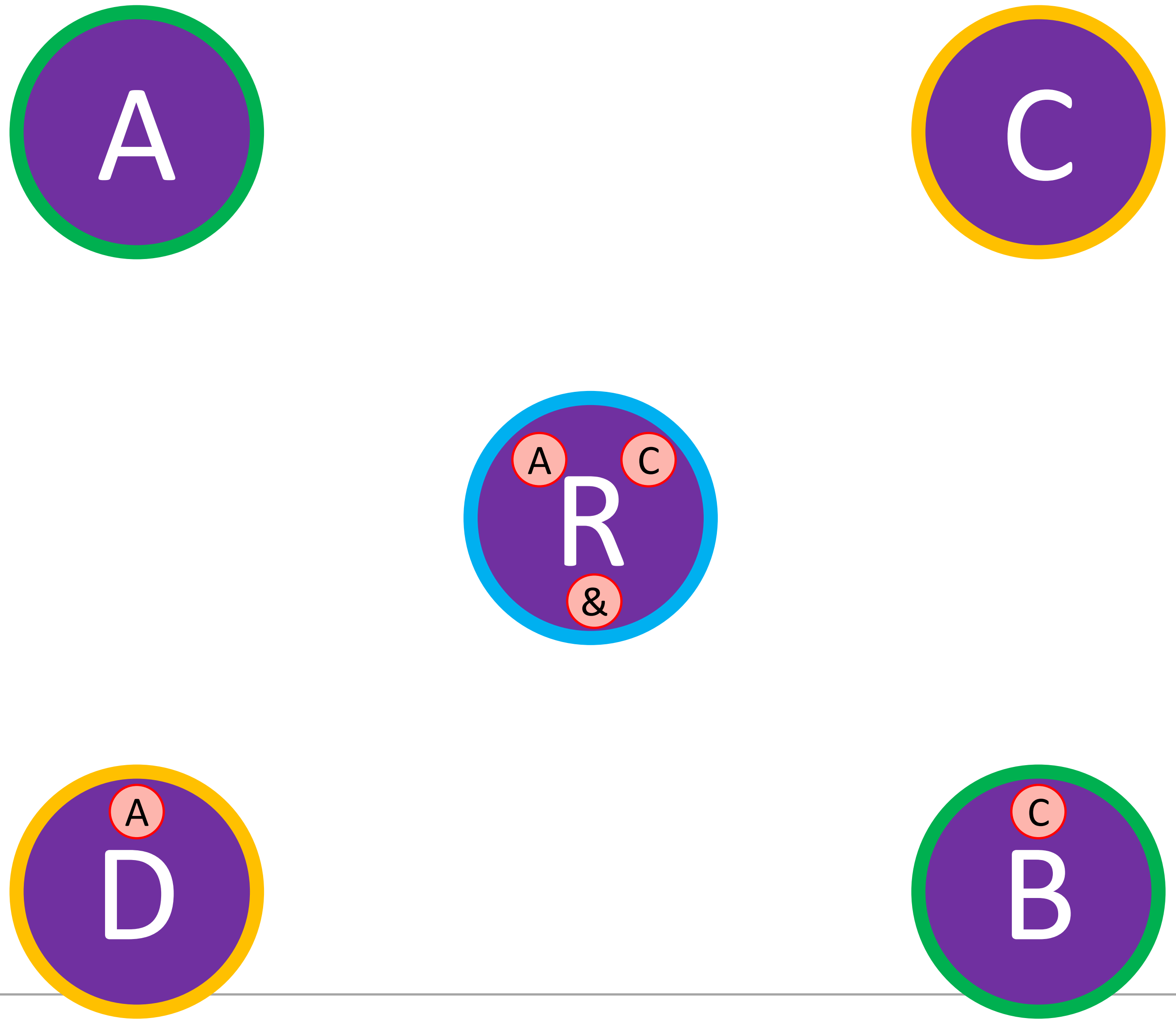
X Topology with Overhearing



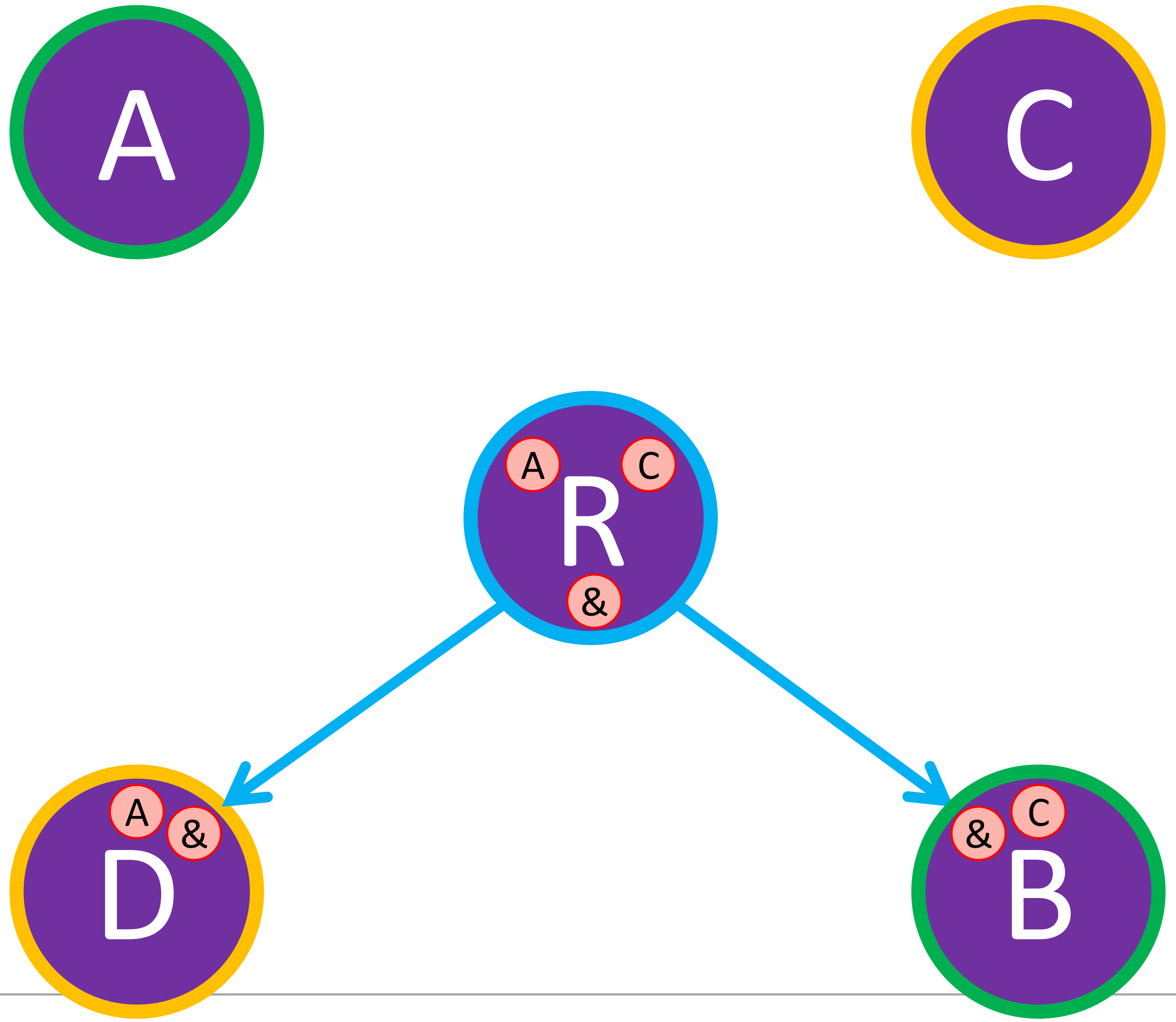
X Topology with Overhearing



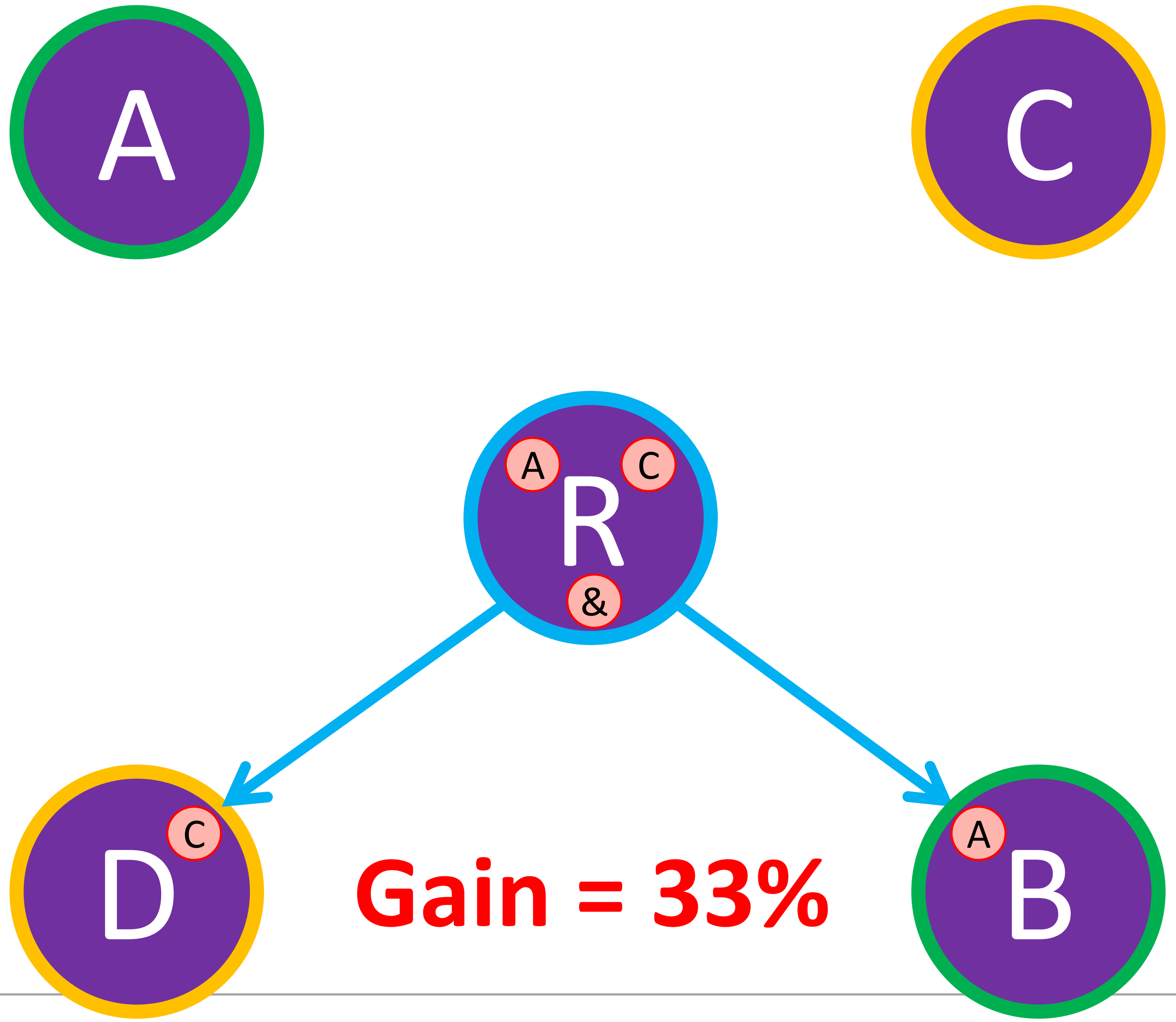
X Topology with Overhearing



X Topology with Overhearing

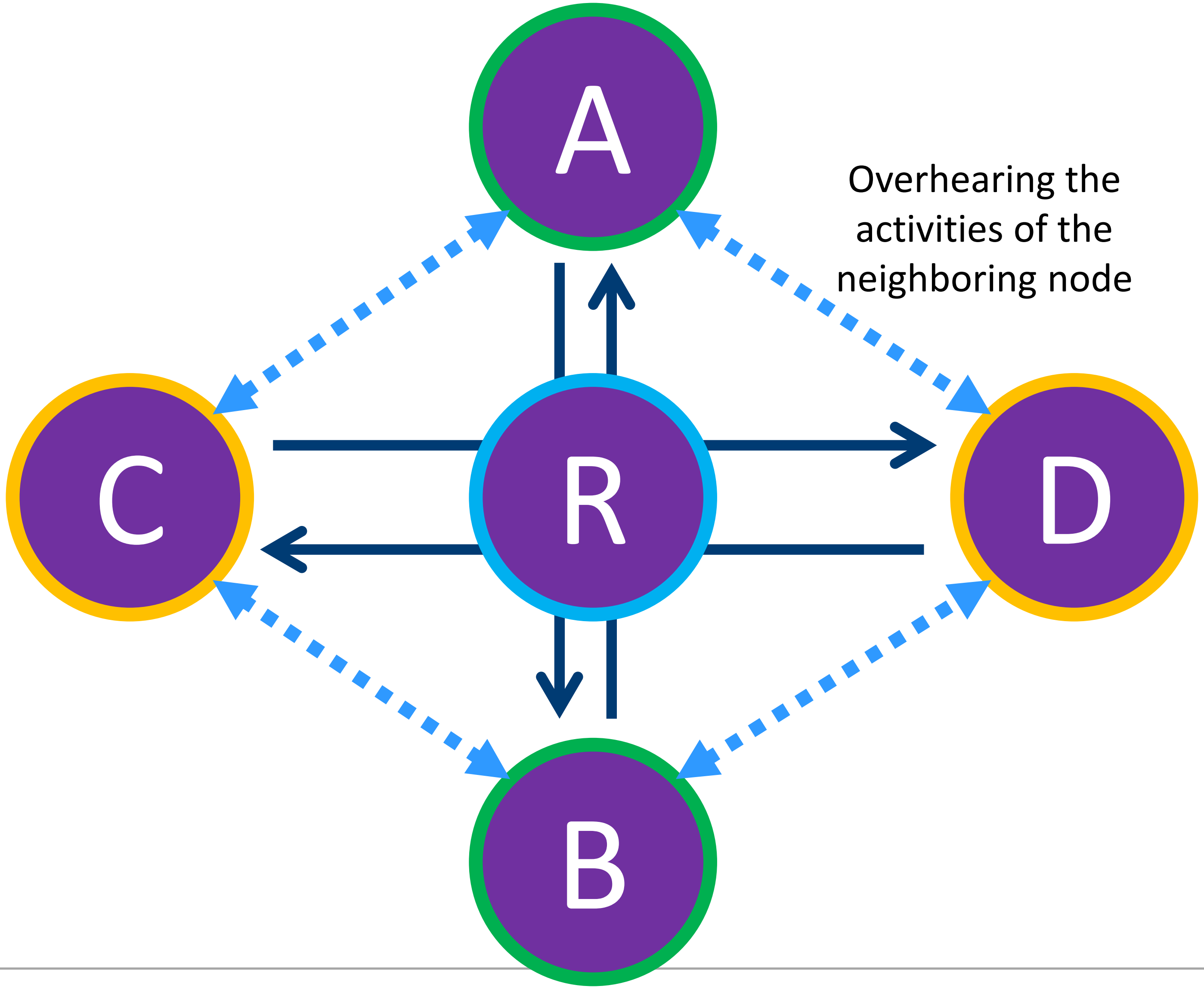


X Topology with Overhearing

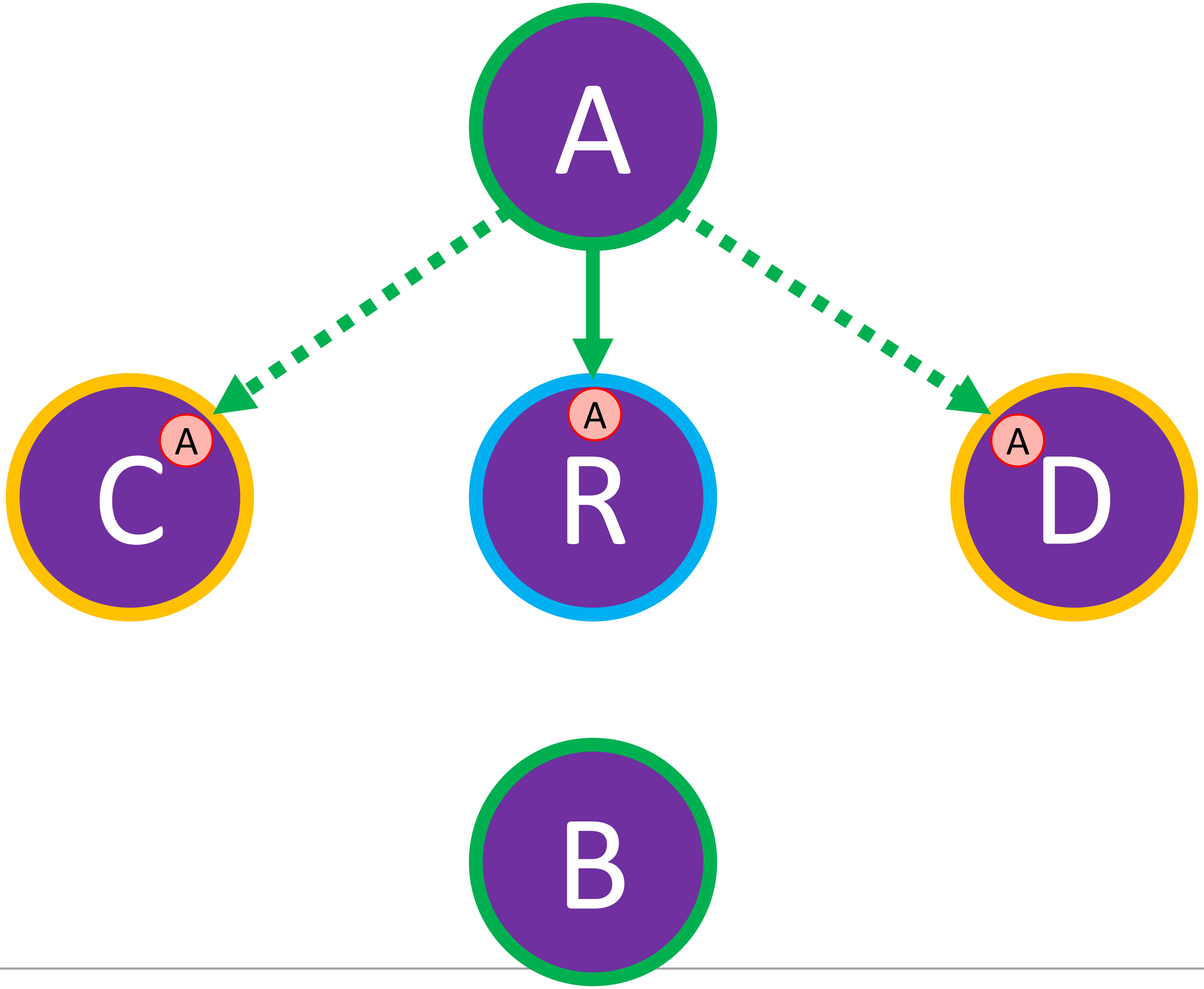


The Cross Topology

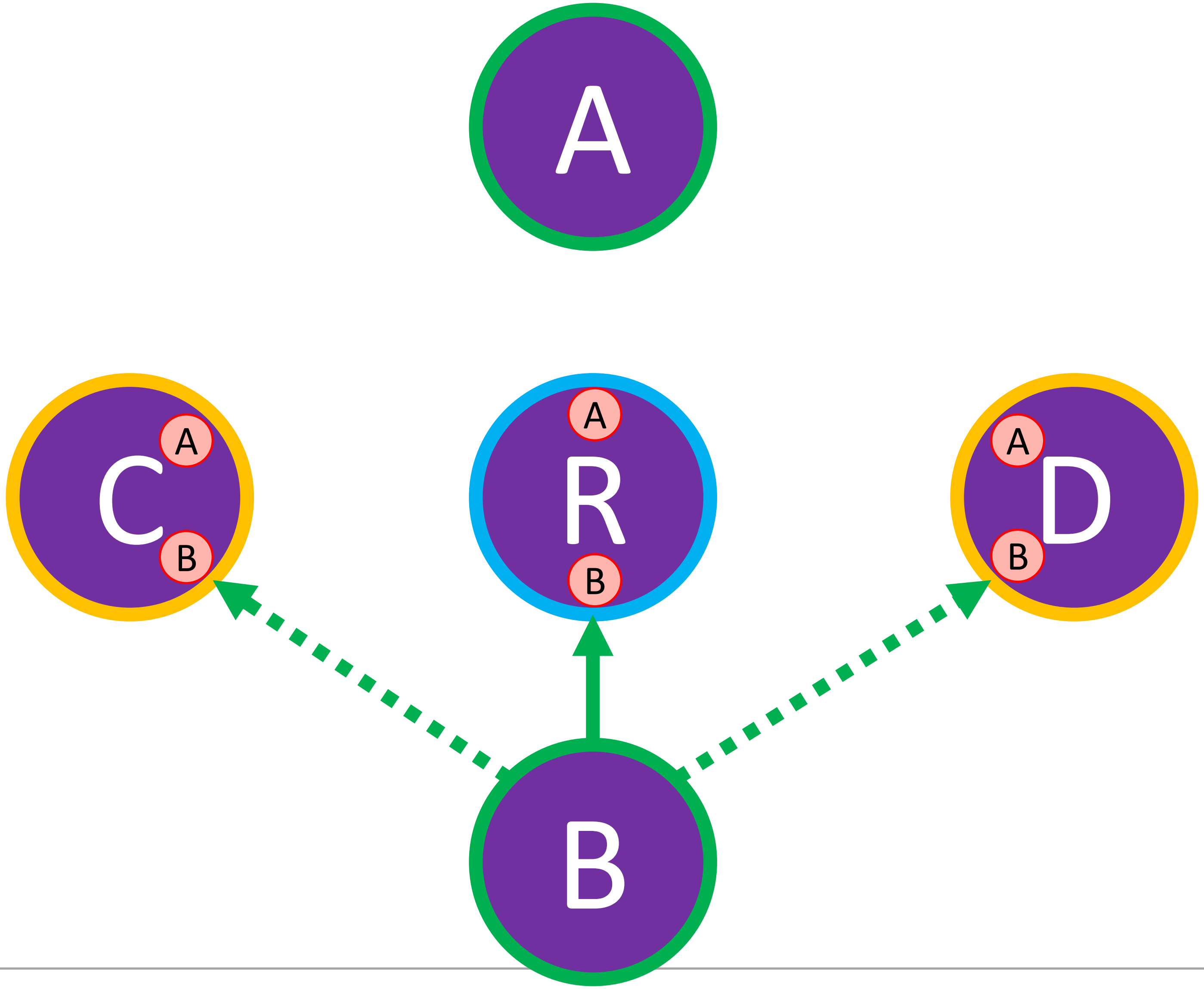
Cross Topology with Overhearing



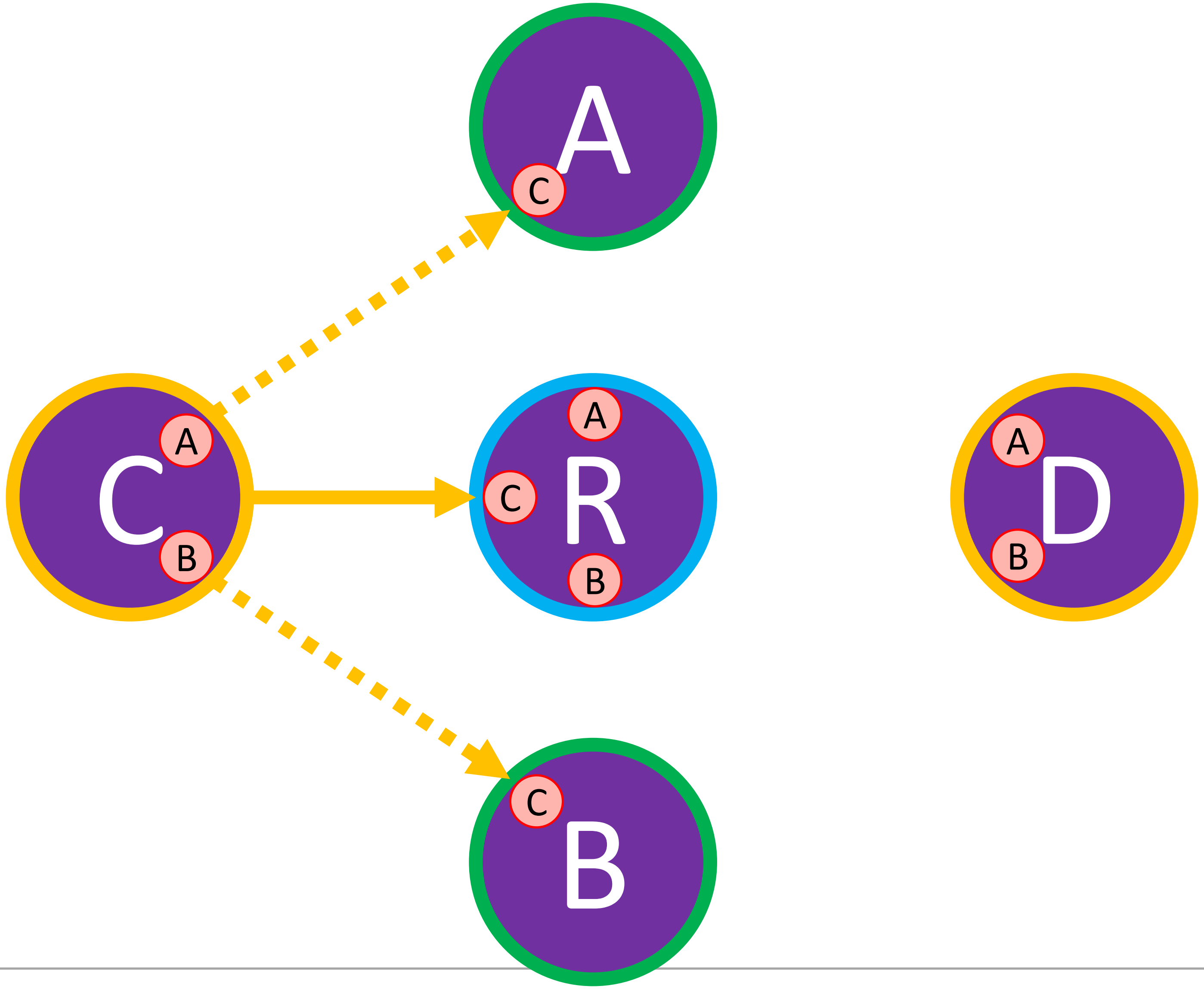
Cross Topology with Overhearing 1/5



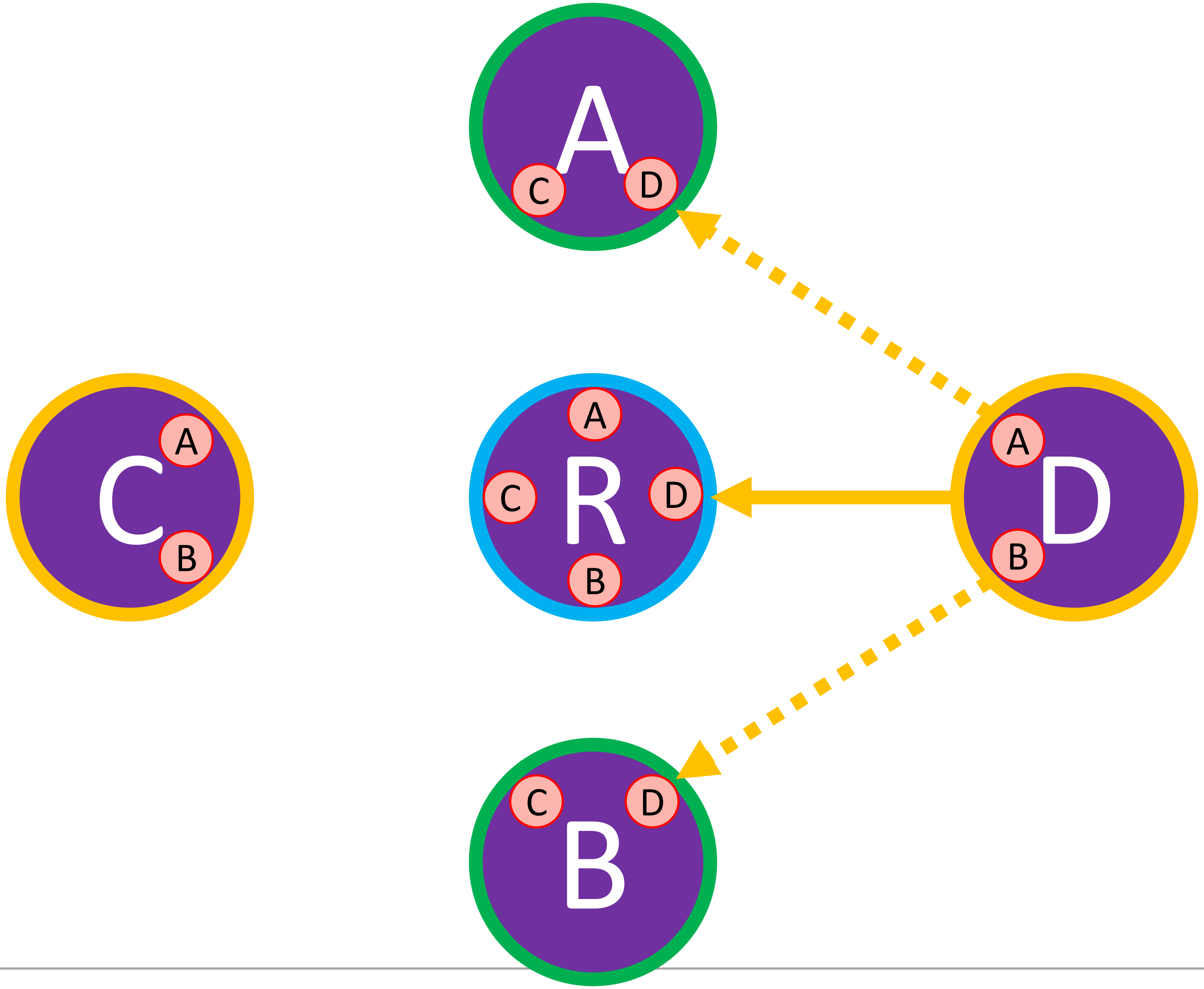
Cross Topology with Overhearing 2/5



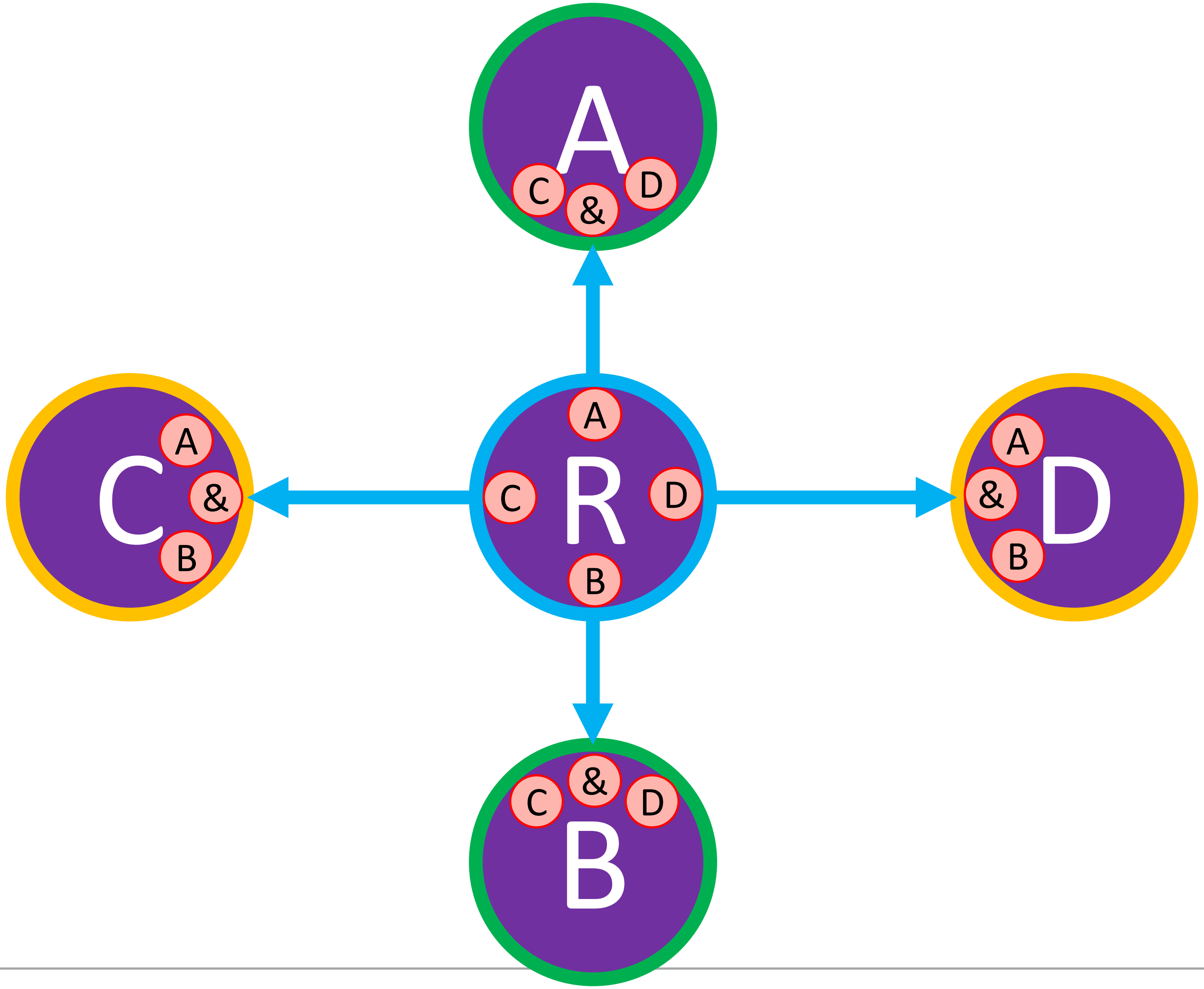
Cross Topology with Overhearing 3/5



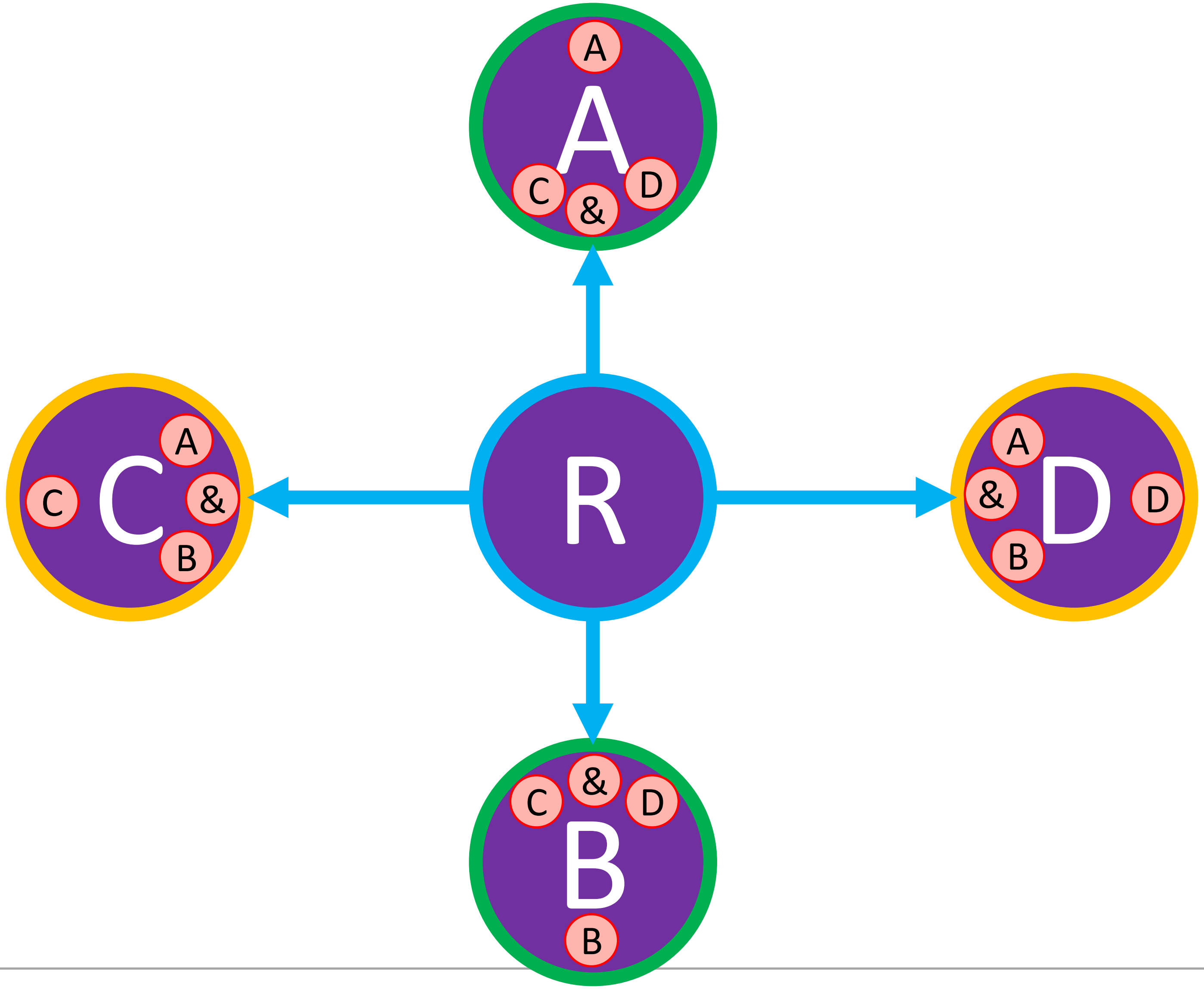
Cross Topology with Overhearing 4/5



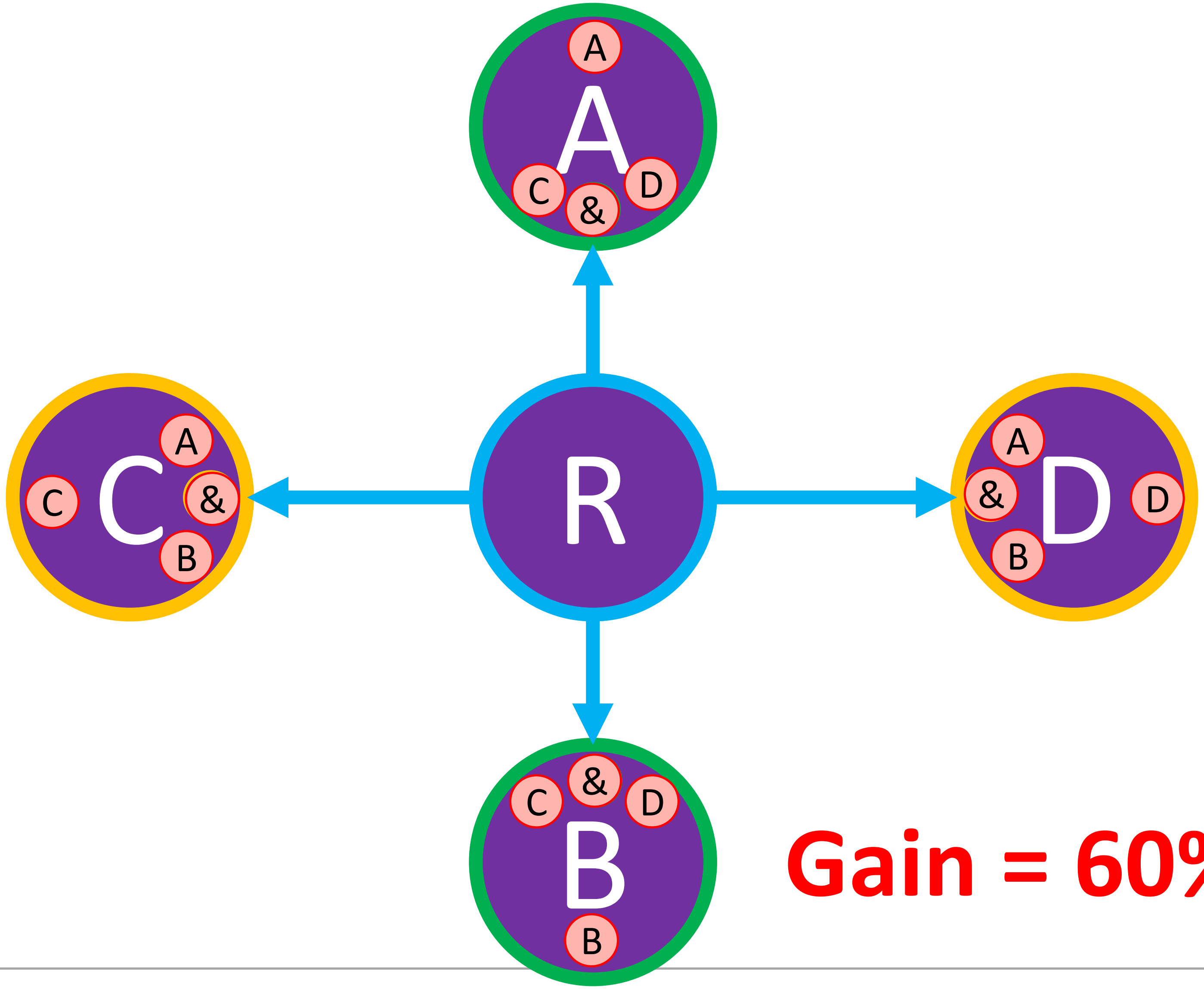
Cross Topology with Overhearing 5/5



Cross Topology with Overhearing 1/2

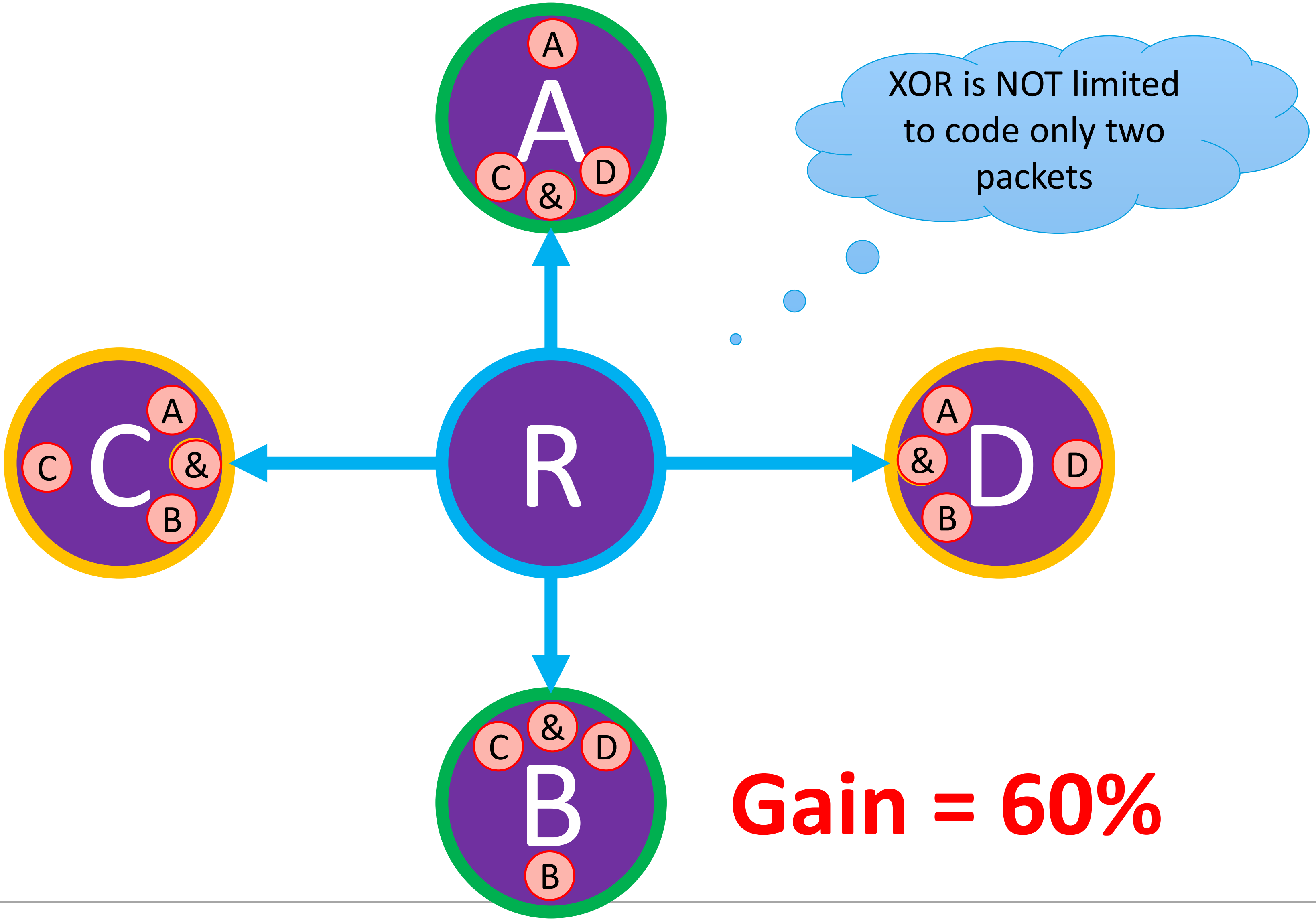


Cross Topology with Overhearing 2/2



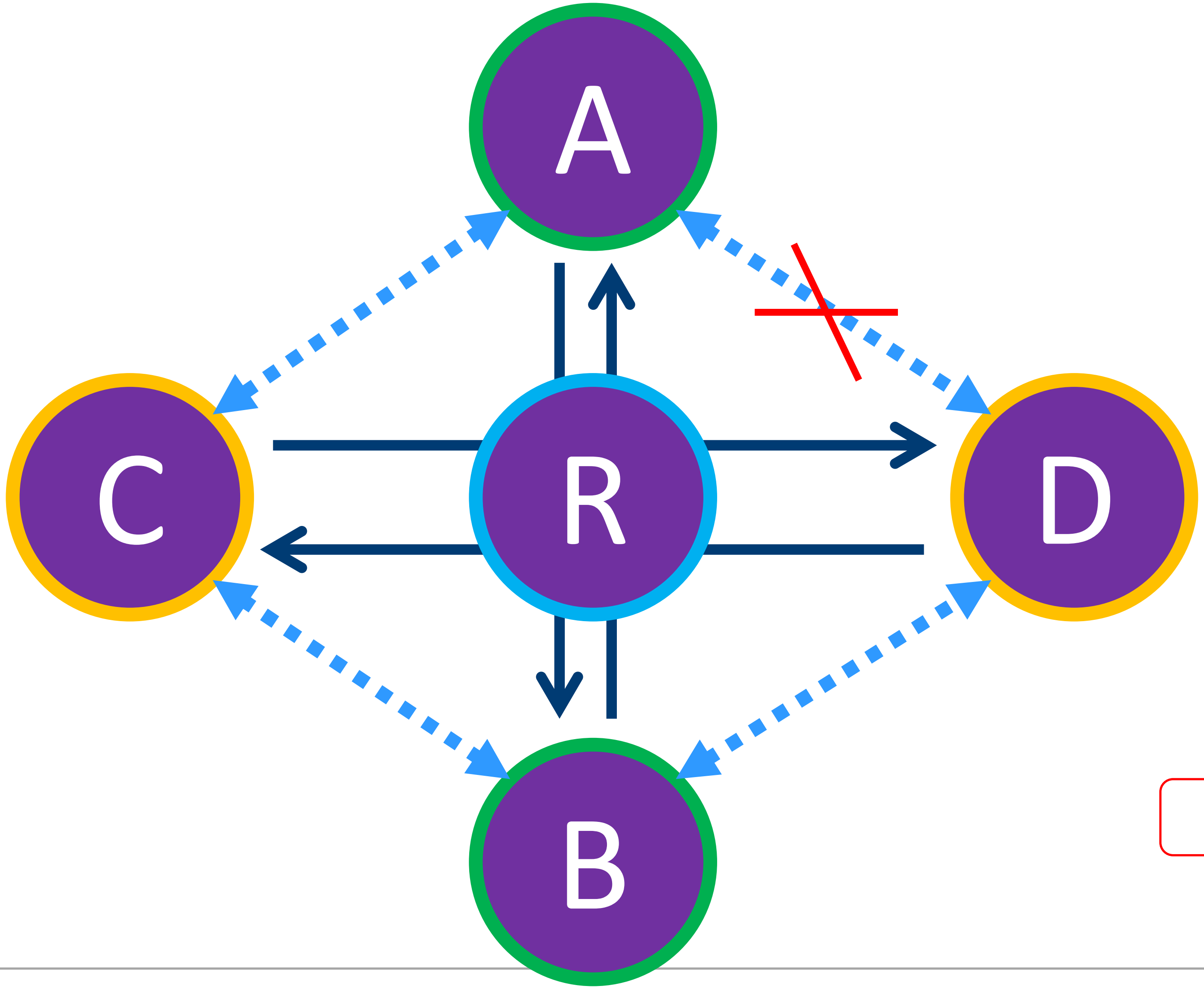
Gain = 60%

Cross Topology with Overhearing 2/2



Gain = 60%

Cross Topology with Overhearing Problems



Hint: CORE protocol

Inter Flow Network Coding

- No delay
- Low complexity
- Easy integration with commercial solutions

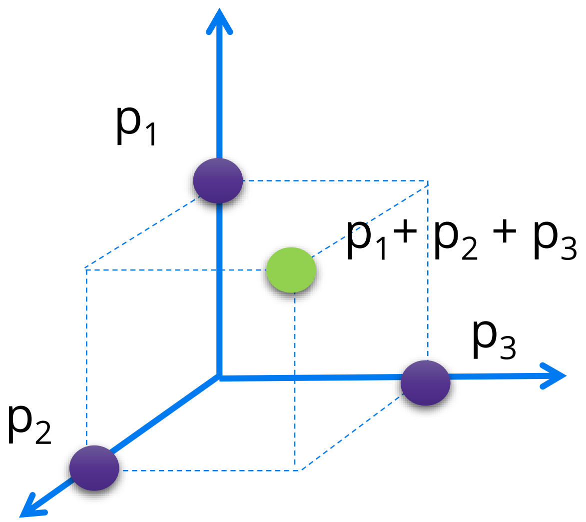
- Some ideas are used in ANALOG network coding

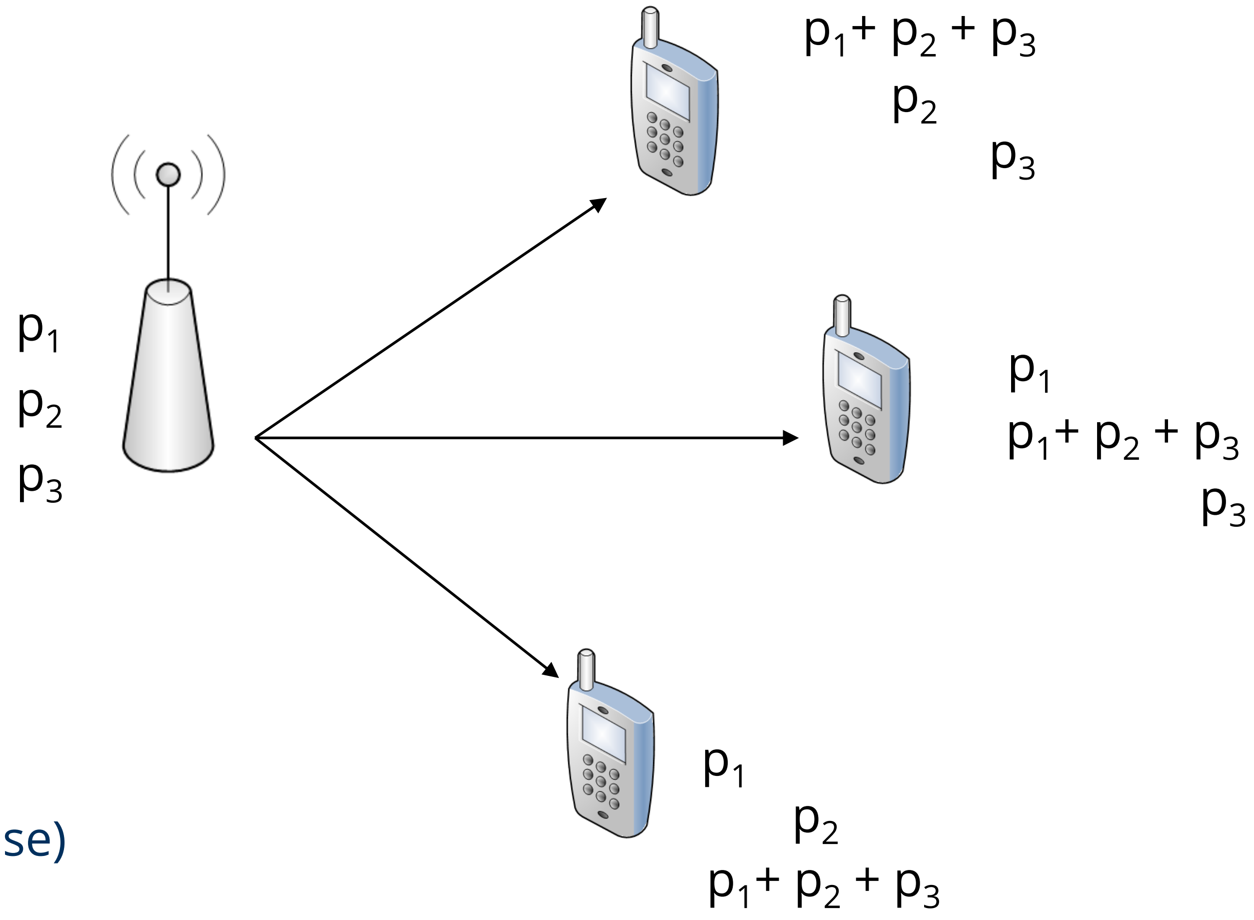
- Planning and book keeping needed
- Certain traffic characterisitcs are beneficial in mesh networks
- Symmetric traffic allows for more coding potential

Index Coding

Index Coding

Index Coding





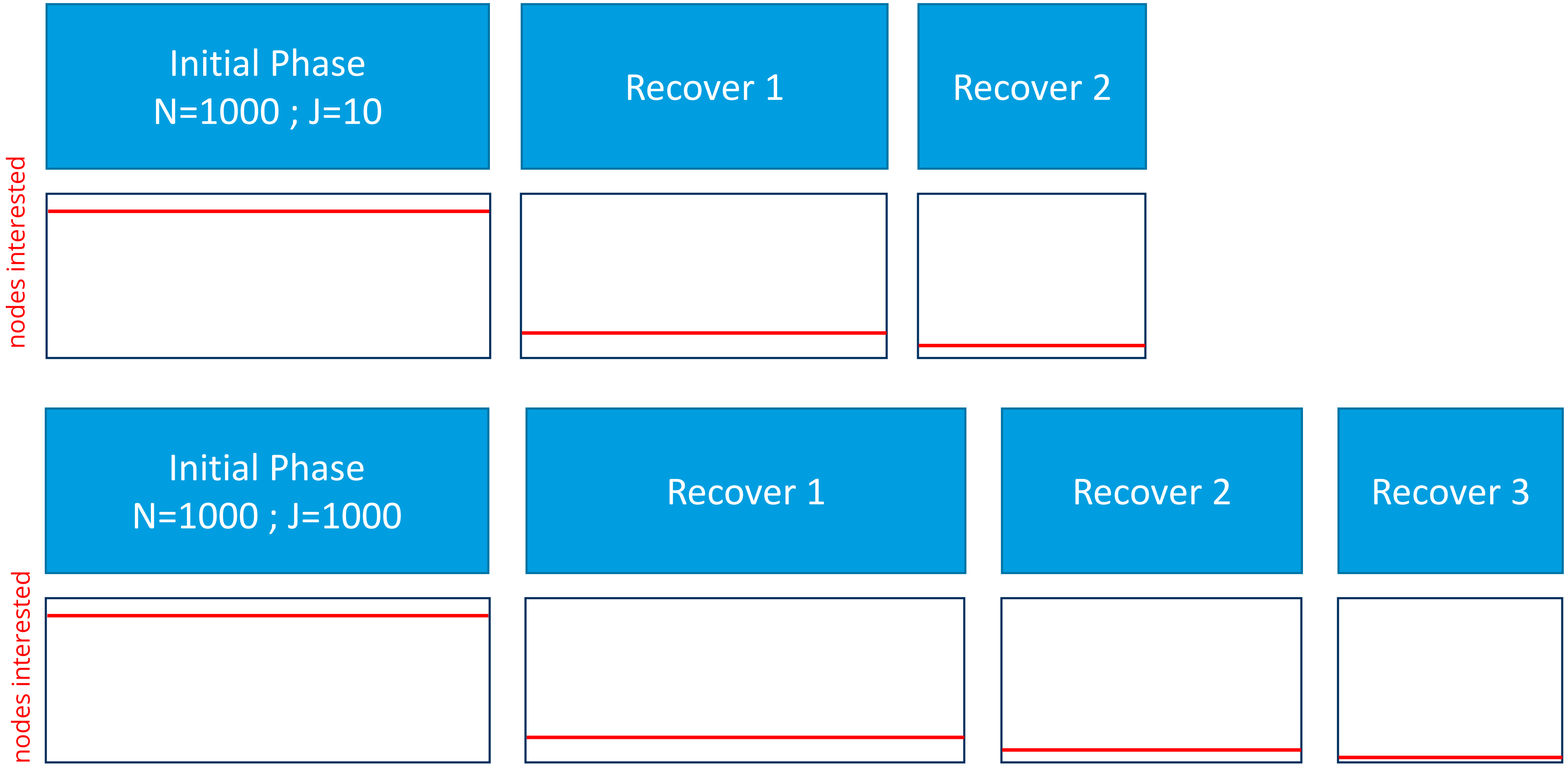
In wireless networks

- Broadcast advantage
- Generation of packets (three in this case)
- Packet erasures (losses)

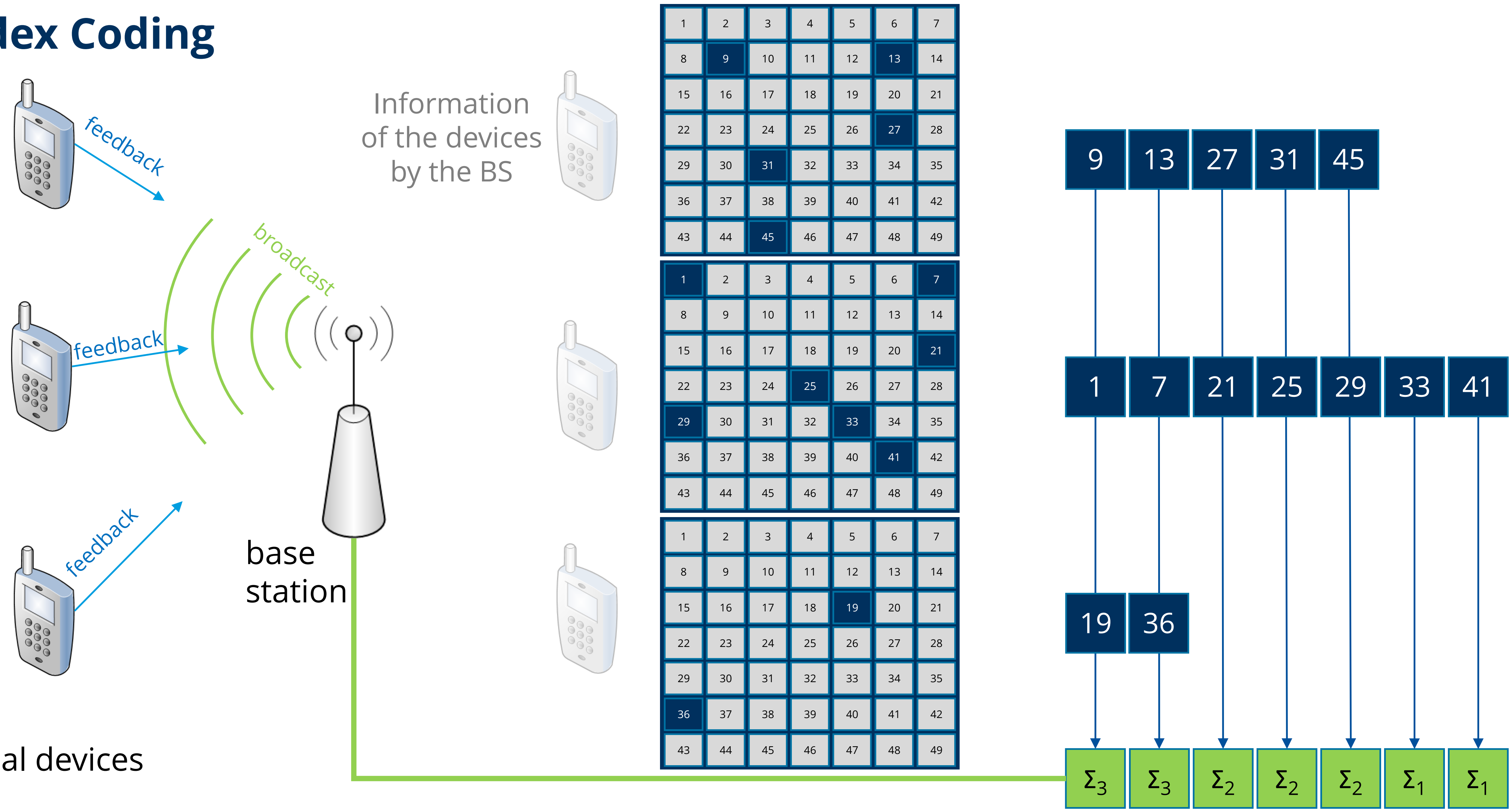
Reliable Multicast: Motivation

- Wireless has the advantage of inherent broadcast
- Wireless is error prone
- Coding versus Retransmissions
- N = number of packets
- J = number of users

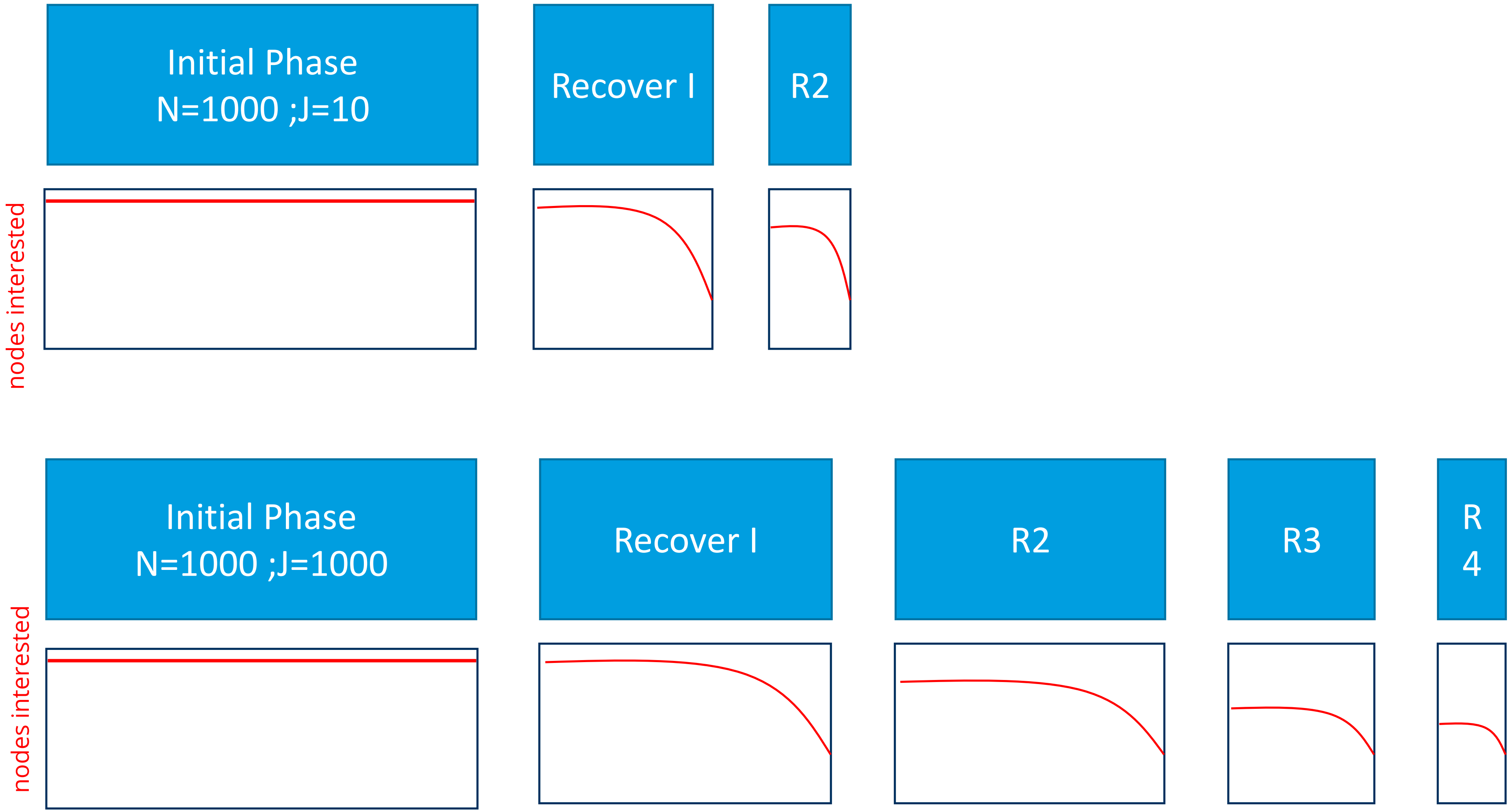
Reliable Multicast: Motivation



Index Coding

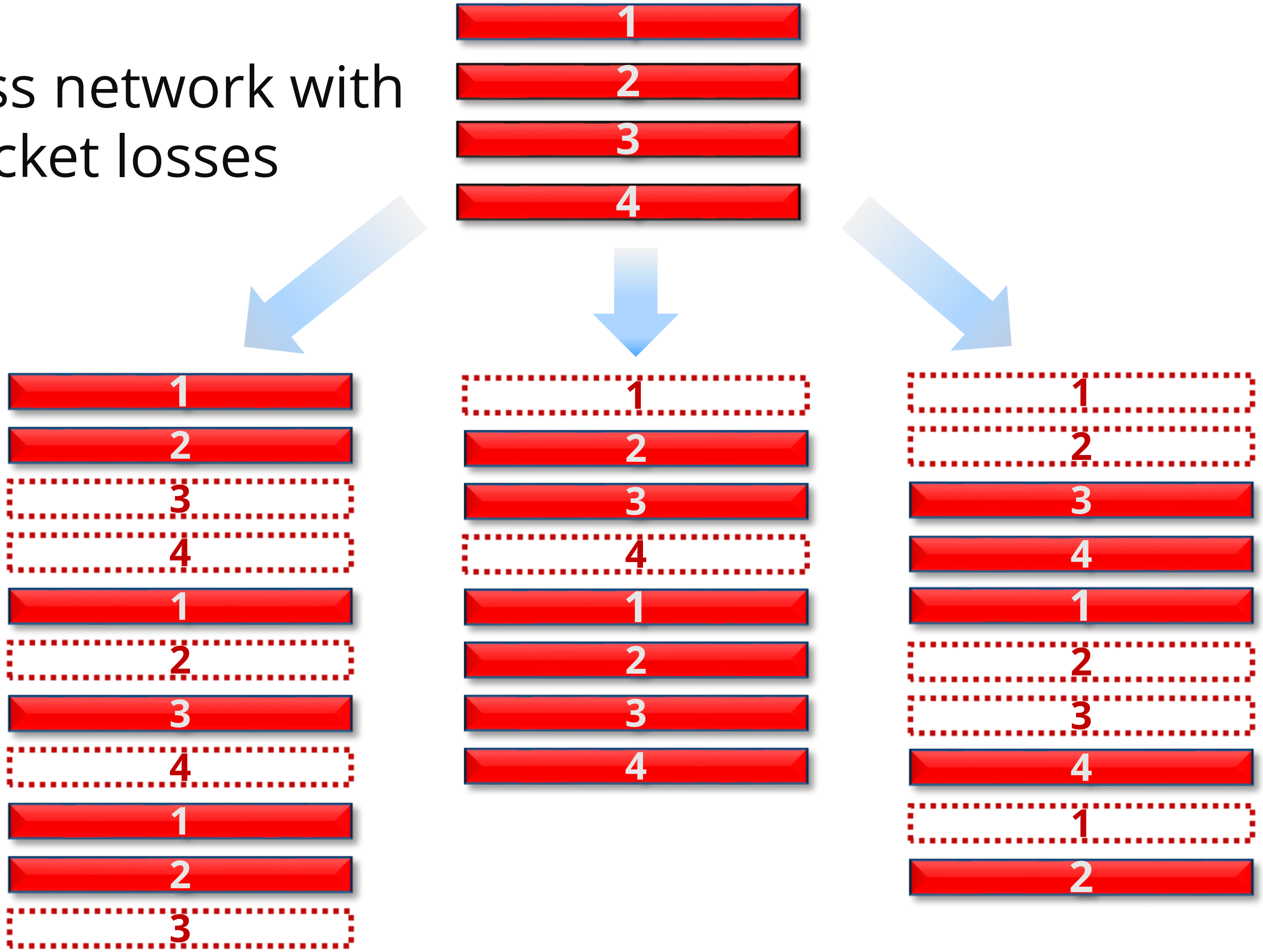


Index Coding



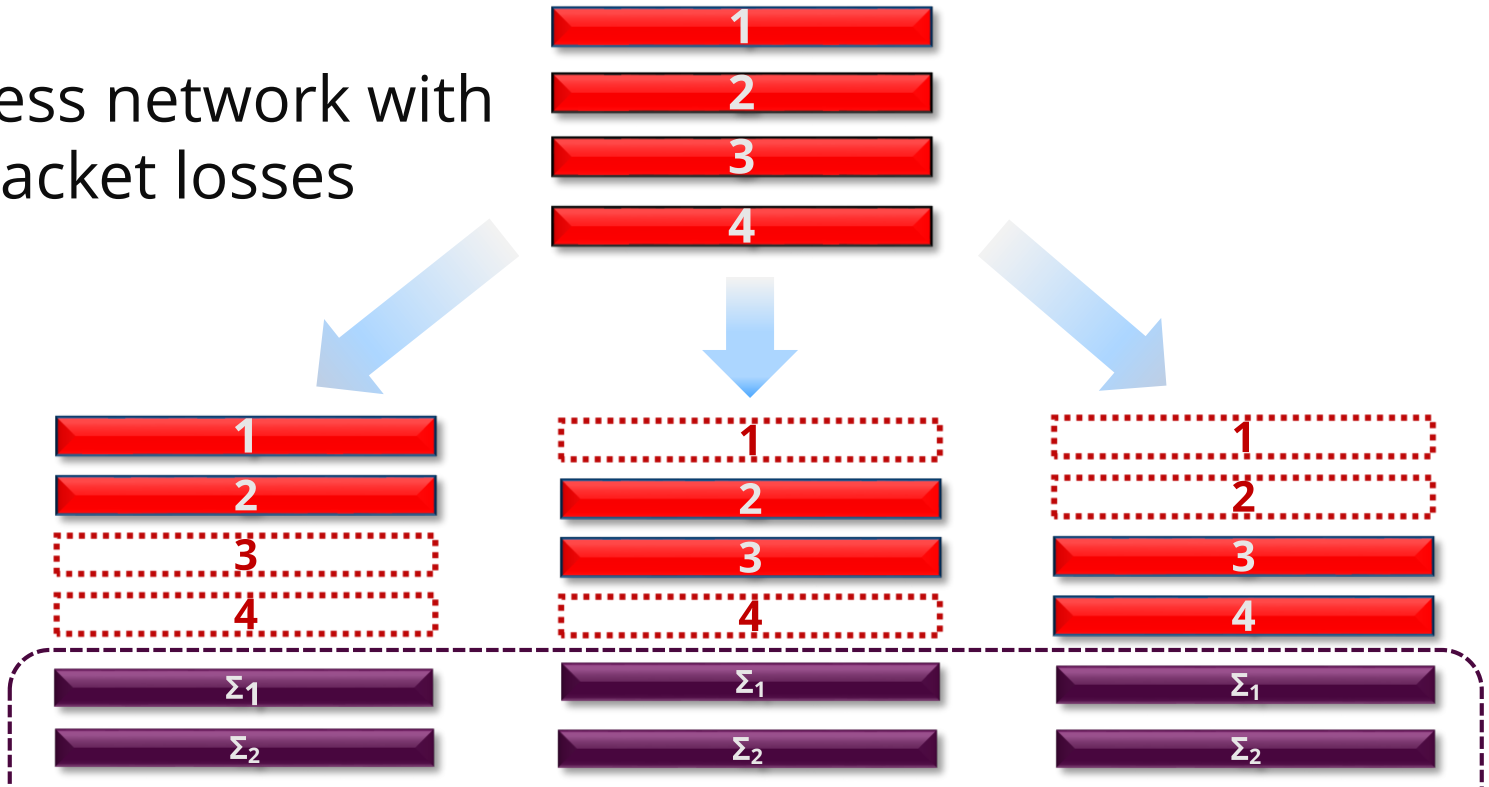
Broadcast Example

Wireless network with packet losses



Broadcast Example

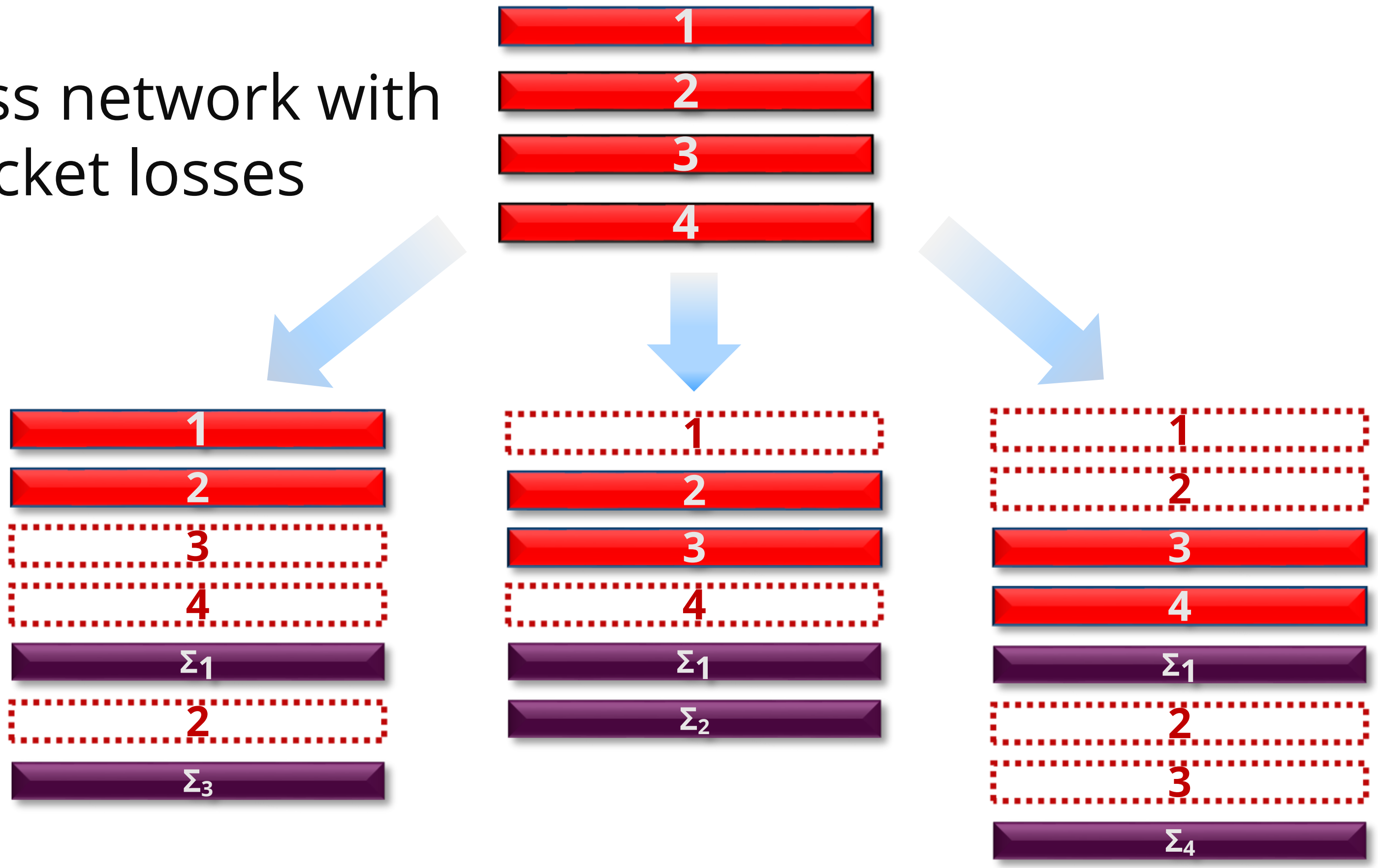
Wireless network with packet losses



Fewer data packet re-sends

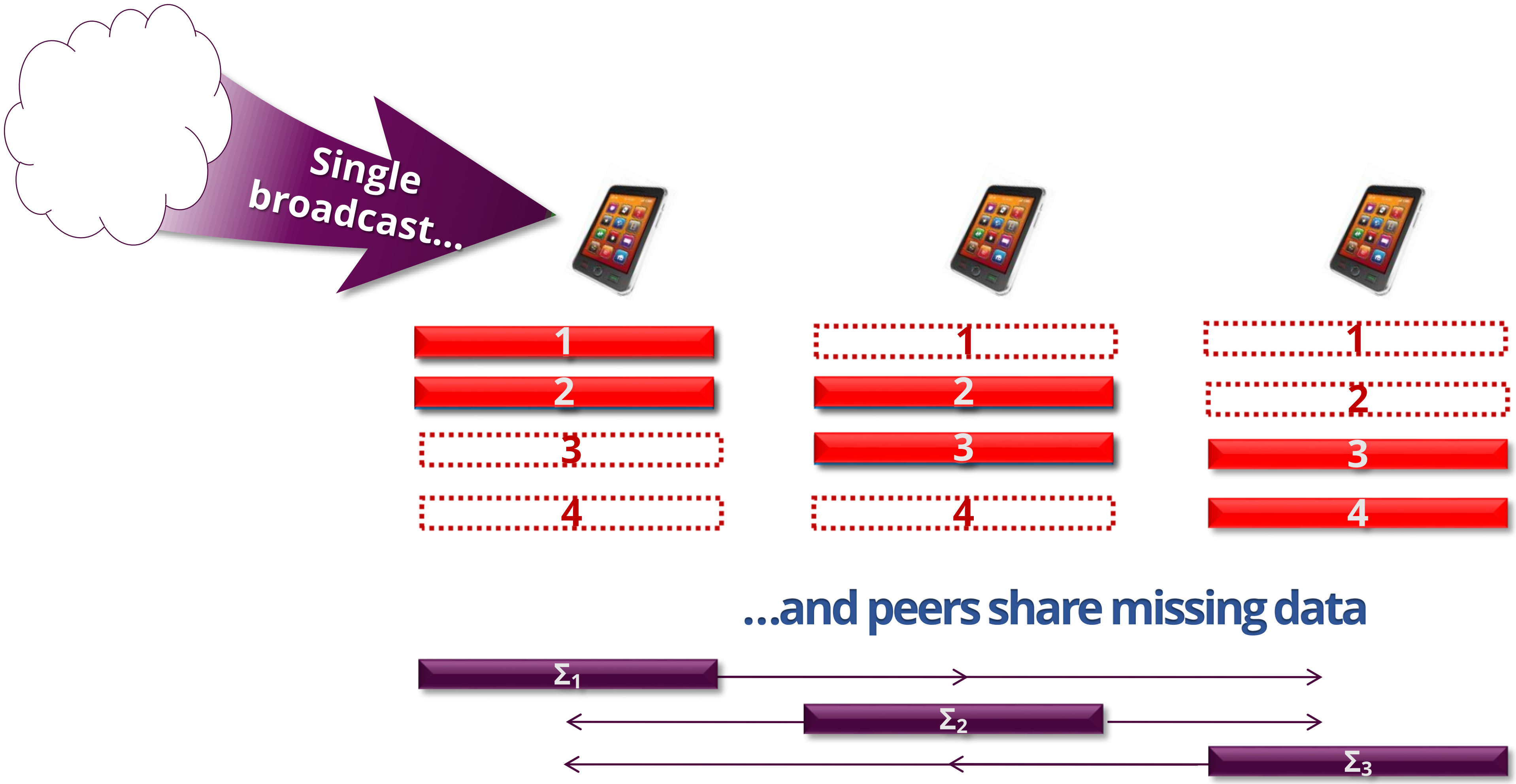
Broadcast Example

Wireless network with packet losses

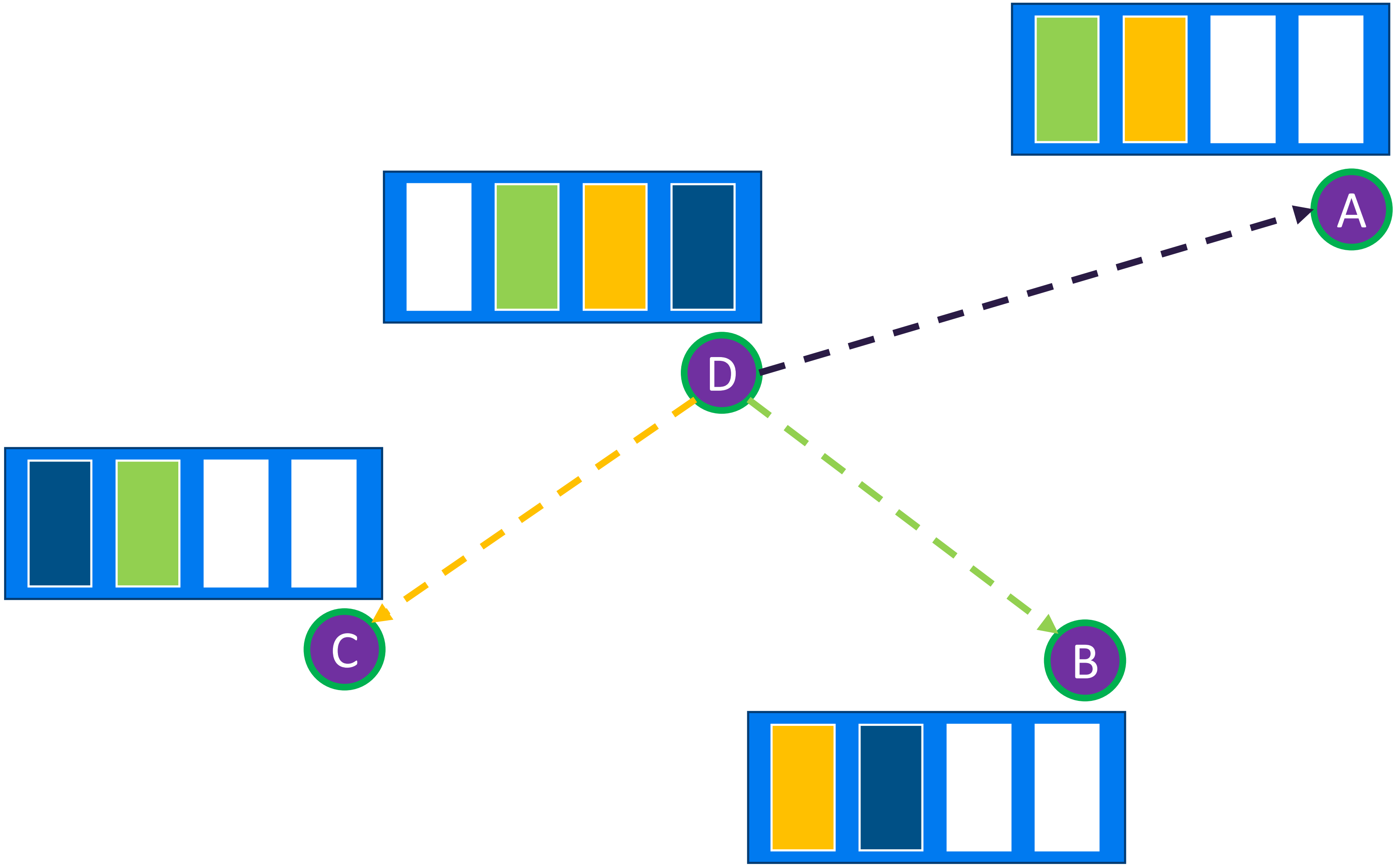


Same errors as before …

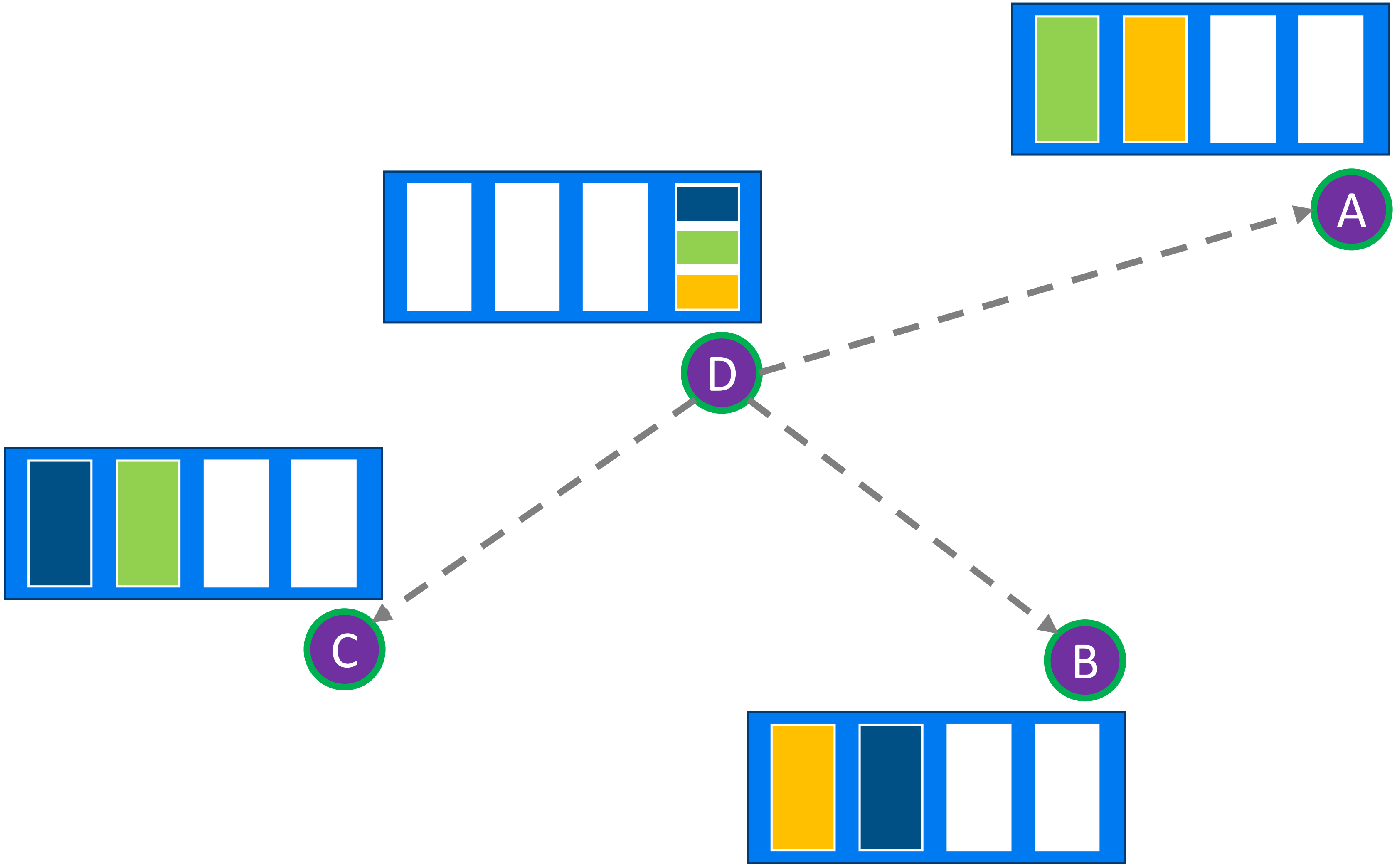
Broadcast Example: Cooperative Advantage



w/o Coding



w Coding

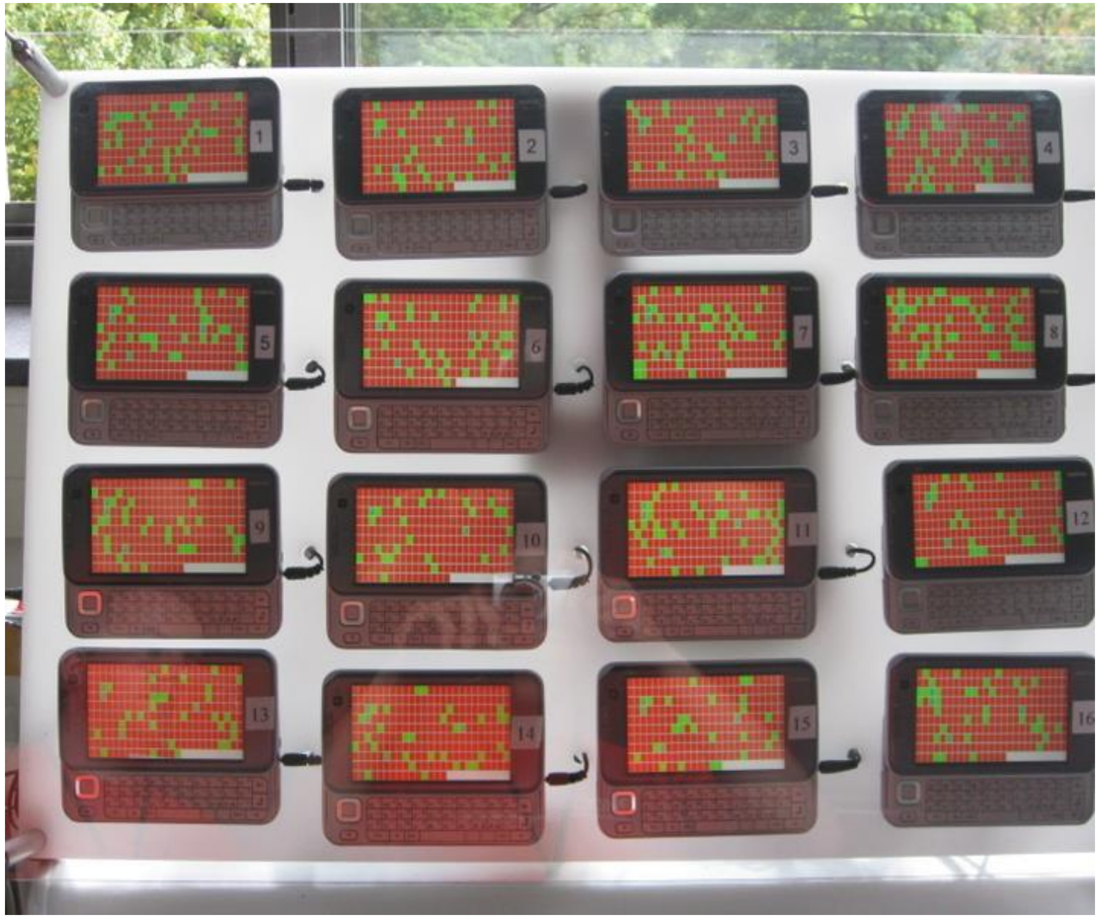


First implementations

K.F. Nielsen, T.K. Madsen, and F.H.P. Fitzek, **“Network coding opportunities for wireless grids formed by mobile devices,”** in The Second International Conference on Networks for Grid Applications, Springer in the ICST Lecture Notes (LNICST) series, Ed. ICST, Oct. 2008.

Inter-Flow NC on N810 (2008)

- XOR coding on N810 (linux device by NOKIA)
- Remote setup
  — Predefined set
  — Random set
- Constantly exchanging reception updates (who needs what)
- Overall goal is to let all devices have all information

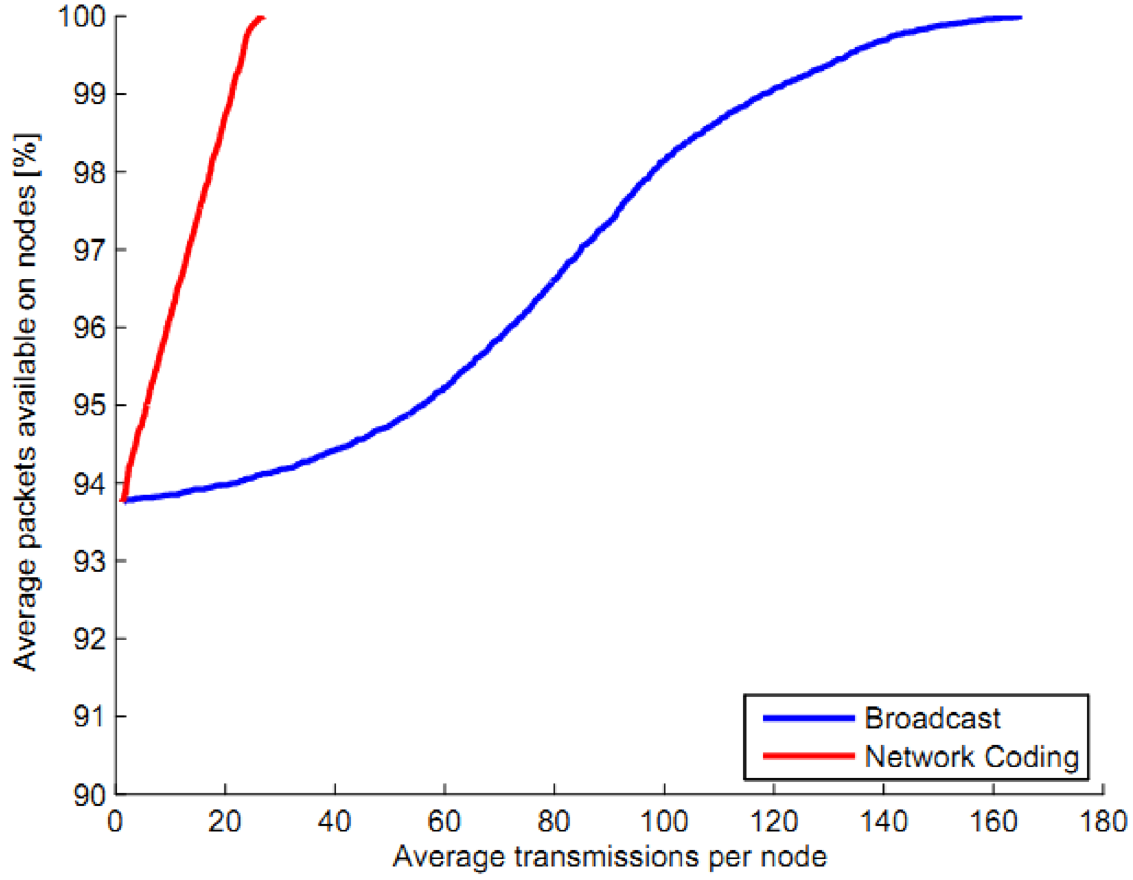


N810 Implementation COPE

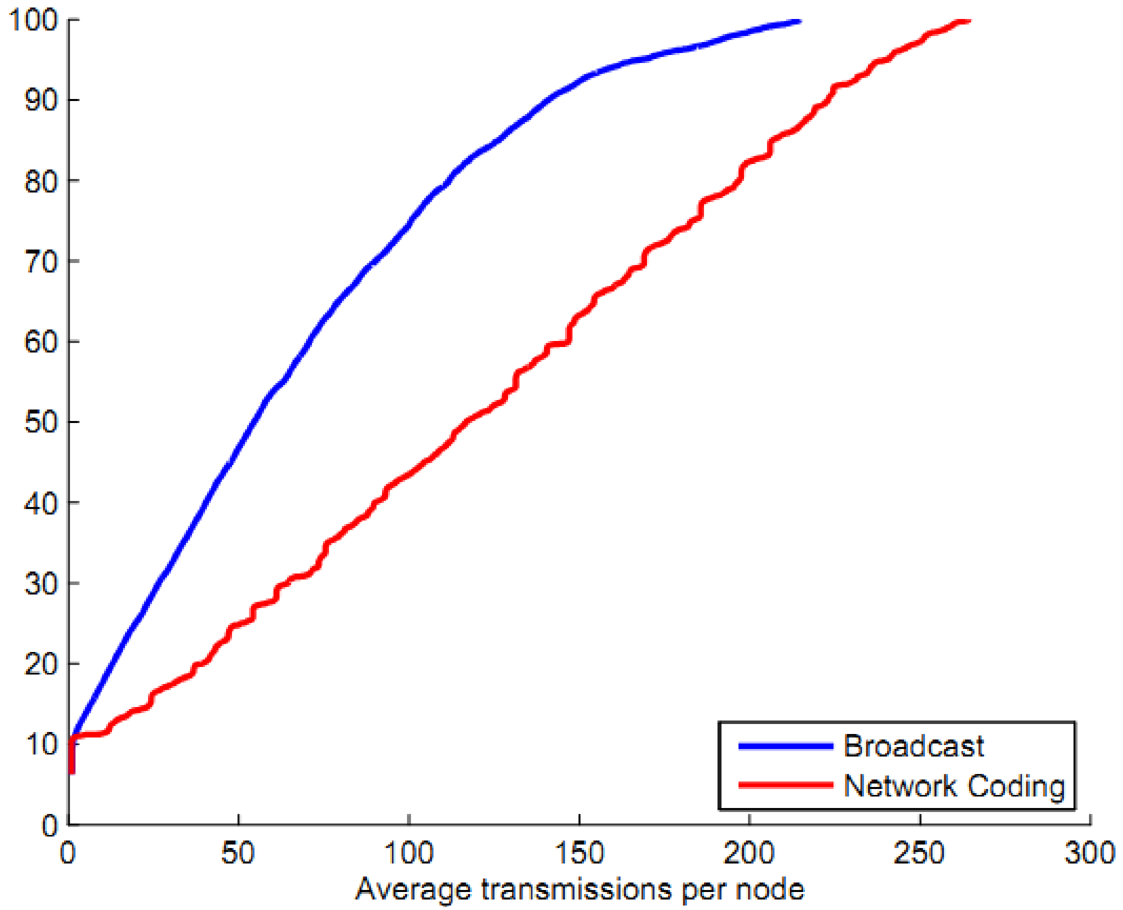
https://www.youtube.com/watch?v=VZYLSyZaEO8

Results: N810

Random Starting phase:
(duplicates are possible)



Disjoint Starting Phase:
(no duplicates on beginning)

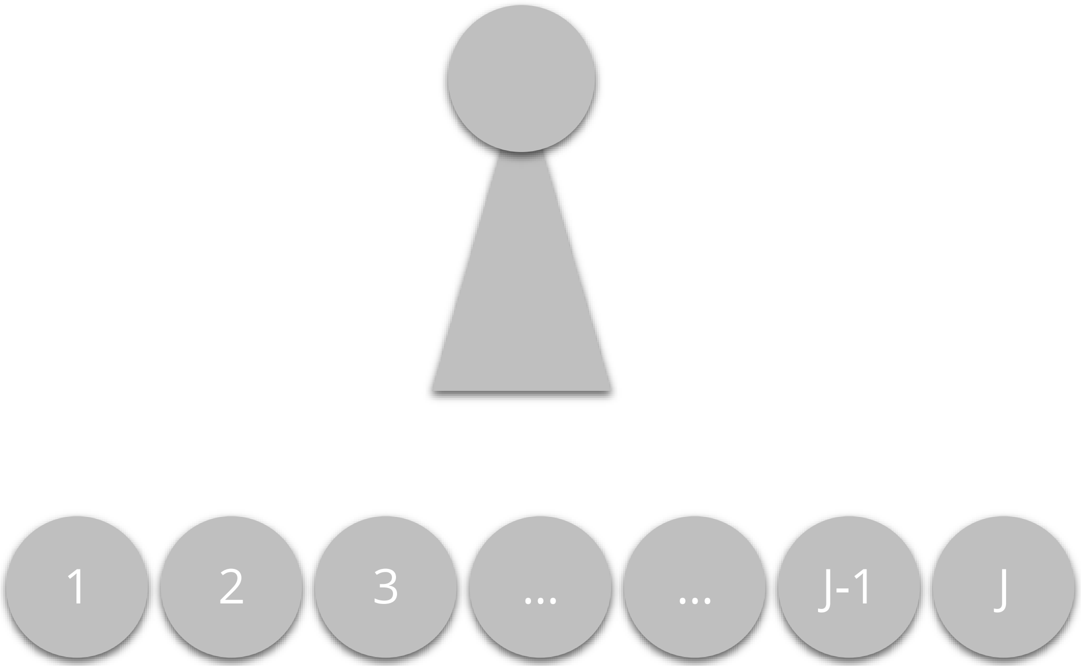


Digital Zig Zag Coding

Sagt es ihnen! Zick, zick, zick, nein zack … die falsche Richtung …
Meister … meine Bilder … meine Leinwand …
Zickzack falsch … sagt es ihnen … falsch…

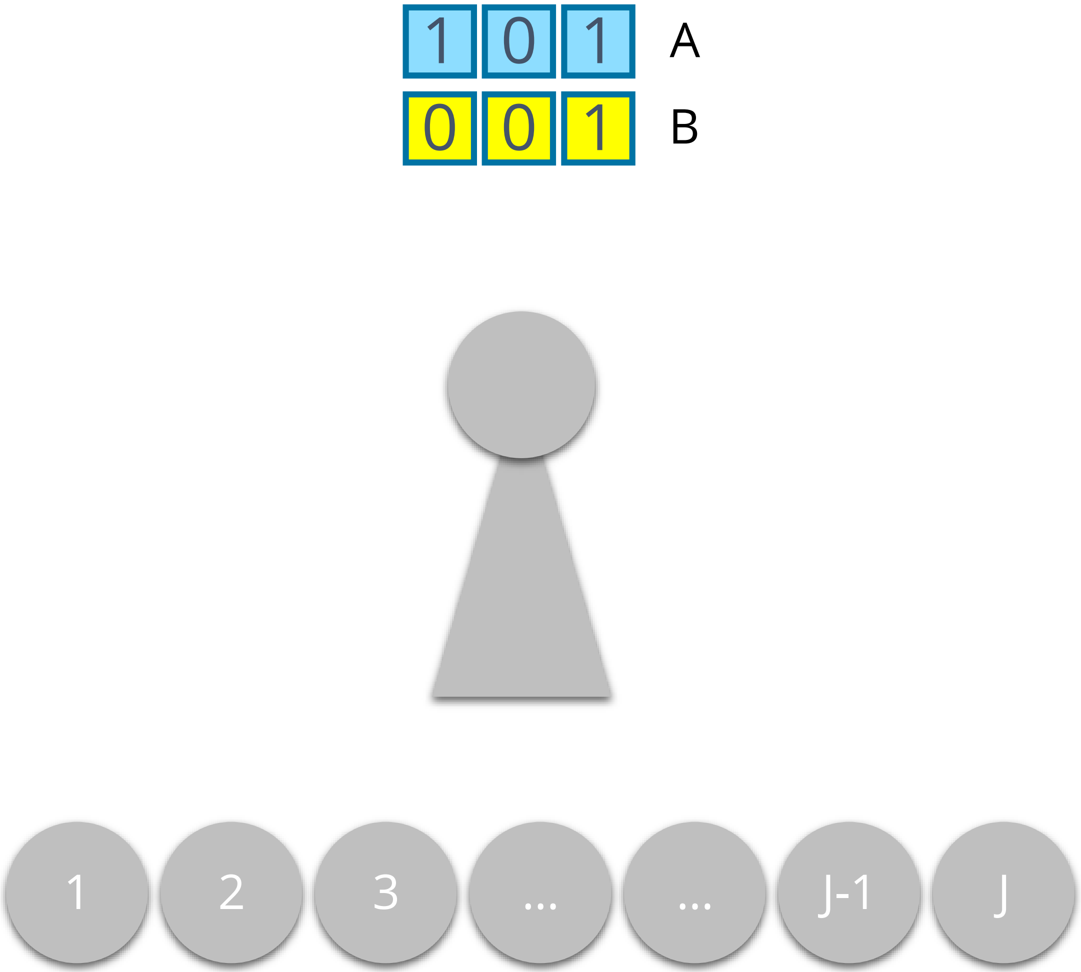
Architecture and Example

- Assuming one node broadcasts information to several nodes over error-prone medium
- All nodes are interested in the same content



Architecture and Example

- Assuming one node broadcasts information to several nodes over error-prone medium
- All nodes are interested in the same content
- Assuming we have only two messages A and B with three bits of information each (to make it easy)



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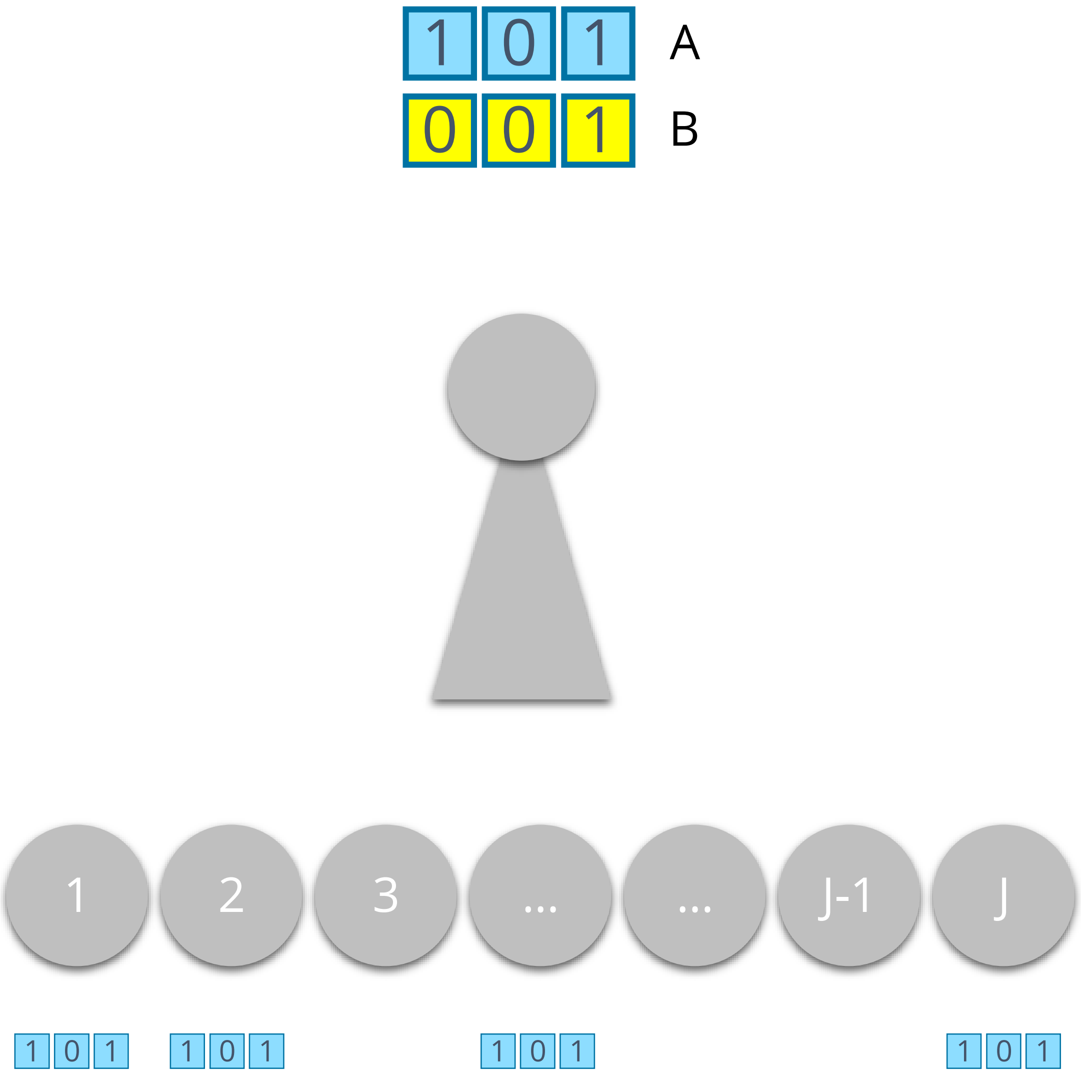

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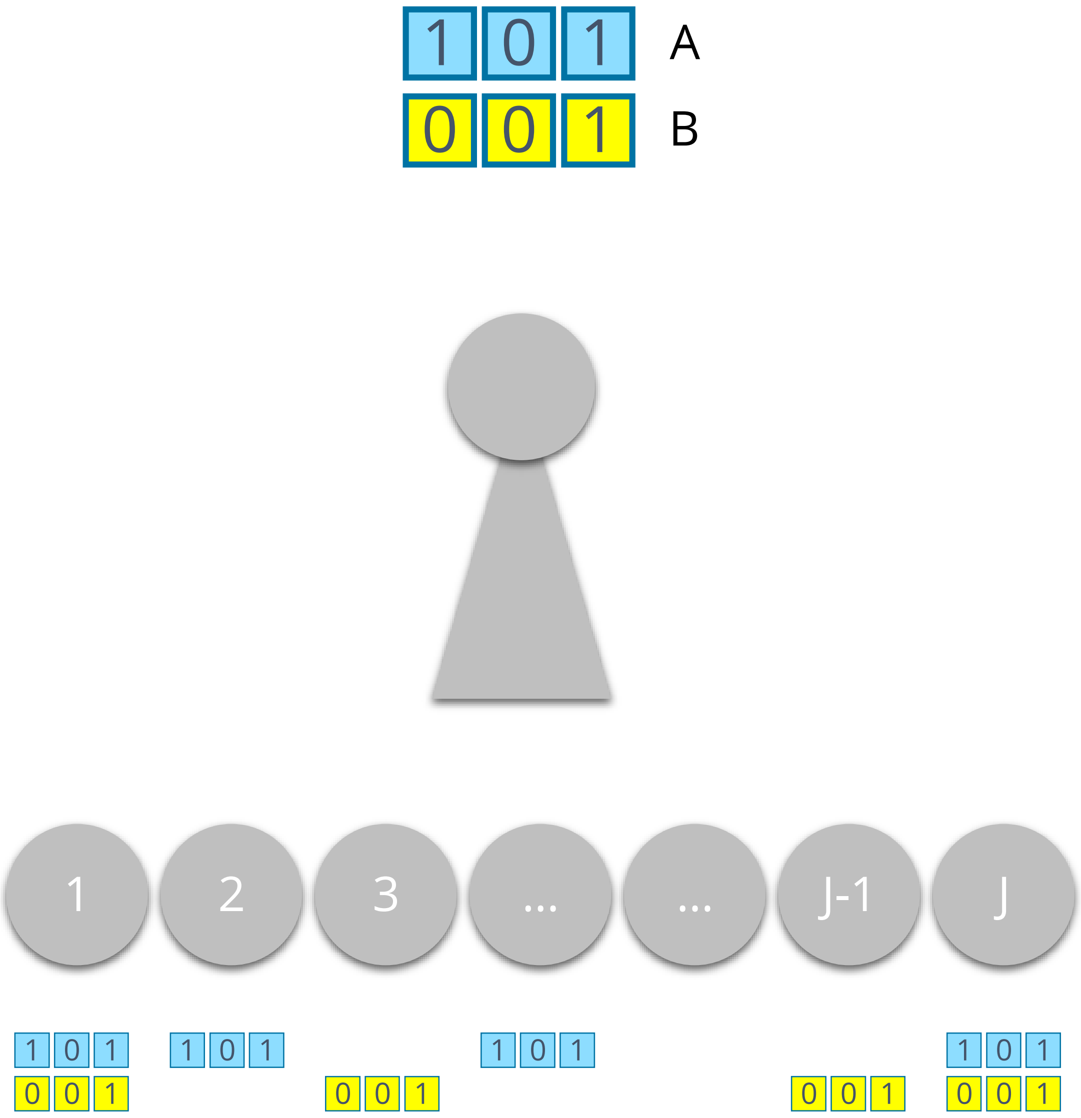
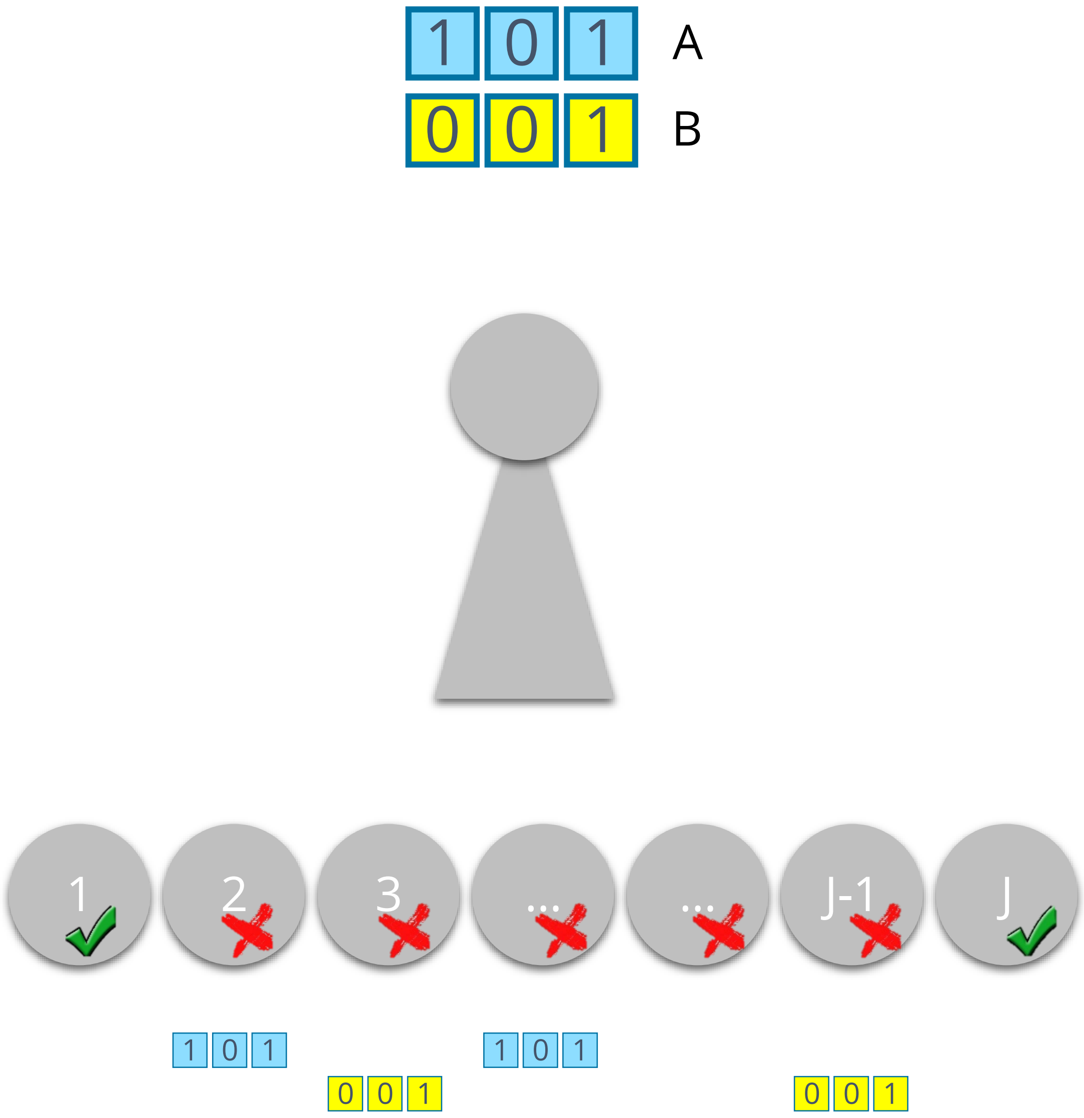


Decoding 1

Original packet A	1	0	1
Original packet B	0	0	1

Architecture and Example

- Assuming one node broadcasts information to several nodes over error-prone medium
- All nodes are interested in the same content
- Assuming we have only two messages A and B with three bits of information each (to make it easy)
- And now? Don't say repetition coding!

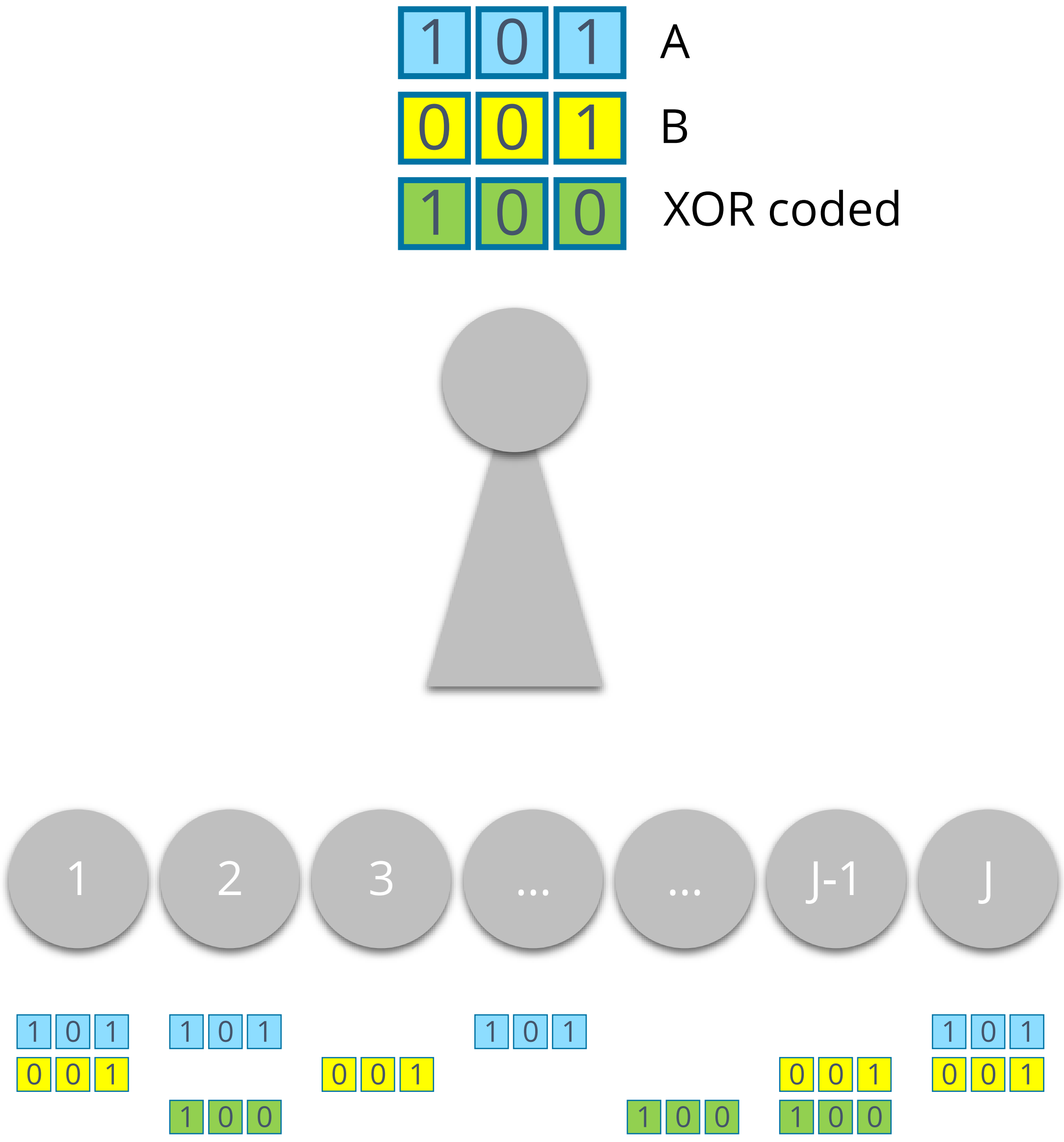


Encoding - XOR

1	0	1	Original packet A
0	0	1	Original packet B
1	0	0	Coded packet A⊕B

Architecture and Example

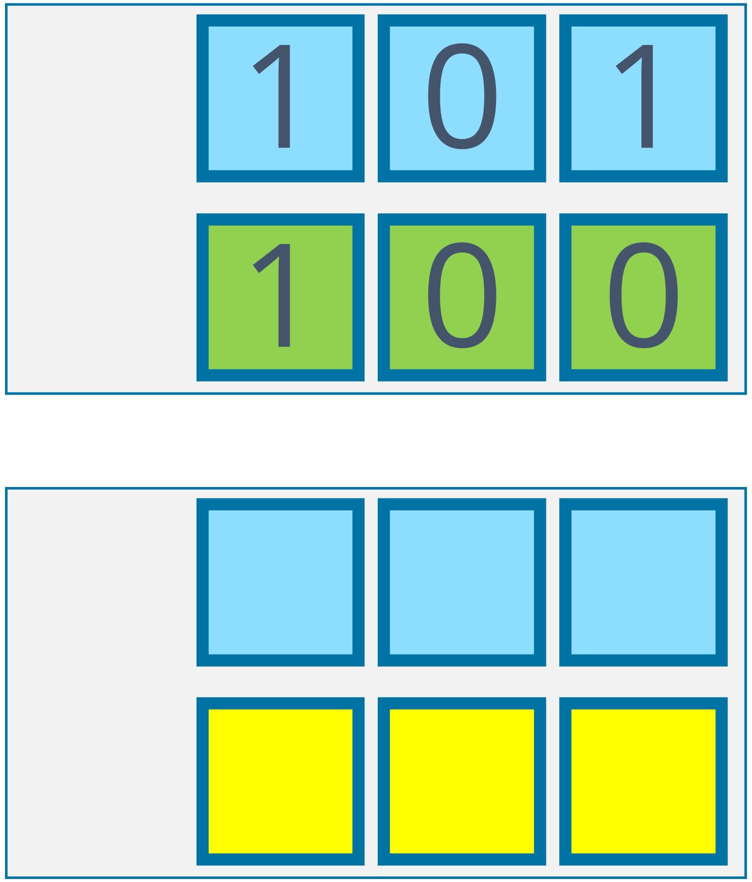
- Assuming one node broadcasting information to several nodes over error-prone medium
- All nodes are interested in the same content
- Assuming we have only two messages A and B with three bits of information (to make it easy)
- Still not good enough now? Don’t say repetition coding!



Decoding 2

Original packet A

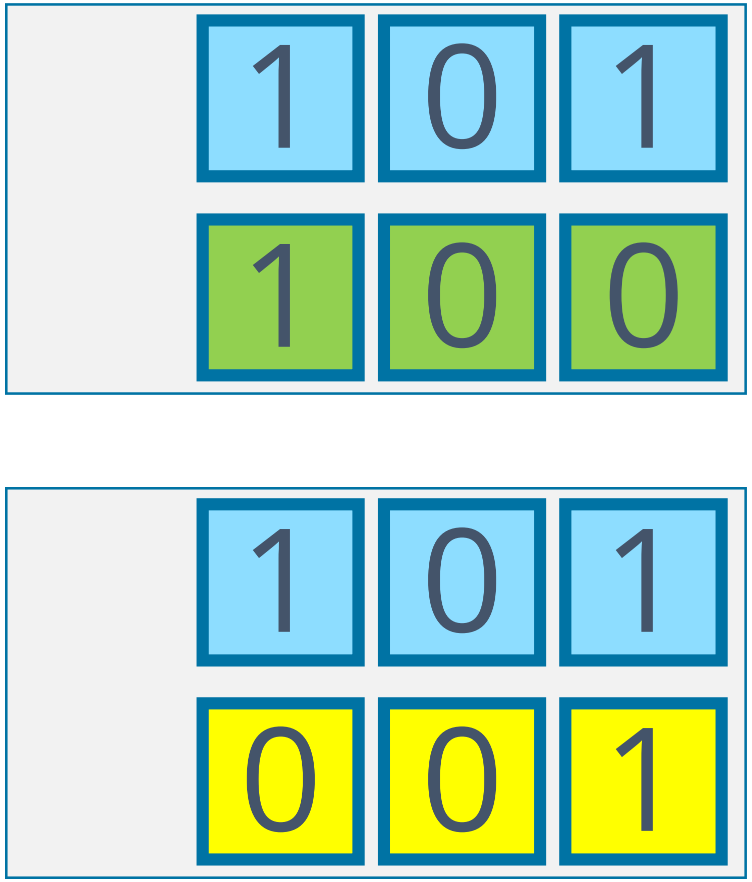
Coded packet A⊕B



Decoding 2

Original packet A

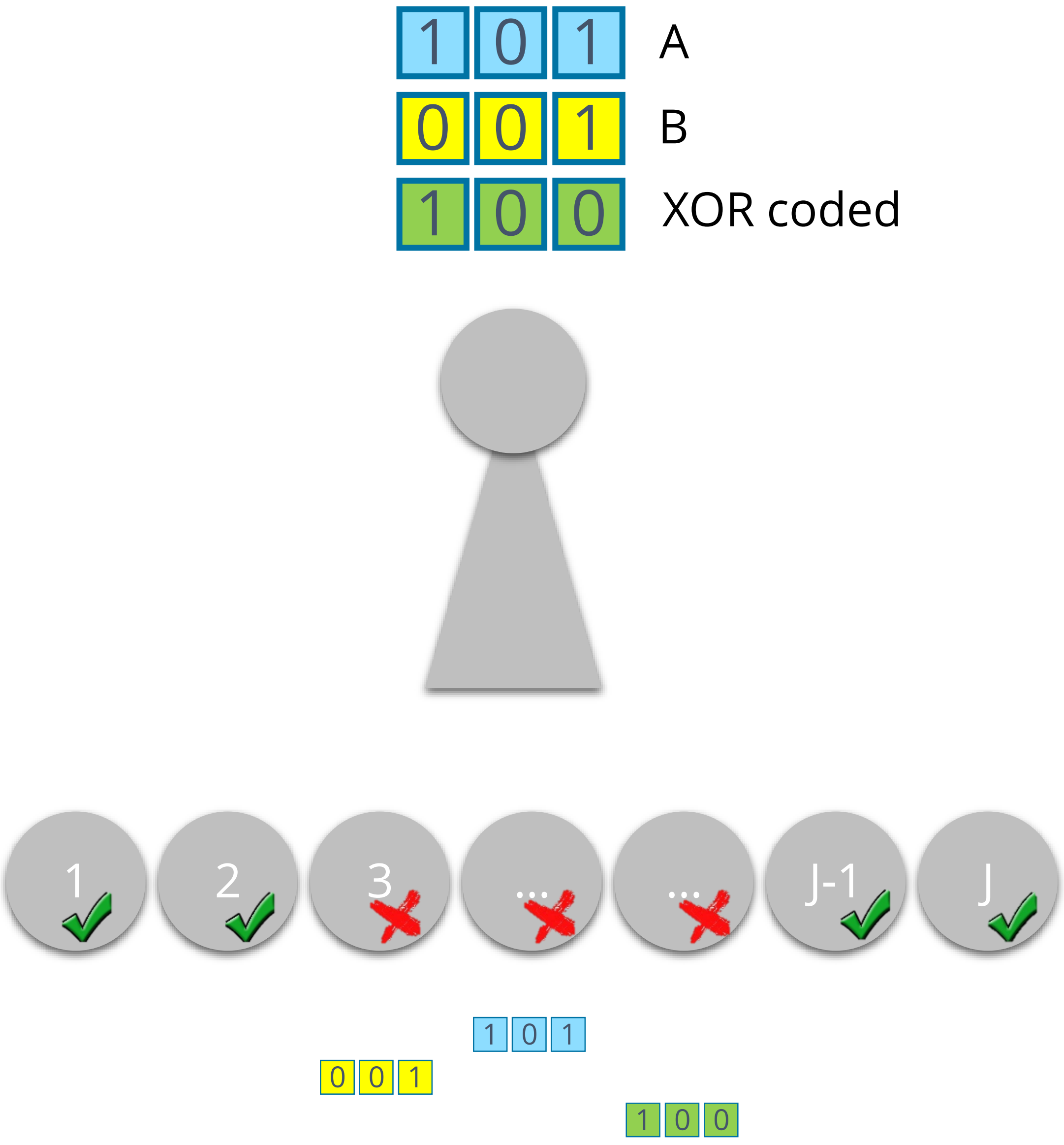
Coded packet $A \oplus B$



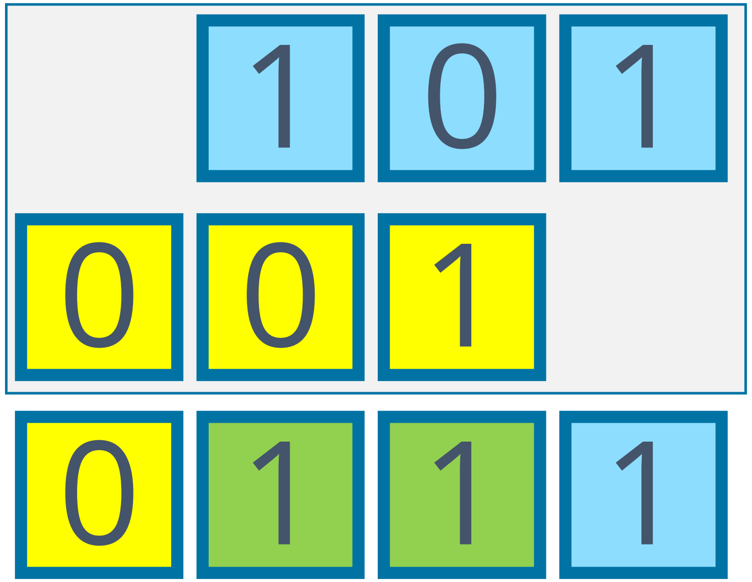
Simple reading & XOR

Architecture and Example

- Assuming one node broadcasting information to several nodes over error-prone medium
- All nodes are interested in the same content
- Assuming we have only two messages A and B with three bits of information (to make it easy)
- Still not good enough now? Don't say repetition coding!



Encoding – Shifted XOR



Original packet A

Original packet B*2

Coded packet A⊕B*2

Legend:

x Bit with value x from packet A

x Bit with value x from packet B

x Coded bit with value x from packet A and packet B

Decoding 3

Coded packet A⊕B*2	0	1	1	1
Original packet B		0	0	1

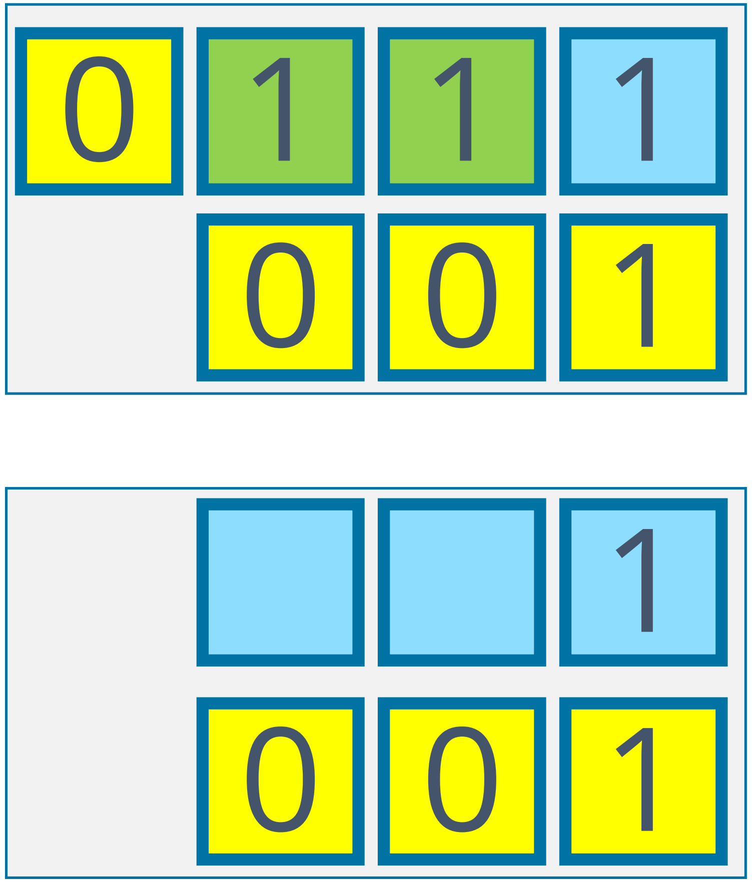
Original packet A			
Original packet B			

Decoding 3

Coded packet A⊕B*2	0	1	1	1
Original packet B		0	0	1

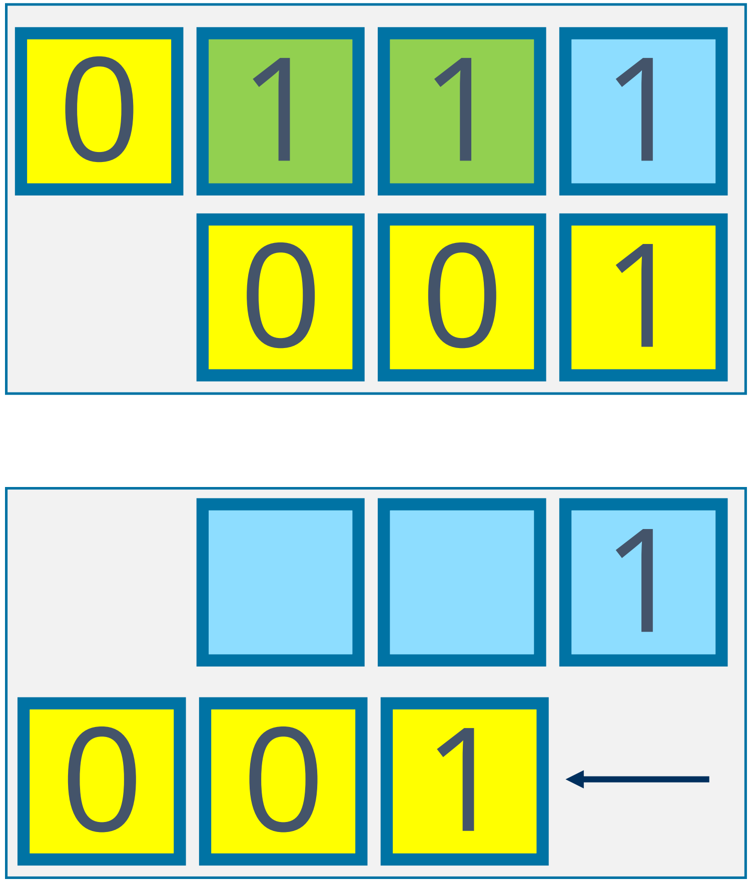
Original packet A				
Original packet B				

Decoding 3



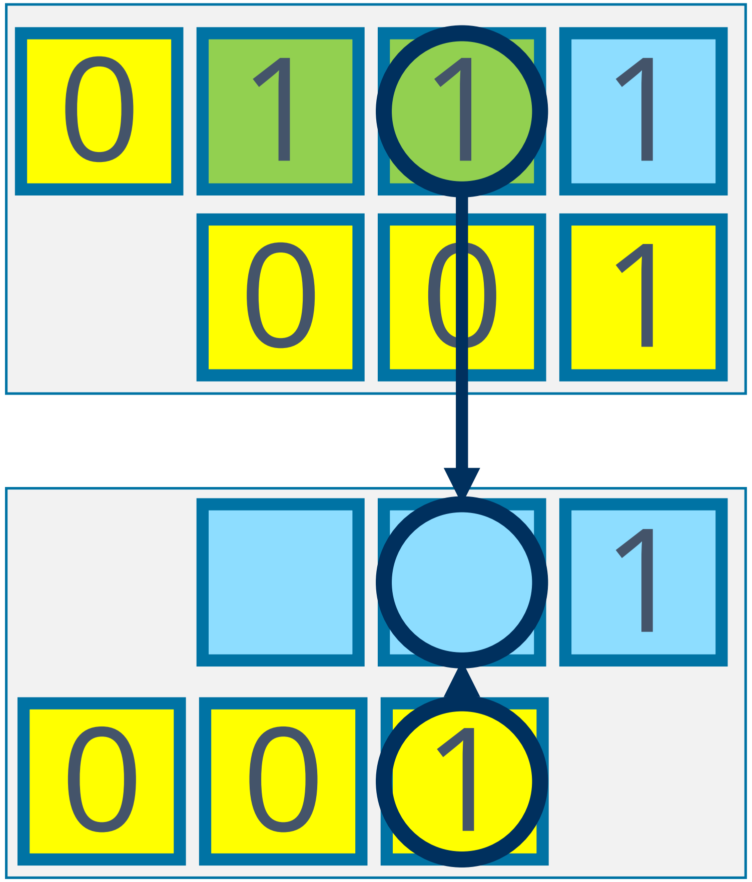
Simple reading

Decoding 3



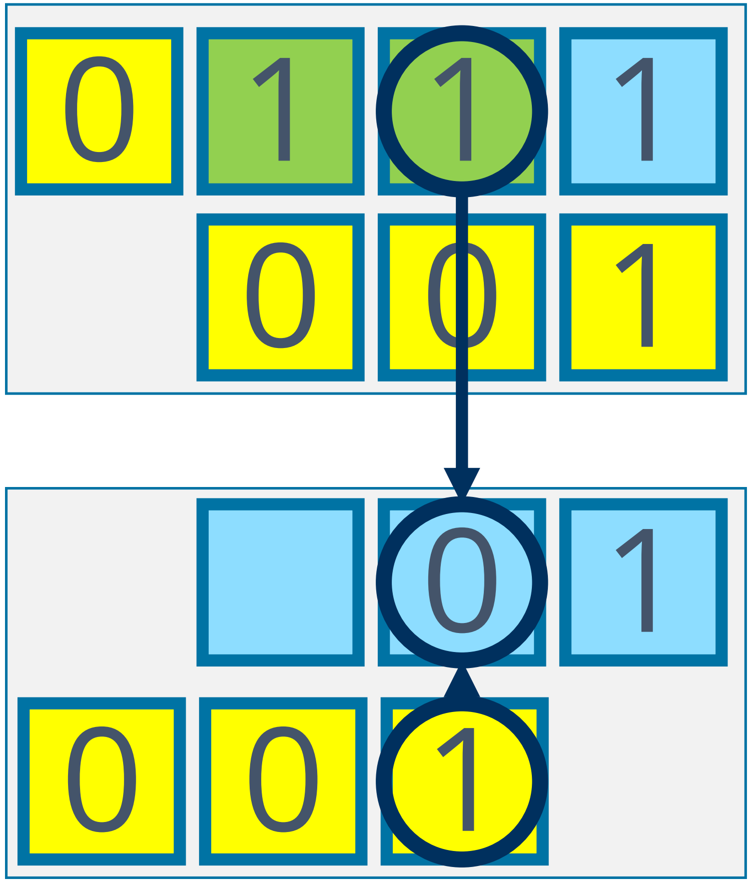
Restore old shift

Decoding 3



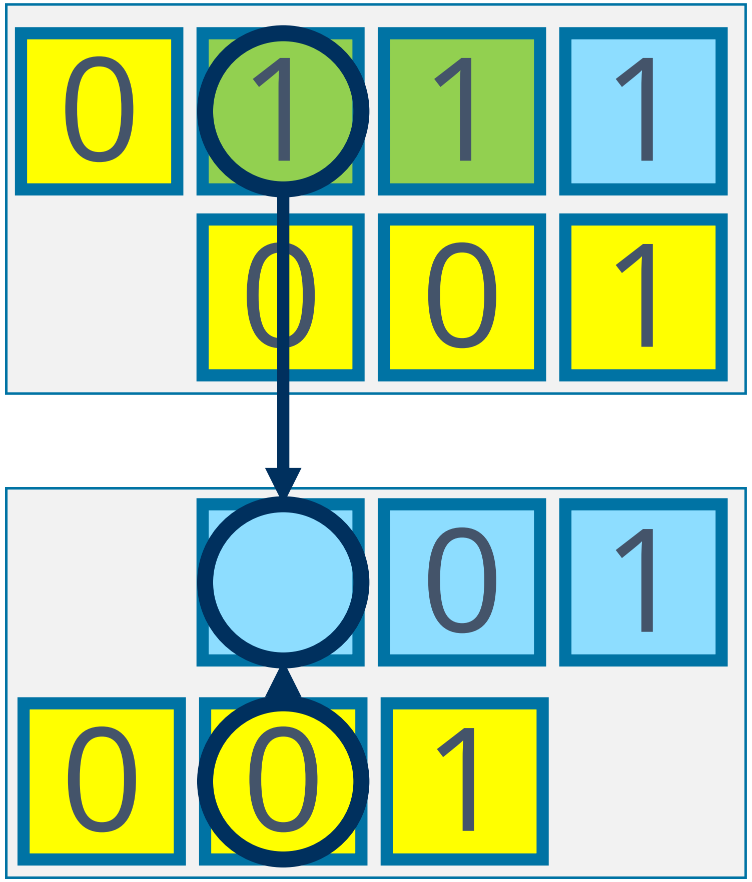
XOR: $1 \oplus 1$

Decoding 3



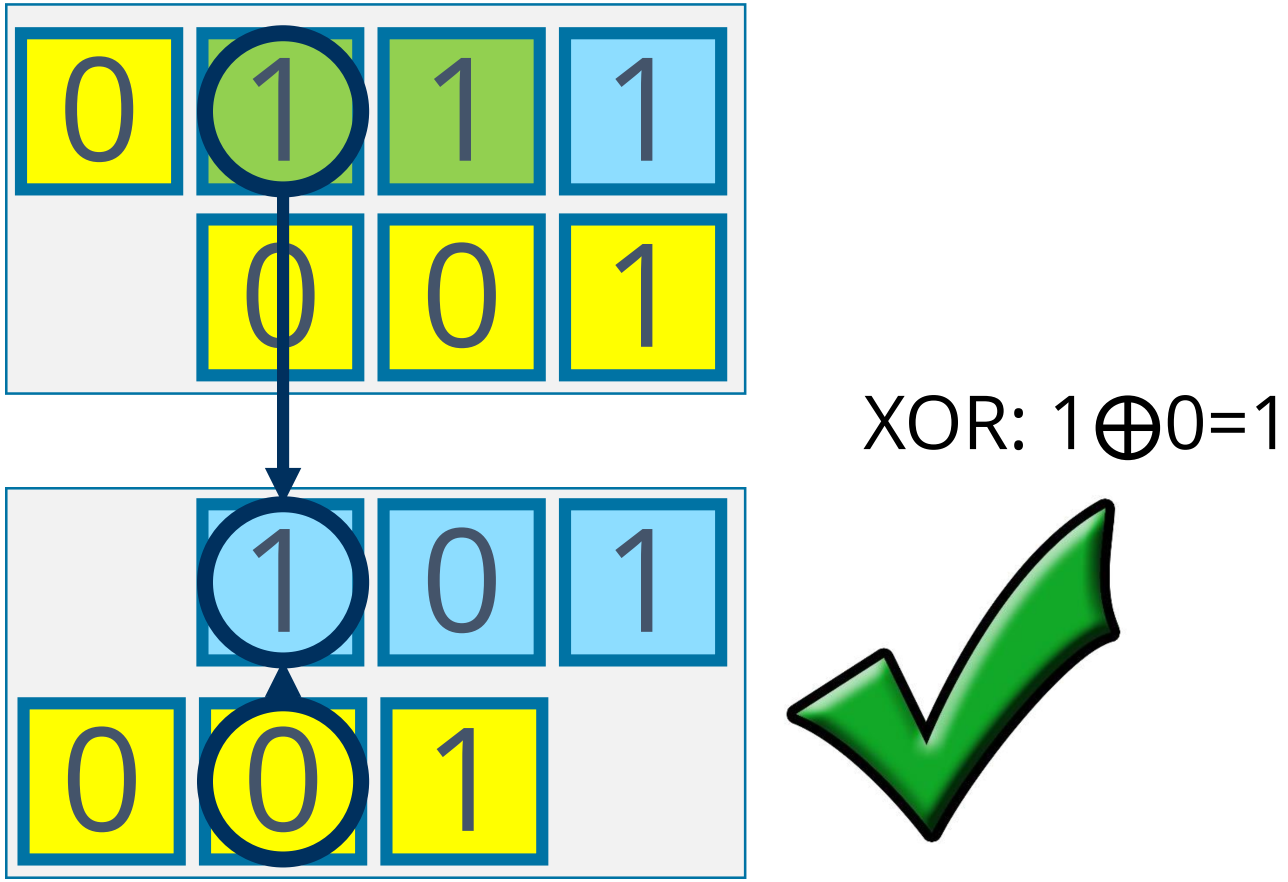
XOR: $1 \oplus 1 = 0$

Decoding 3



XOR: $1 \oplus 0$

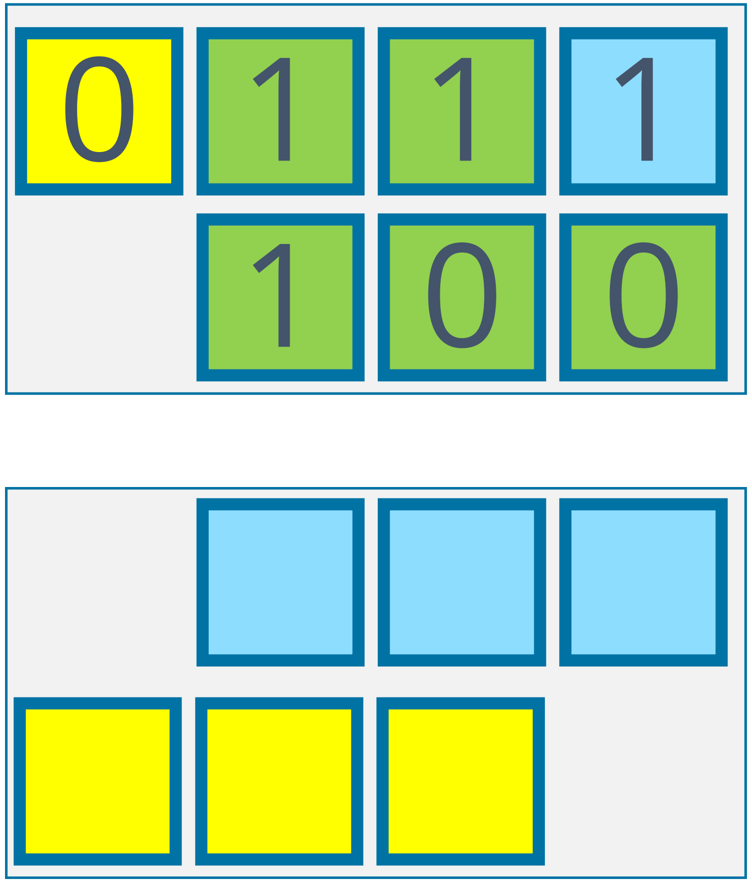
Decoding 3



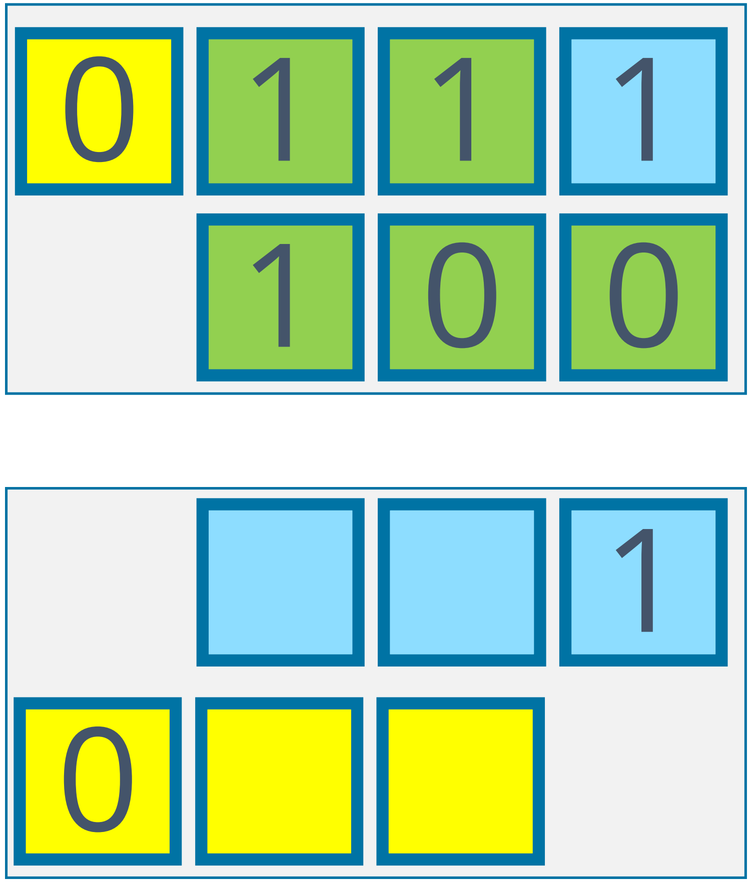
Decoding 4

Coded packet A⊕B*2

Coded packet A⊕B

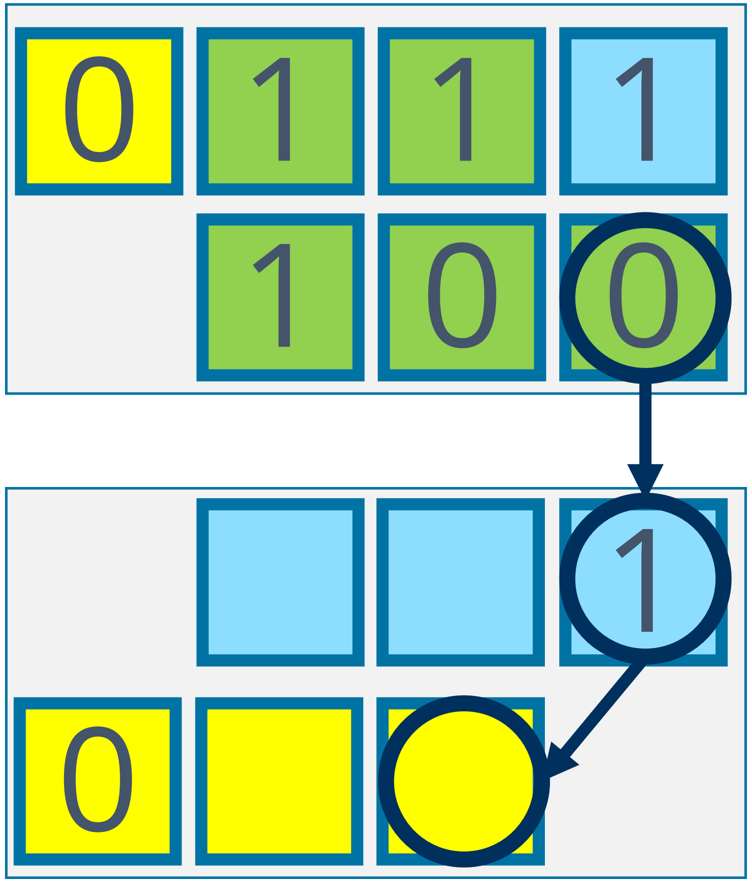


Decoding 4



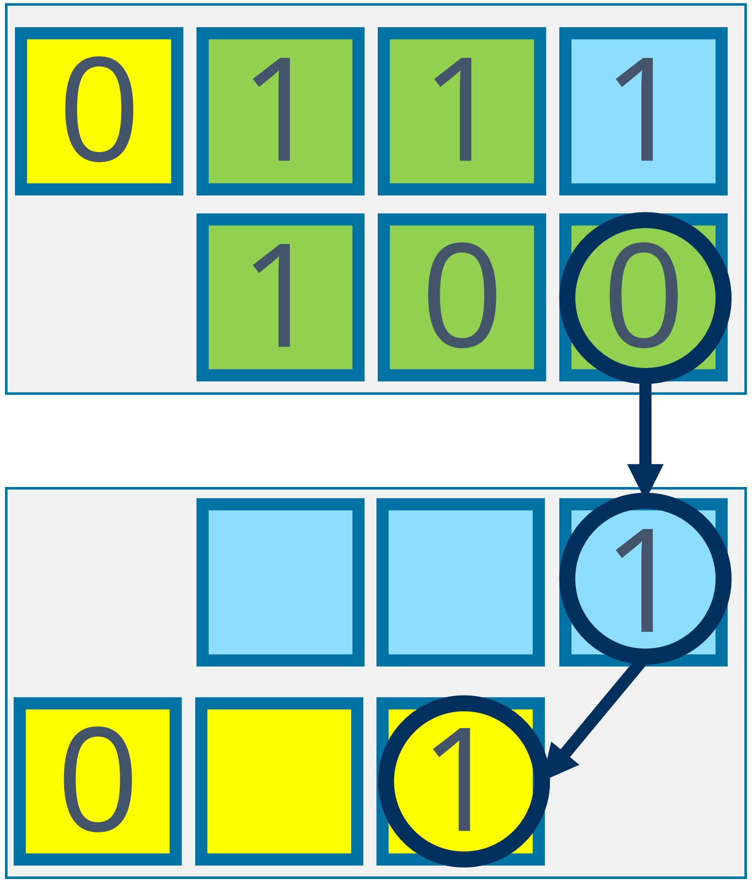
Simple reading

Decoding 4



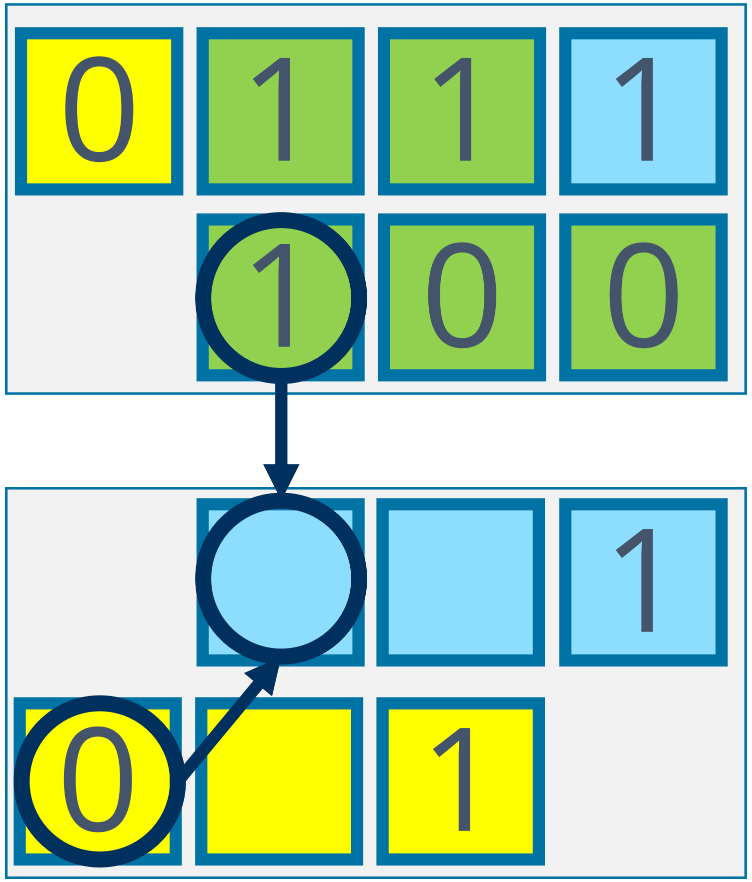
XOR: $0 \oplus 1$

Decoding 4



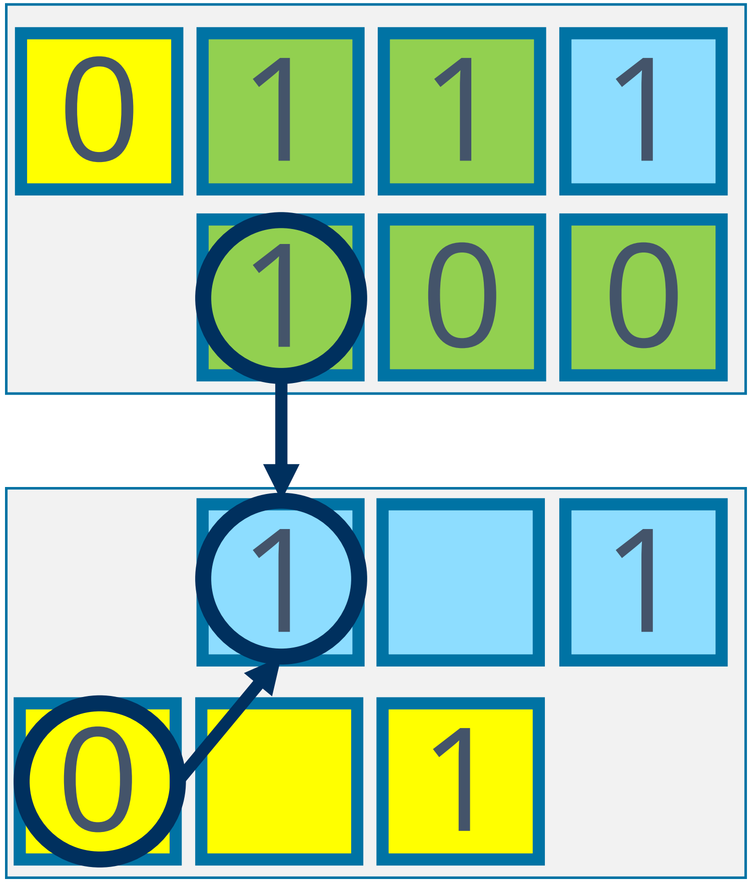
XOR: $0 \oplus 1$

Decoding 4



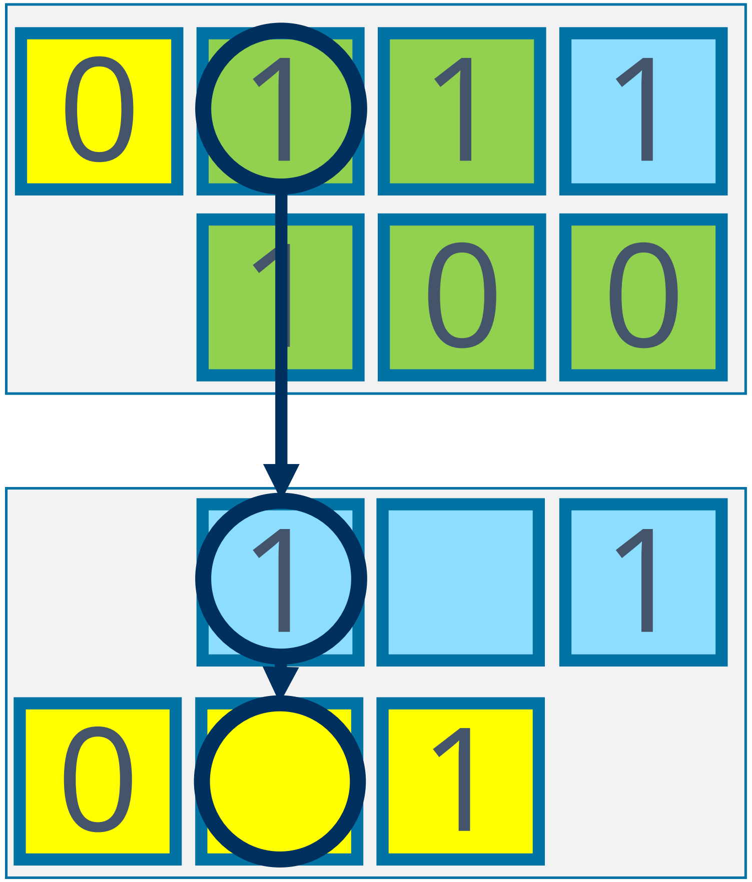
XOR: 1⊕0

Decoding 4



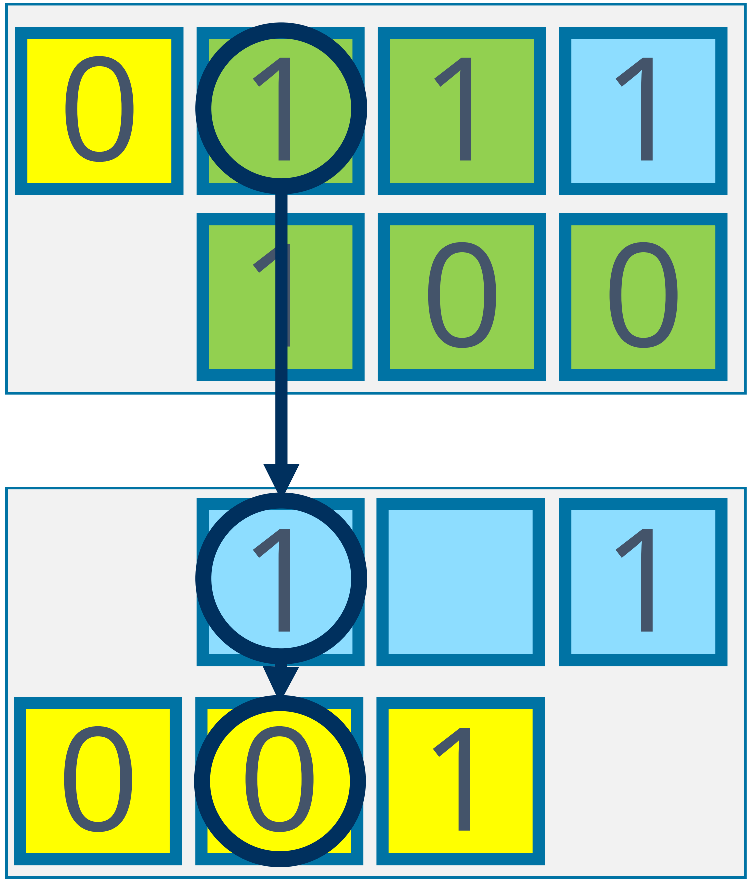
XOR: 1⊕0=1

Decoding 4



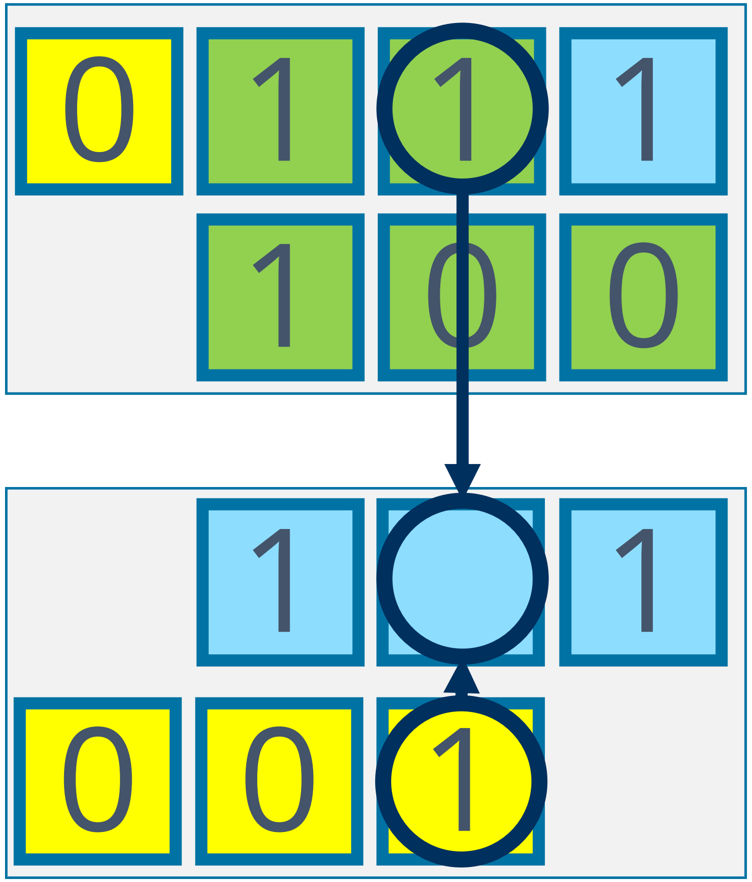
XOR: 1⊕1

Decoding 4



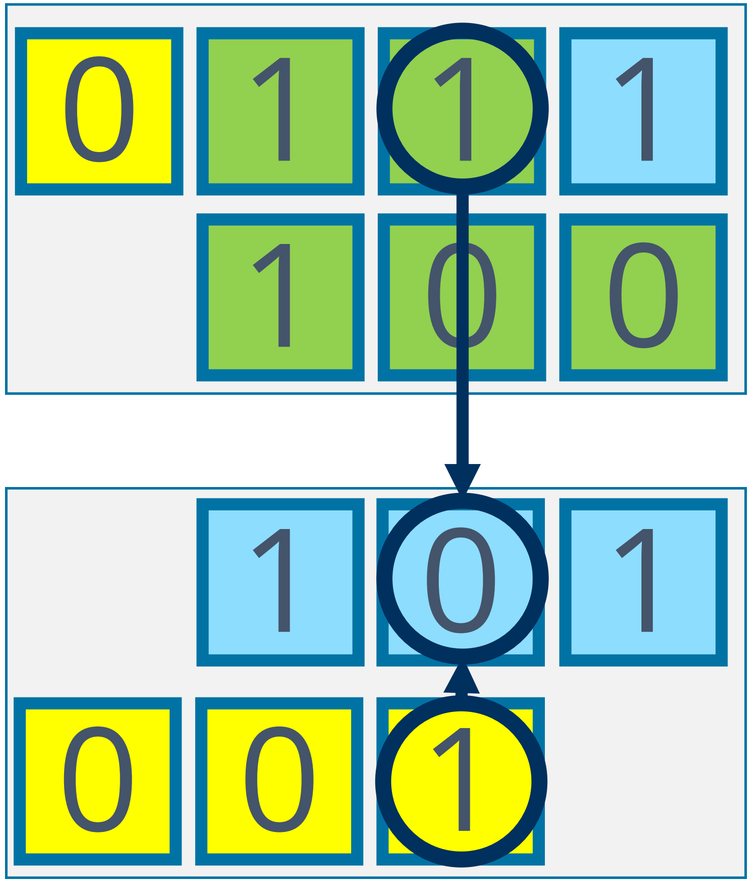
XOR: $1 \oplus 1 = 0$

Decoding 4



XOR: 1⊕1

Decoding 4



XOR: $1 \oplus 1 = 0$

Architecture and Example

- Assuming one node broadcasting information to several nodes over error-prone medium
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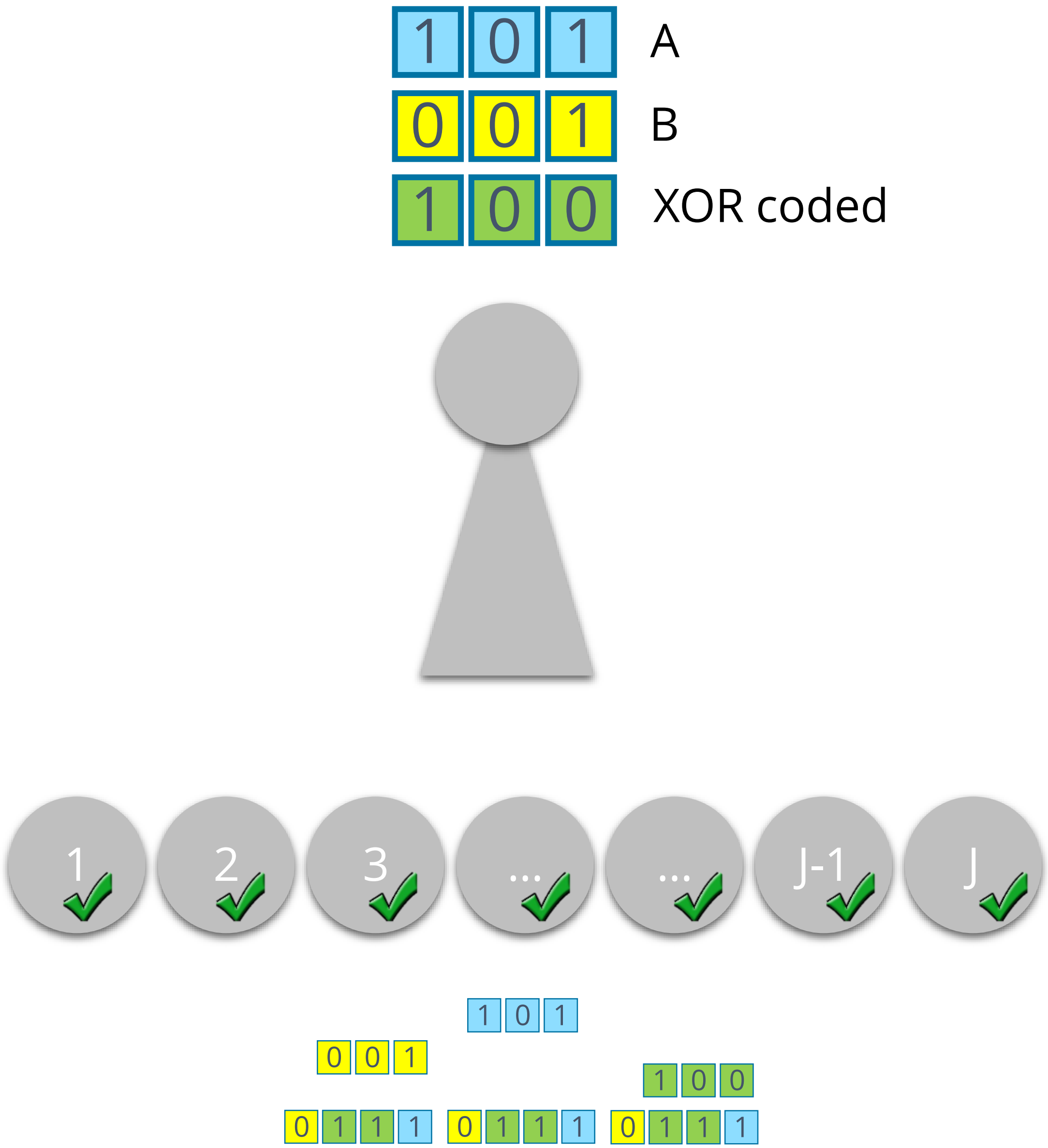
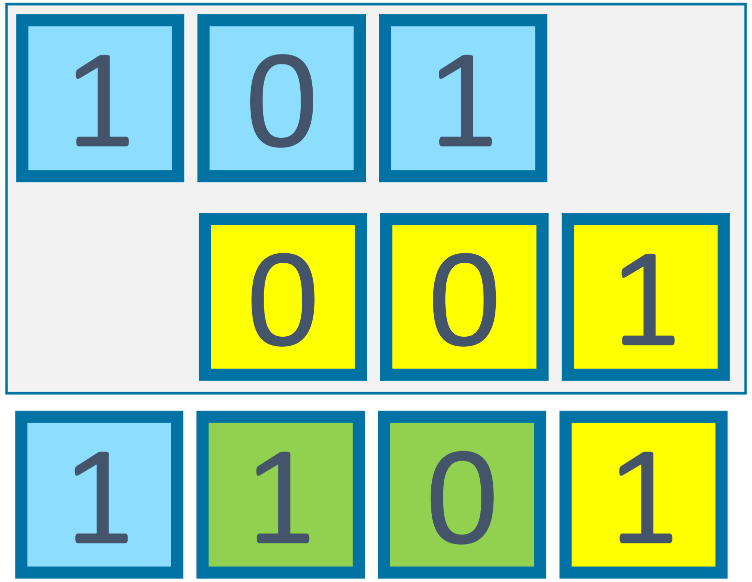


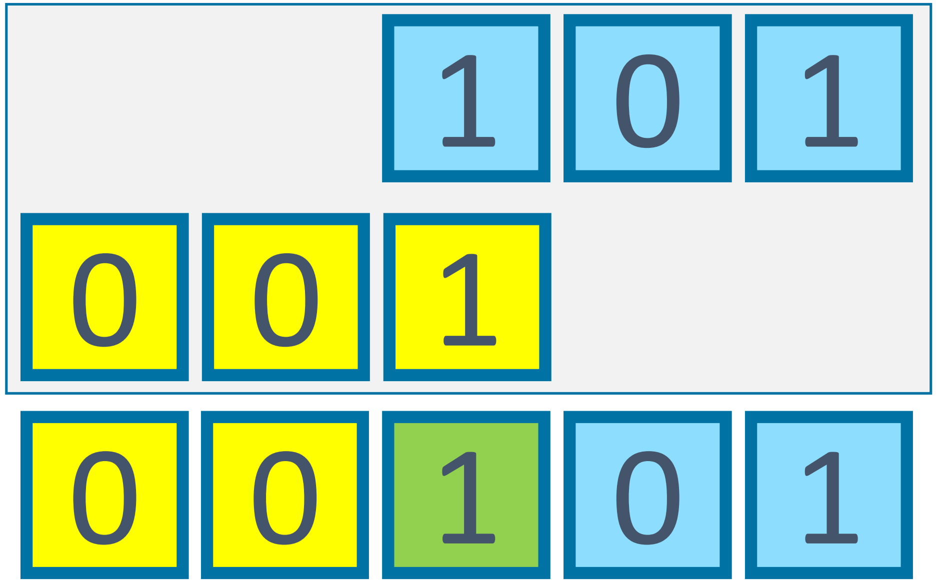
Overhead consideration

- For packets with B bits and S shift bits, the overhead O is simply S/B.
- IP packets of size 1500 byte and 2 bits shift → overhead is marginal.
- How to code multiple packets with bit shifting?
- How many combinations can be achieved with G packets and S shifts?
- What else would be needed?

Encoding – Shifted XOR



Different direction



More shift

Zig Zag Summary

- Very simple extension to the XOR world
- Overhead due to shifting (in our example from 3 to 4 bits)
- Very low complexity due to simple XOR operations
- Same can be achieved with Reed-Solomon and Random Linear Network Coding without overhead but more complexity
- Maybe interesting for IoT device (simple sensor networks)

Digital Inter-Flow Network Coding:

The Medium Access

COPE

Katti, Rahul, Hu, Katabi, Medard, Crowcroft, **“XORs in the air: practical wireless network coding“**, SIGCOMM '06 Proceedings of the 2006 conference on Applications, technologies, architectures, and protocols for computer communications

Network Coding in Wireless Networks

Core contribution by Katti et. al. „XOR in the Air“ applying XOR coding to WIFI enabled meshed networks

Figure 7—Node locations for one floor of the testbed.

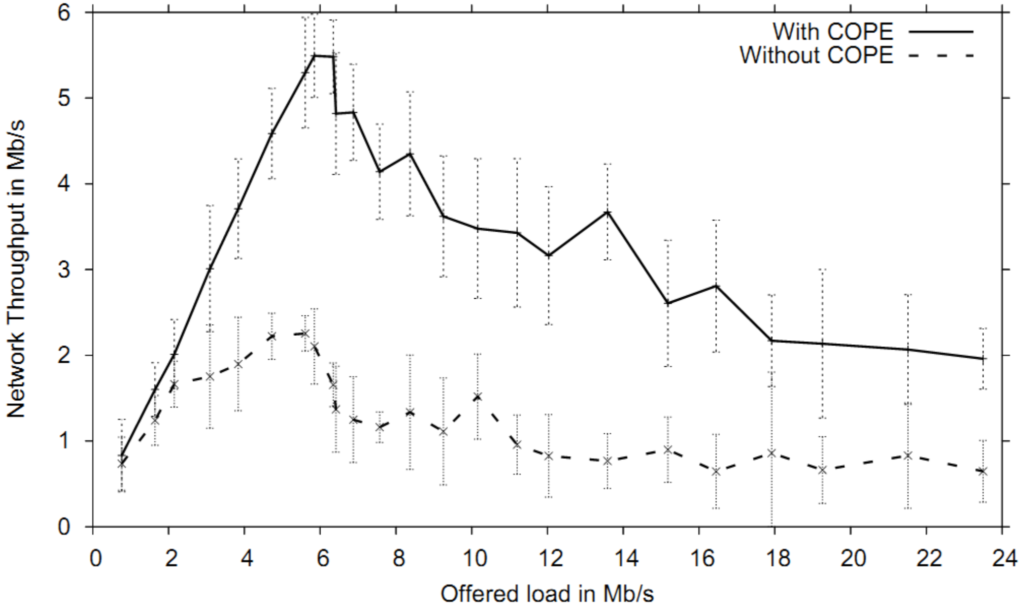


Figure 12—COPE can provide a several-fold (*3-4x*) increase in the throughput of wireless Ad hoc networks. Results are for UDP flows with randomly picked source-destination pairs, Poisson arrivals, and heavy-tail size distribution.

Network Coding in Wireless Networks

COPE characteristics:

- — Desktops
- — Click software (user space)
- — SRCR as routing algorithm
- — Ad hoc mode
- — RTS/CTS disabled
- — Netgear hardware chips
- — 802.11 a/g

CATWOMAN

M. Hundeboll, J. Leddet-Pedersen, J. Heide, M.V. Pedersen, S.A. Rein, and F.H.P. Fitzek, **"Catwoman: Implementation and performance evaluation of ieee 802.11 based multi-hop networks using network coding,"** in I E E E V T S Vehicular Technology Conference. Proceedings. 2012, IEEE.

F. Zjao, M. Medard, M. Hundeboll, J. Ledet-Pedersen, S.A. Rein, and F.H.P. Fitzek, **"Comparison of analytical and measured performance results on network coding in ieee 802.11 ad-hoc networks,"** in The 2012 International Symposium on Network Coding, June 2012.

CATWOMAN (2011)

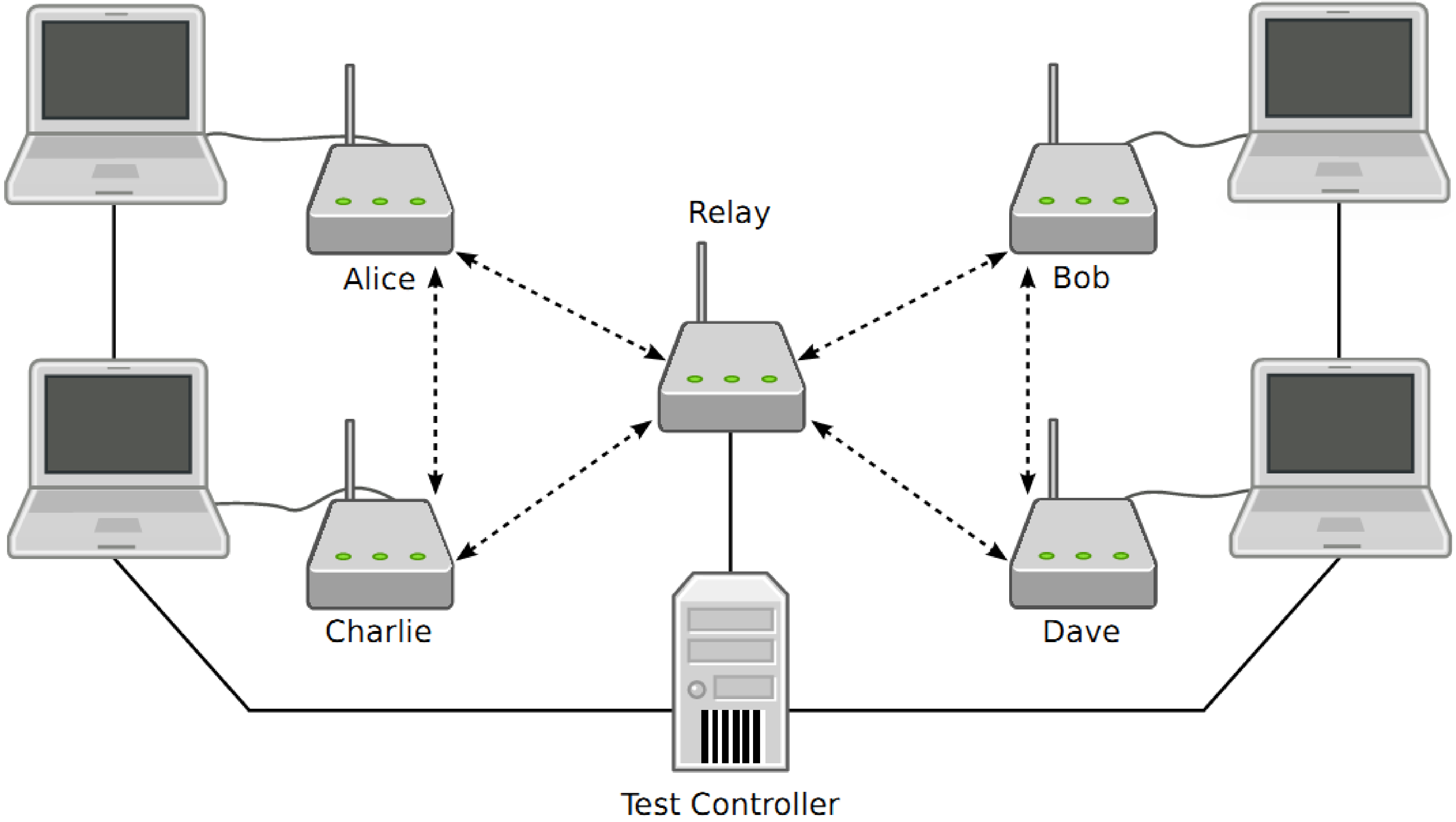
Foto: Torsten Proß, Jeibmann Photographik

CATWOMAN (2011)

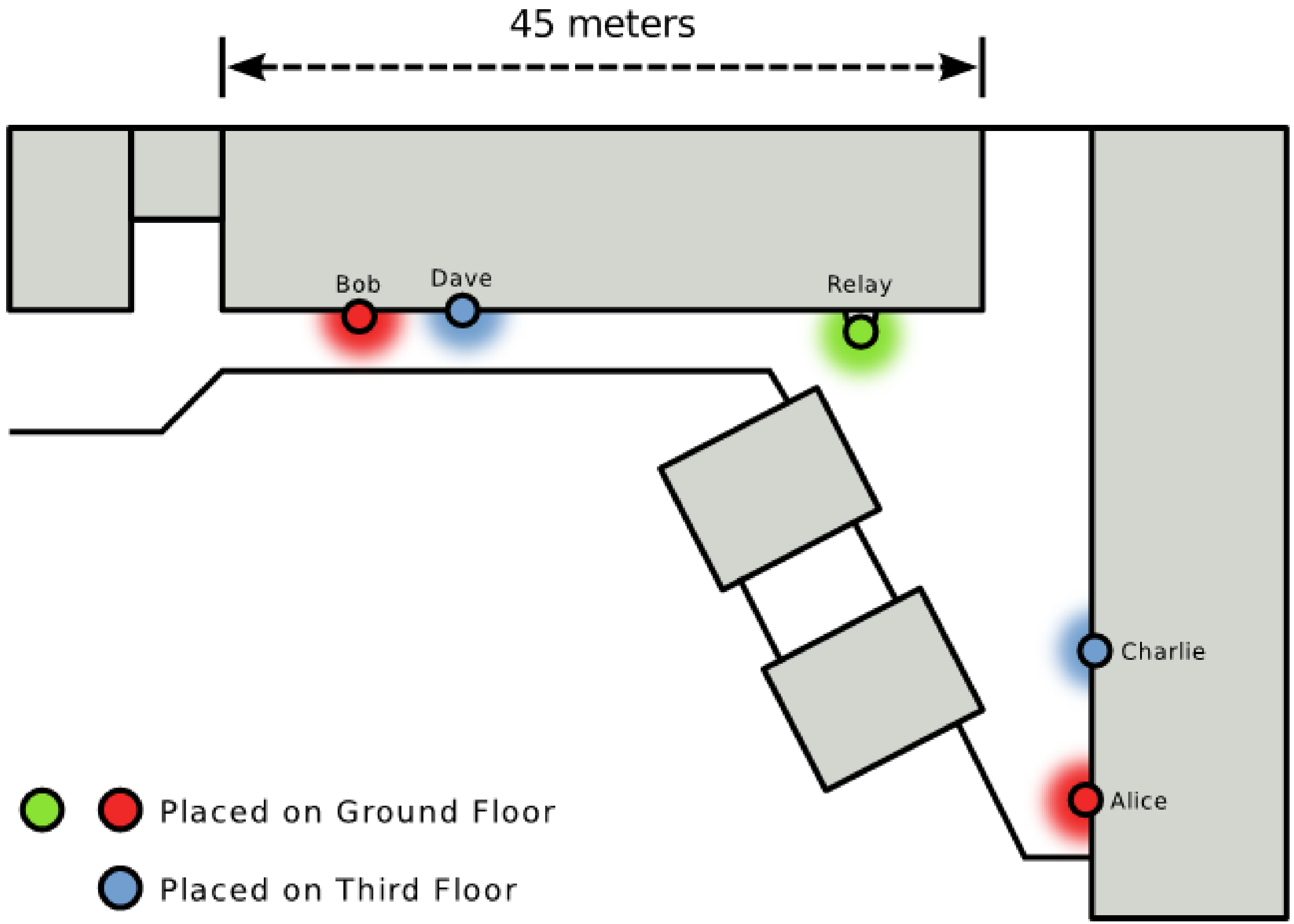
- Multihop network based on BATMAN routing (draft RFC)
- Implementation of network coding on real WiFi access points
- Multi hop
- Part of Linux Kernel 3.10

CATWOMAN: Scenarios under Investigation

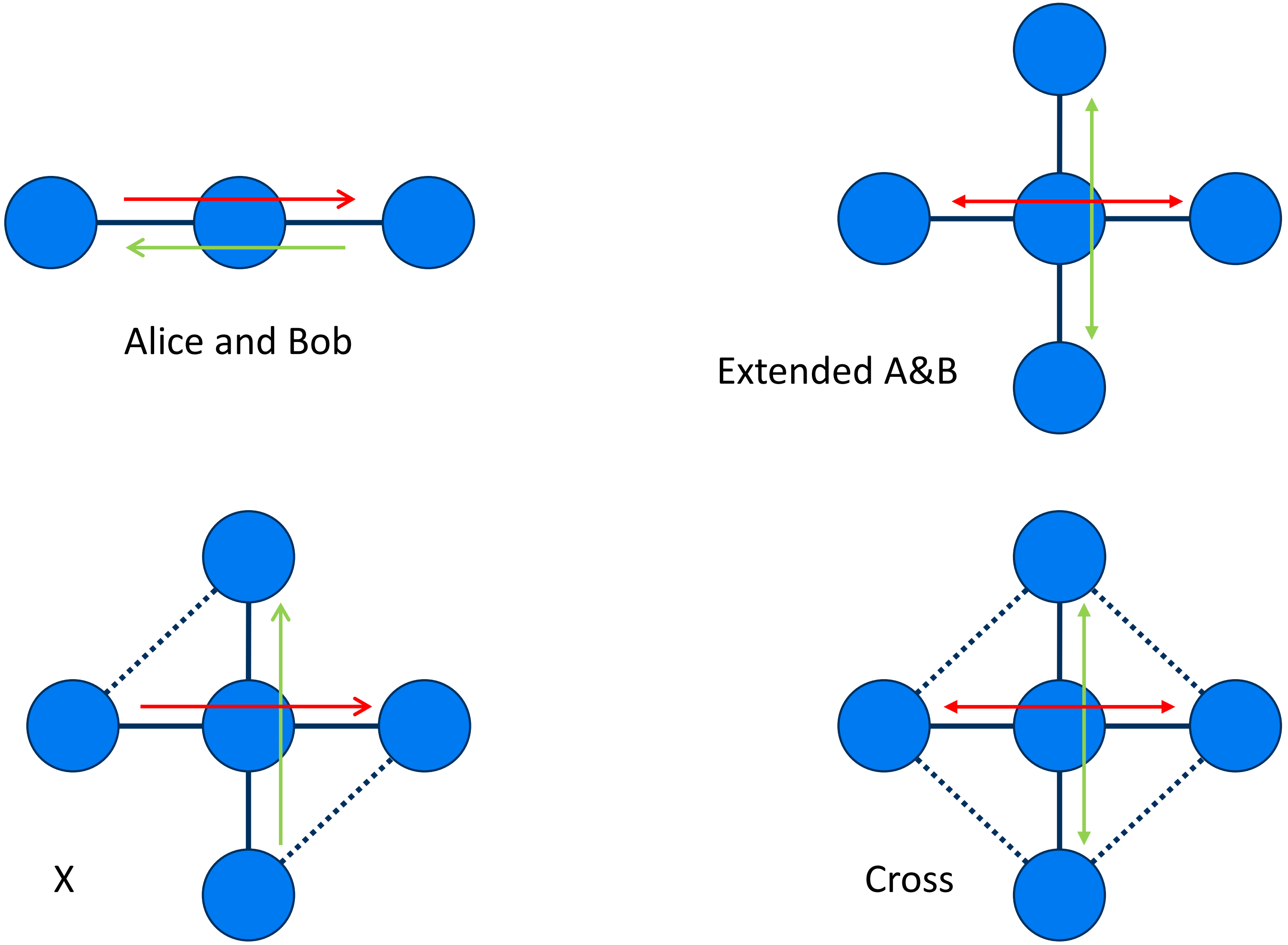
CATWOMAN: Testbed



CATWOMAN: Testbed Placement



CATWOMAN Topologies



CATWOMAN Metric

- Throughput [bit/s]
  - Bandwidth used
- Losses [%]
- Energy [J]
  - Activity level of send, receive, idle
  - CPU load
- Delay [s]

Model for Alice and Bob (symmetric traffic)

Assumption

- Alice and Bob have no direct connection
- Same amount of traffic is generated by Alice and Bob
- Medium Access Control (MAC) is based on IEEE802.11, i.e. CSMA/CA

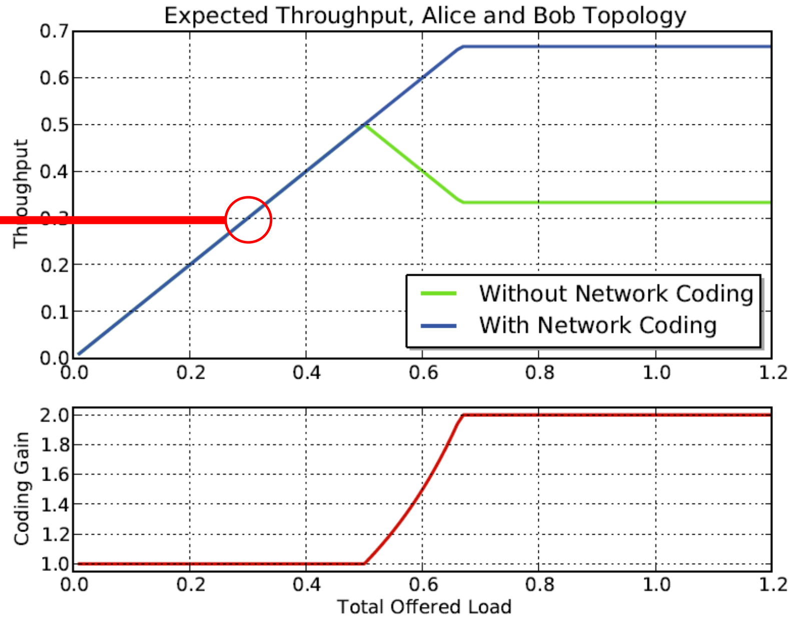
IEEE802.11 Alice & Bob Throughput Model

15%

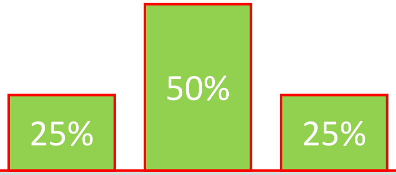
30%

15%

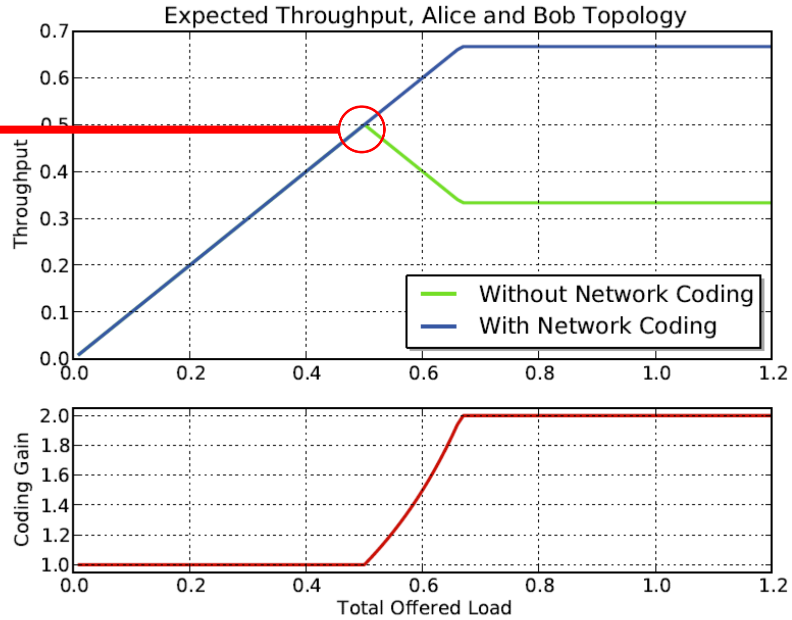
<u>Load 1:</u>
w/o NC the relay sends twice as much as Alice and Bob. No impact on the throughput.



IEEE802.11 Alice & Bob Throughput Model



Load 2:
w/o NC the relay sends twice as much as Alice and Bob and channel capacity is reached. Still no impact on the throughput.



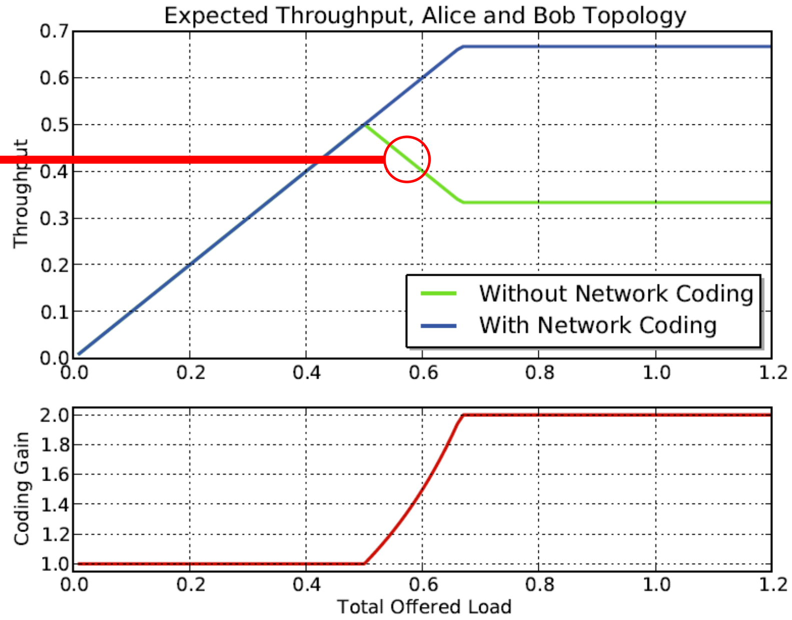
IEEE802.11 Alice & Bob Throughput Model

29%

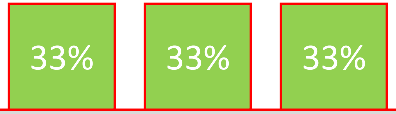
42%

29%

Load 3:
w/o NC Alice and Bob are „stealing“ the capacity from the relay. 802.11 fairness destroys the performance of the system.



IEEE802.11 Alice & Bob Throughput Model



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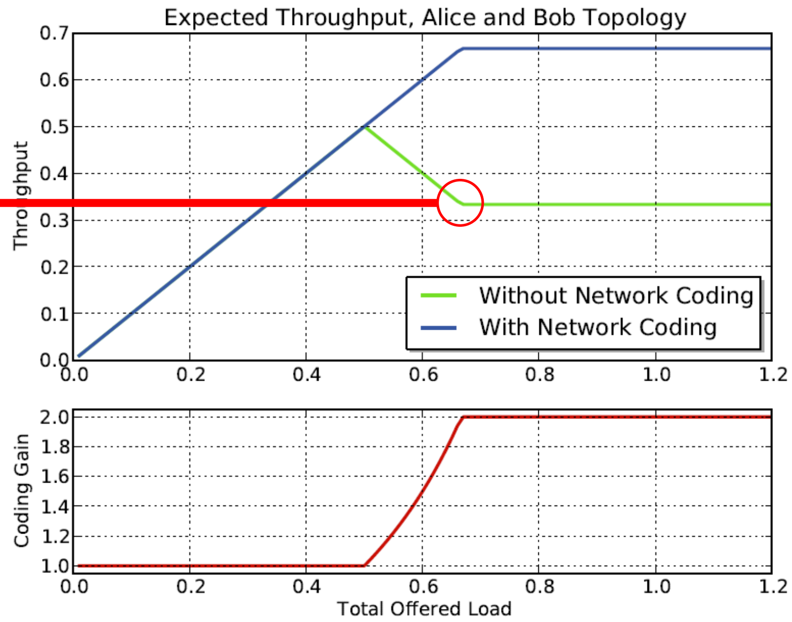
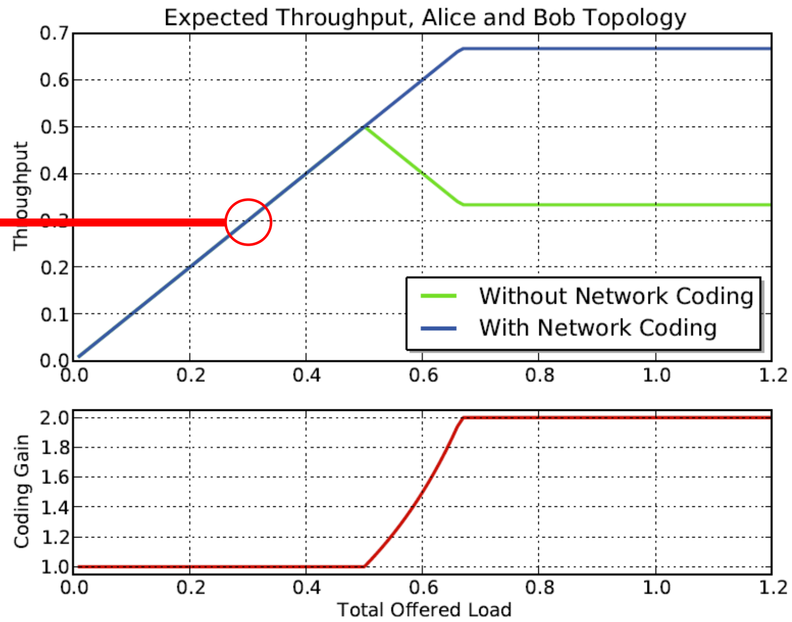


IEEE802.11 Alice & Bob Throughput Model

15% 15% 15%

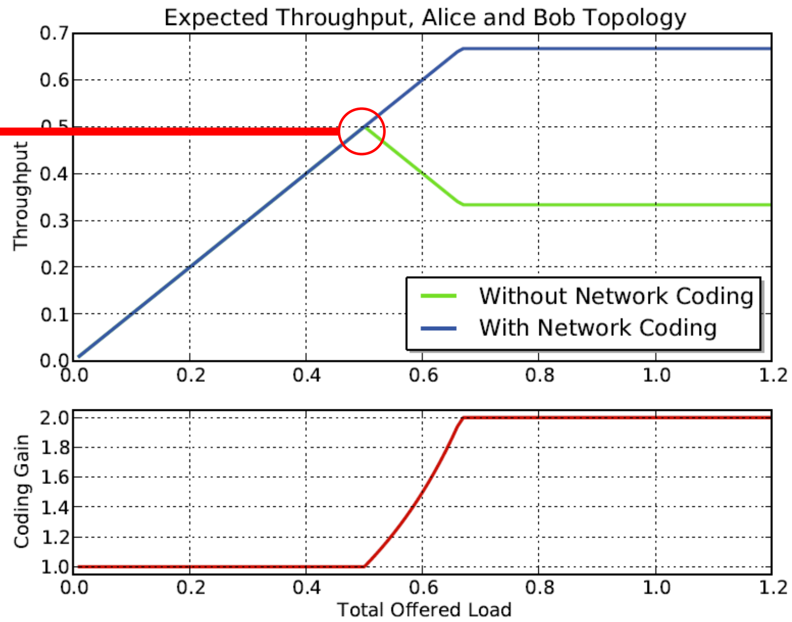
Load 1:
w NC the relay sends the same amount of data as Alice or Bob.



IEEE802.11 Alice & Bob Throughput Model

25% 25% 25%

Load 2:
w NC channel capacity is **NOT** reached



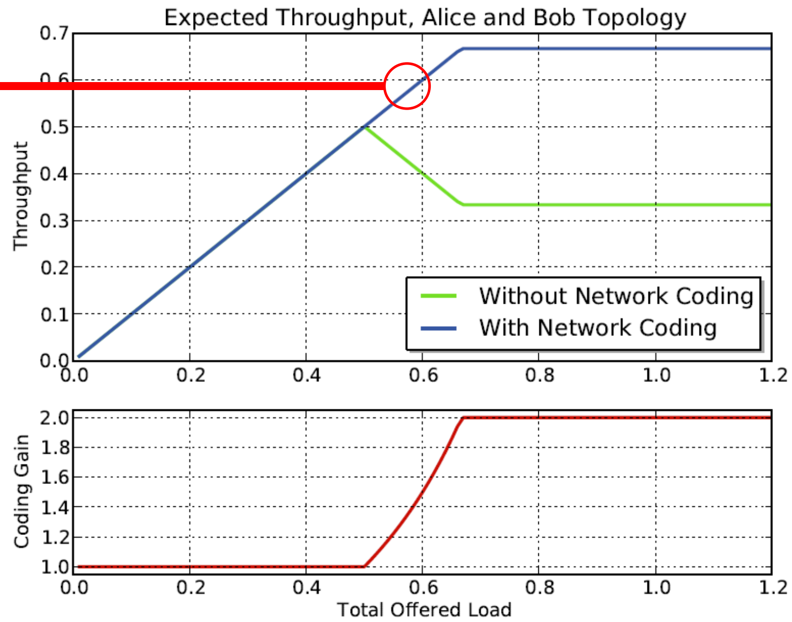
IEEE802.11 Alice & Bob Throughput Model

29%

29%

29%

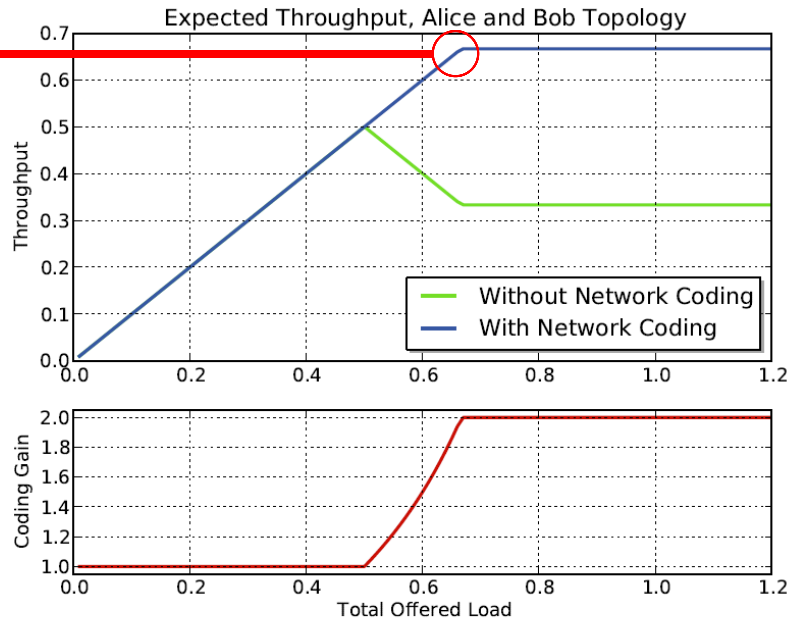
<u>Load 3:</u>
w NC Alice, Bob and the relay live in perfect harmony, each of the entities requests one third of the capacity



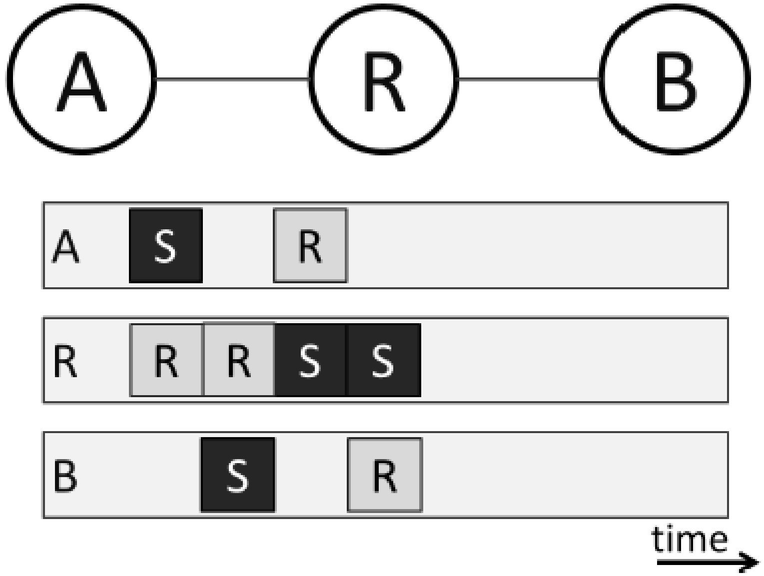
IEEE802.11 Alice & Bob Throughput Model

33% 33% 33%

Load 4:
w NC Alice, Bob and the relay live in perfect harmony now the channel capacity is reach and therefore the throughput remains constant.



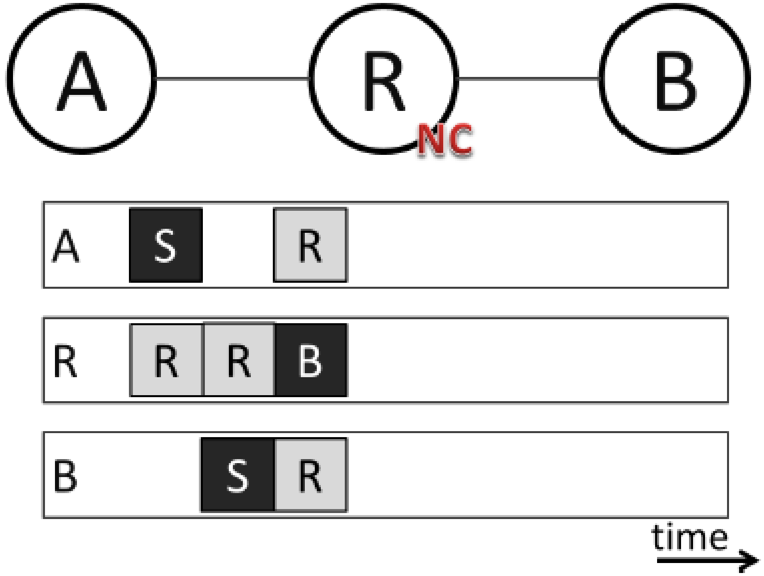
Alice and Bob: Activity Chart



4 send

4 receive

rest idle

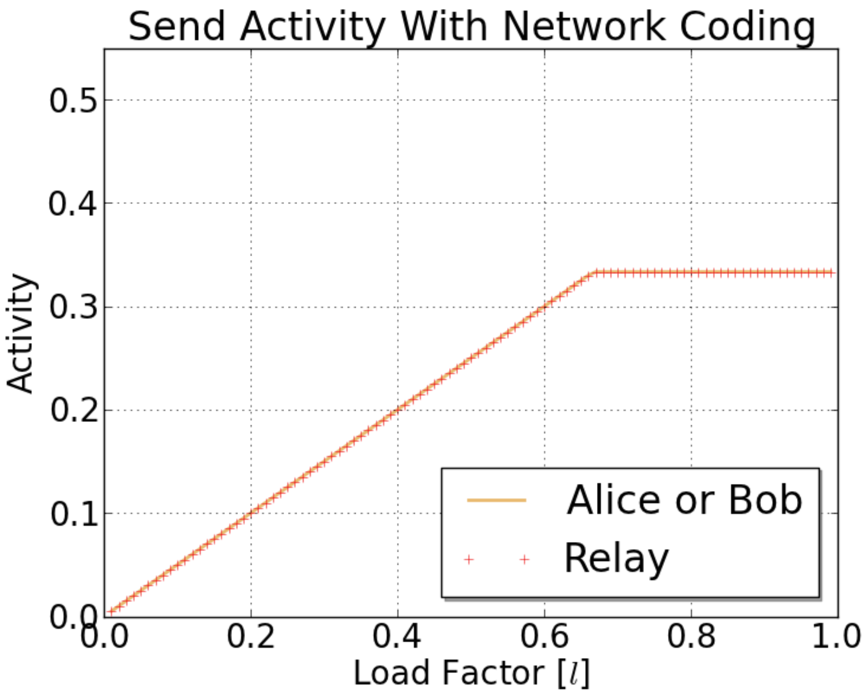


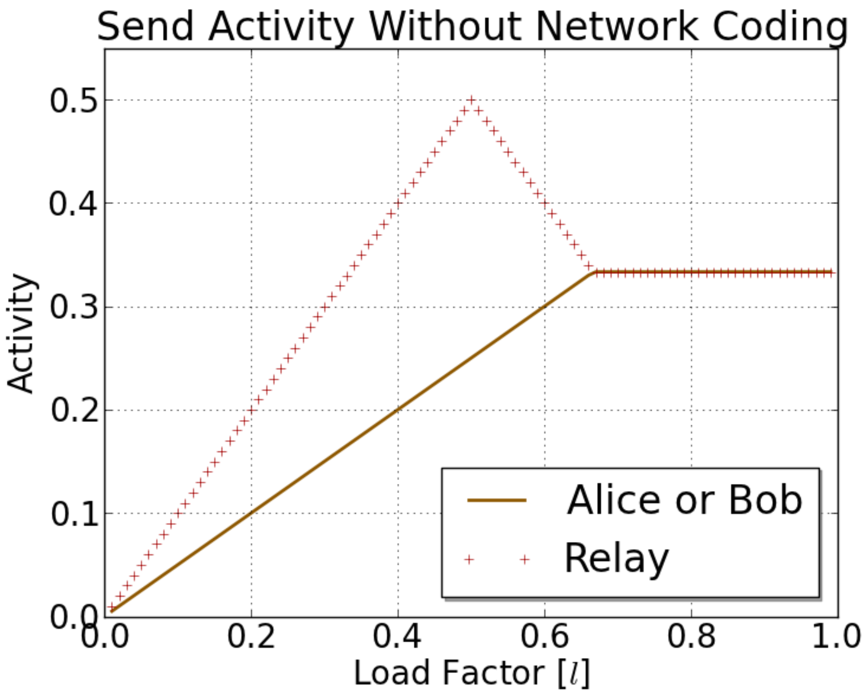
3 send

4 receive

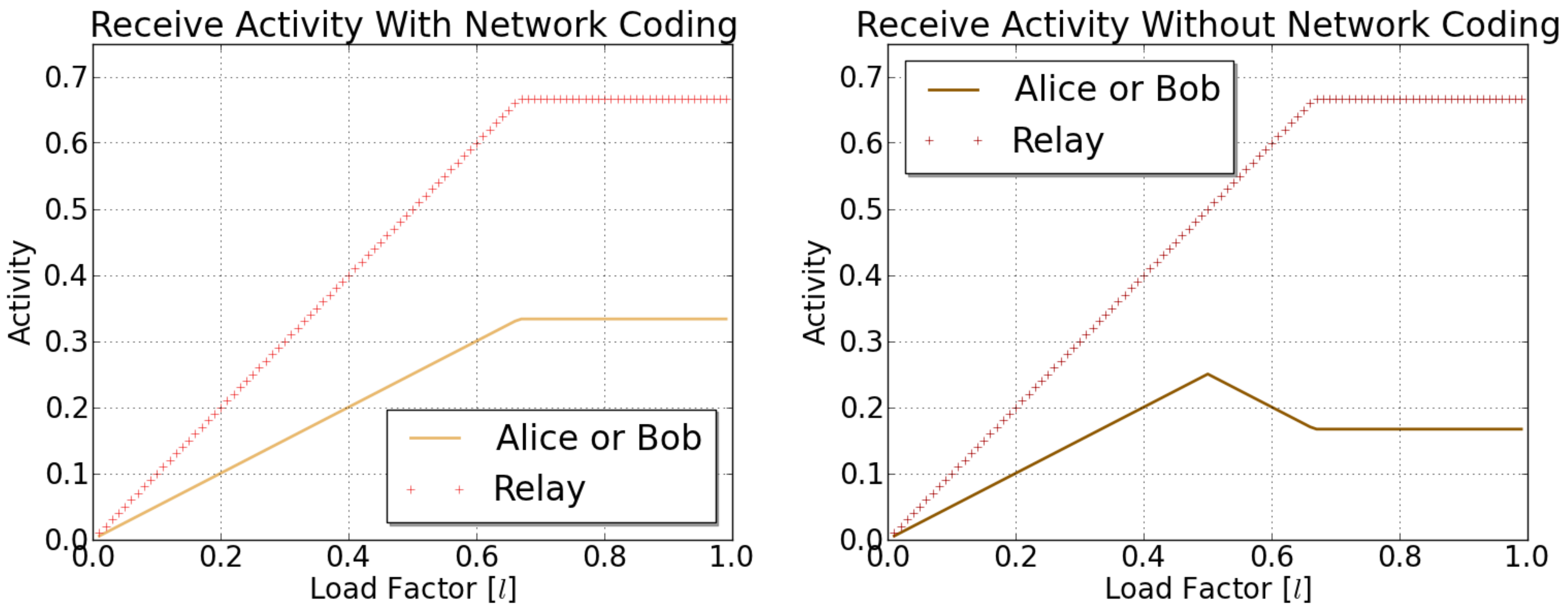
rest idle

Send Activity Model

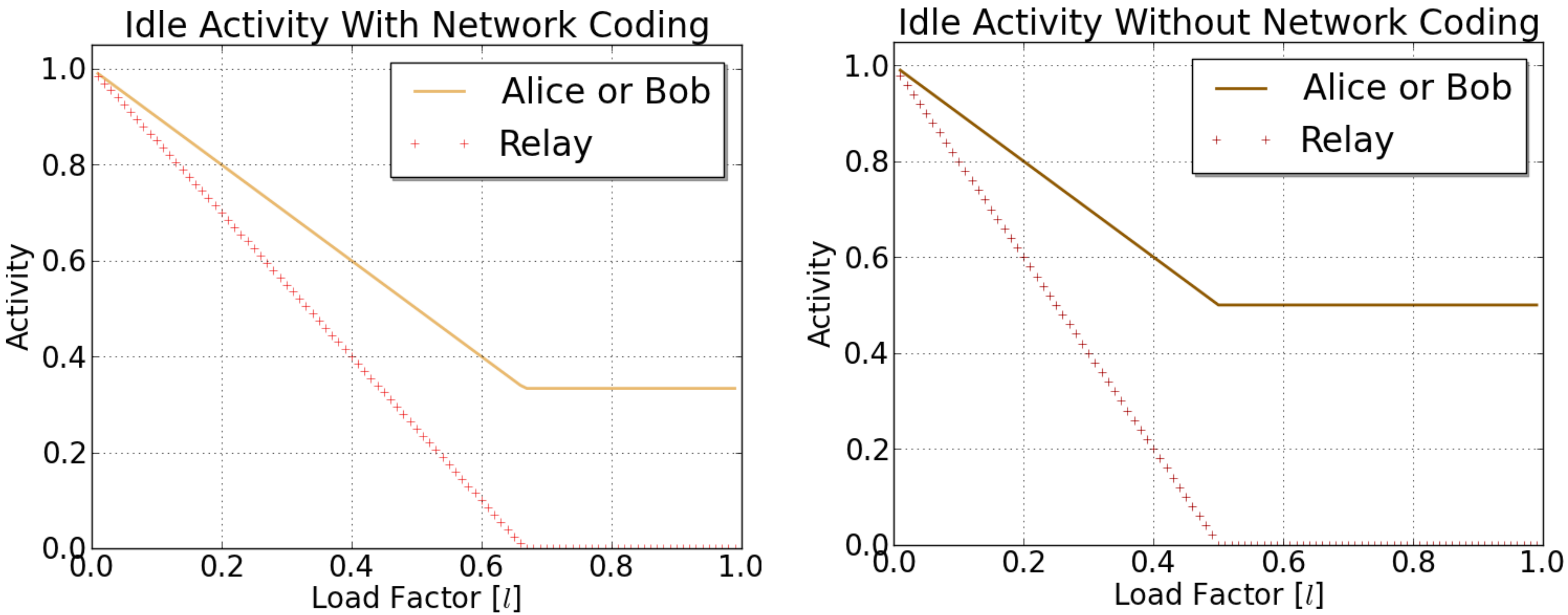




Receive Activity Model

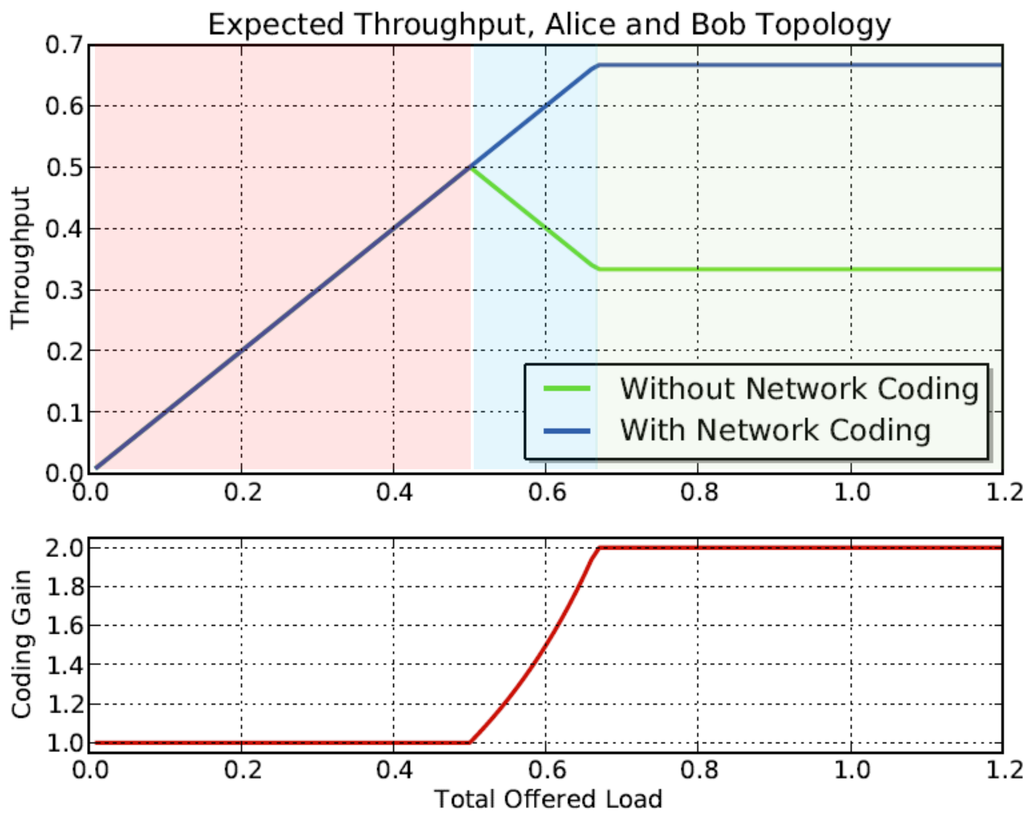


Idle Activity Model



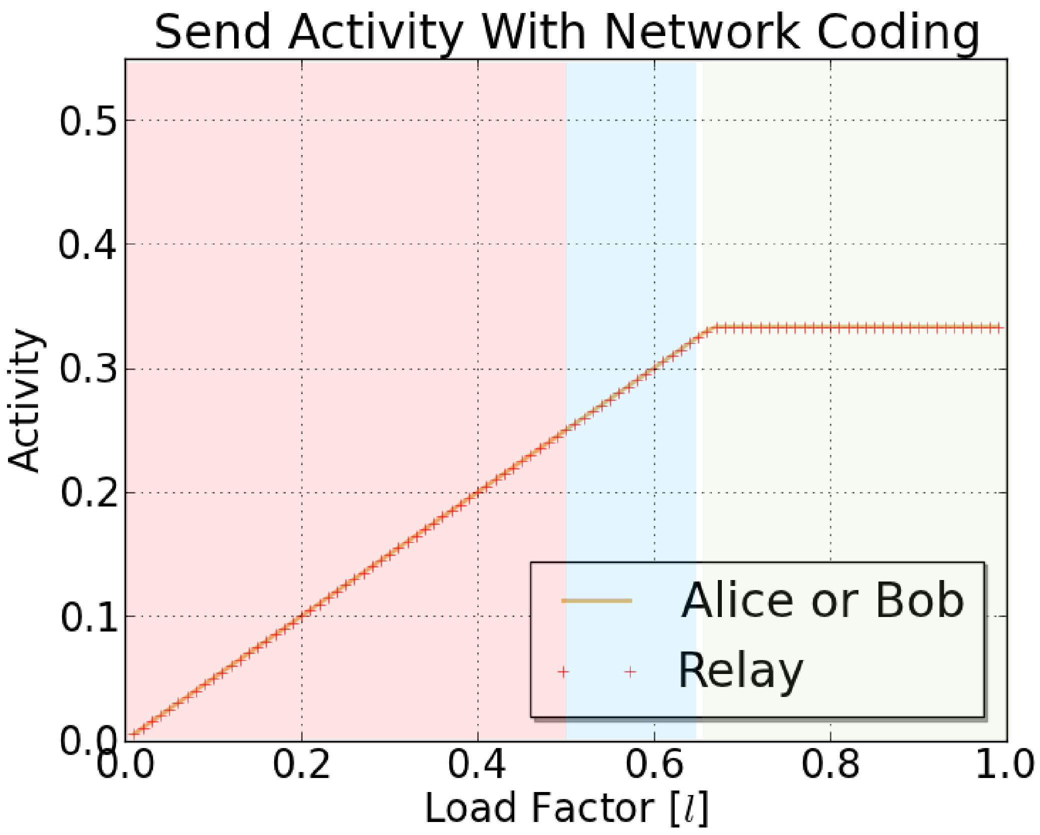
Activity Model

		Phase	I	II	III
		Load [l]	0-0.5	0.5-0.$\overline{6}$	0.$\overline{6}$-1.0
Send [α_s]	WoNC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	l	$1-l$	$\frac{1}{3}$
	NC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
Receive [α_r]	WoNC	A&B	$\frac{1}{2}l$	$\frac{1-l}{2}$	$\frac{1}{6}$
		R	l	l	$\frac{2}{3}$
	NC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	l	l	$\frac{2}{3}$



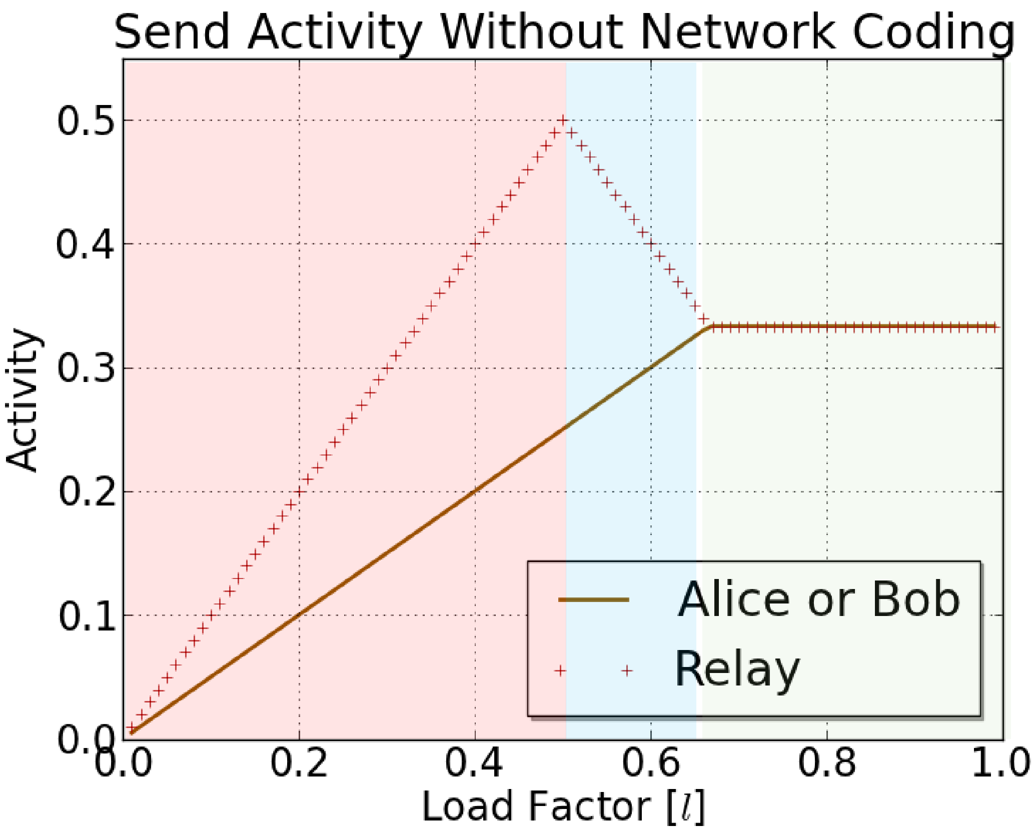
Activity Model

		Phase	I	II	III
		Load [l]	0-0.5	$0.5\text{-}0.\overline{6}$	$0.\overline{6}\text{-}1.0$
Send [α_s]	WoNC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	l	$1-l$	$\frac{1}{3}$
	NC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
Receive [α_r]	WoNC	A&B	$\frac{1}{2}l$	$\frac{1-l}{2}$	$\frac{1}{6}$
		R	l	l	$\frac{2}{3}$
	NC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	l	l	$\frac{2}{3}$



Activity Model

		Phase	I	II	III
		Load [l]	0-0.5	0.5-0.$\overline{6}$	0.$\overline{6}$-1.0
Send [α_s]	WoNC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	l	$1-l$	$\frac{1}{3}$
	NC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
Receive [α_r]	WoNC	A&B	$\frac{1}{2}l$	$\frac{1-l}{2}$	$\frac{1}{6}$
		R	l	l	$\frac{2}{3}$
	NC	A&B	$\frac{1}{2}l$	$\frac{1}{2}l$	$\frac{1}{3}$
		R	l	l	$\frac{2}{3}$



Power Model

In order to derive total power we sum up the product of the activity level a and power level P of the individual states.

$$P_{total} = P_r * a_r + P_s * a_s + P_i * a_i$$

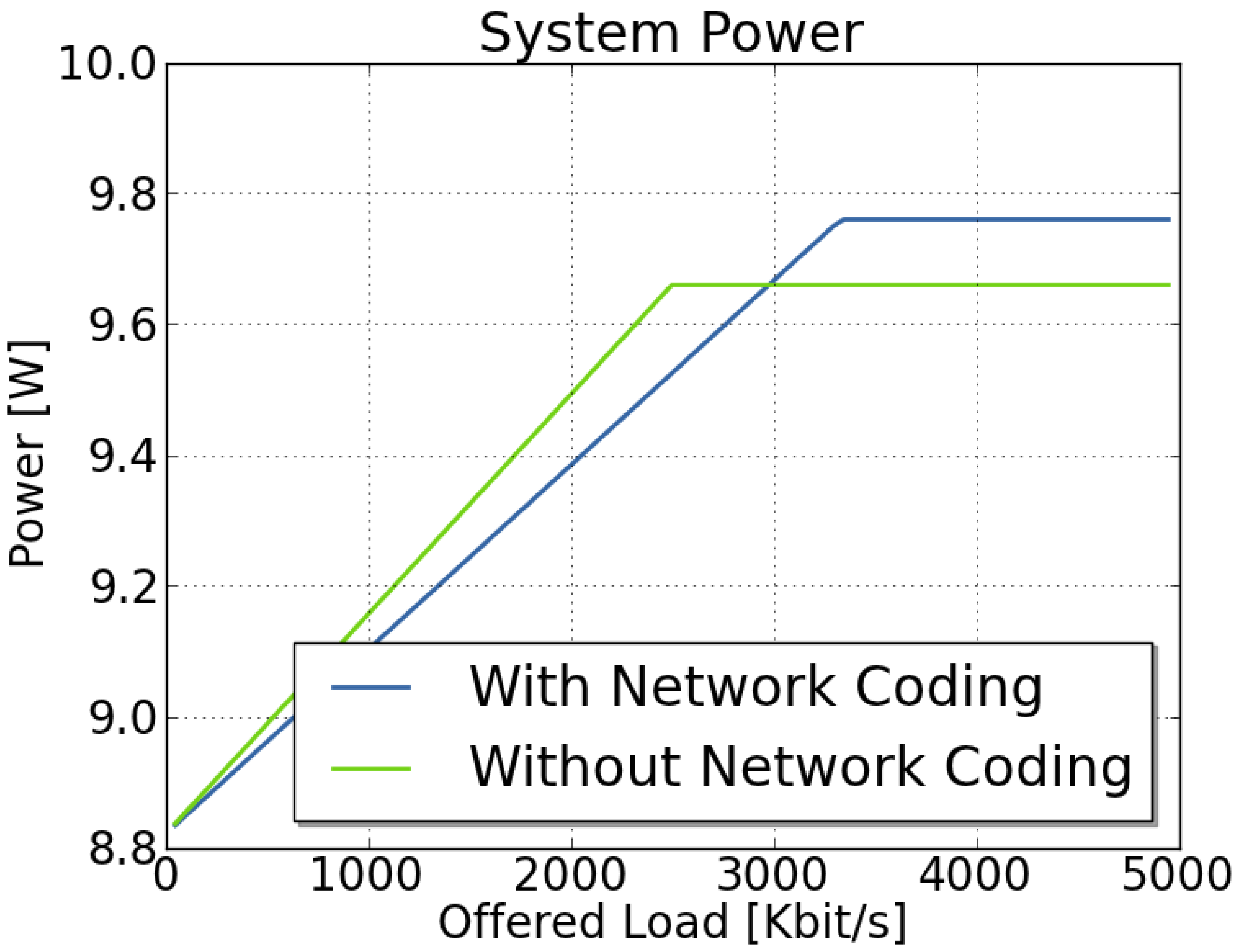
Power Model

Out of our measurements for WHITEBOX we derive:

- Total power level sending: $P_{send} = 3.48$ W
- Total power level receiving: $P_{receive} = 3.24$ W
- Total power level idle: $P_{idle} = 2.94$ W

Later we assume a maxium capacity of the channel of 4.9 Mbit/s

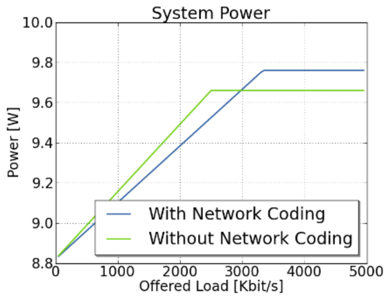
Power Rate Model



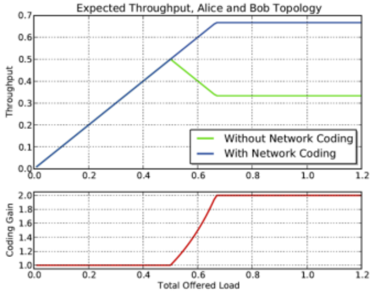
Energy Model

$$Energy = Power * Time$$

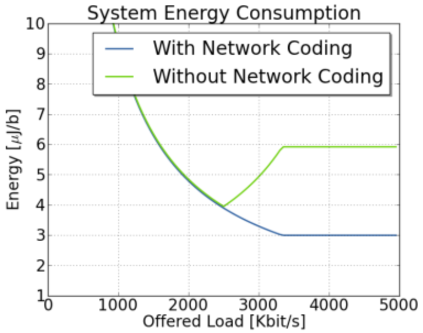
$$Energy\ per\ bit = \frac{Power}{Throughput} = \frac{Joule}{bit}$$



:



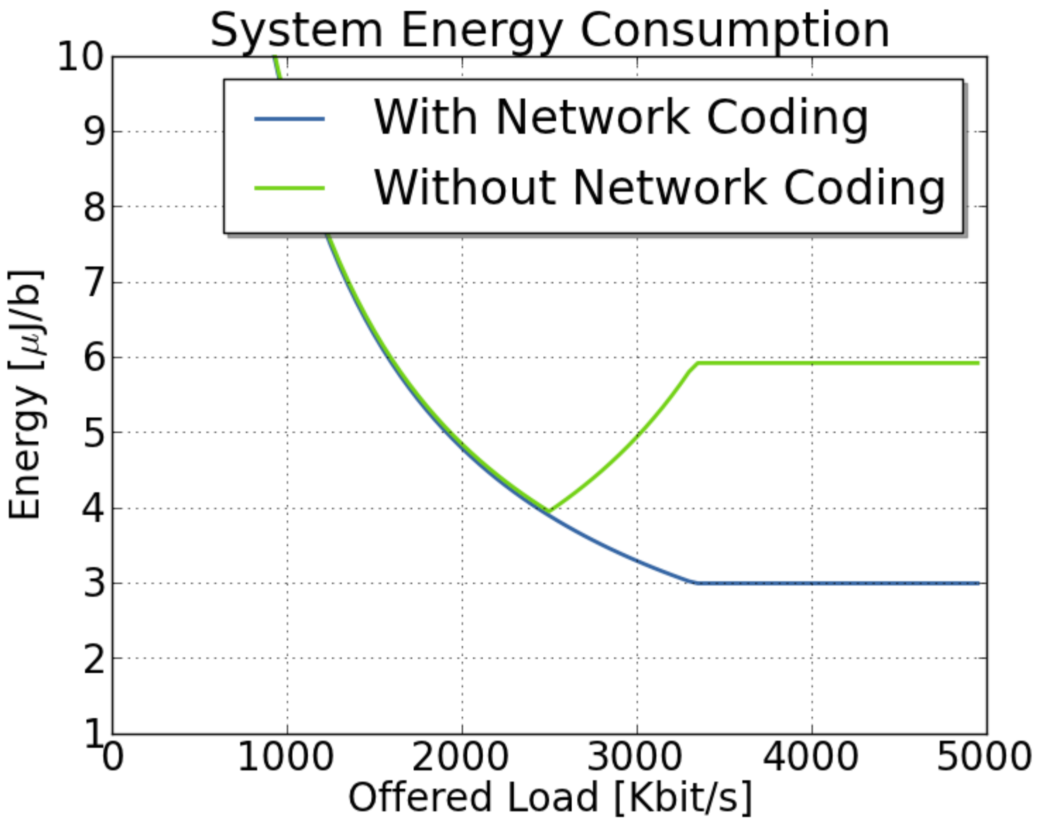
=



power throughput energy/bit

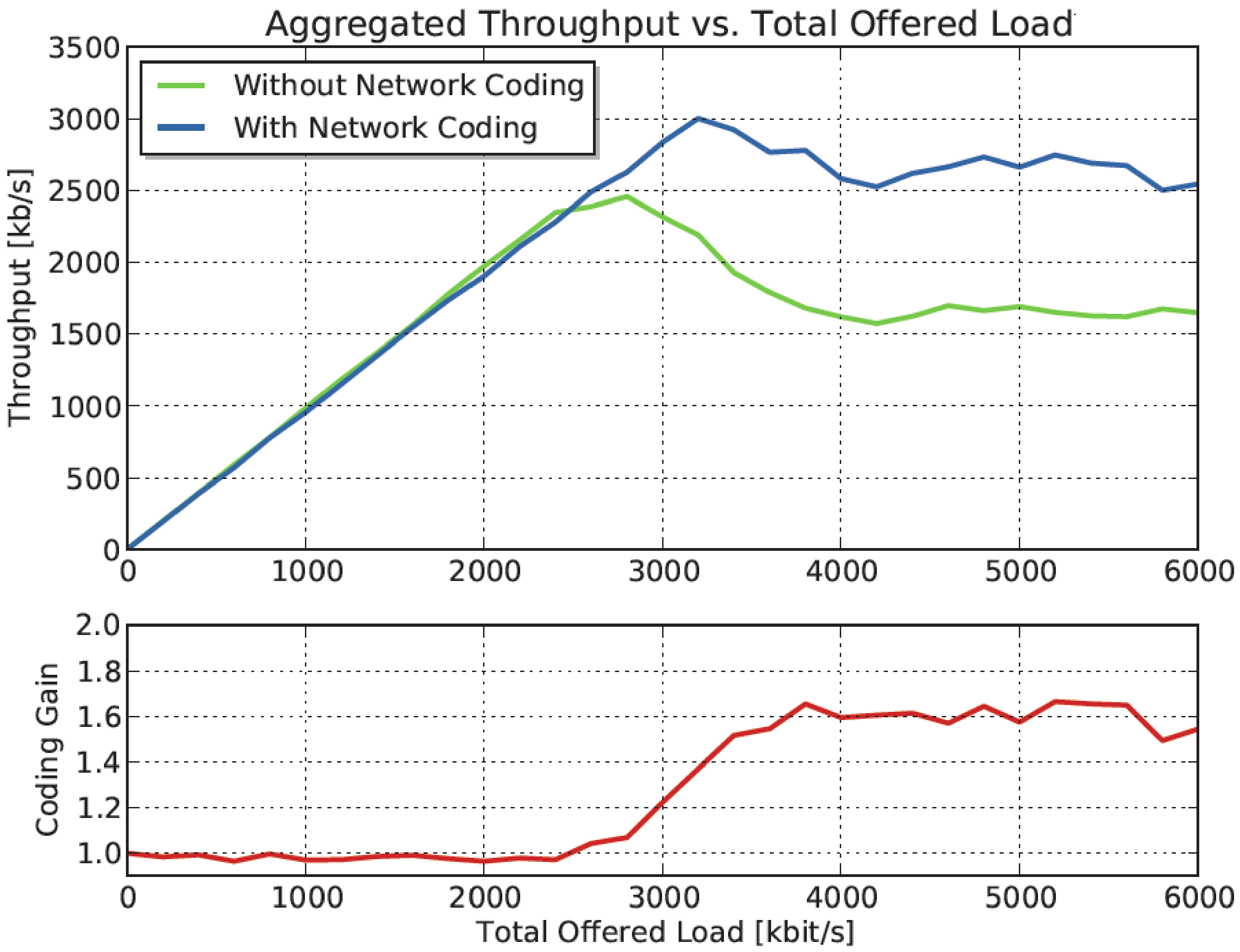
Energy Model

$$Energy\ per\ bit = \frac{Power}{Throughput} = \frac{Joule}{bit}$$

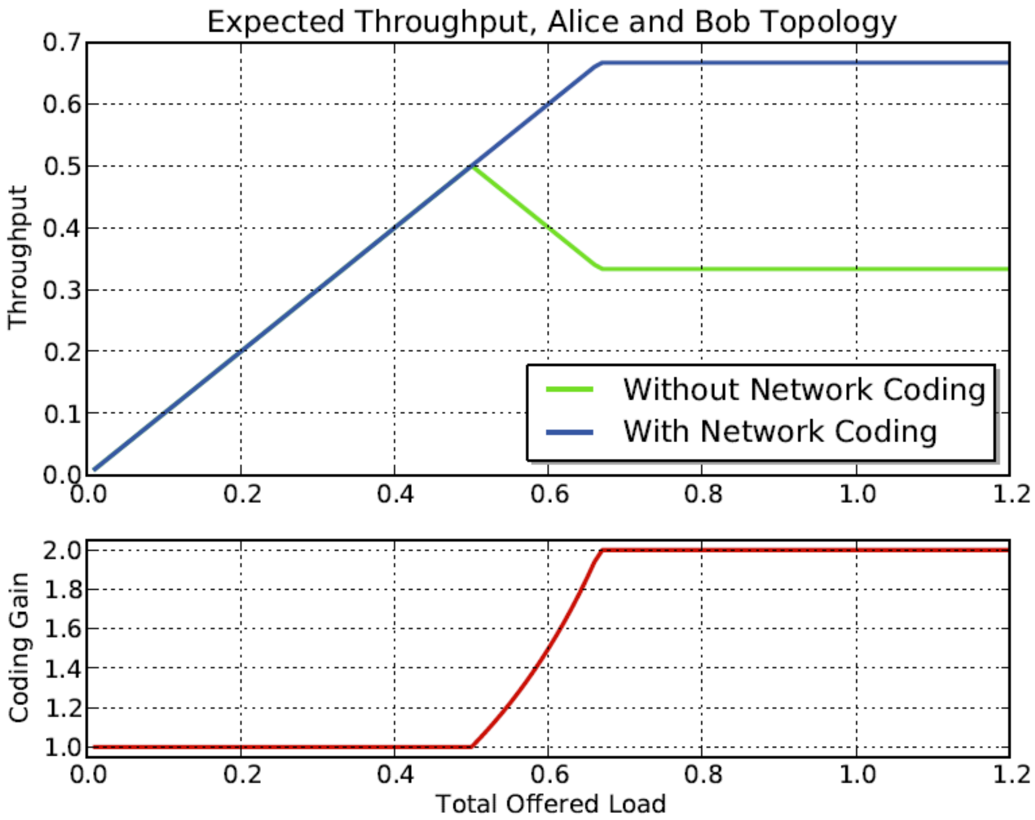


CATWOMAN Measurement Results

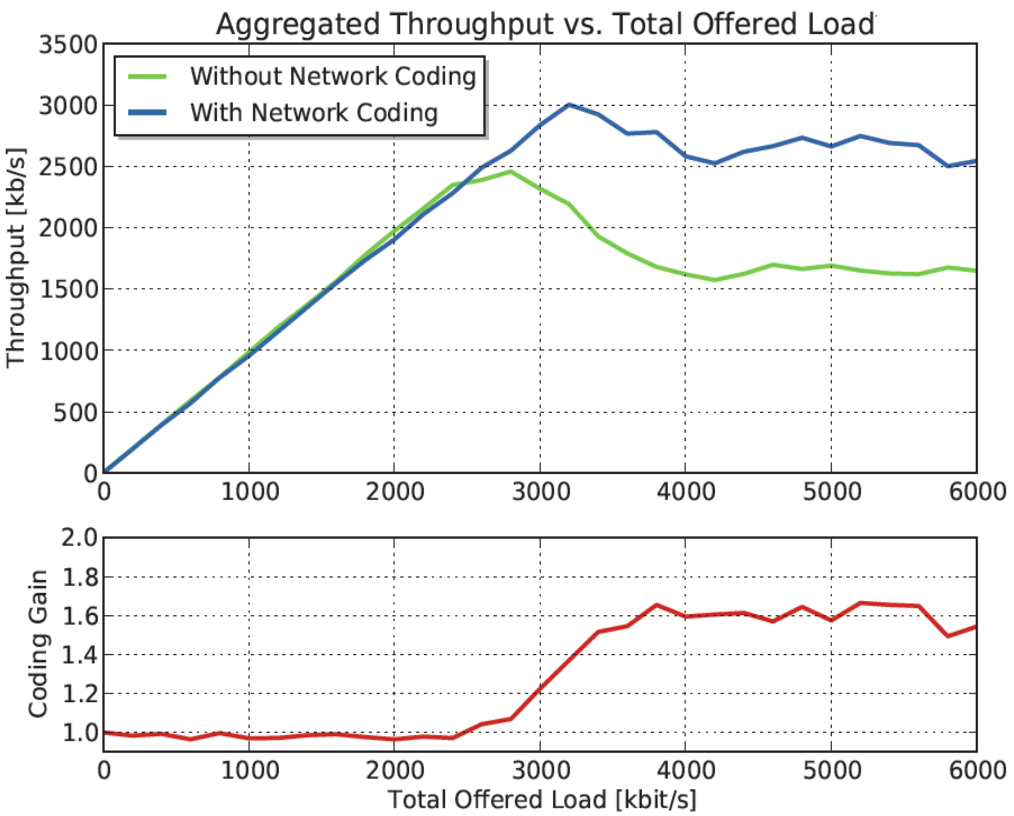
CATWOMAN: Results



Analytical results



Measurement results



Discussion

Results fit nicely

But

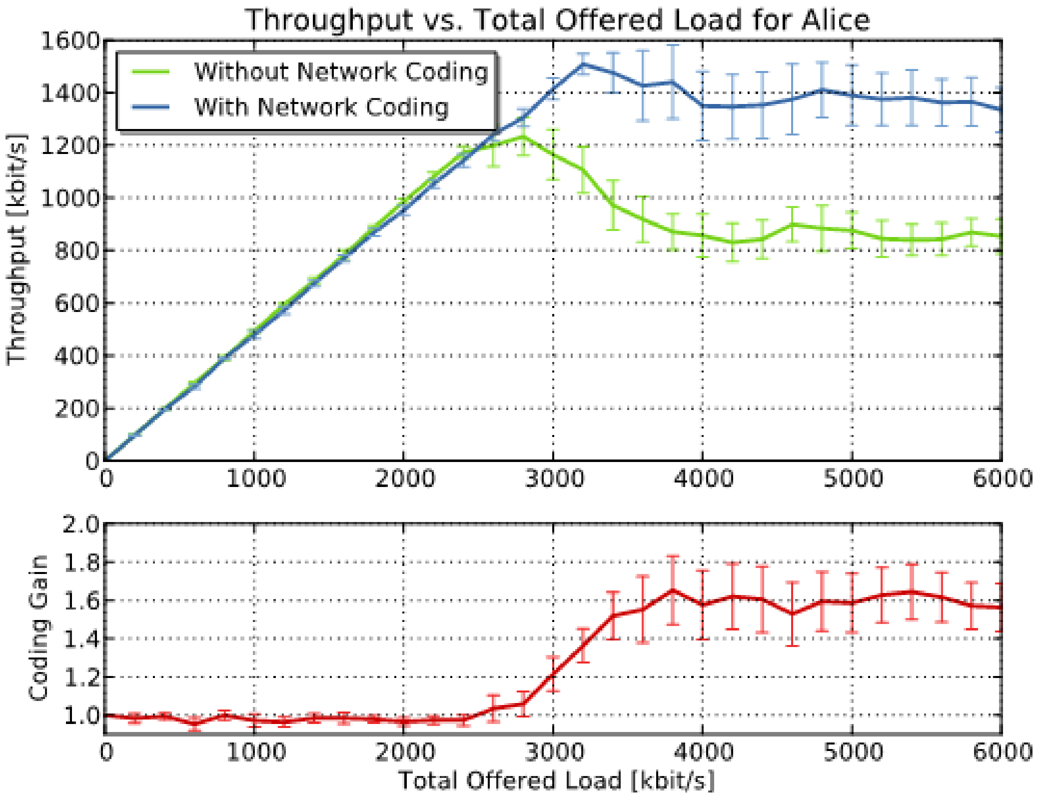
— The coding gain is with 1.6 lower than expected with 2.0

— The throughput of NC is not stable after reaching its maximum

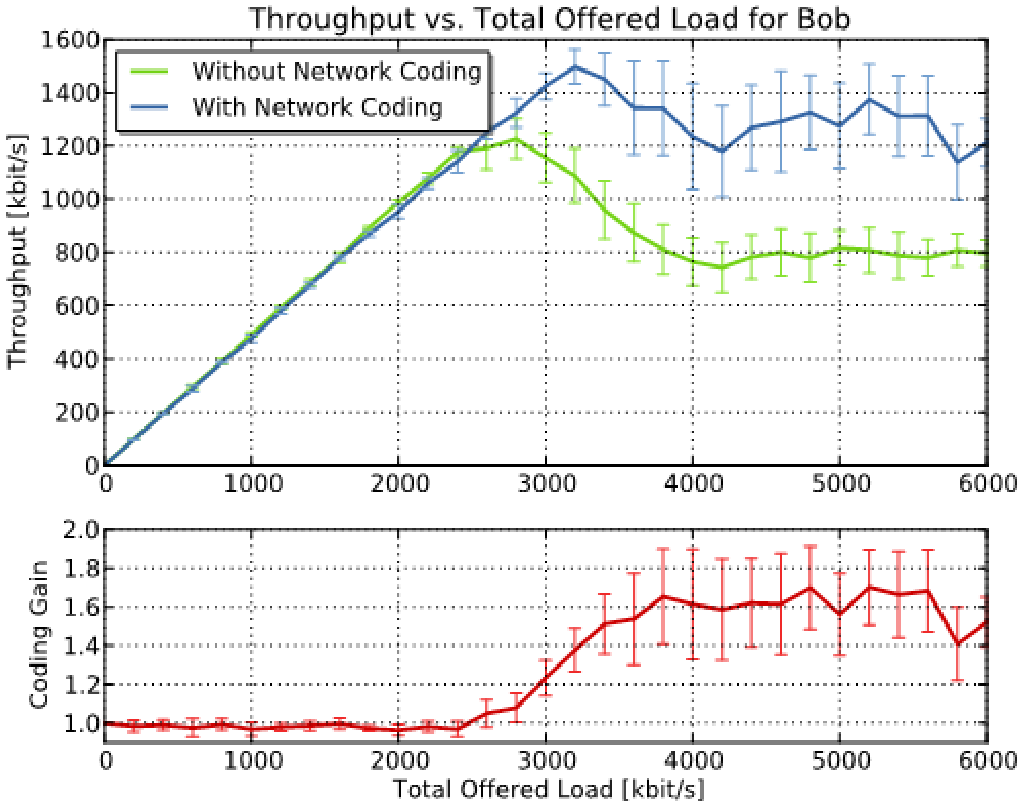
Why?

CATWOMAN: Results

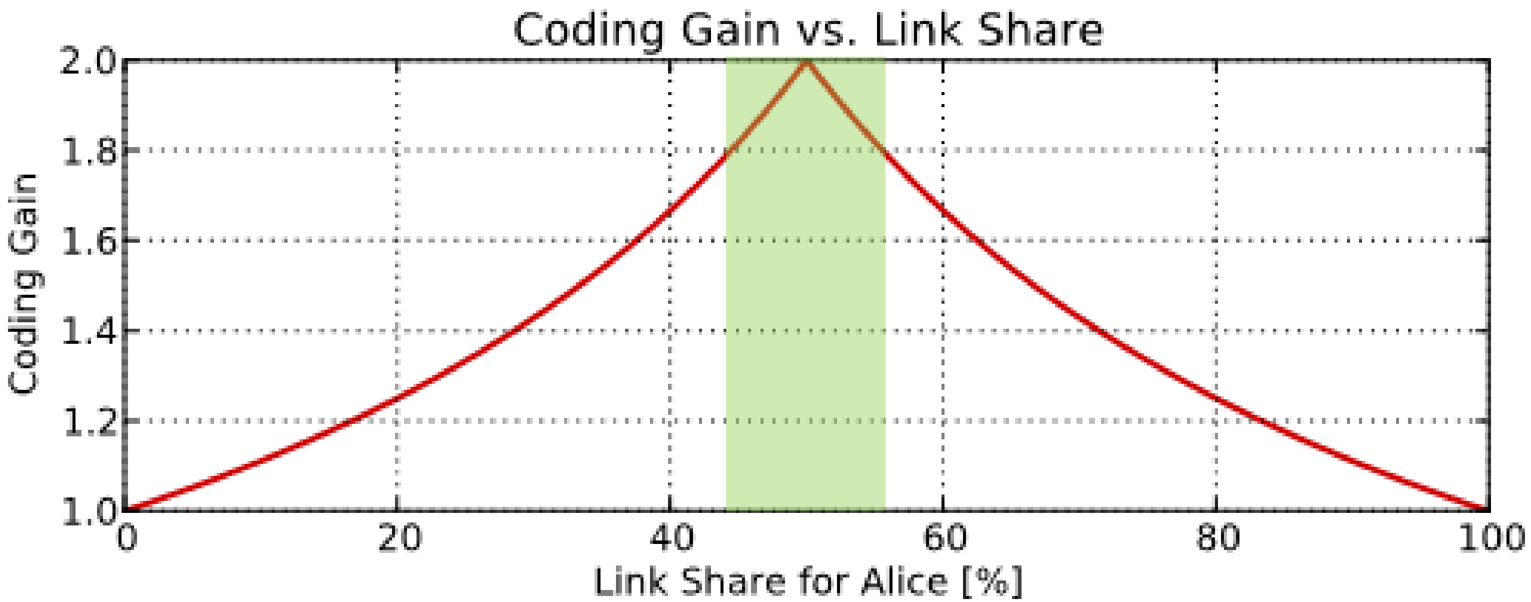
Alice



Bob



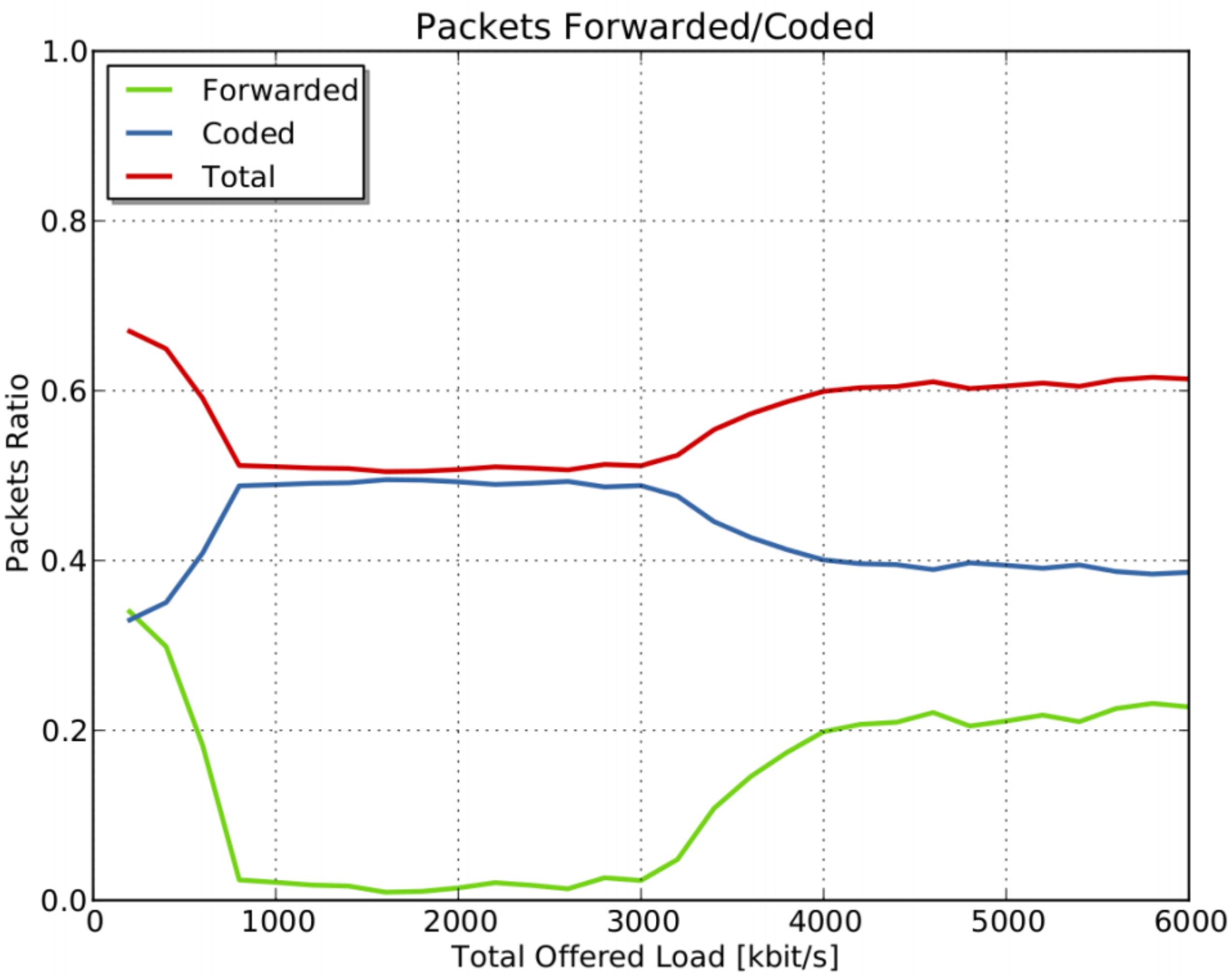
CATWOMAN: Results



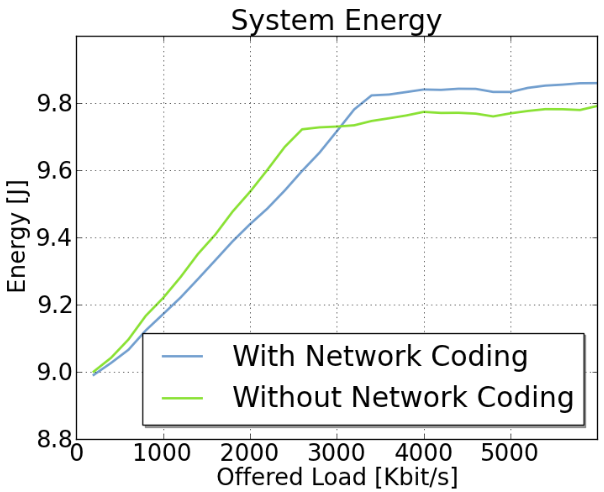
$$g_C = \frac{N}{N \cdot x + N((1-x)-x)} =$$

$$\frac{1}{1-x}, \qquad 0 \leq x \leq 0.5.$$

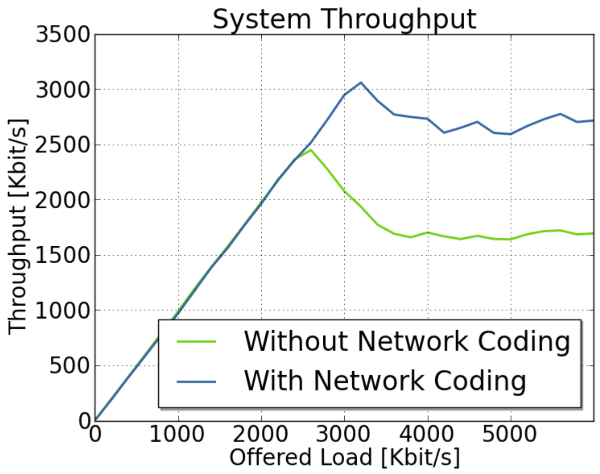
CATWOMAN: Results



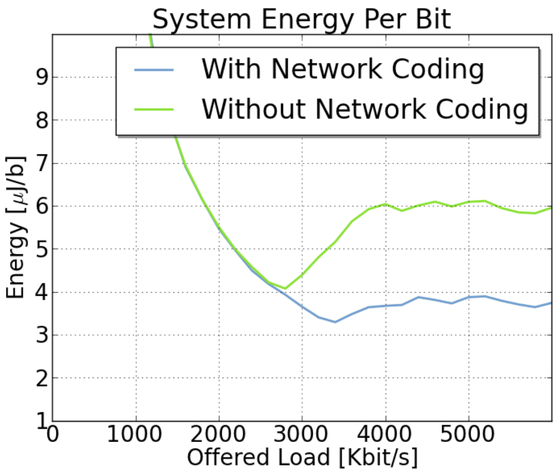
First Measurement Result



power

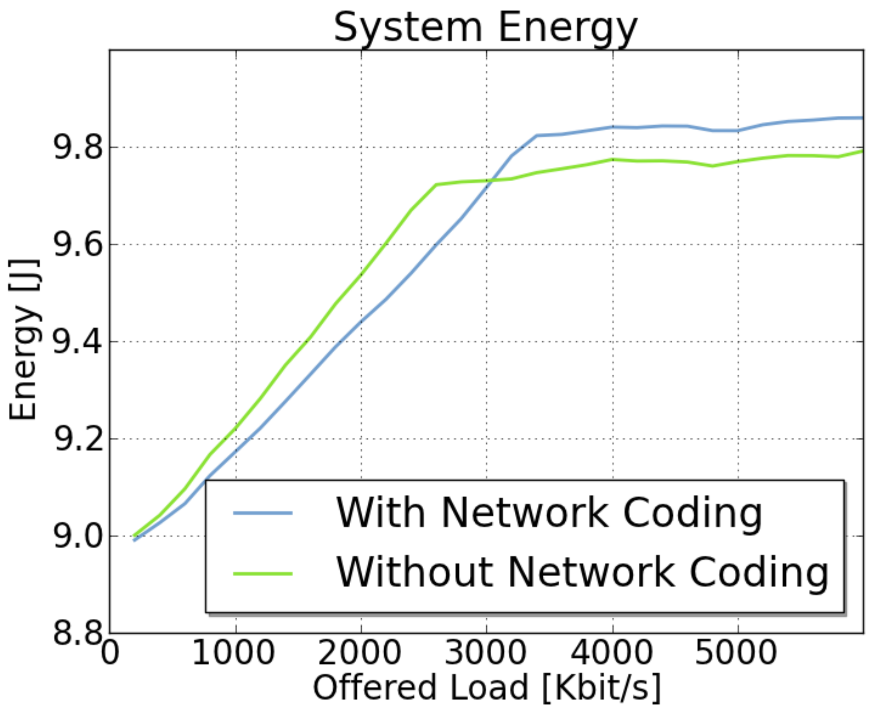


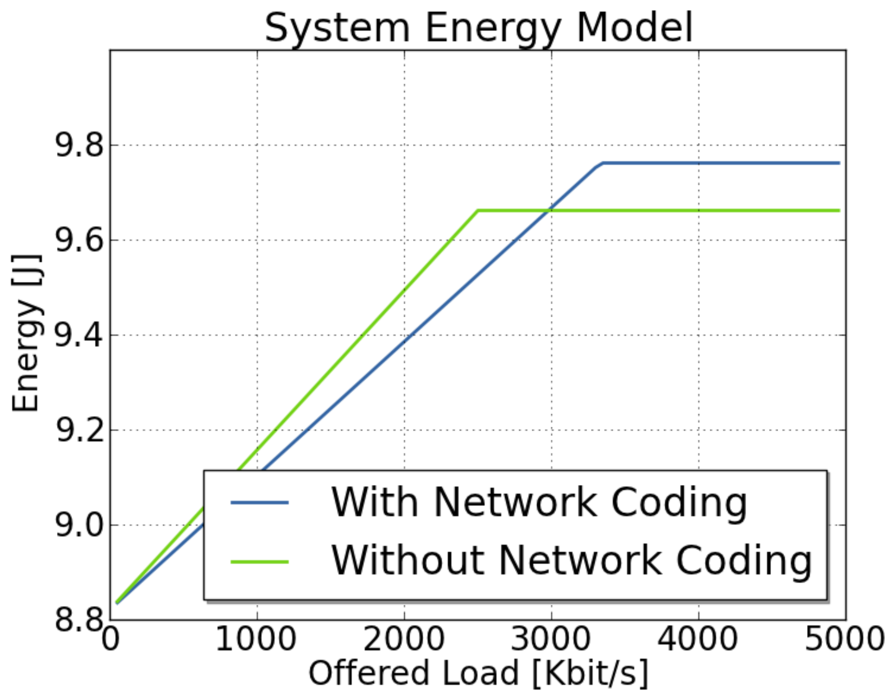
throughput



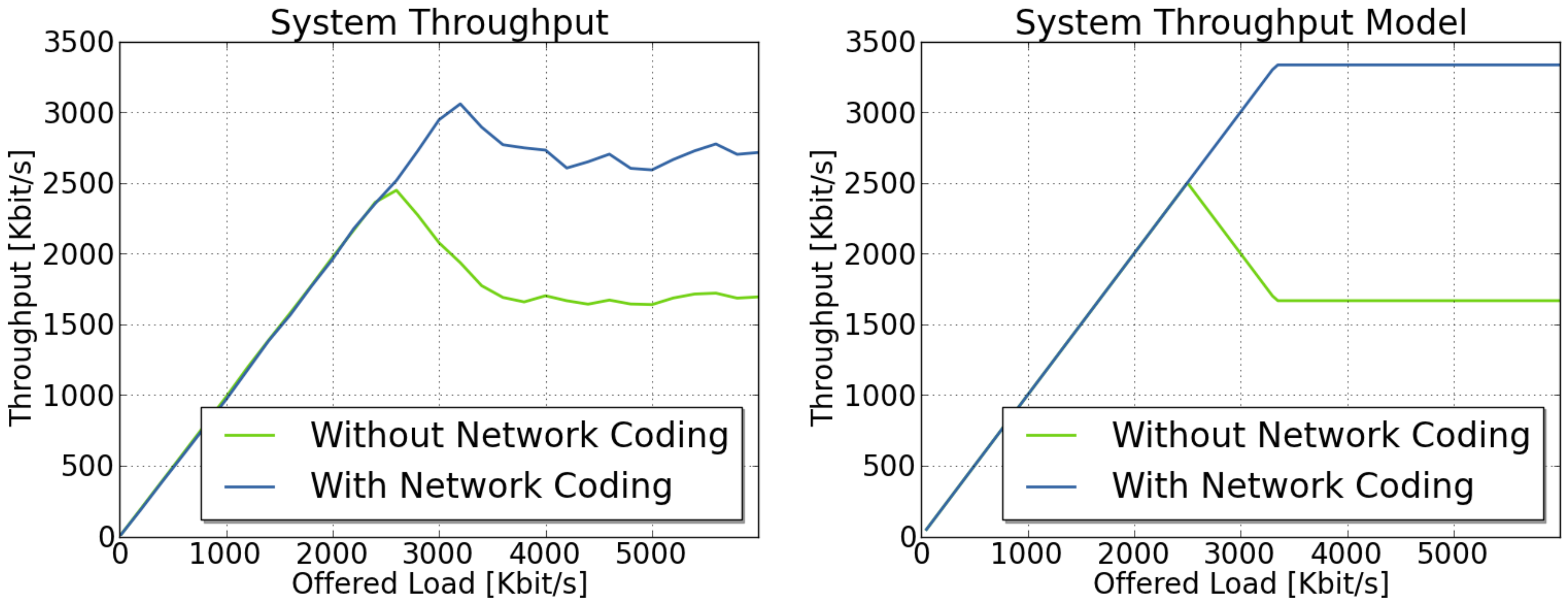
energy/bit

Comparion: Energy

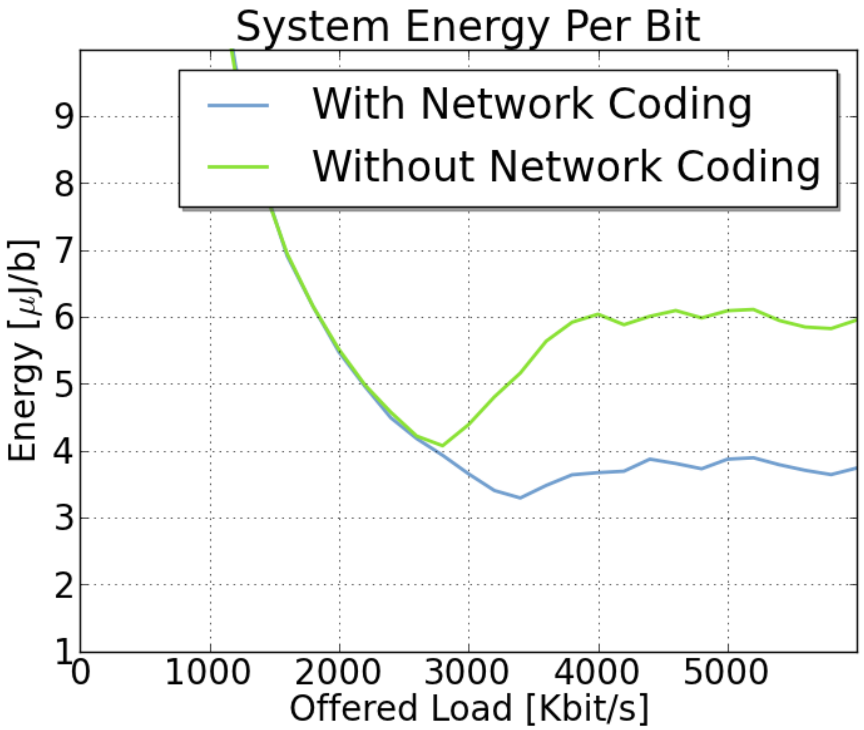


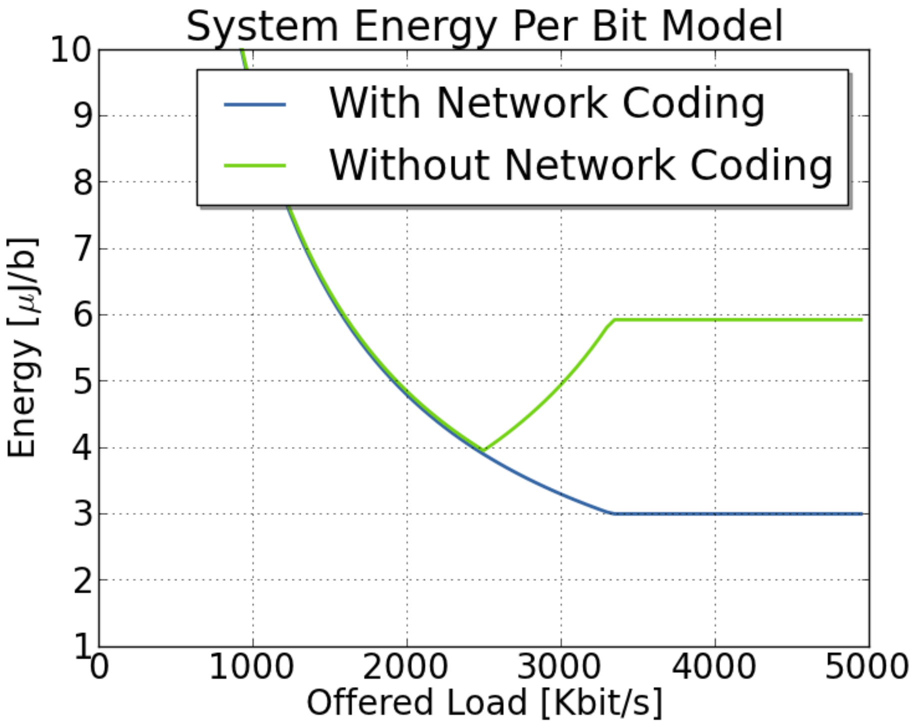


Comparion: Throughput



Comparion: Energy Per Bit



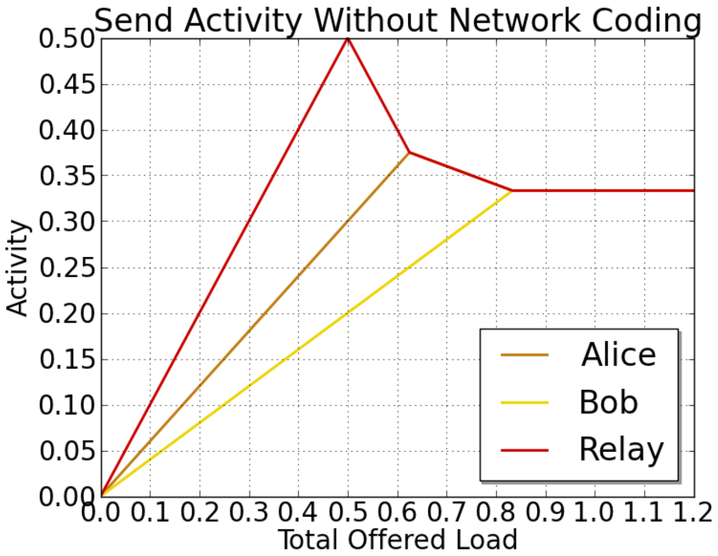


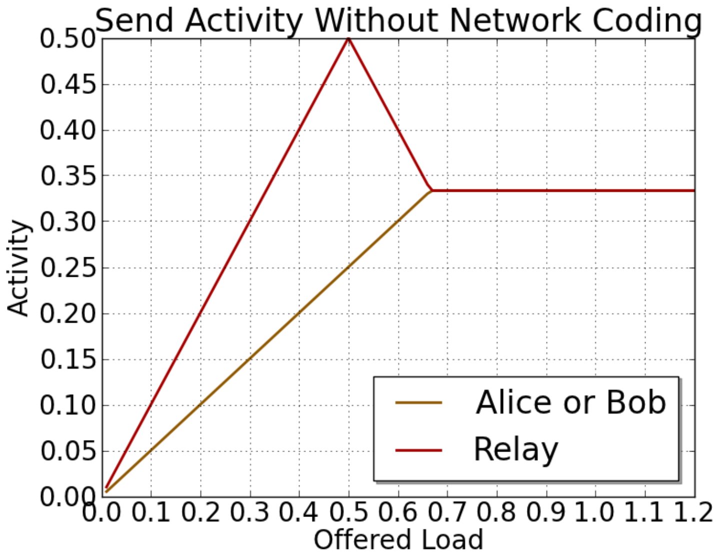
Model for Alice and Bob (asymmetric traffic)

A. Paramanathan, J. Heide, P. Pahlavani, M. Hundeboll, S.A. Rein, F.H.P. Fitzek, and G. Ertli, **"Energy and data throughput for asymmetric inter-session network coding,"** in IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD), Barcelona, Spain.

Model for asymmetric traffic (vs. symmetric traffic): SEND

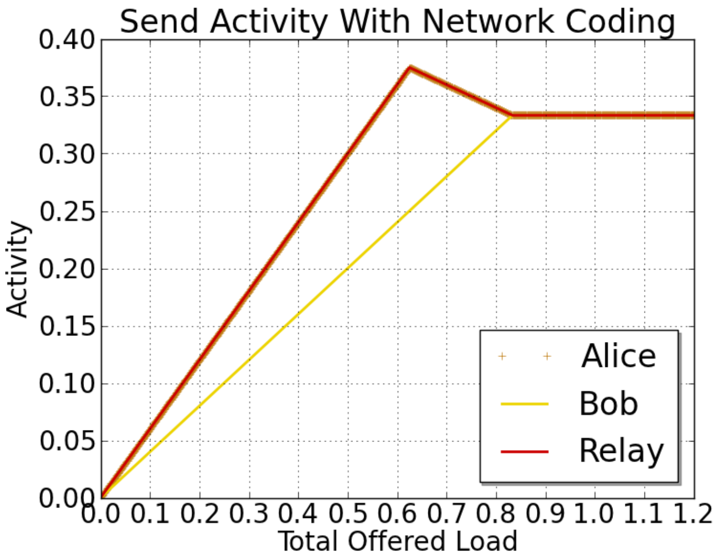
w/o NC

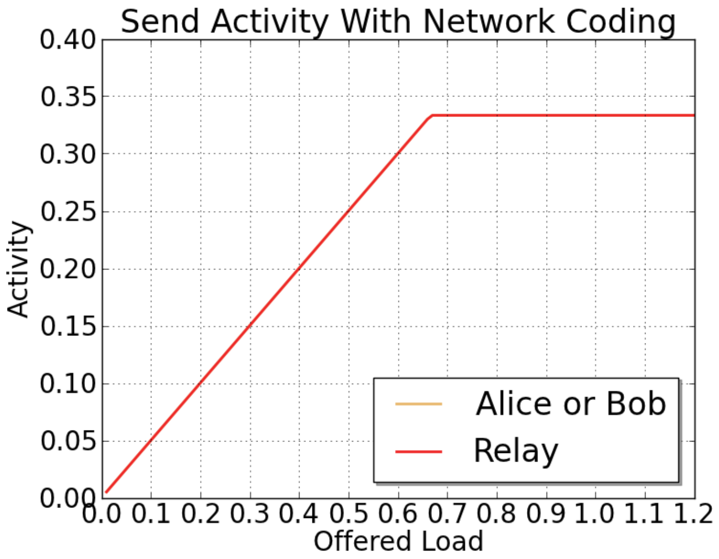




Asymmetric with link share of 60%(A)/40%(B)

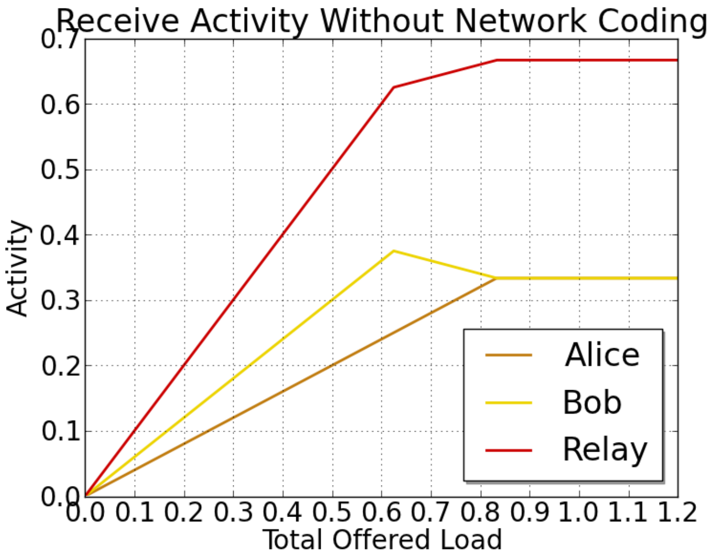
w NC

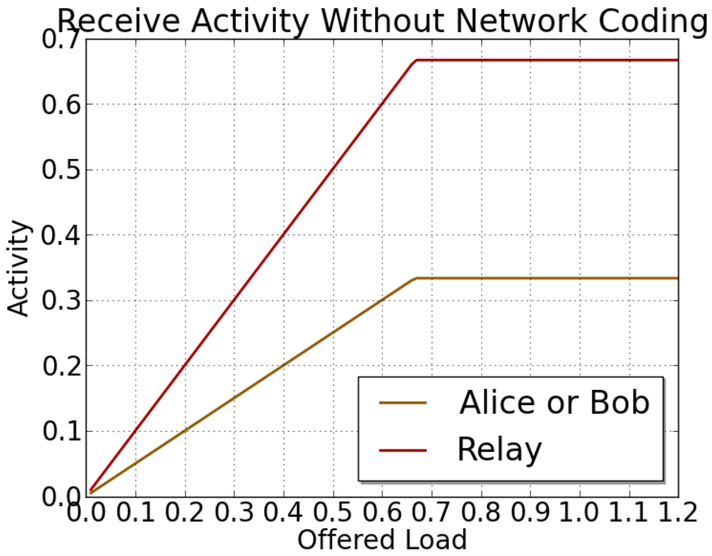




Model for asymmetric traffic (vs. symmetric traffic): RECEIVE

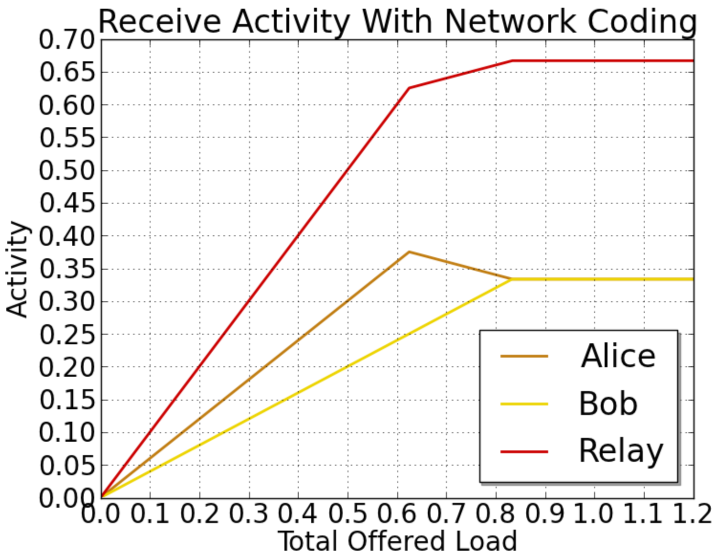
w/o NC

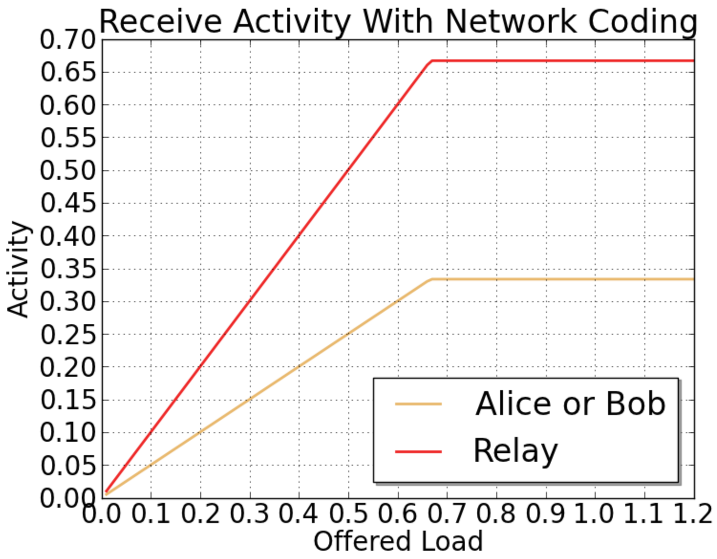




Asymmetric with link share of 60%(A)/40%(B)

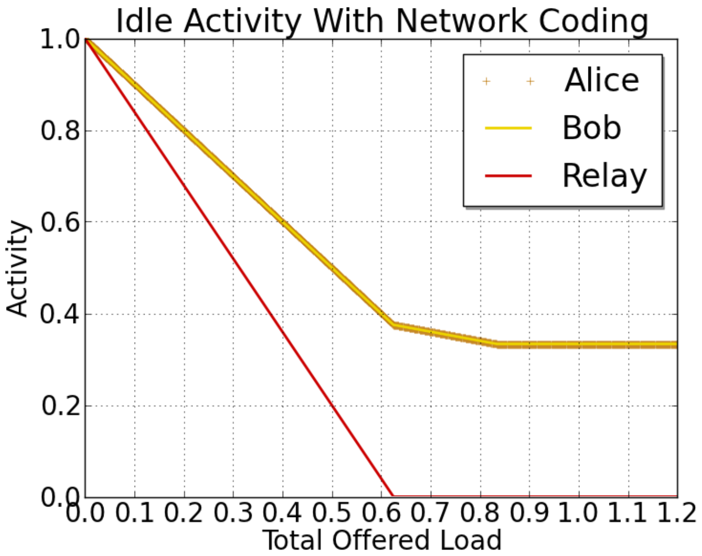
w NC

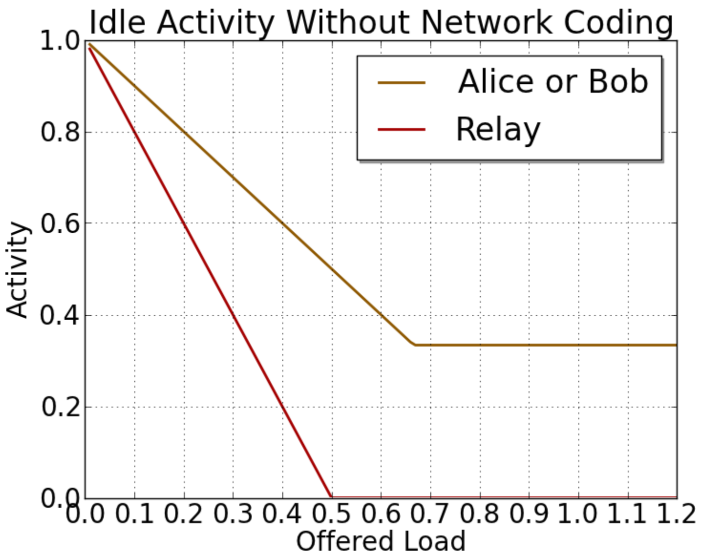




Model for asymmetric traffic (vs. symmetric traffic): IDLE

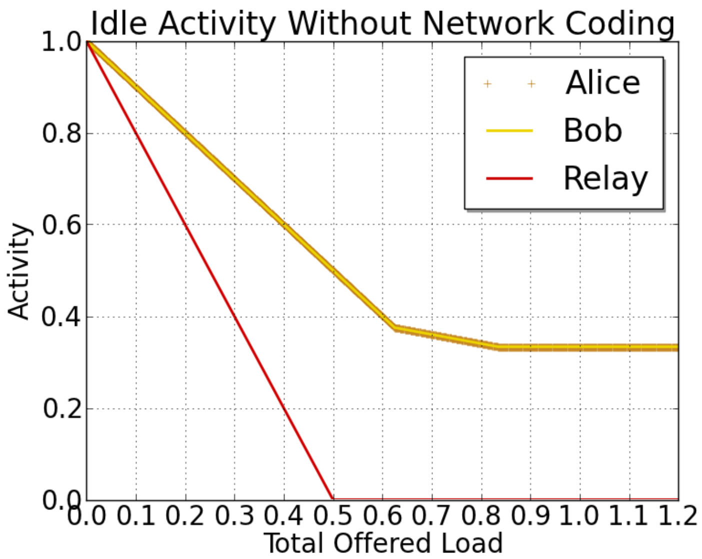
w/o NC

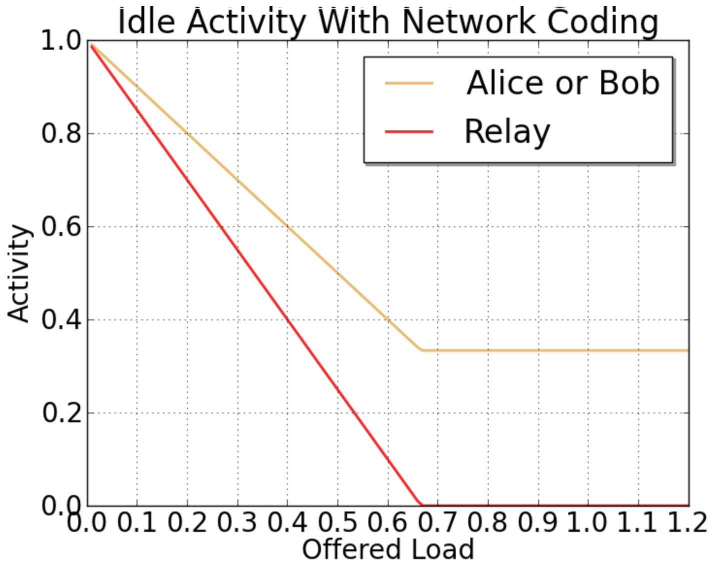




Asymmetric with link share of 60%(A)/40%(B)

w NC

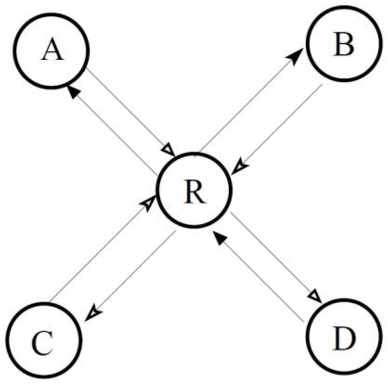




Model for THE CROSS (symmetric traffic)

Cross Forwarding

pure relaying



R	r	r	r	r	s	s	s	s
A	s	i	i	i	r	i	i	i
B	i	s	i	i	i	r	i	i
C	i	i	s	i	i	i	r	i
D	i	i	i	s	i	i	i	r

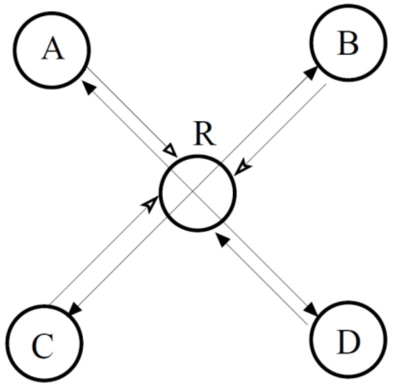
R	r	r	r	r	s
A	s	i	i	i	r
B	i	s	i	i	i
C	i	i	s	i	i
D	i	i	i	s	i

Whatever goes into the relay has to be forwarded.

What to do if there is not enough capacity?

XOR Network Coding

NC w/o overhearing

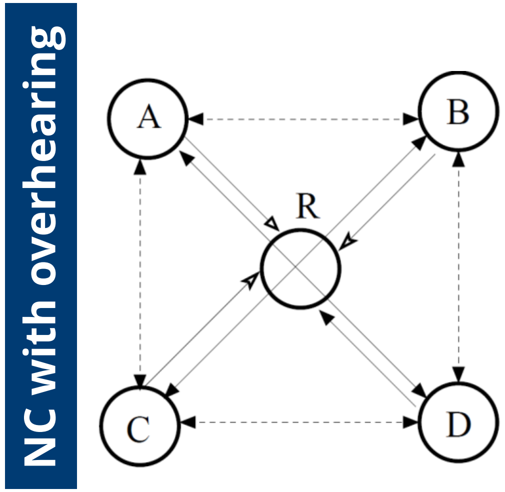


R	r	r	r	r	s	s
A	s	i	i	i	r	i
B	i	s	i	i	i	r
C	i	i	s	i	i	r
D	i	i	i	s	r	i

R	r	r	r	r	s
A	s	i	i	i	r
B	i	s	i	i	i
C	i	i	s	i	i
D	i	i	i	s	r

- Each out node sends to the relay
- And for each pair the relay sends out one coded packet

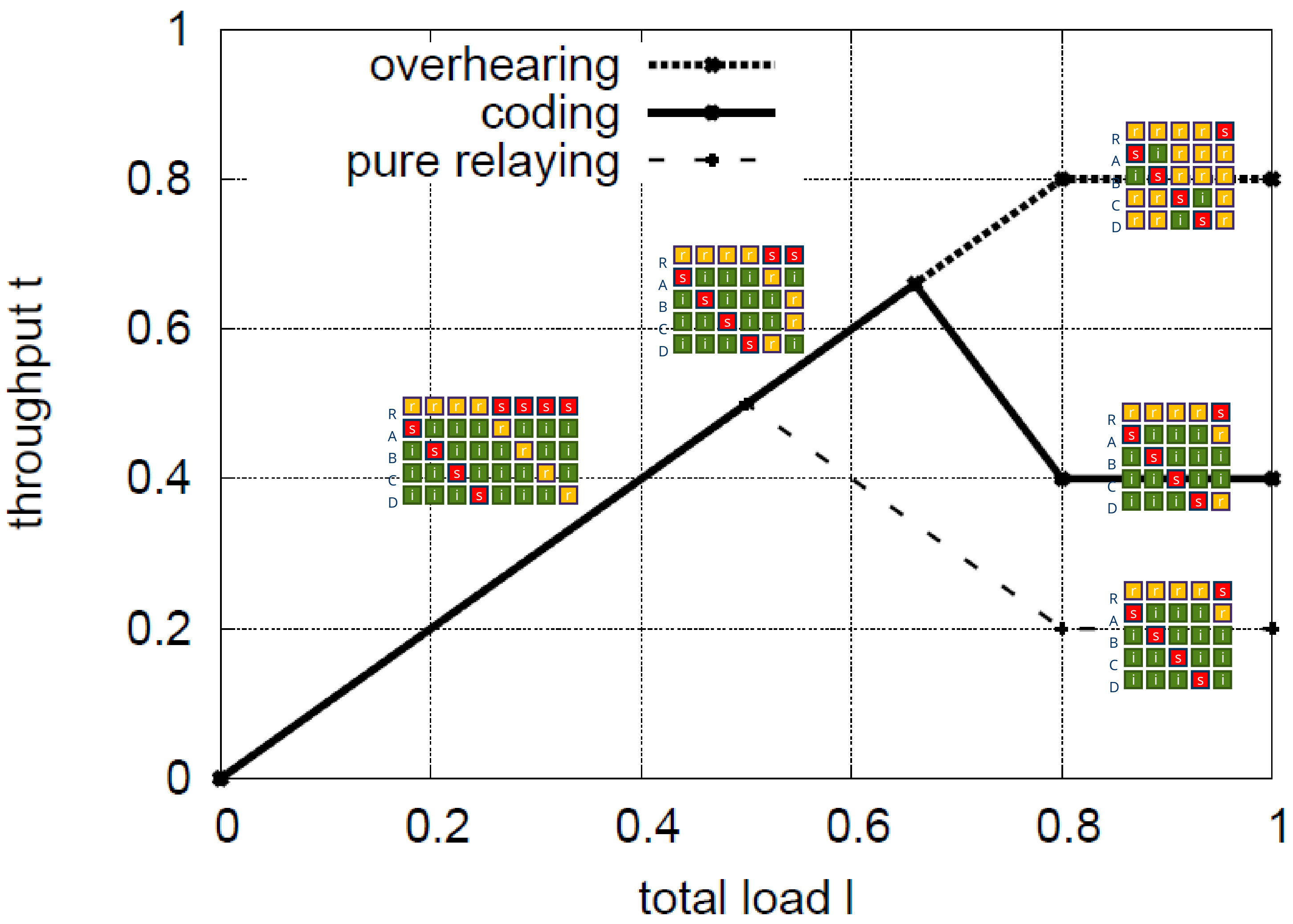
XOR Network Coding with overhearing



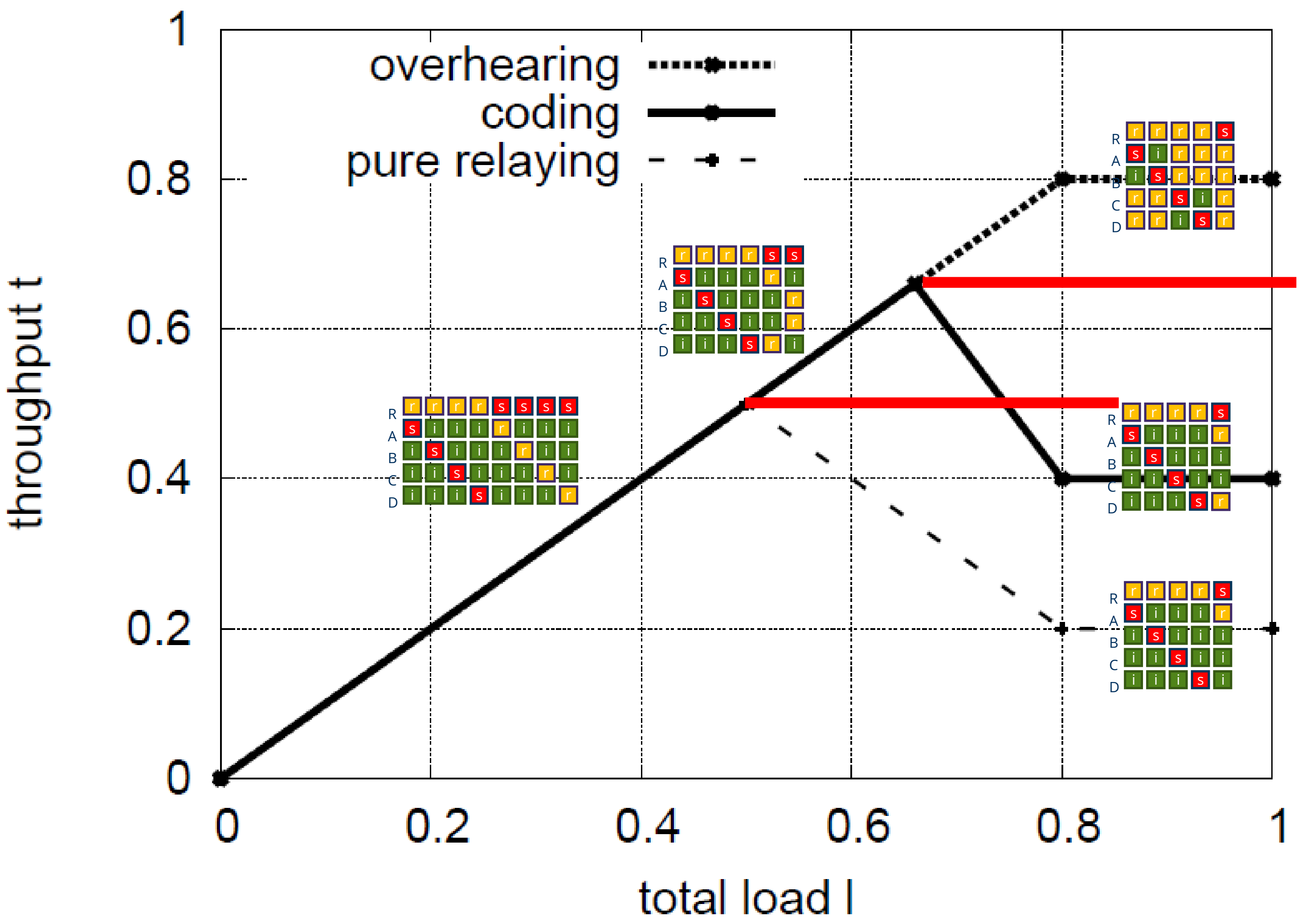
R	r	r	r	r	s
A	s	r	r	i	r
B	r	s	i	r	r
C	r	i	s	r	r
D	i	r	r	s	r

- Each outer node sends a packet to the relay
- Each outer node will overhear two packets from neighboring nodes
- Relay sends out one full coded packet

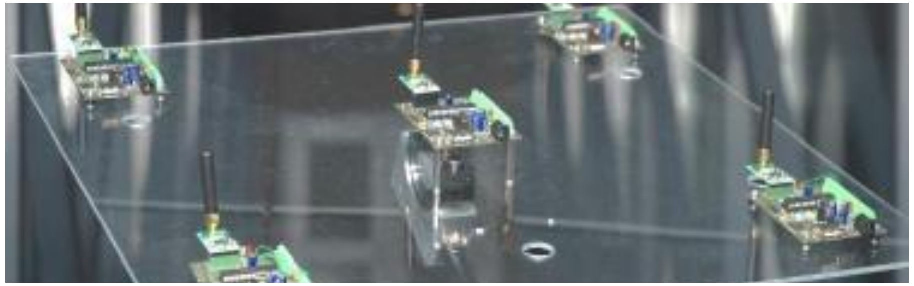
Cross Throughput

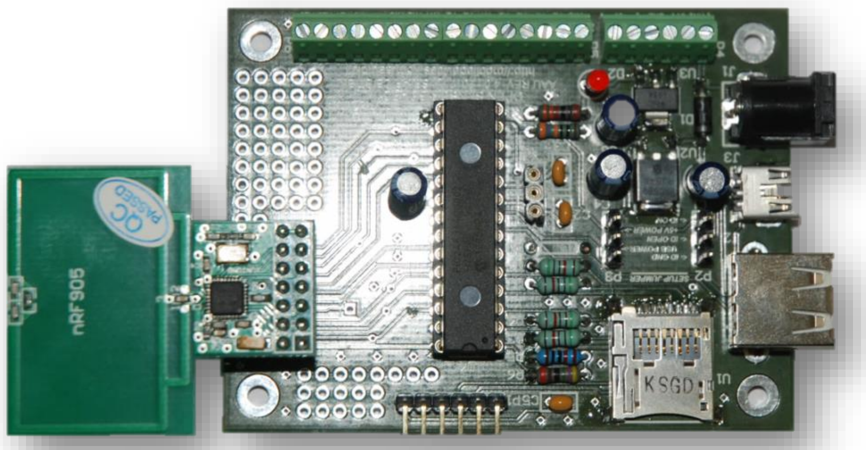


Cross Throughput



The Cross (MAC)





Hardware

16bit PIC24 microprocessor

nRF905 transceiver (433 MHz, 50 kbps)

Software

MAC-Protocol: A CSMA/CA design

Network Coding: A simple XOR design [COPE06]

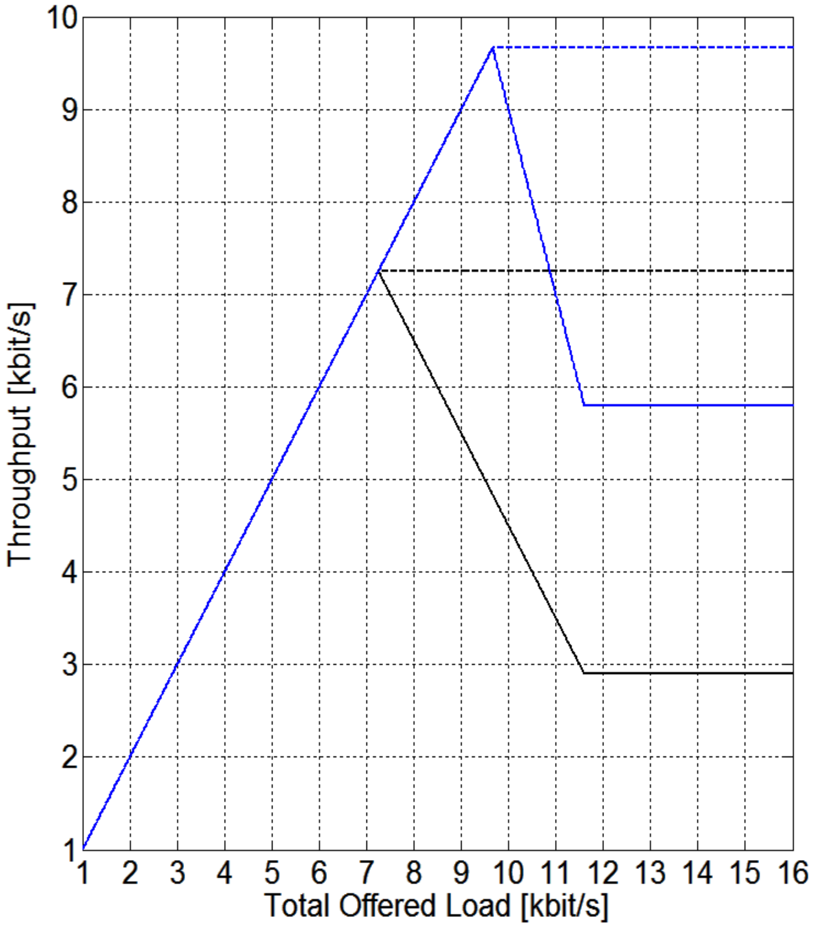
Capability

Easy access to the software

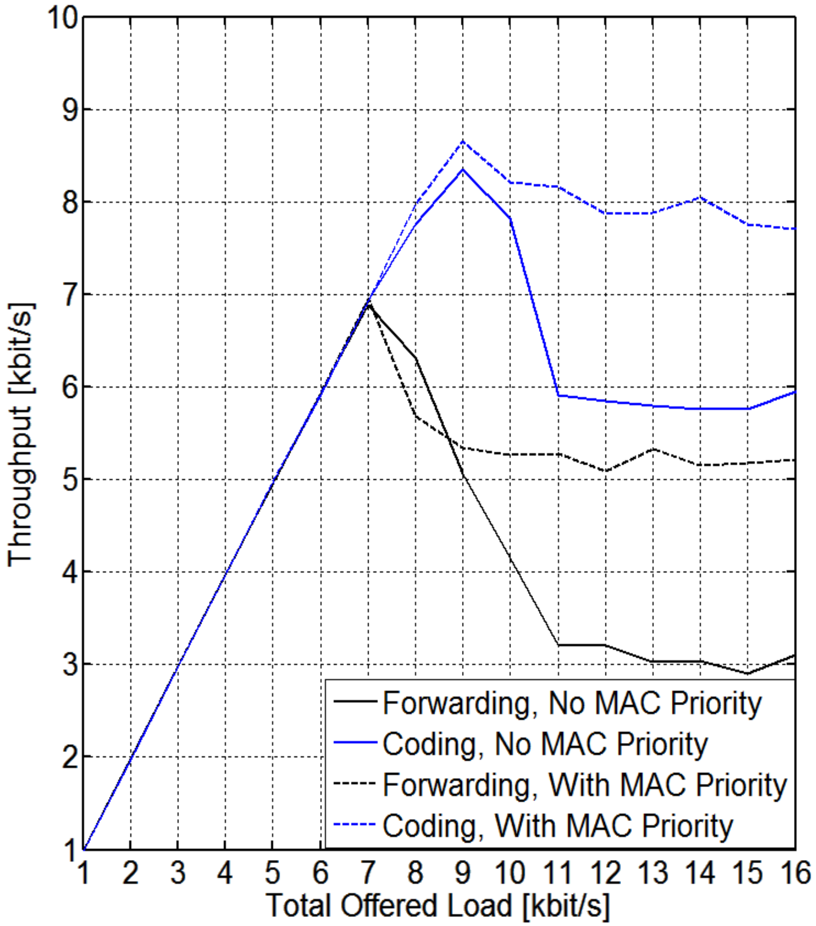
Full control of both HW and SW

The Cross (MAC)

Expected



Measurement

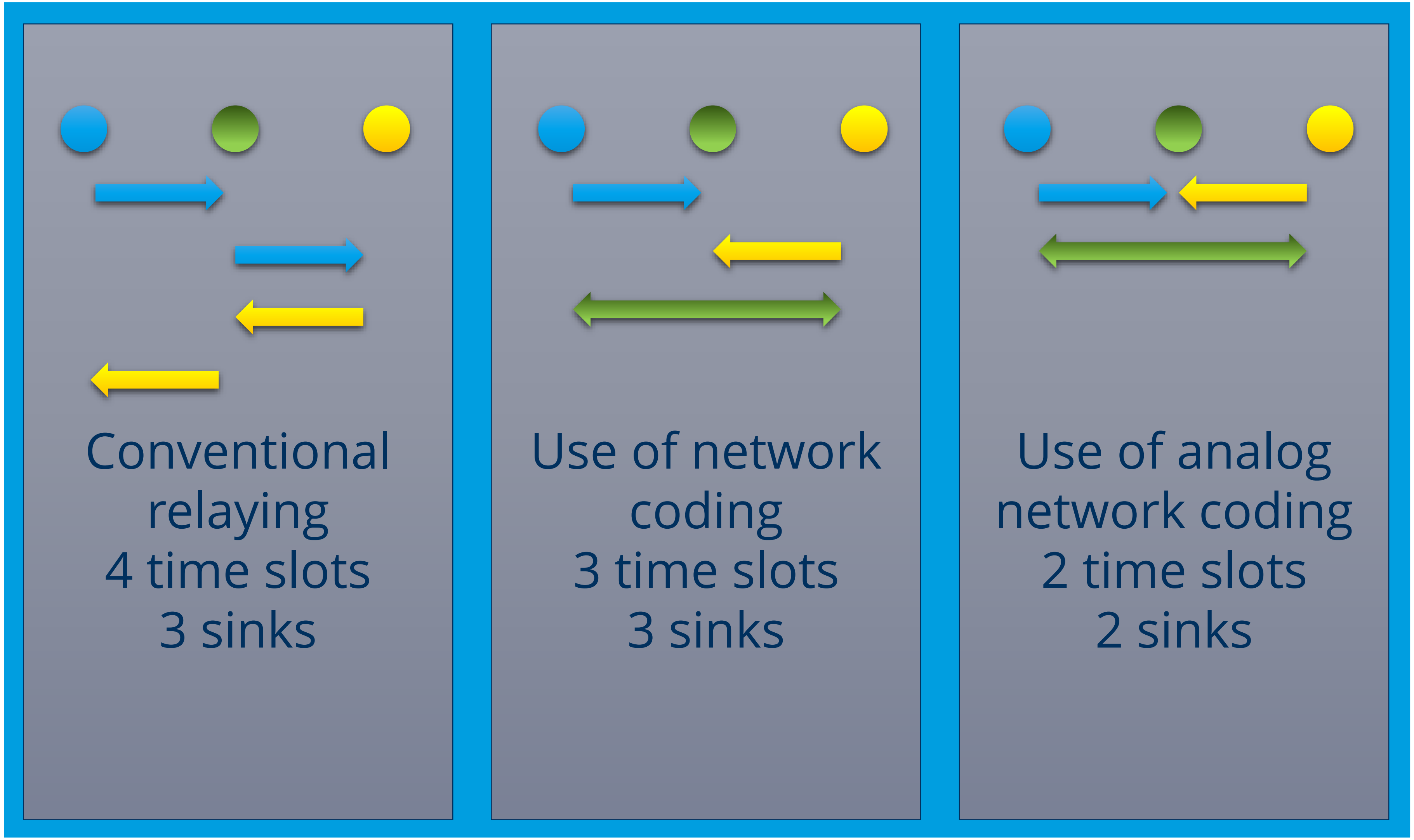


Analog Network Coding

Overview

- So far network coding was done in the packet domain
- Network coding can be applied in any ISO/OSI layer
- Analog and physical network coding is a special case at the physical layer (lowest ISO/OSI layer) coding “symbols”
- Coding symbols is nothing else than a superposition of signals. Analog network coding breaks with the paradigm to separate signals in time and force “collision” to achieve higher coding gains

Analog Network Coding for Wireless Networks



Analog Network Coding for Wireless Networks

Analog network coding seems to be more efficient than digital network coding

For the two way relay it reduces the number of necessary transmissions to two (three for digital network coding and four for store and forward)

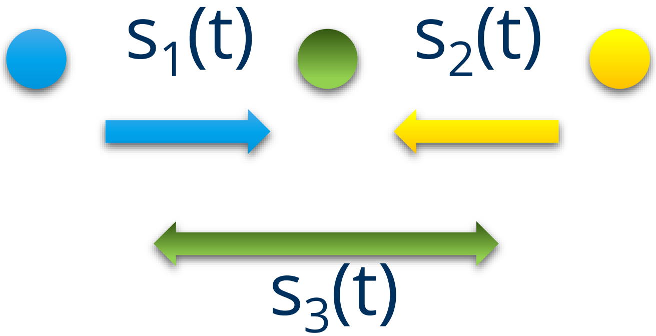
Advantages
- Throughput
- Energy
- Security (role of the relay differs)

Physical Layer Network Coding

Presented by [Zhang et al 2006]

First, simple example: no fading

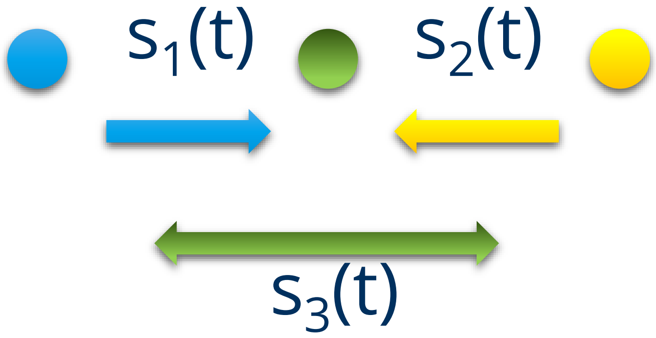
Let us look at bandpass signals



$$
\begin{aligned}
r_3(t) &= s_1(t) + s_2(t) + n(t) \\
&= [a_1 \cos(\omega t) + b_1 \sin(\omega t)] + [a_2 \cos(\omega t) + b_2 \sin(\omega t)] + n(t) \\
&= (a_1 + a_2)\cos(\omega t) + (b_1 + b_2)\sin(\omega t) + n(t)
\end{aligned}
$$

How to generate $s_3(t)$?

Physical Layer Network Coding



How to generate $s_3(t)$?

Amplify and forward?

Decode and forward?

Initial approach: decode and forward

Example with BPSK: say $b_i = 0,\ \ a_i \in \{-1,1\}\ \ i = 1,2,3$

$$r_3(t) = s_1(t) + s_2(t) + n(t) = (a_1 + a_2)\cos(\omega t) + n(t)$$

Note that there are 3 possible values of $a_1 + a_2$:

"-2" and "2" correspond to $a_1 = a_2$

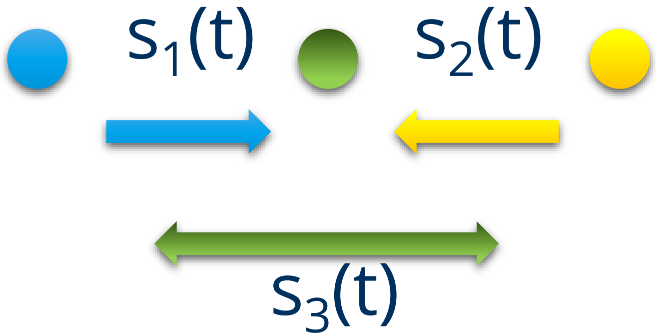
"0" corresponds to $a_1 = -a_2$

Physical Layer Network Coding

Example with BPSK:

Let us generate $s_3(t)$

(hint: XOR-like operation)



If $a_1 = a_2$ then $a_3 = 1$ (logical "0")

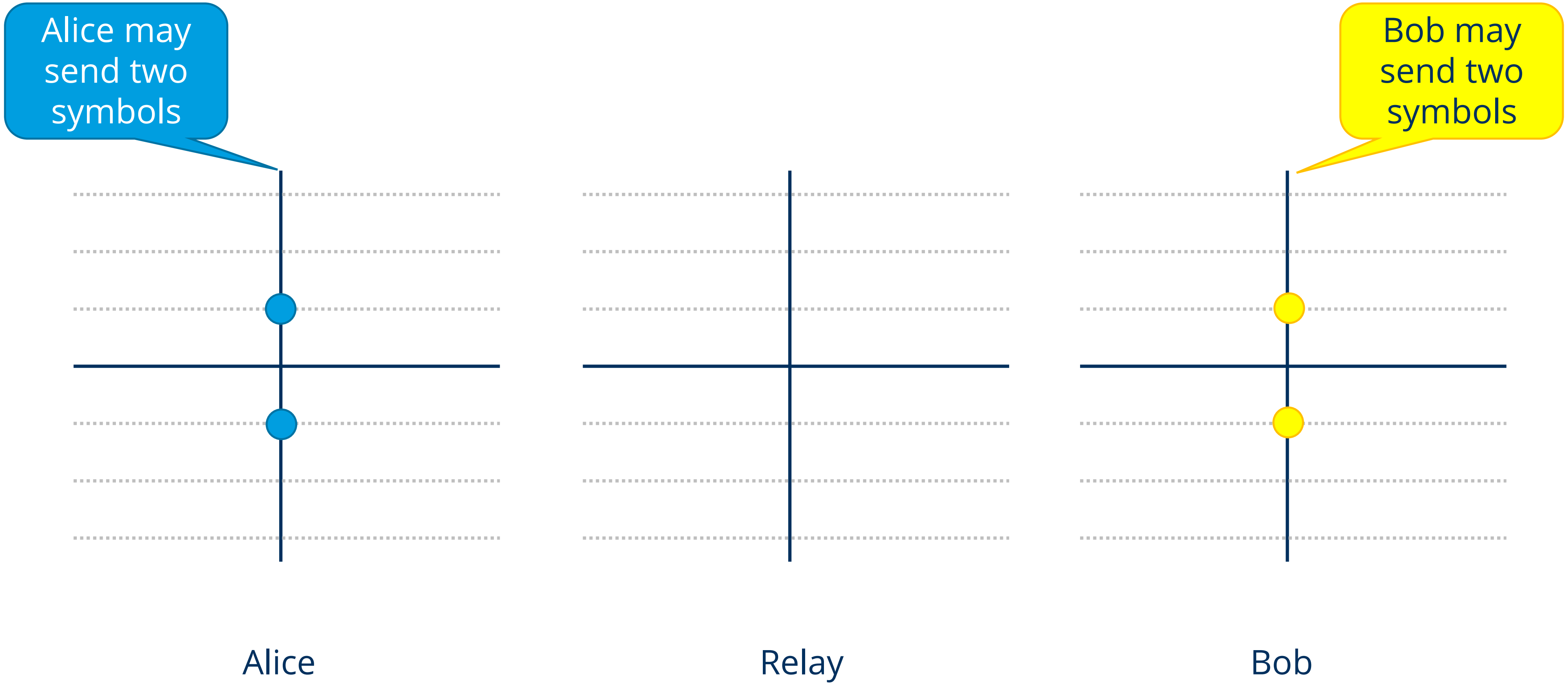
If $a_1 = -a_2$ then $a_3 = -1$ (logical " 1")

Alice and Bob receive as standard BPSK modulation

Then, *XOR bit by bit* with the sent packet

Physical Layer Network Coding

What if we A&F? 1st step – coding in the air

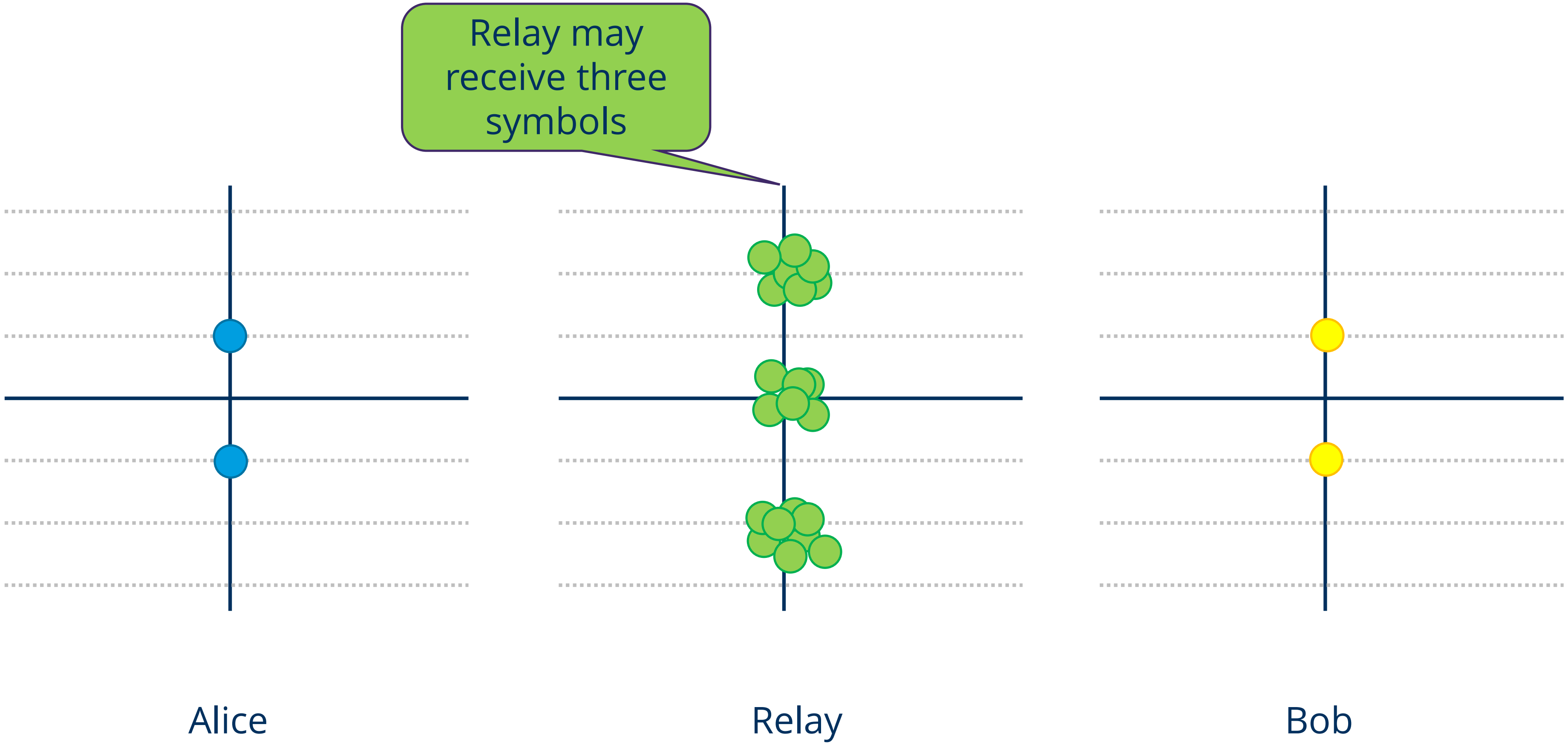


BPSK Example

Physical Layer Network Coding

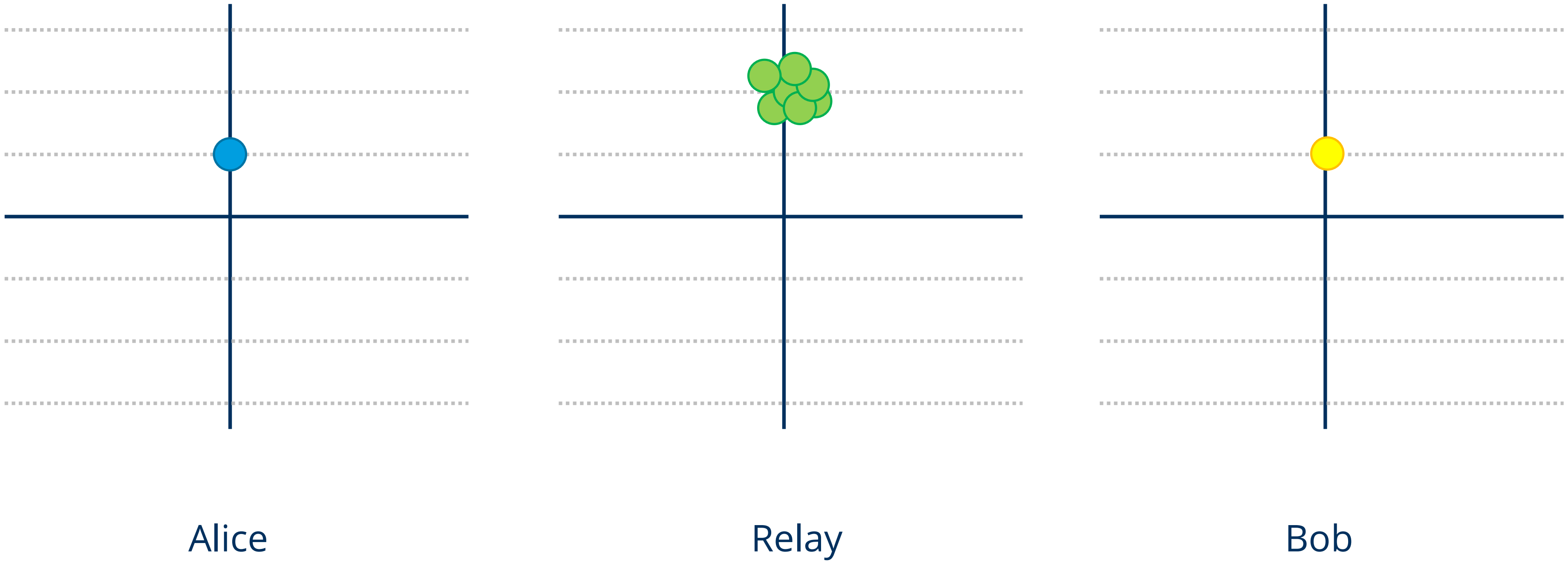
What if we A&F?

1st step – coding in the air



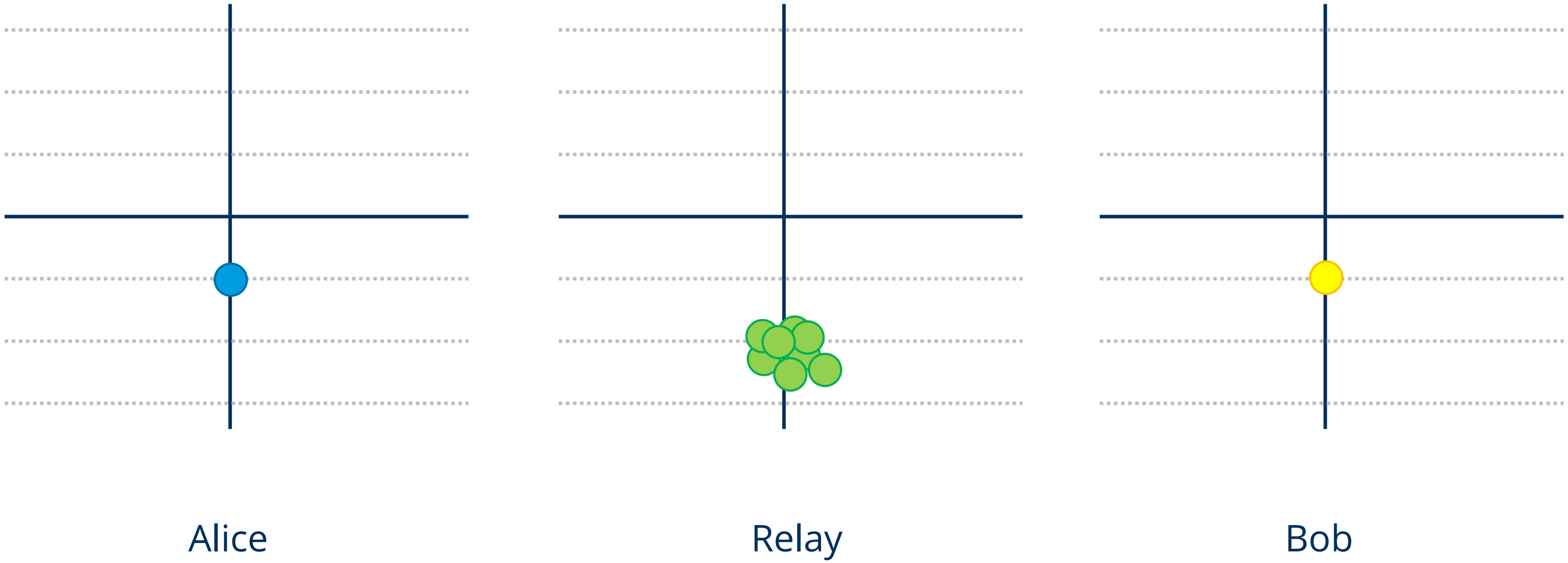
Physical Layer Network Coding

1st step – coding in the air – e.g. 1/1



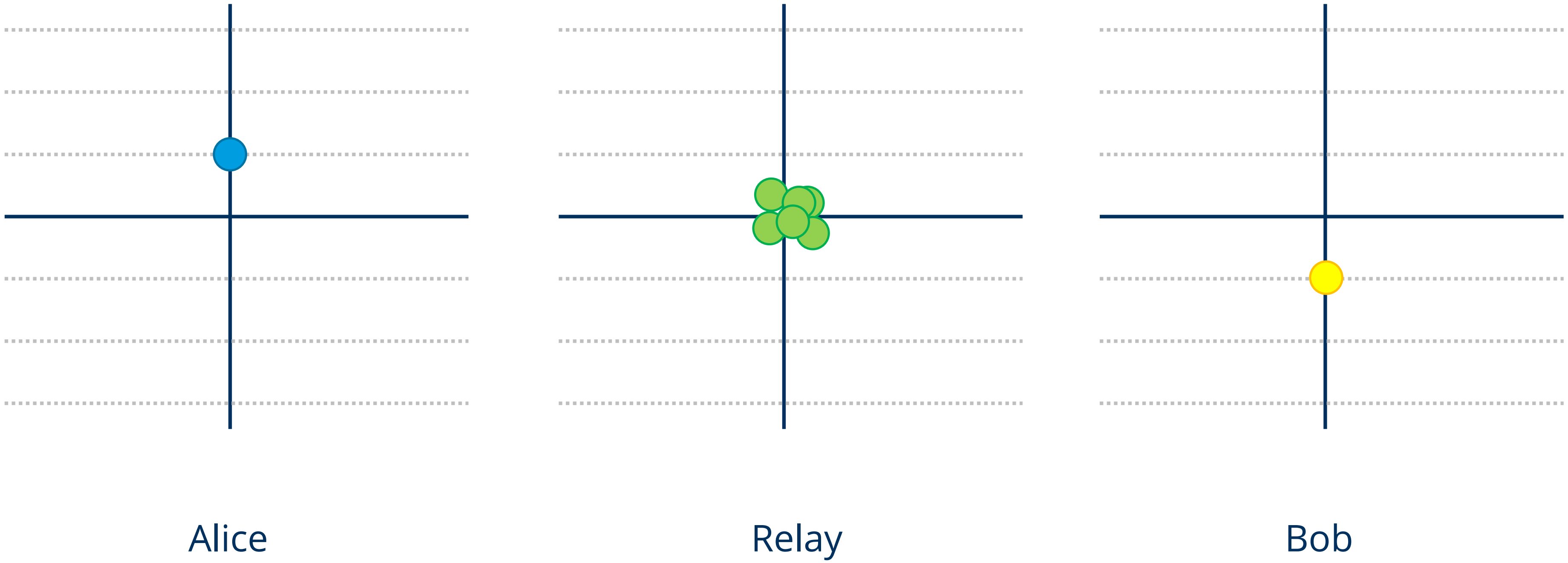
Physical Layer Network Coding

1st step – coding in the air – e.g. 0/0



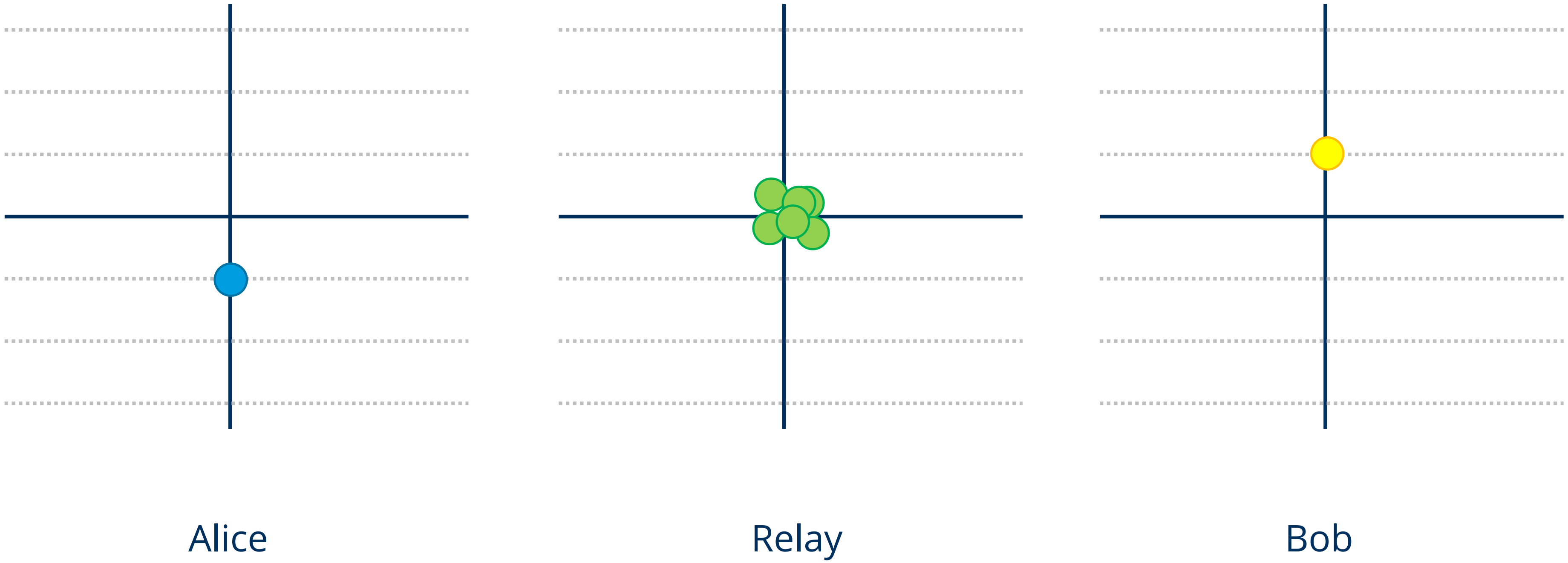
Physical Layer Network Coding

1st step – coding in the air – e.g. 1/0

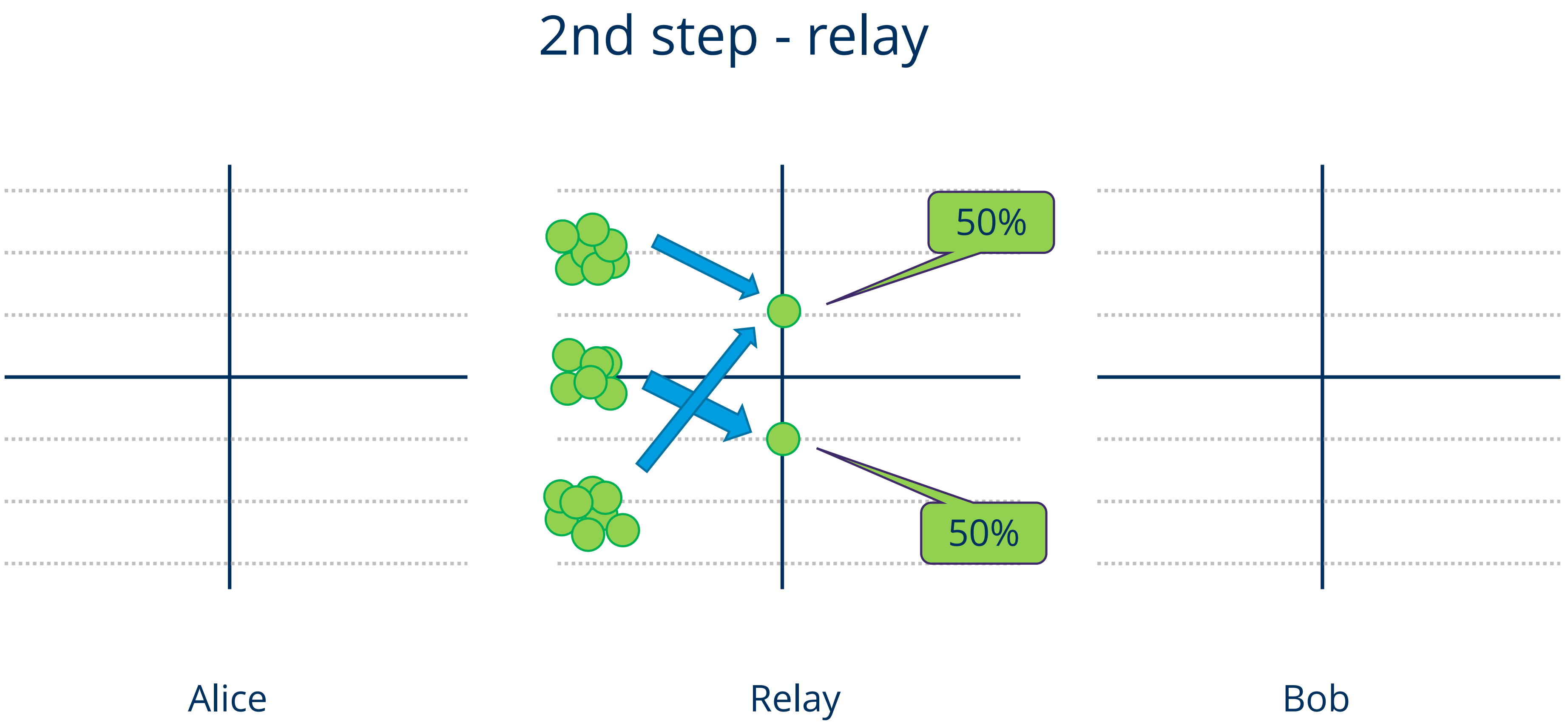


Physical Layer Network Coding

1st step – coding in the air – e.g. 0/1

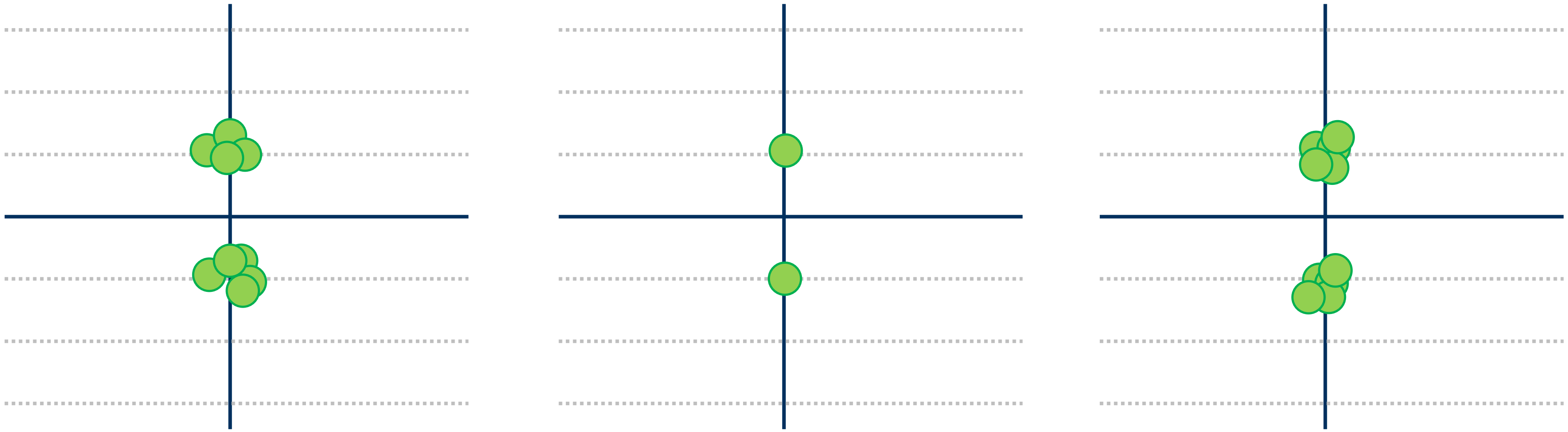


Physical Layer Network Coding



Physical Layer Network Coding

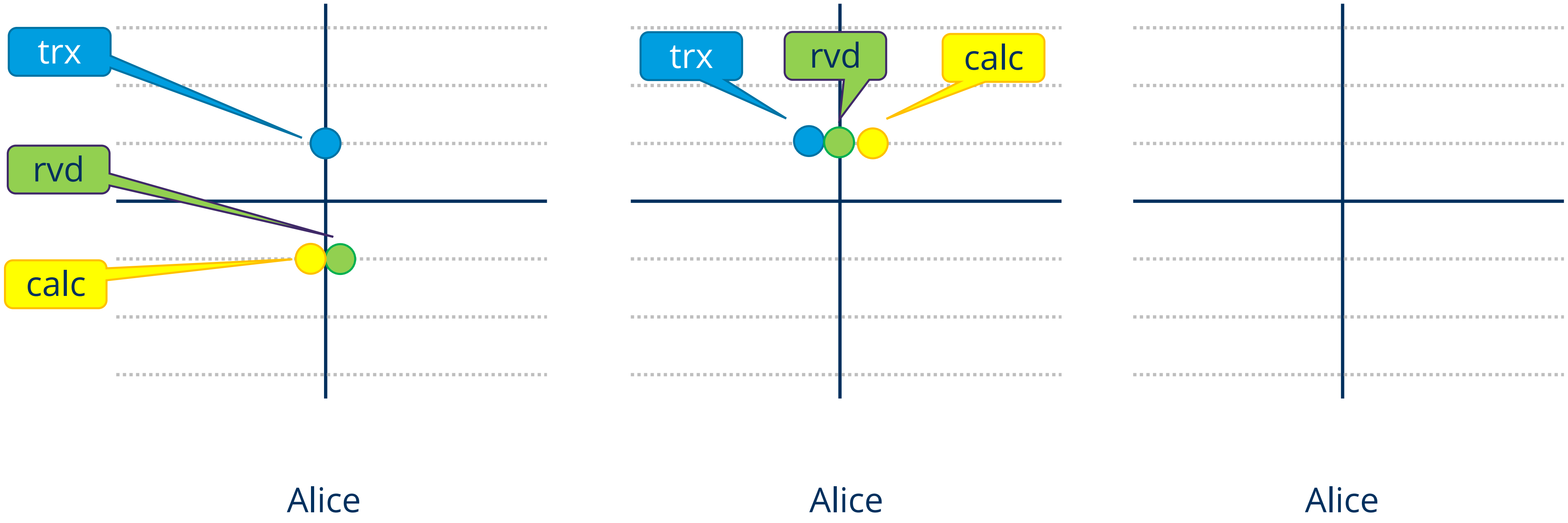
2nd step - relay



Alice Relay Bob

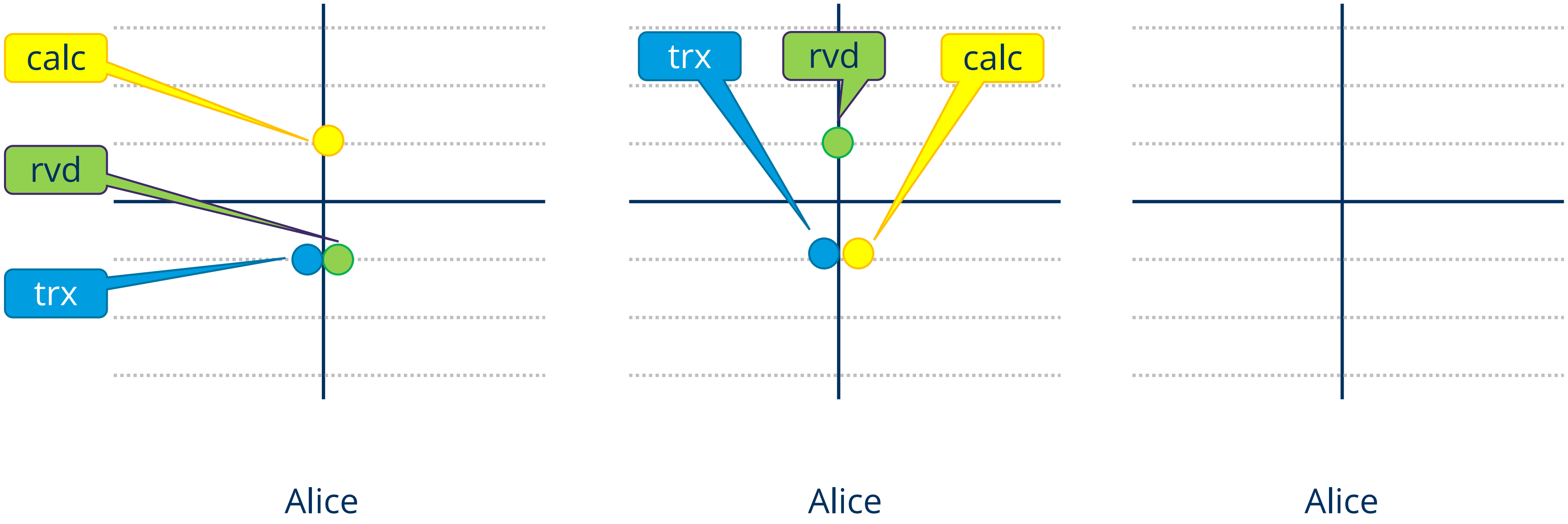
Physical Layer Network Coding

3rd step decoding



Physical Layer Network Coding

3rd step decoding



Analog Network Coding

What were our assumptions so far?

- No fading → there is amplitude + phase distortion
- Perfect sync
- Perfect detection of a collision
- Perfect knowledge of packet used for decoding at Alice and Bob
- The ”right” packets interfere (MAC / Network impact)

How to make it practical?

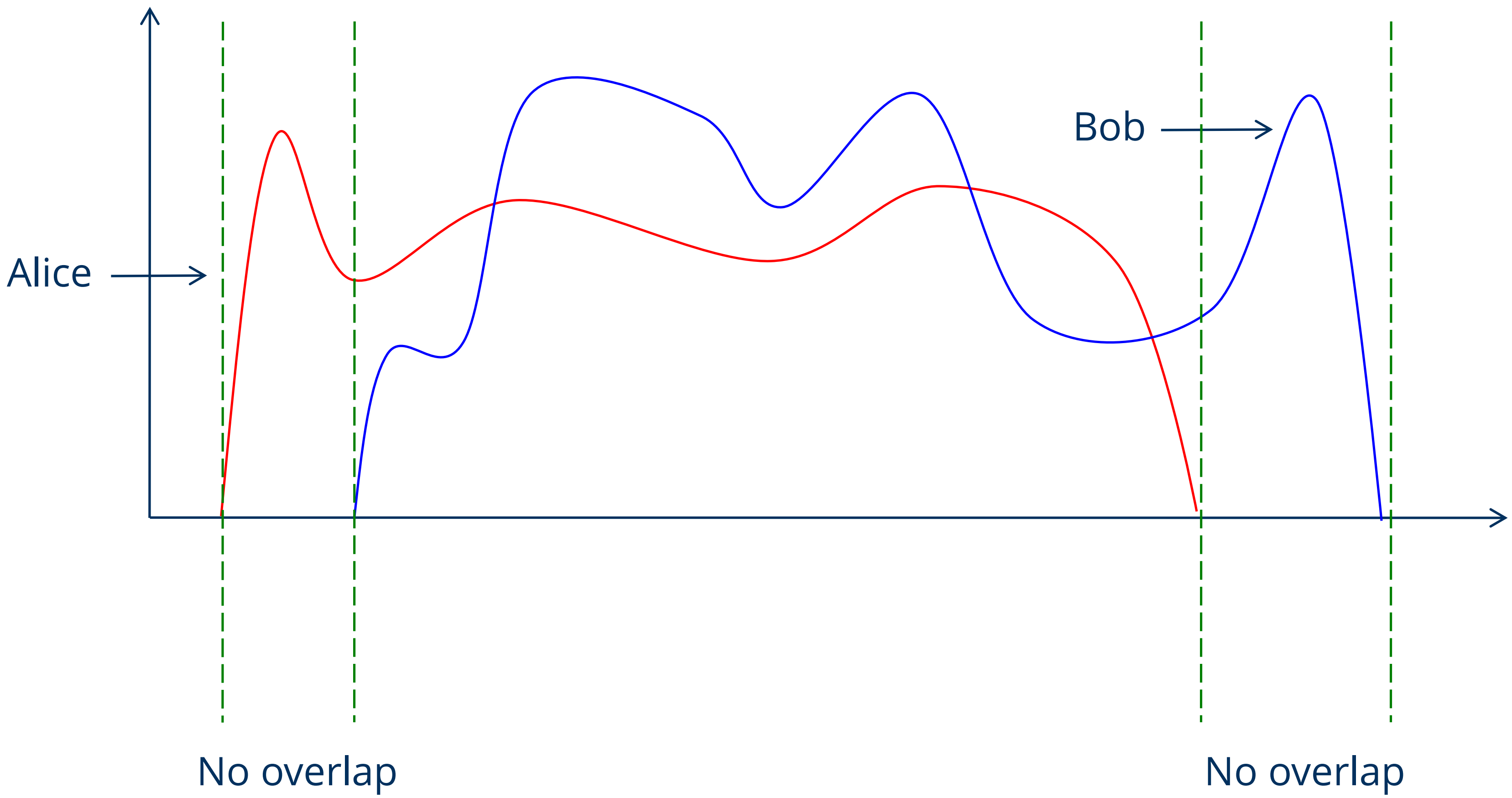
[Katti et al 2007] Analog network coding

[Gollakota et al 2008] ZigZag decoding

(different problem, similar intuition)

Analog Network Coding

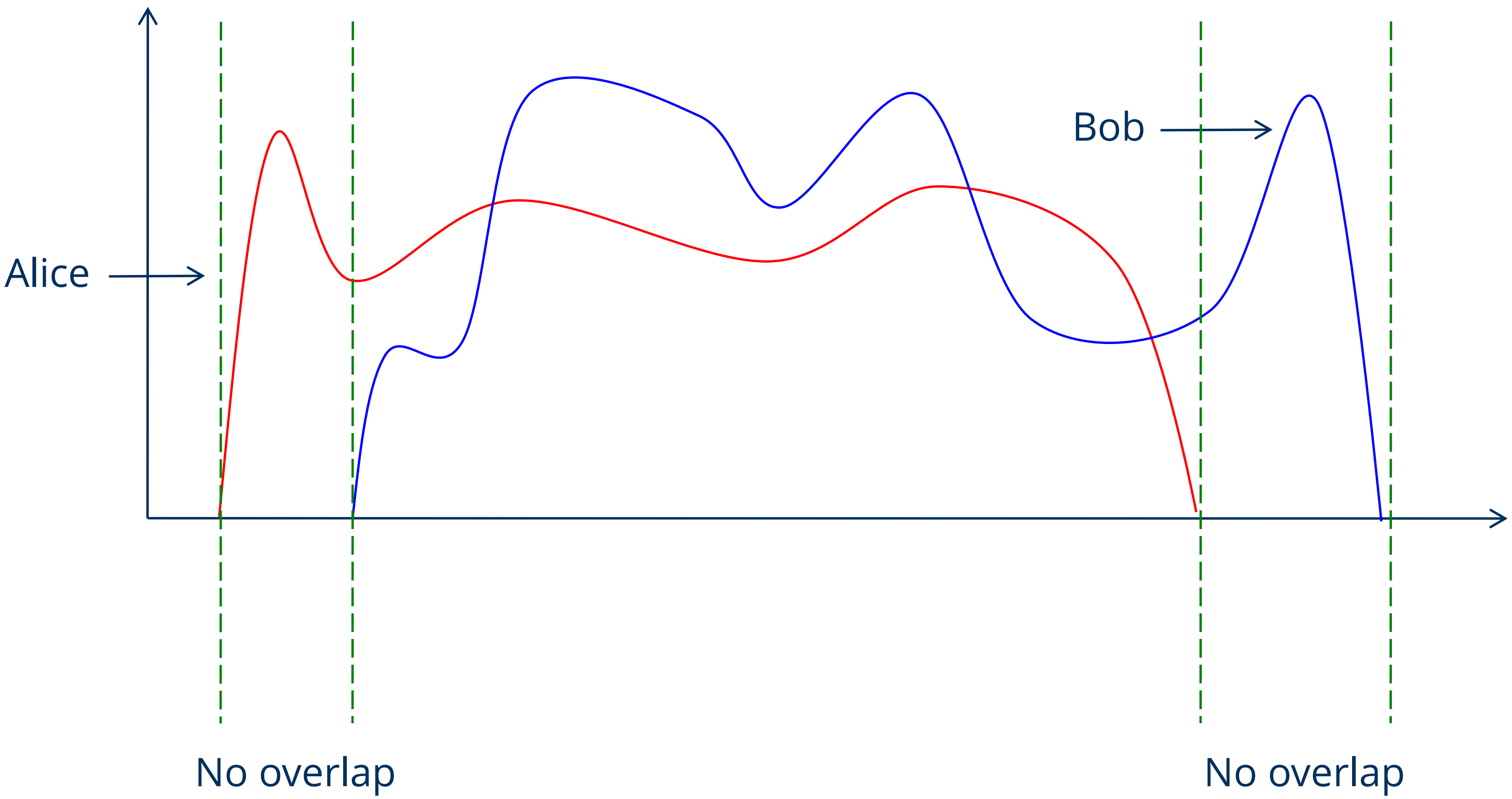
Key intuition: exploit asynchrony [Katti et al 2007]



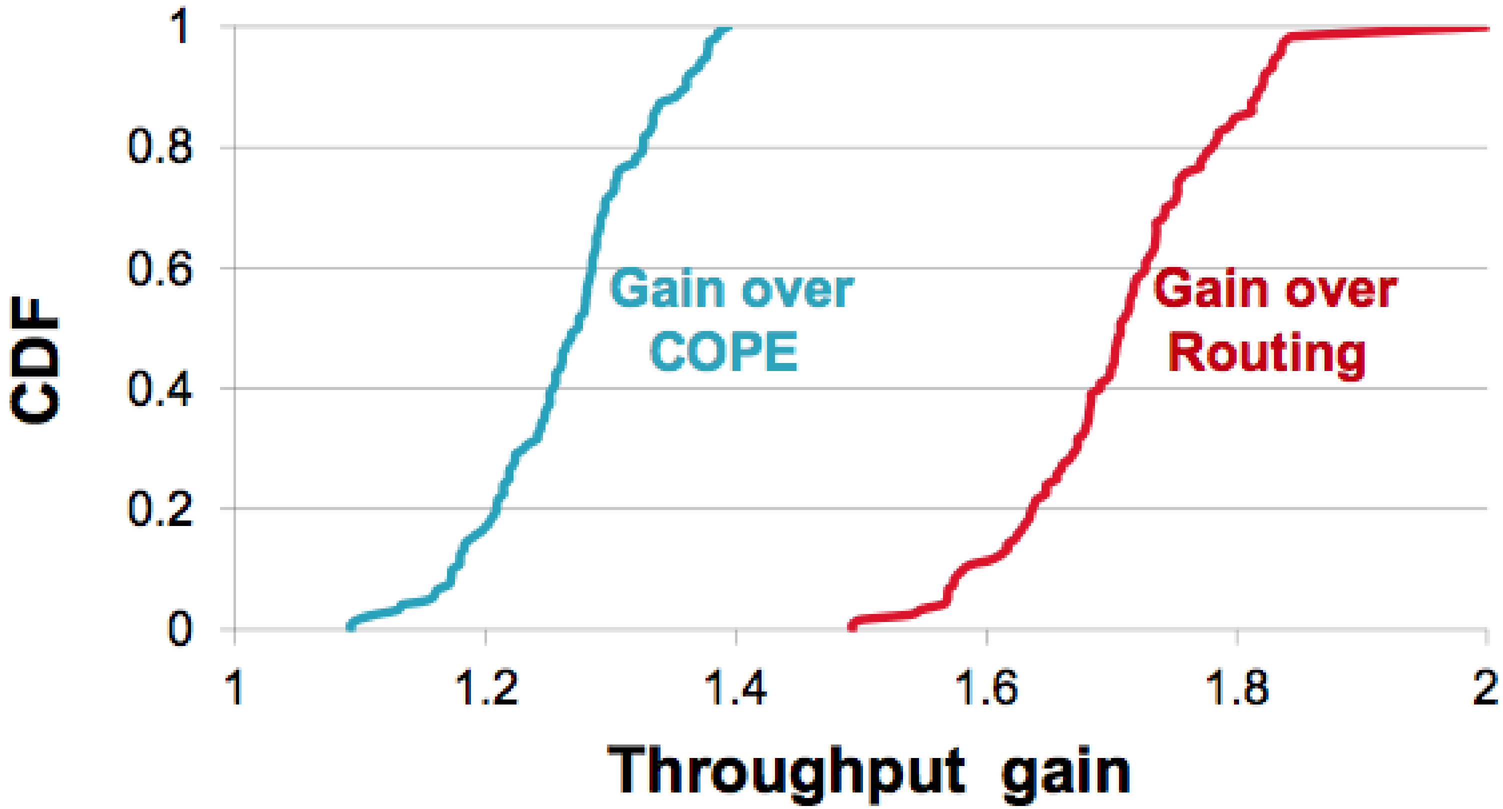
Analog Network Coding

Pilot sequence: channel estimation ID of sender + destination + sequence number of the packet: active session and to determine which packet was used

Construct „header“ and „footer“ for each packet



Analog Network Coding



ZigZag Decoding

Draws from the same intuition as the above problem

Difference:

- More general setting
- A node can use it to recover several interfering signals (no knowledge required on its end)
- We need to receive n collisions of n packets to recover

Where is it useful?

- Hidden terminal problem
- In high SNR, to boost overall data rate from multiple sources to a single receiver [ParandehGheibi et al 2010]

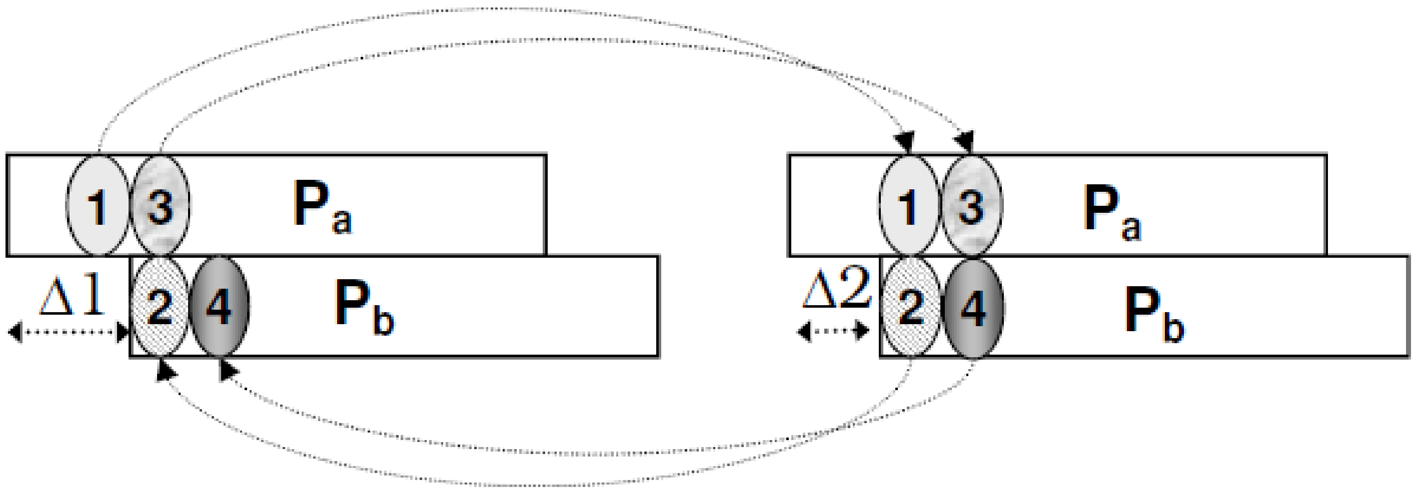
ZigZag Decoding: Basic Idea

Again: asynchrony

Chunk 1 of bits from user A from 1st collision is decoded successfully

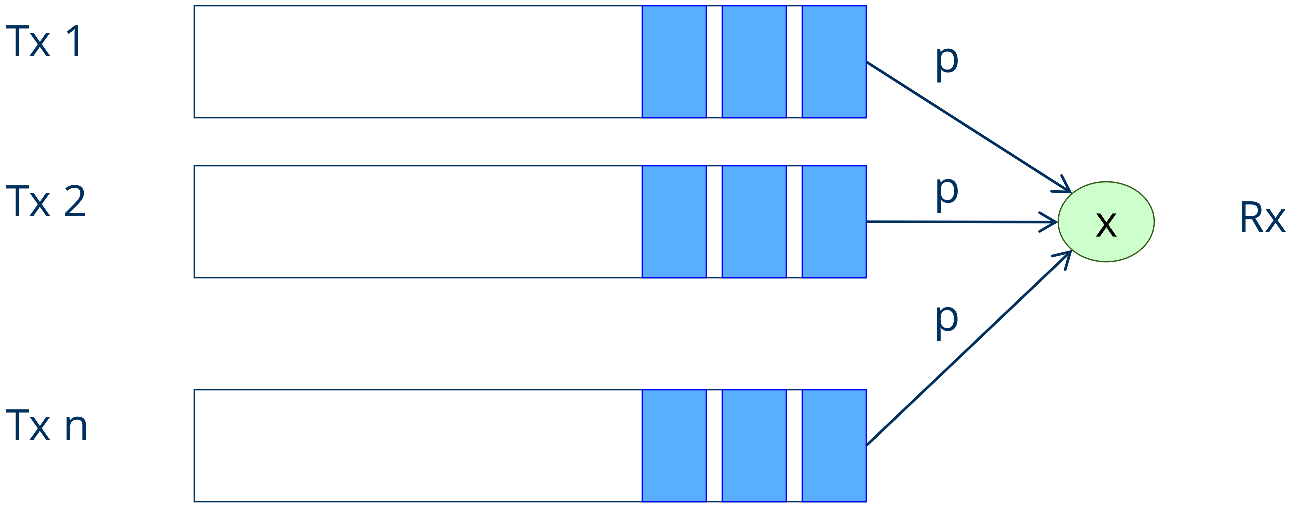
Thus, can subtract it from 2nd collision to decode Chunk 2 of bits of user B

Once Chunk 2 is free, can use to free Chunk 3, and so on



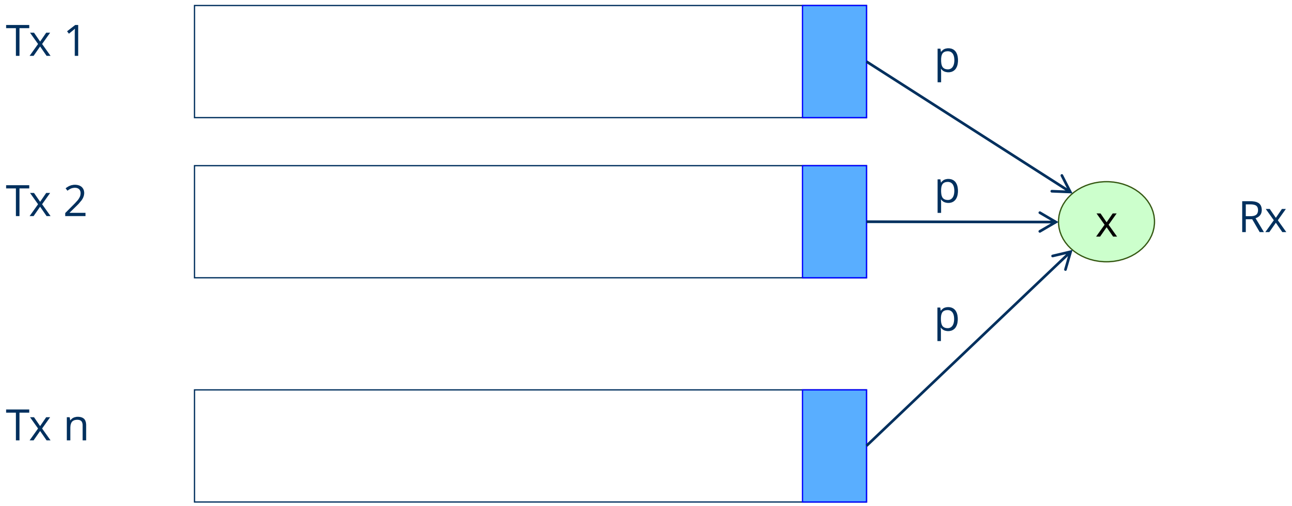
ZigZag Decoding: Single Hop Analysis

Work in [ParandehGheibi et al 2010]



ZigZag Decoding: Single Hop Analysis

Work in [ParandehGheibi et al 2010]



First result: Mean time to deliver one packet each

With zigzag: $$\frac{n}{1-p^n} \leq E[T_D] \leq \sum_{i=1}^{n} \frac{1}{1-p^{n-i+1}}$$

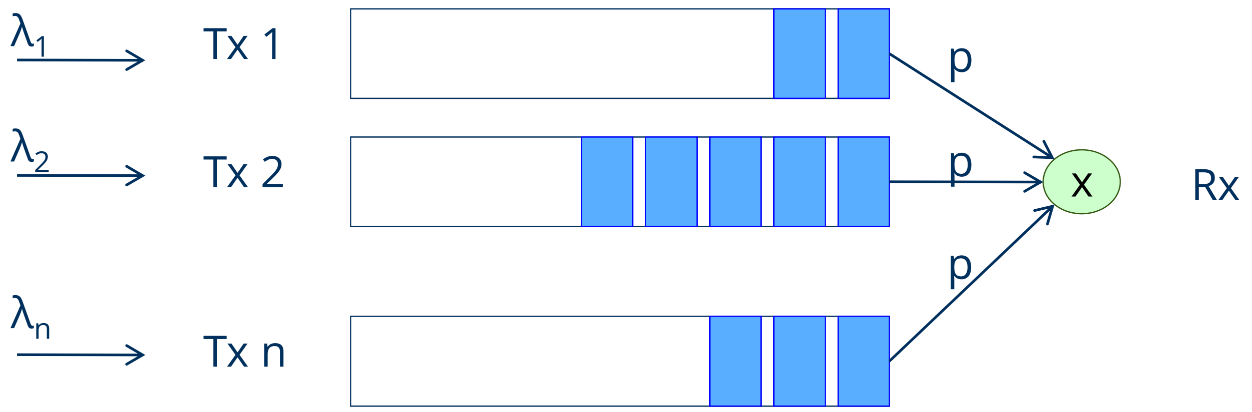
Perfect scheduler (no collisions): $$E[T_D] = \frac{n}{1-p}$$

p = ½, n = 3
ZZ: 4+
10/21
PS: 6

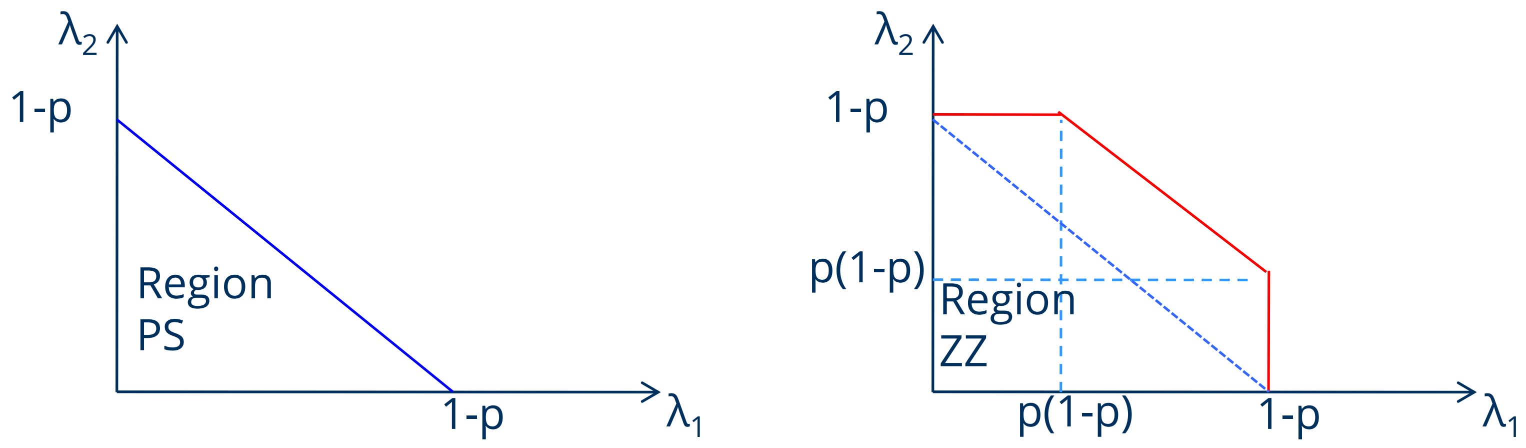
ZigZag Decoding: Single Hop Analysis

http://arxiv.org/pdf/1001.1948v1.pdf

Work in [ParandehGheibi et al 2010]



Second result: Stable throughput increases



Coded Access

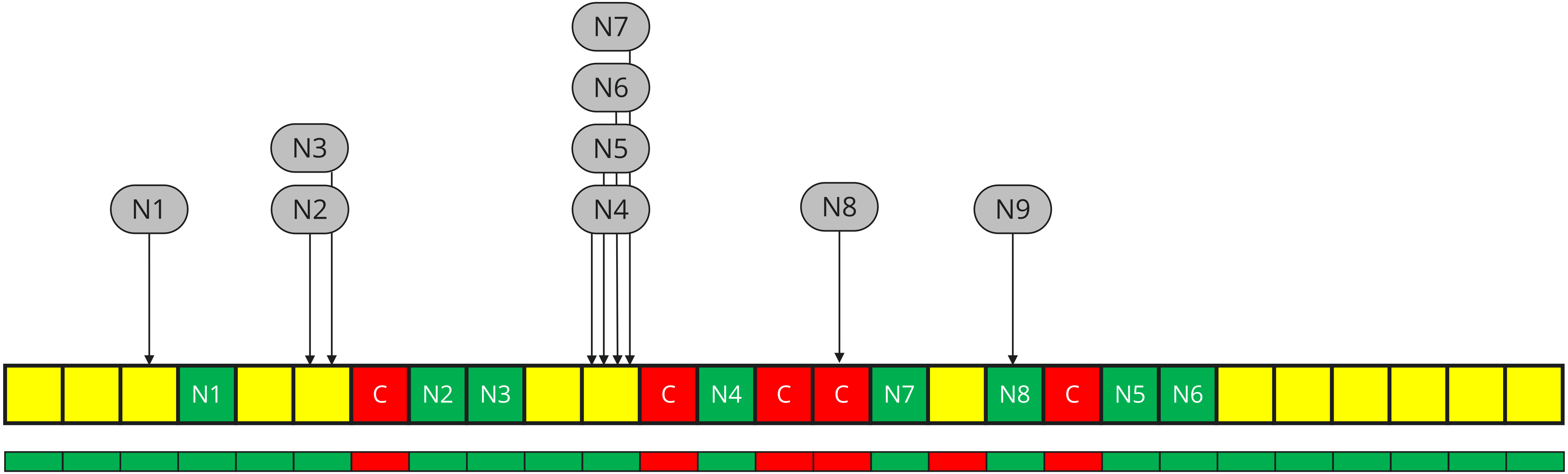
Multiple Access SoA

Random access was the key to get access to the wireless channel

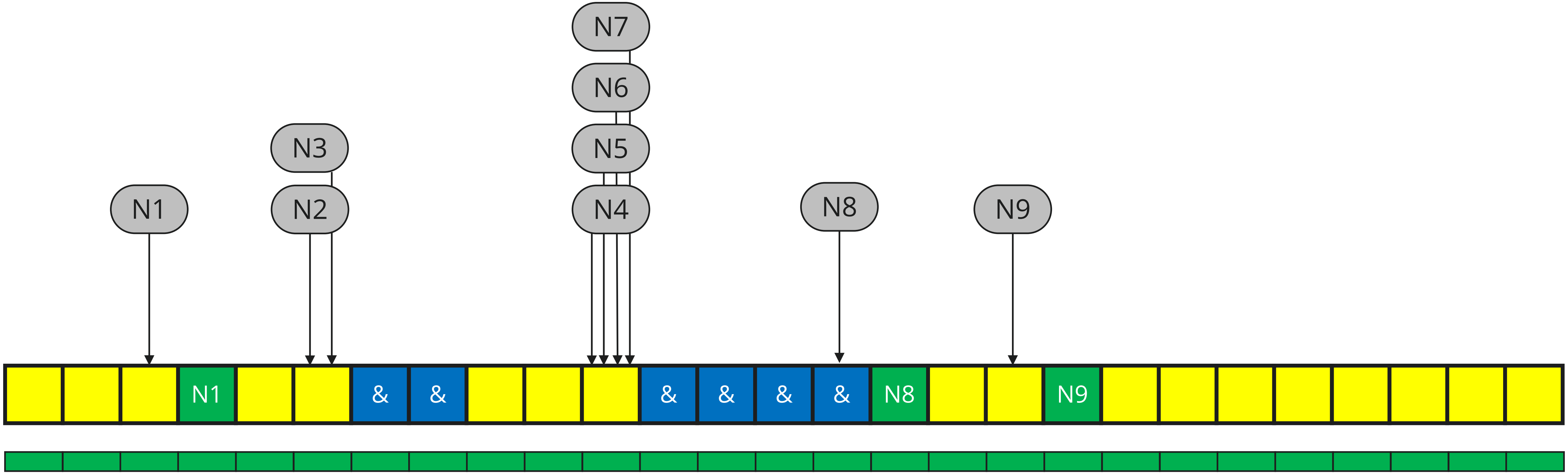
In time slotted systems

- Idle slots: nobody was transmitting
- One transmission: successful access to the resources
- More than one transmission: Collision

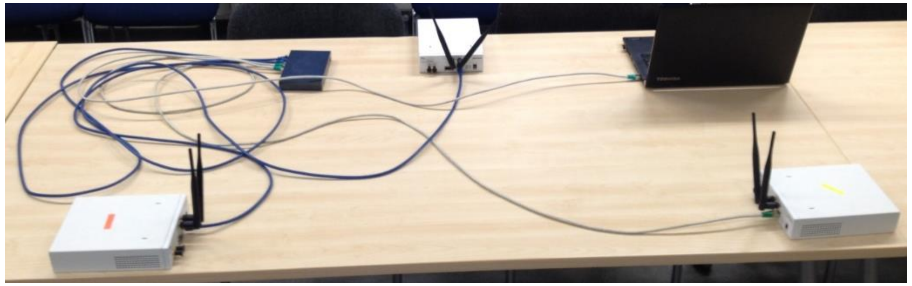
SoA Multiple Access

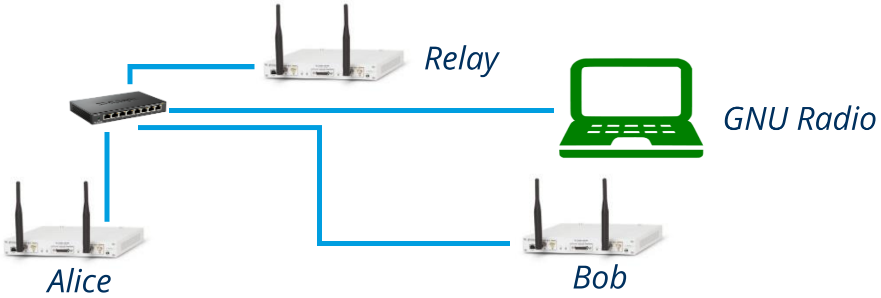


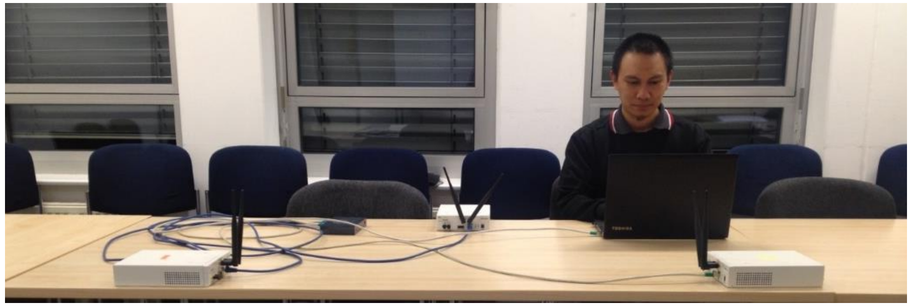
Coded Acess



Our Analog Network Coding Testbed







GNU Radio, from design to deployment

- With GNU Radio you can simulate, prototype, and deploy, all from the same workflow

Active Community

- http://www.cgran.org/
- http://list.gnu.org/archive/html/discuss-gnuradio

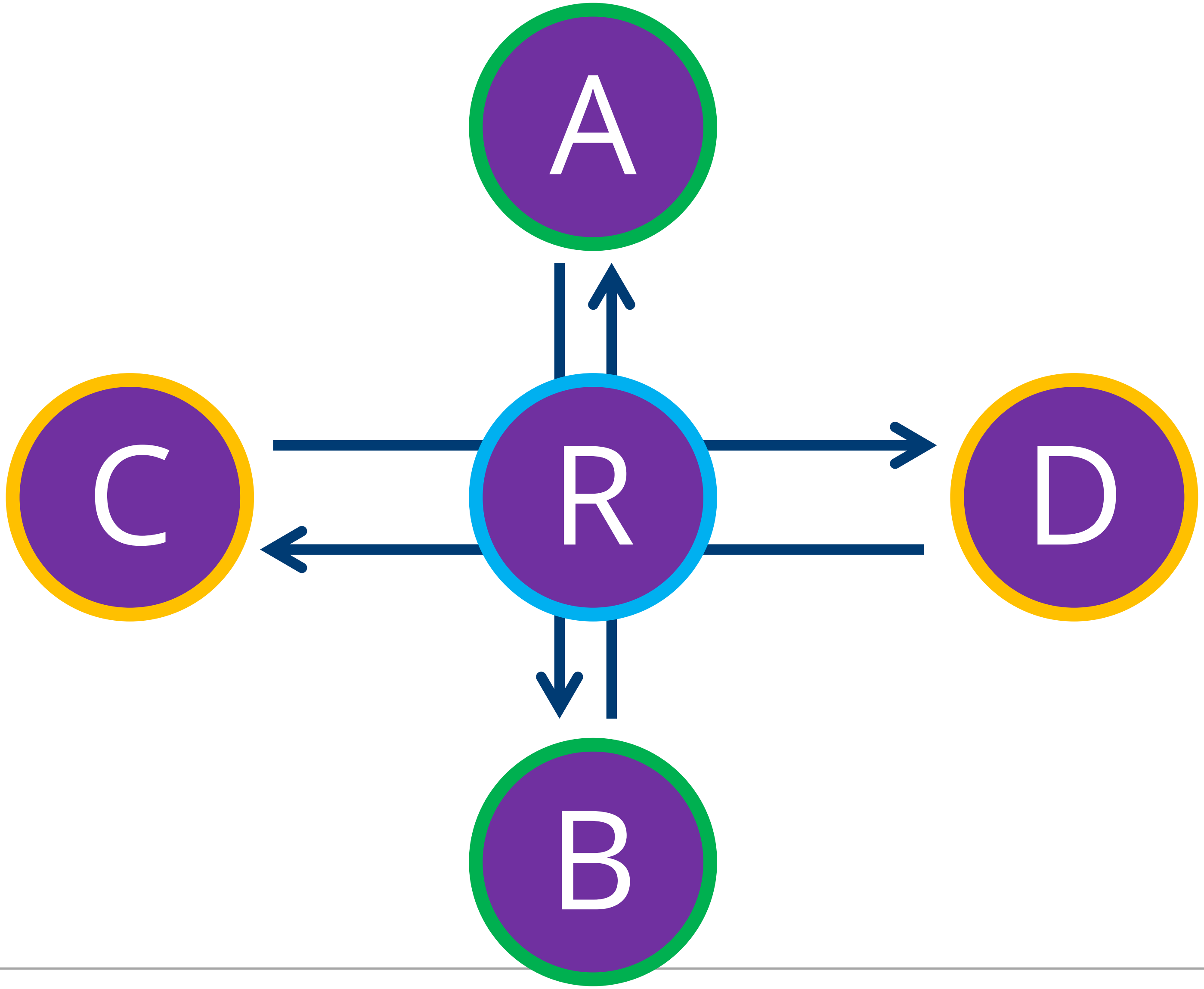
Free Software

- GNU Radio is free software. That means you have the liberty to use it and modify it as you wish
- https://www.gnuradio.org/

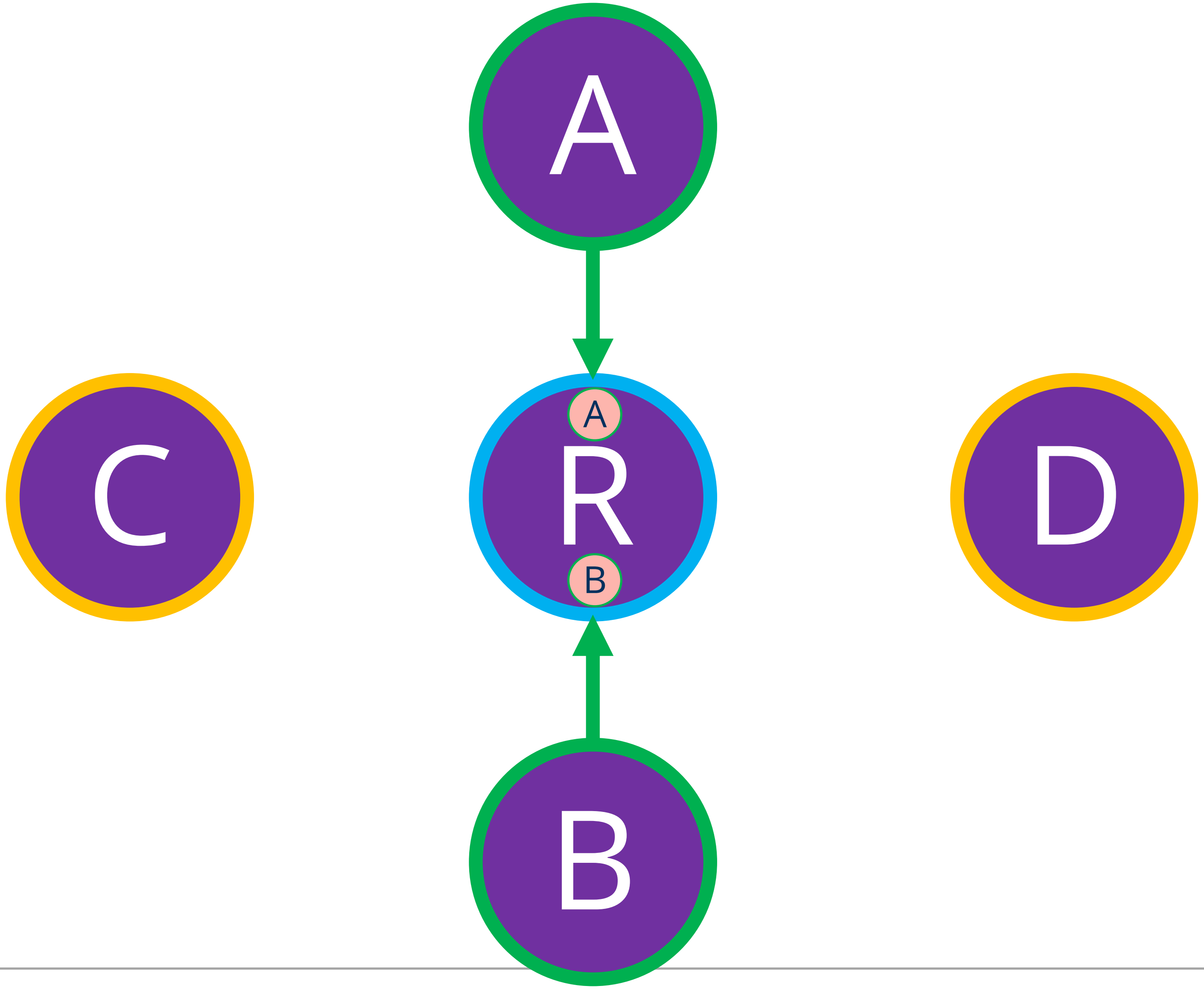
GNURadio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

ANC for cross topologies

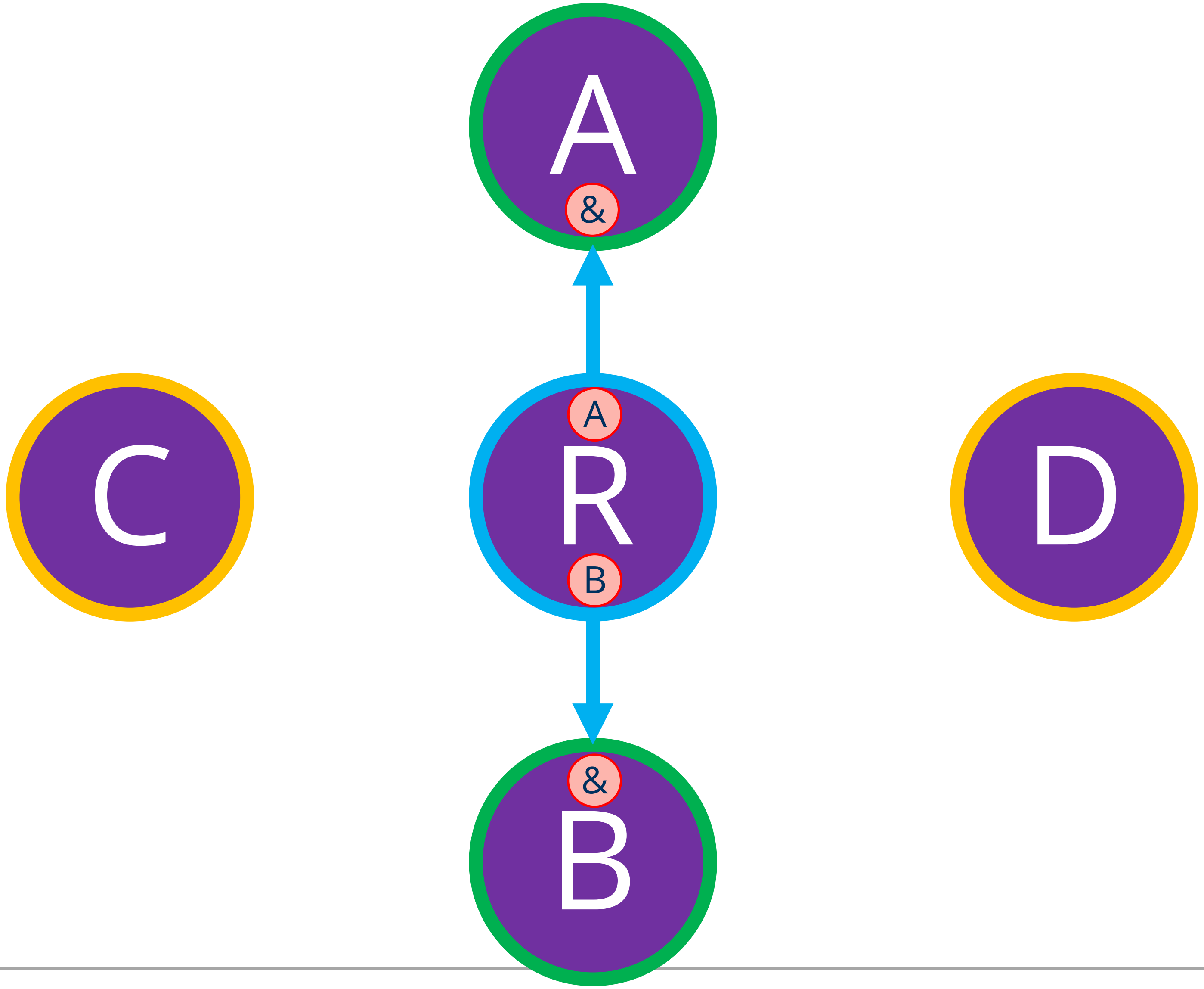
Cross Topology ANC without Overhearing



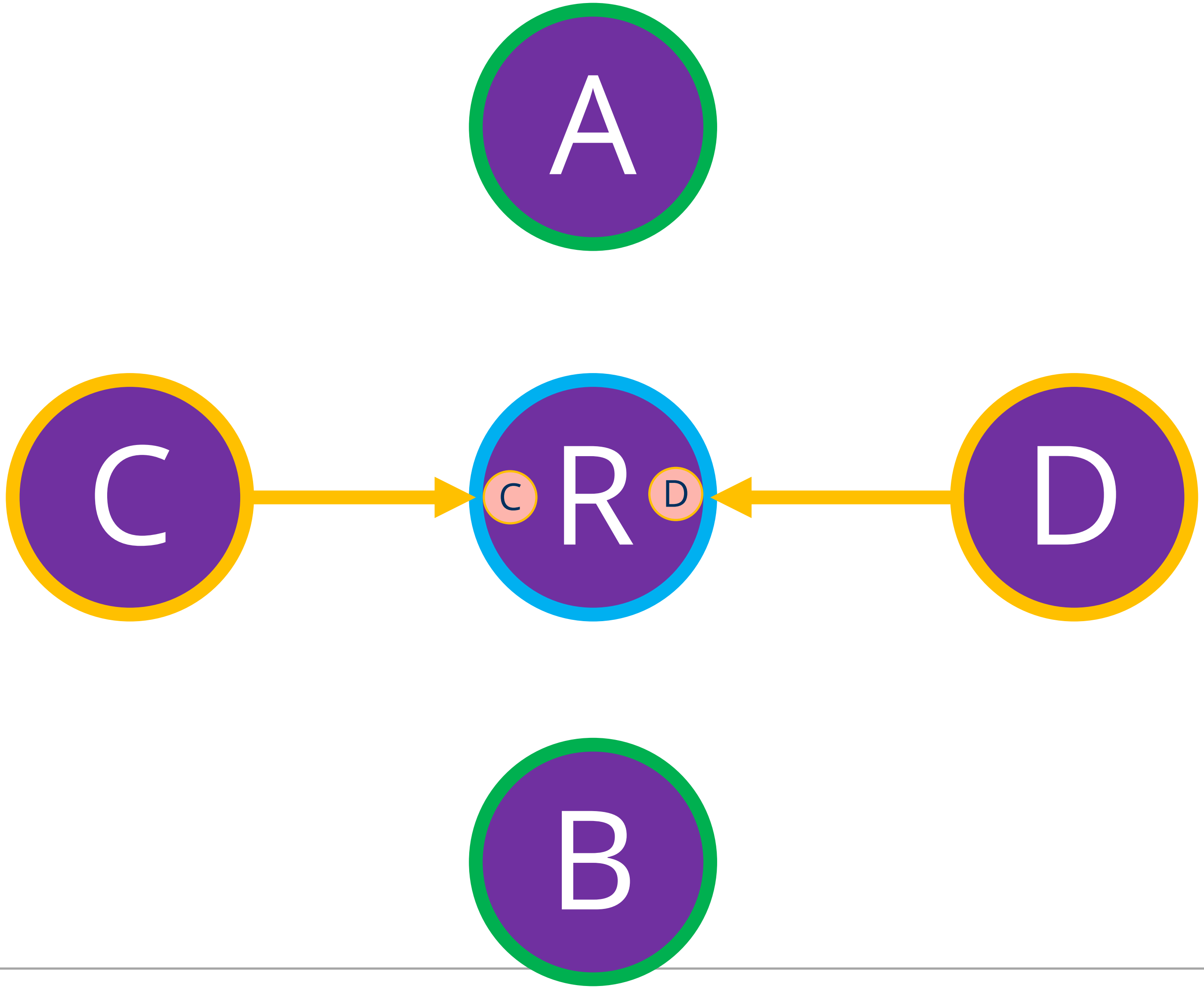
Cross Topology ANC without Overhearing – Slot 1



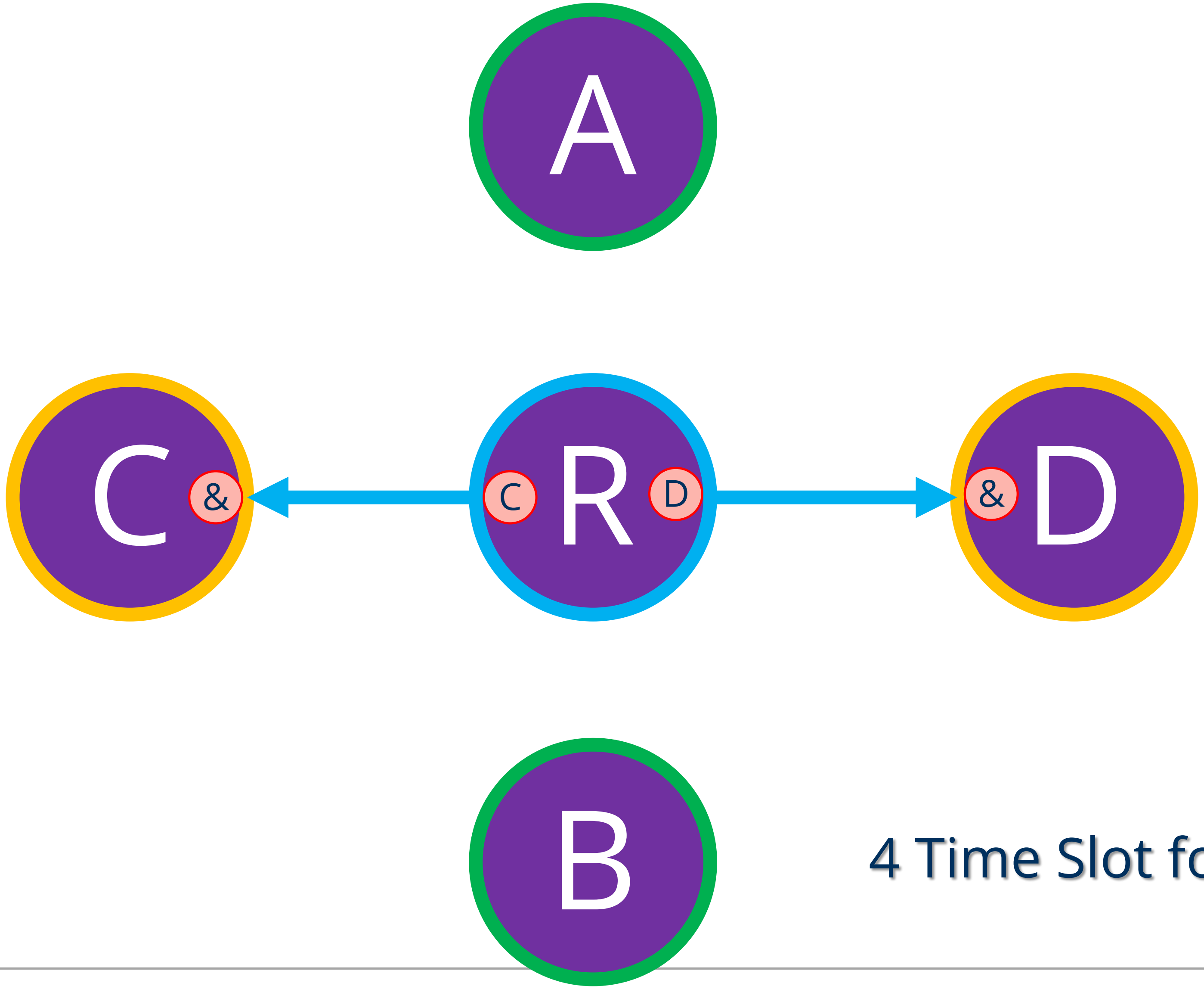
Cross Topology ANC without Overhearing – Slot 2



Cross Topology ANC without Overhearing – Slot 3

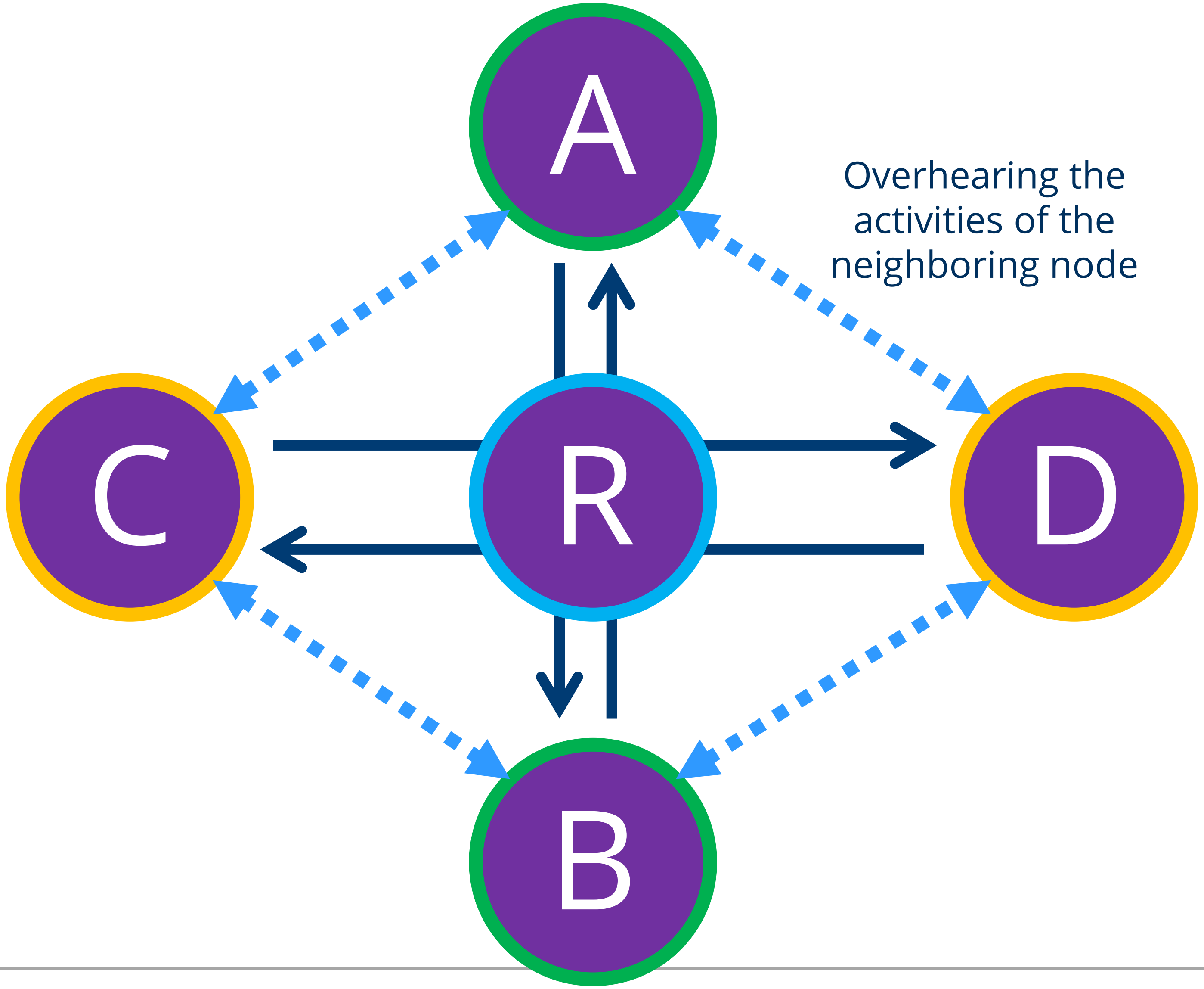


Cross Topology ANC without Overhearing – Slot 4

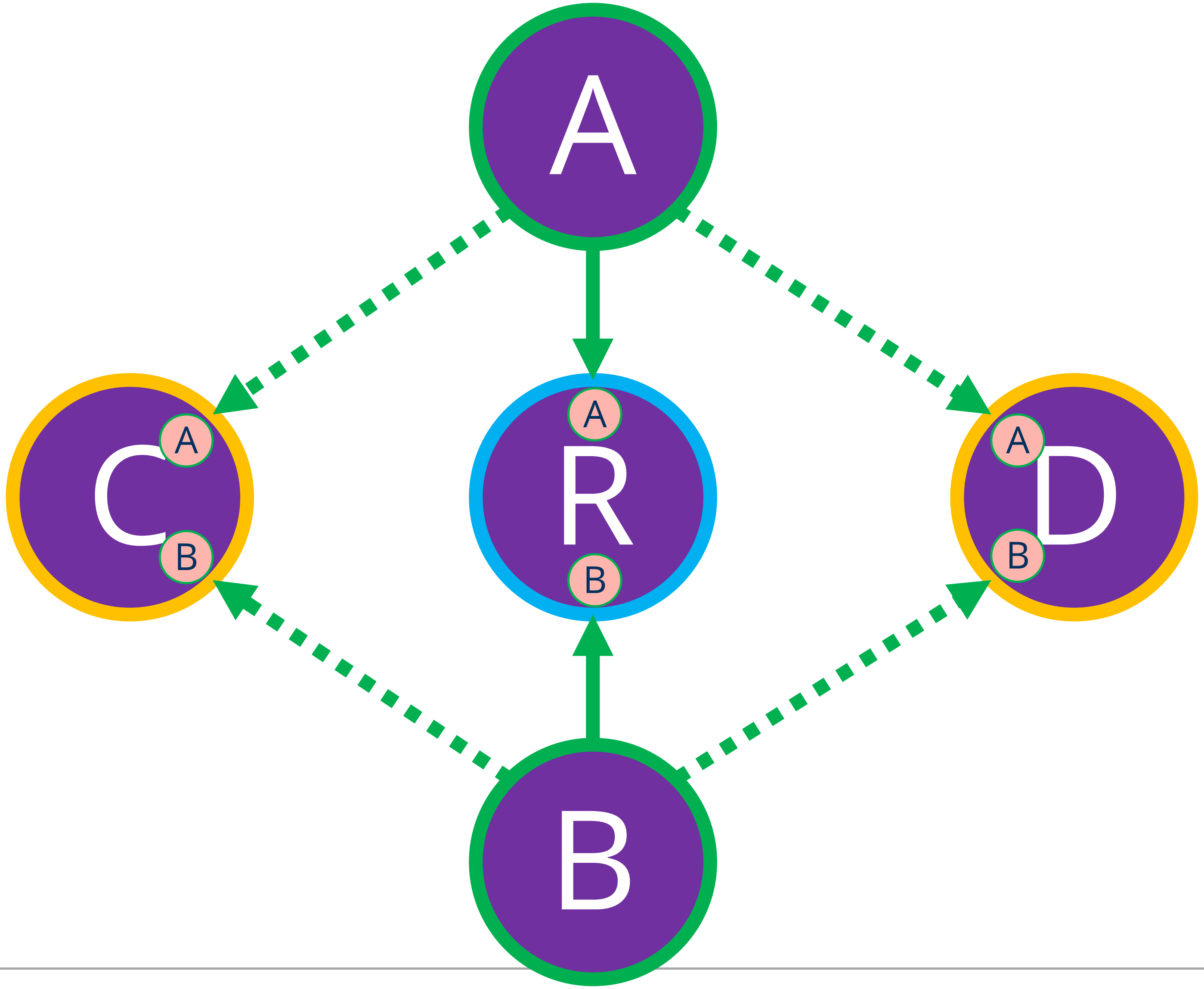


4 Time Slot for full exchange

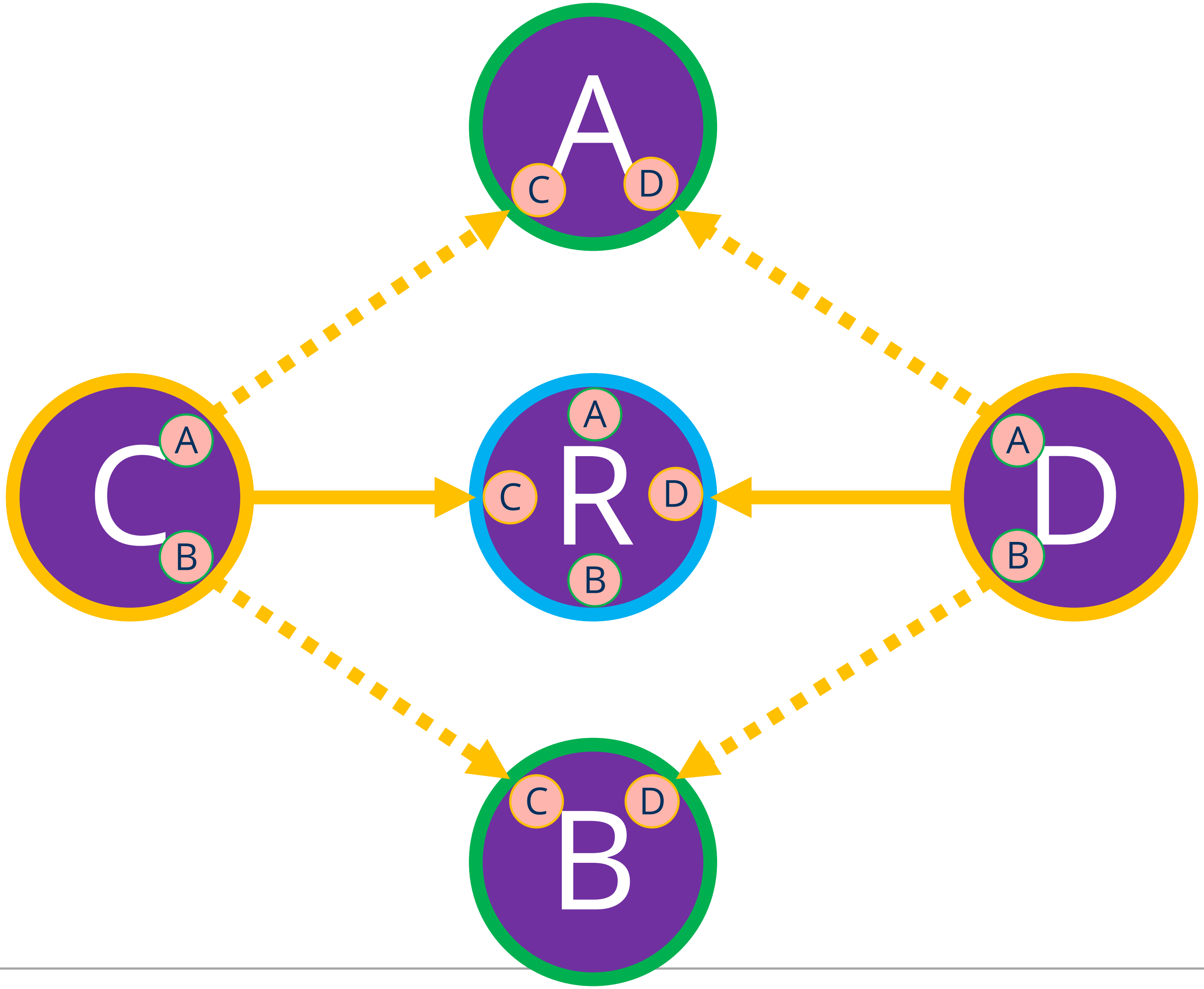
Cross Topology ANC with Overhearing



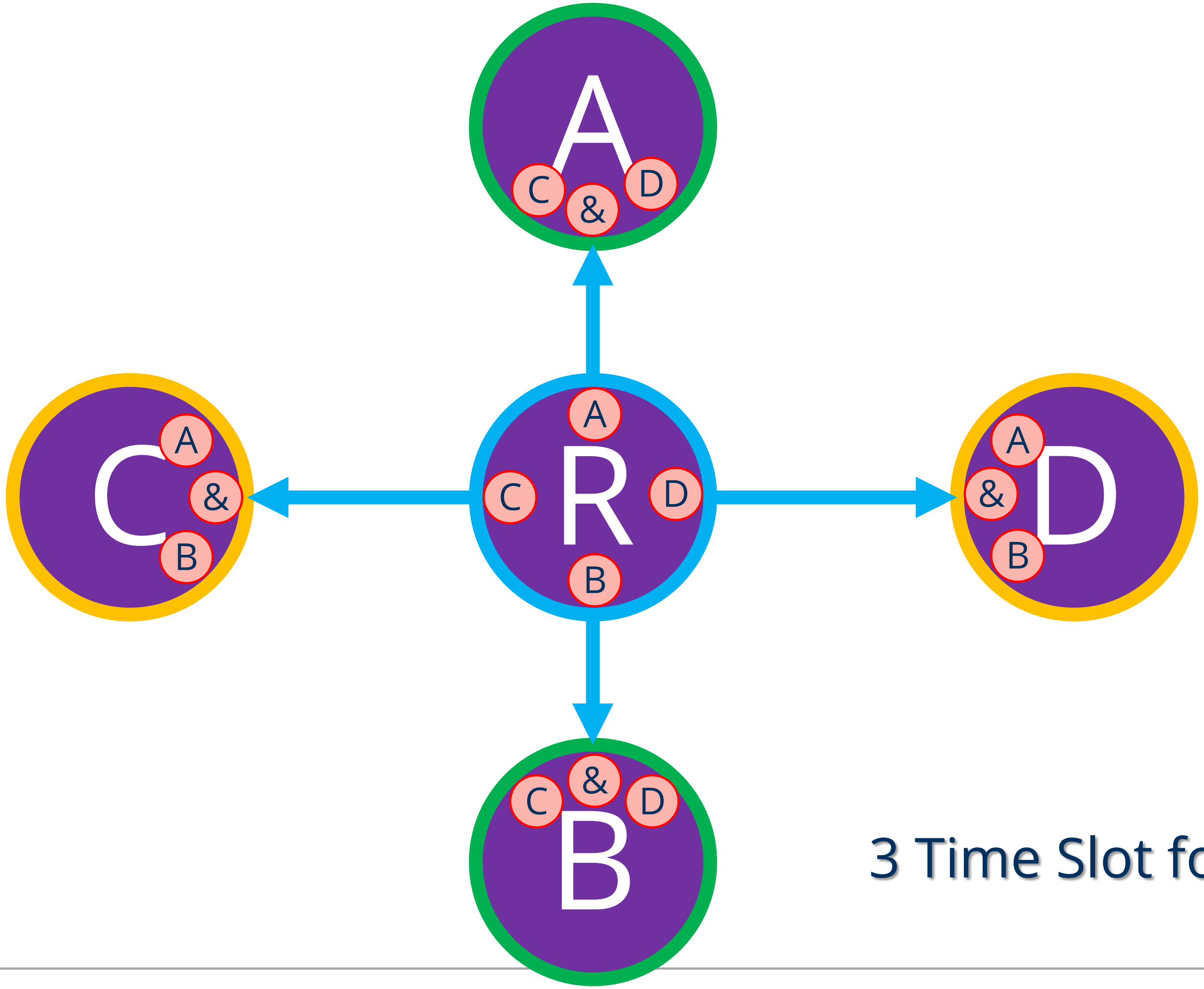
Cross Topology ANC with Overhearing – Slot 1



Cross Topology ANC with Overhearing – Slot 2

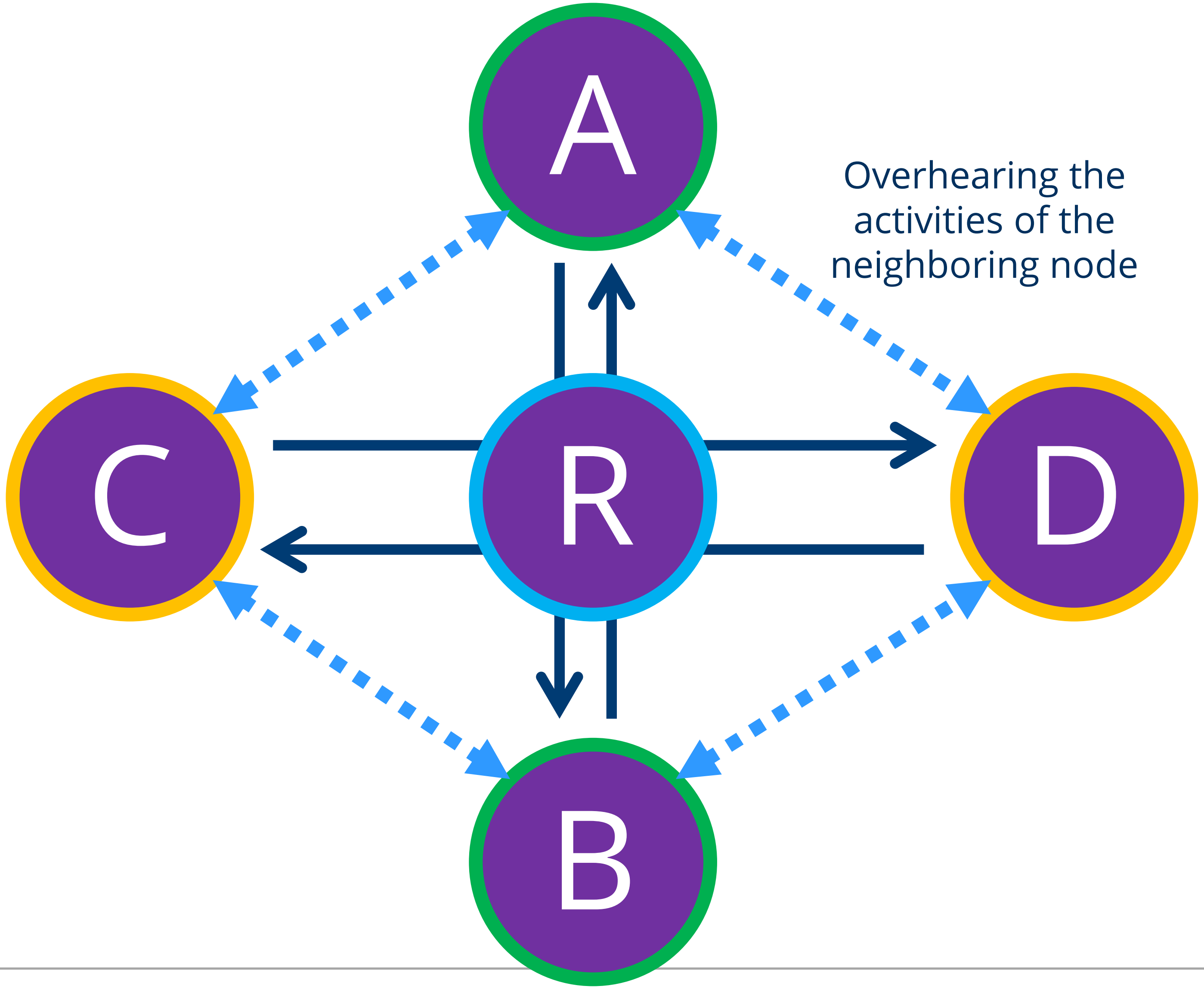


Cross Topology ANC with Overhearing – Slot 3

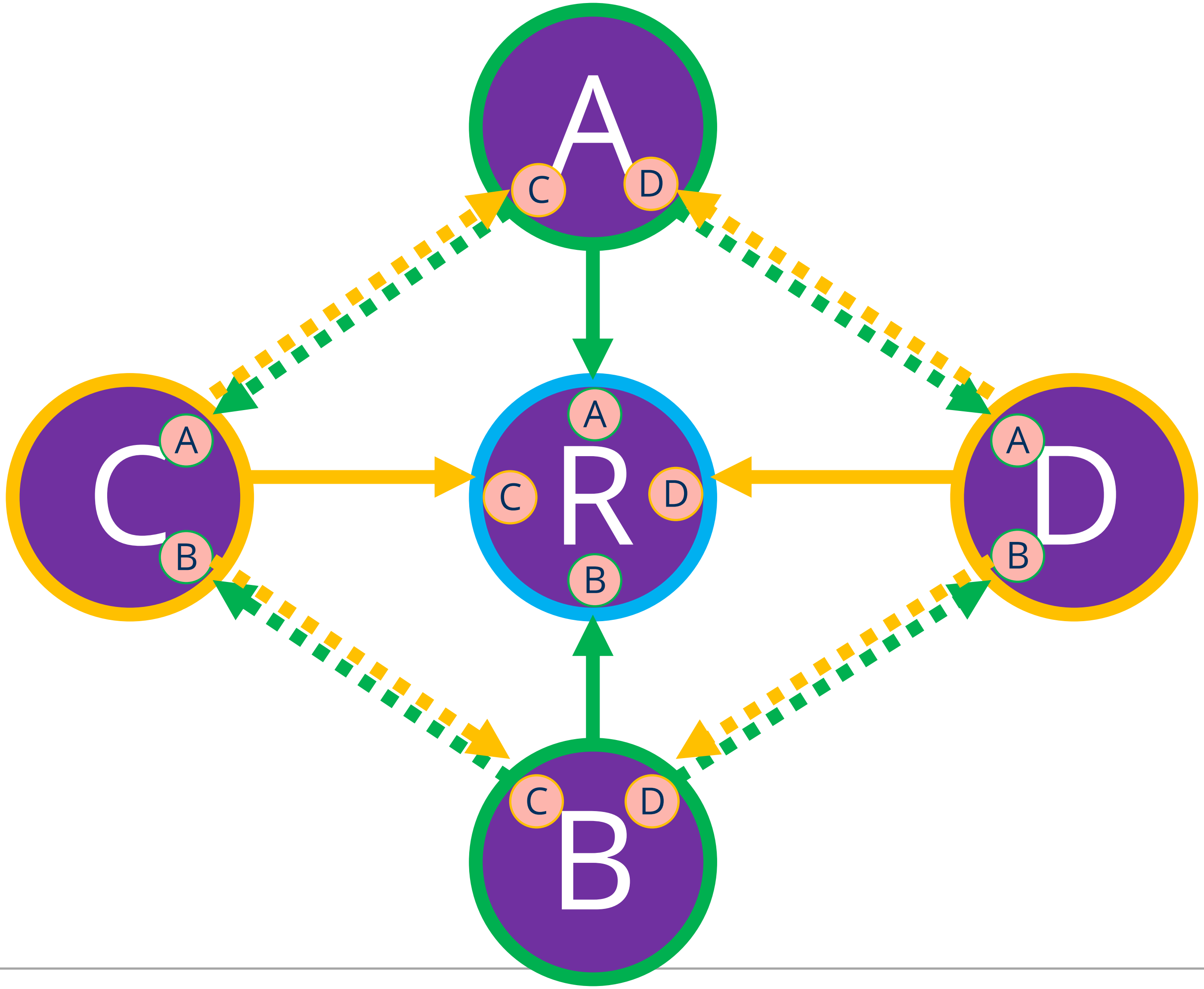


3 Time Slot for full exchange

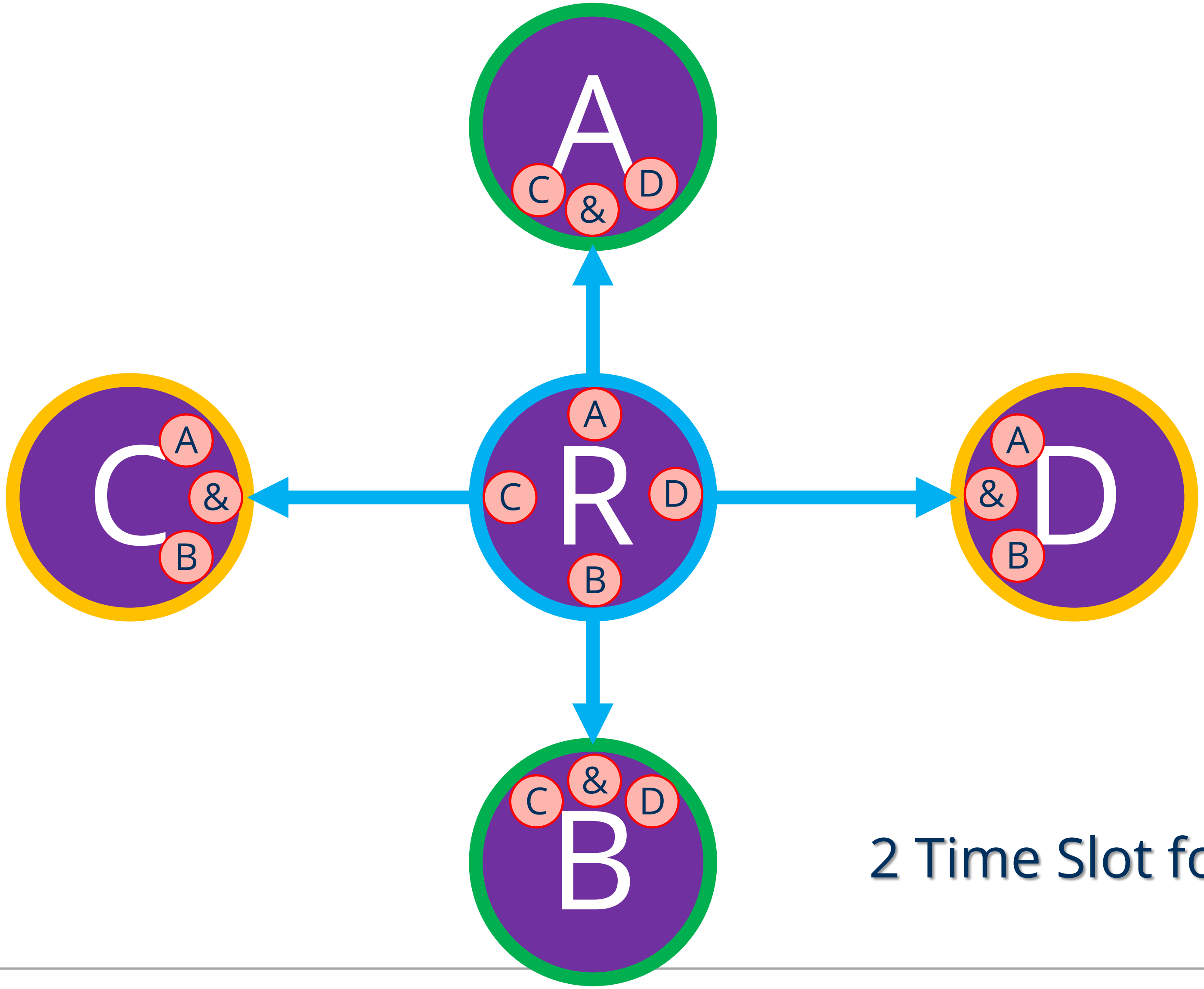
Cross Topology ANC with Overhearing Duplex



Cross Topology ANC with Overhearing Duplex – Slot 1

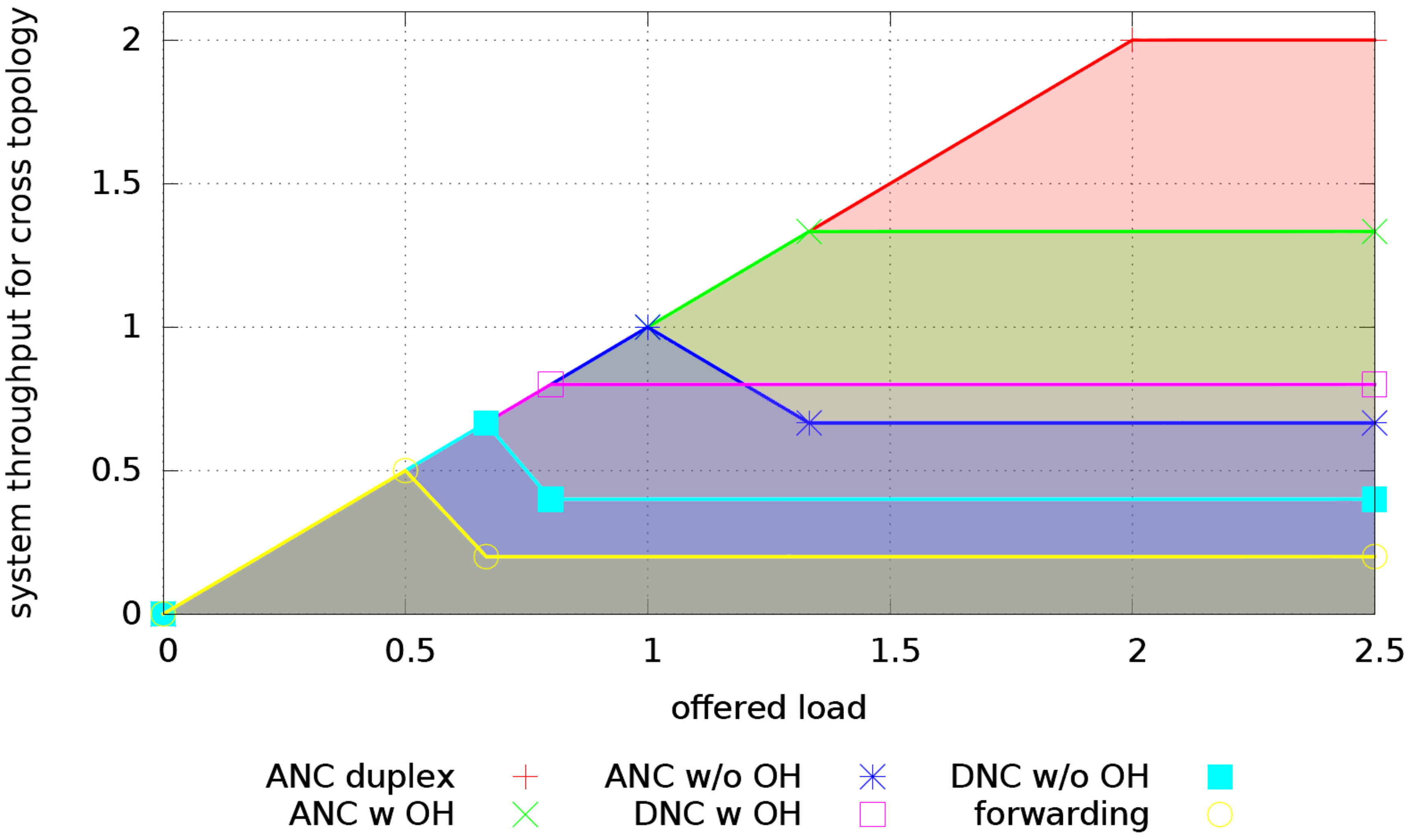


Cross Topology ANC with Overhearing Duplex – Slot 2



2 Time Slot for full exchange

Throughput for the Cross Topology



Inter-Flow Network Coding on CAN Bus

Courtesy of BOSCH

Plug-and-Secure Communication for CAN

Andreas Müller & Timo Lothspeich

Robert Bosch GmbH, Germany

1

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Inter-Flow Network Coding on CAN Bus

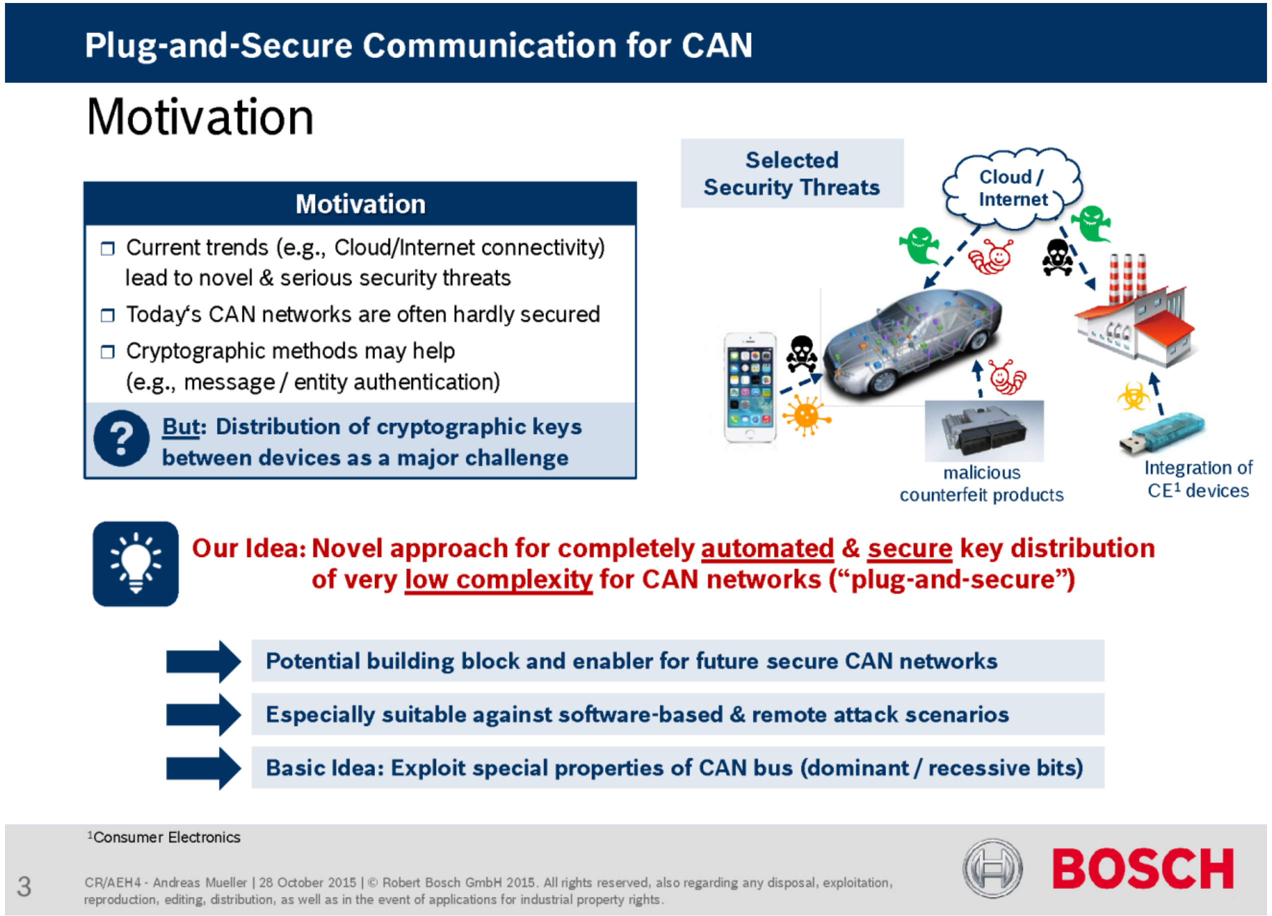
Courtesy of BOSCH

Plug-and-Secure Communication for CAN

Outline

1. Motivation
2. Fundamental Idea
3. Implementation Aspects
4. Security Considerations
5. Conclusion

Inter-Flow Network Coding on CAN Bus
Courtesy of BOSCH



Inter-Flow Network Coding on CAN Bus

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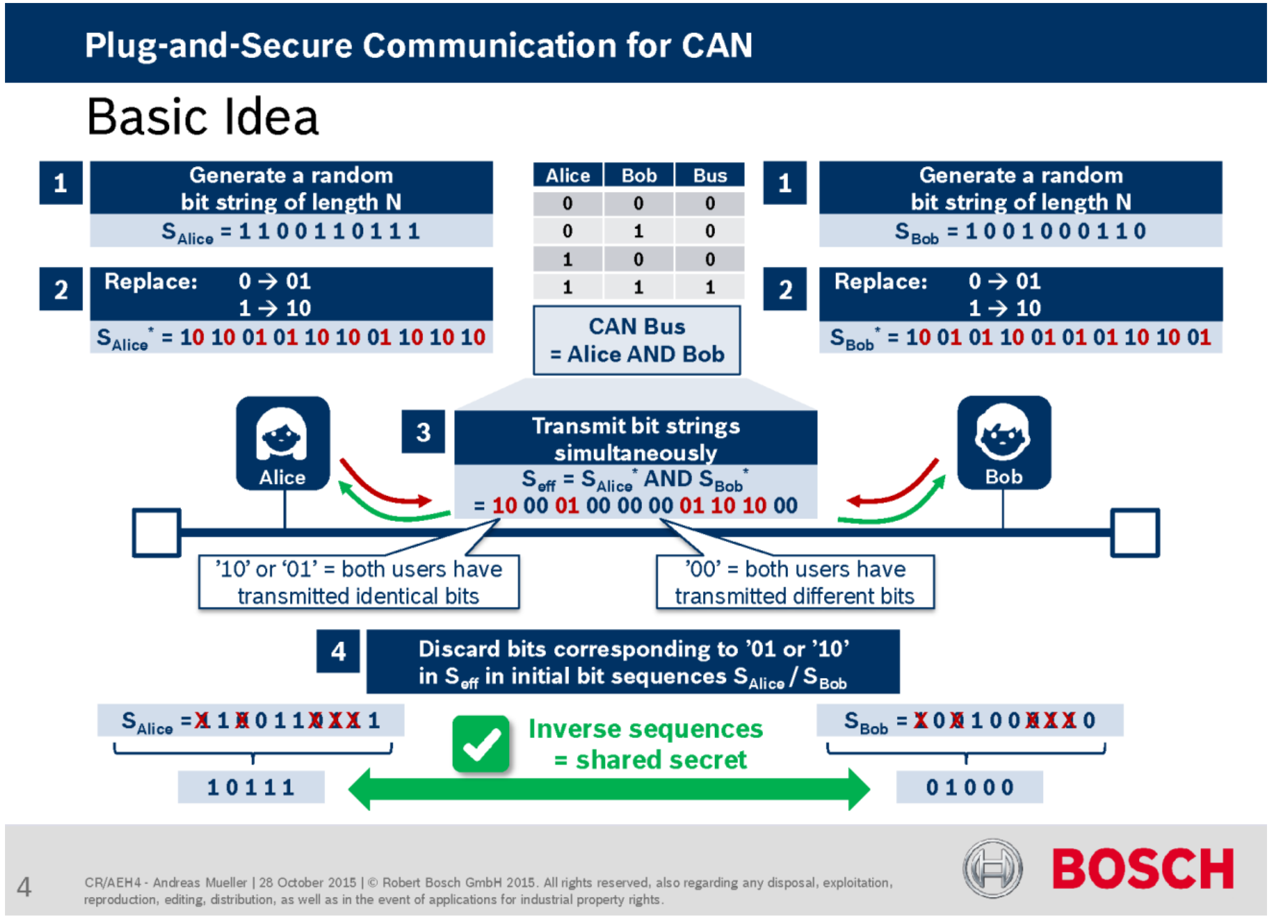

Inter-Flow Network Coding on CAN Bus

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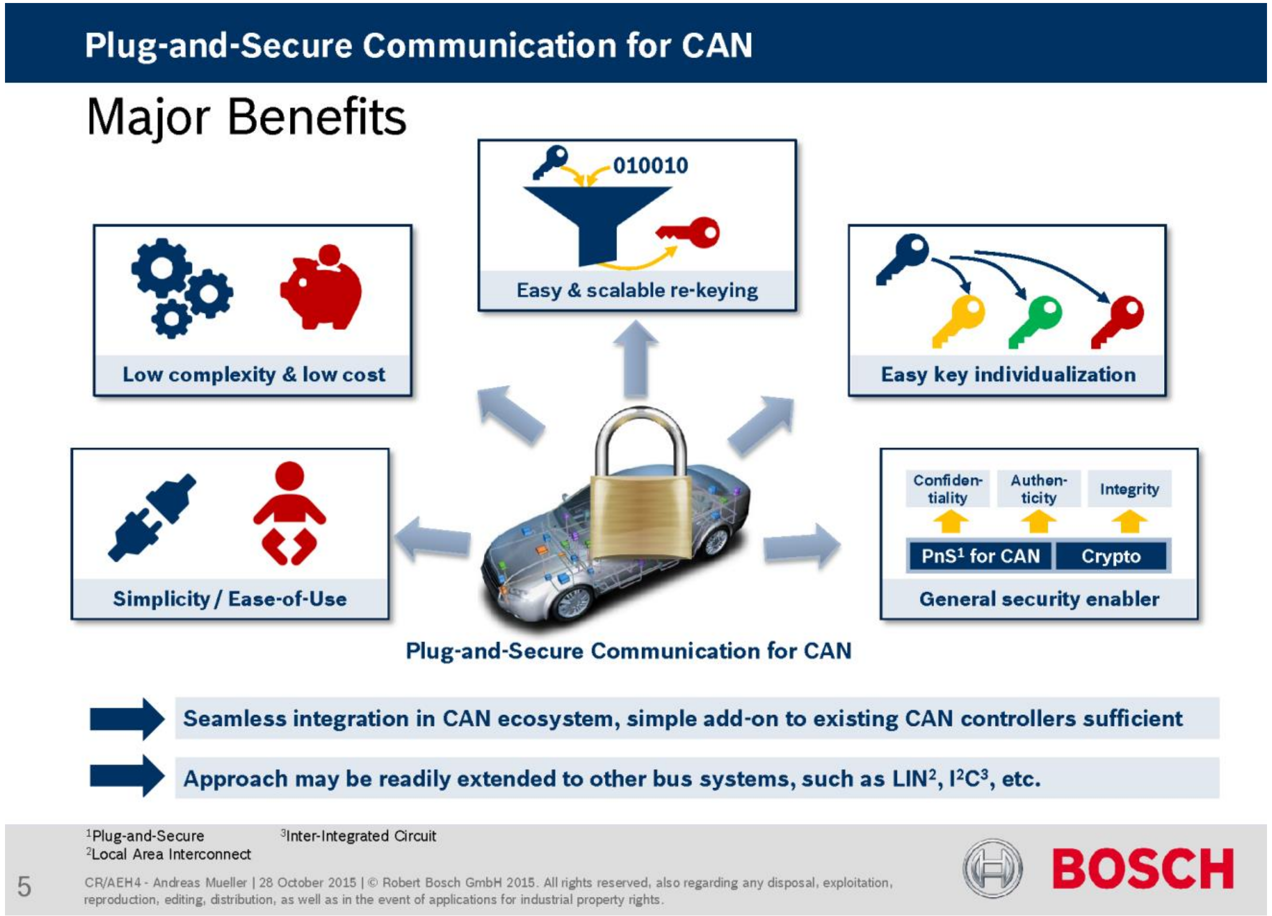

Inter-Flow Network Coding on CAN Bus

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Implementation Aspects

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Inter-Flow Network Coding on CAN Bus

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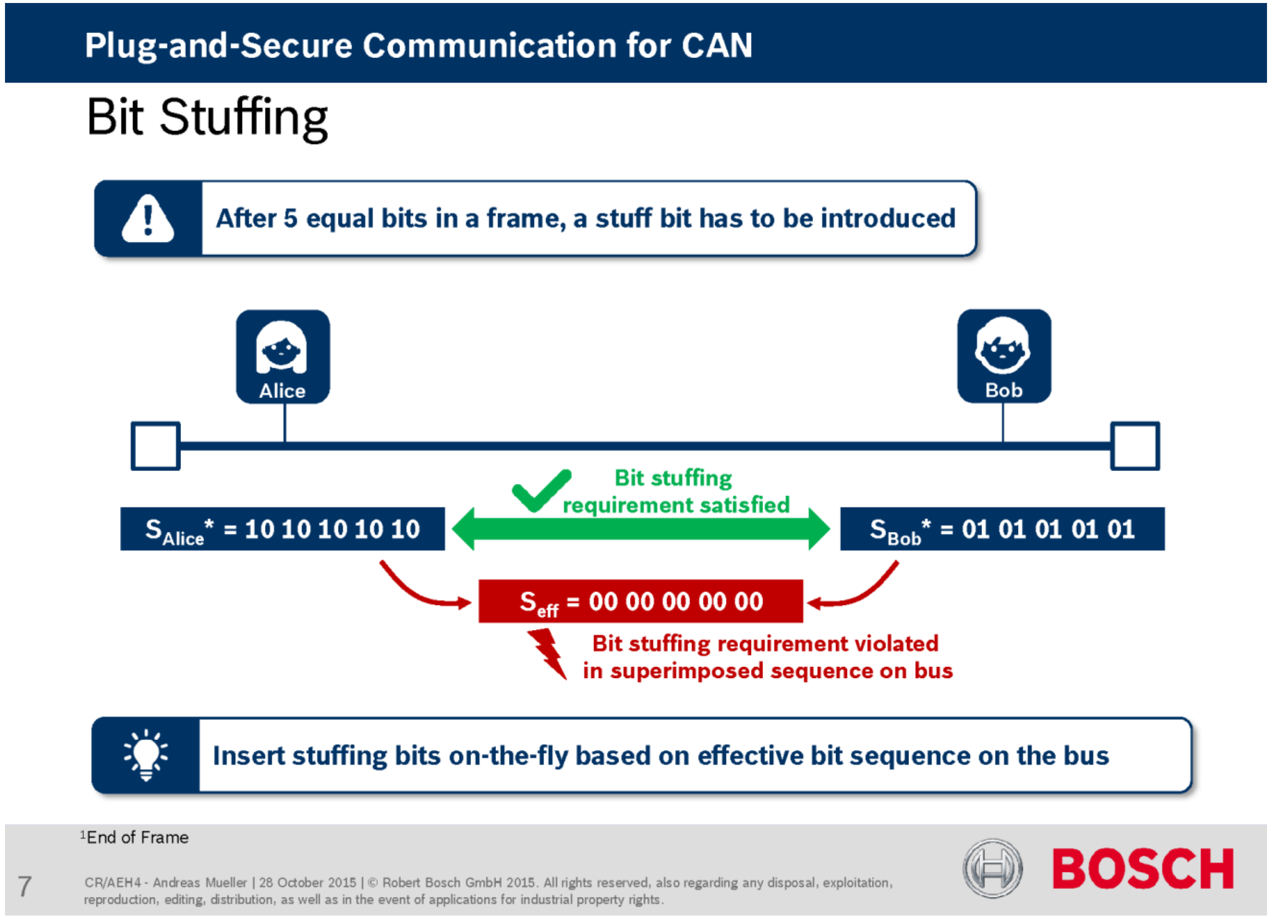
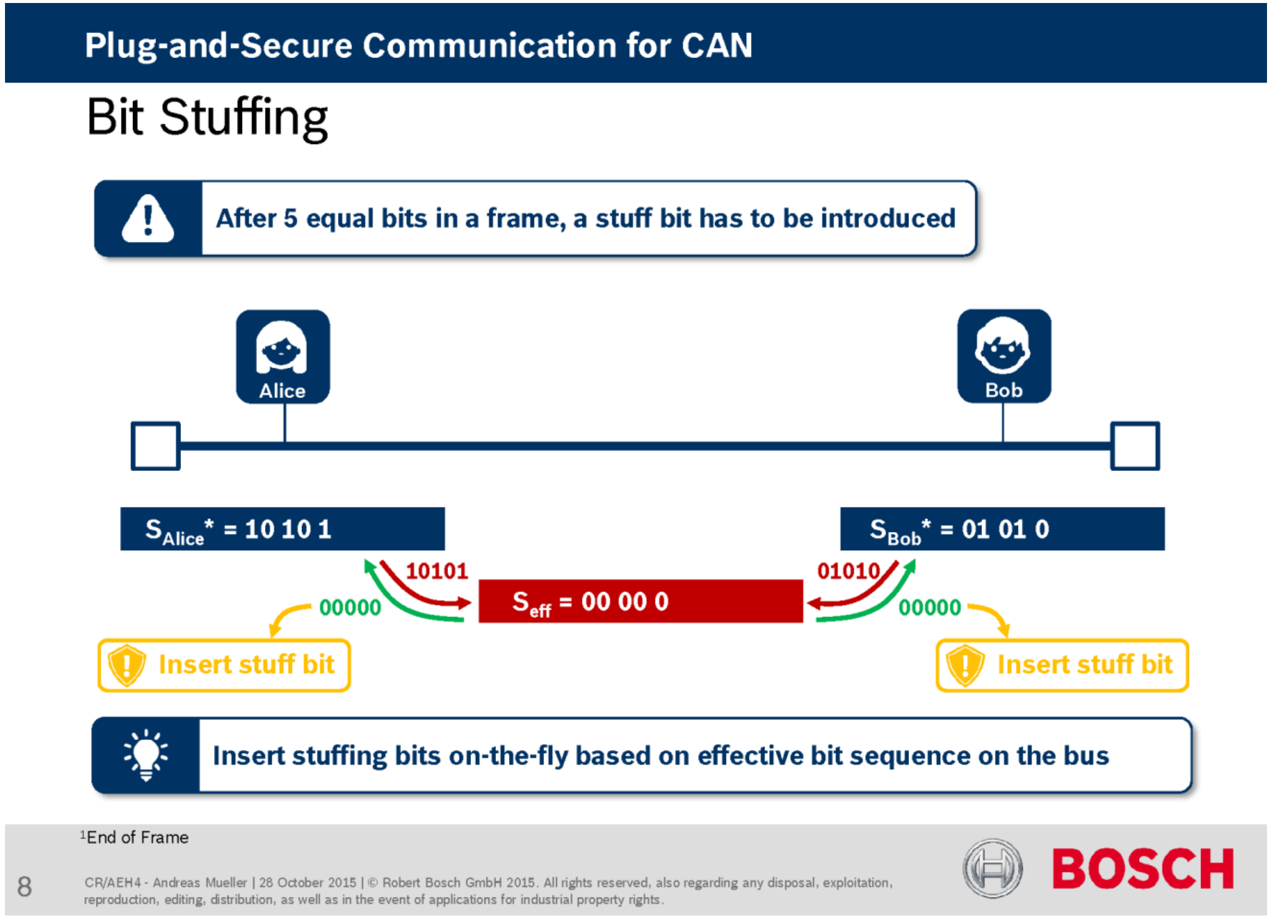


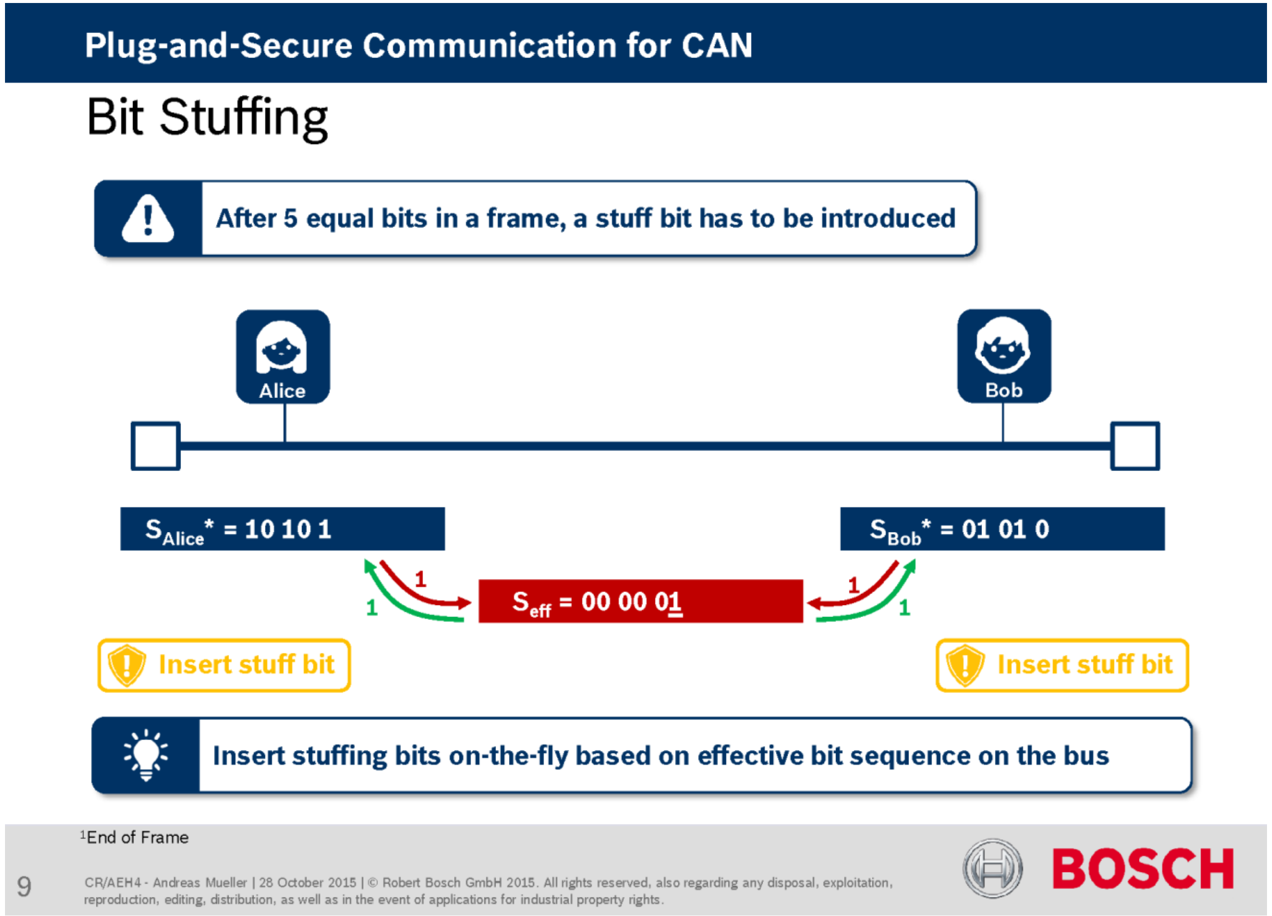
Inter-Flow Network Coding on CAN Bus

Courtesy of BOSCH



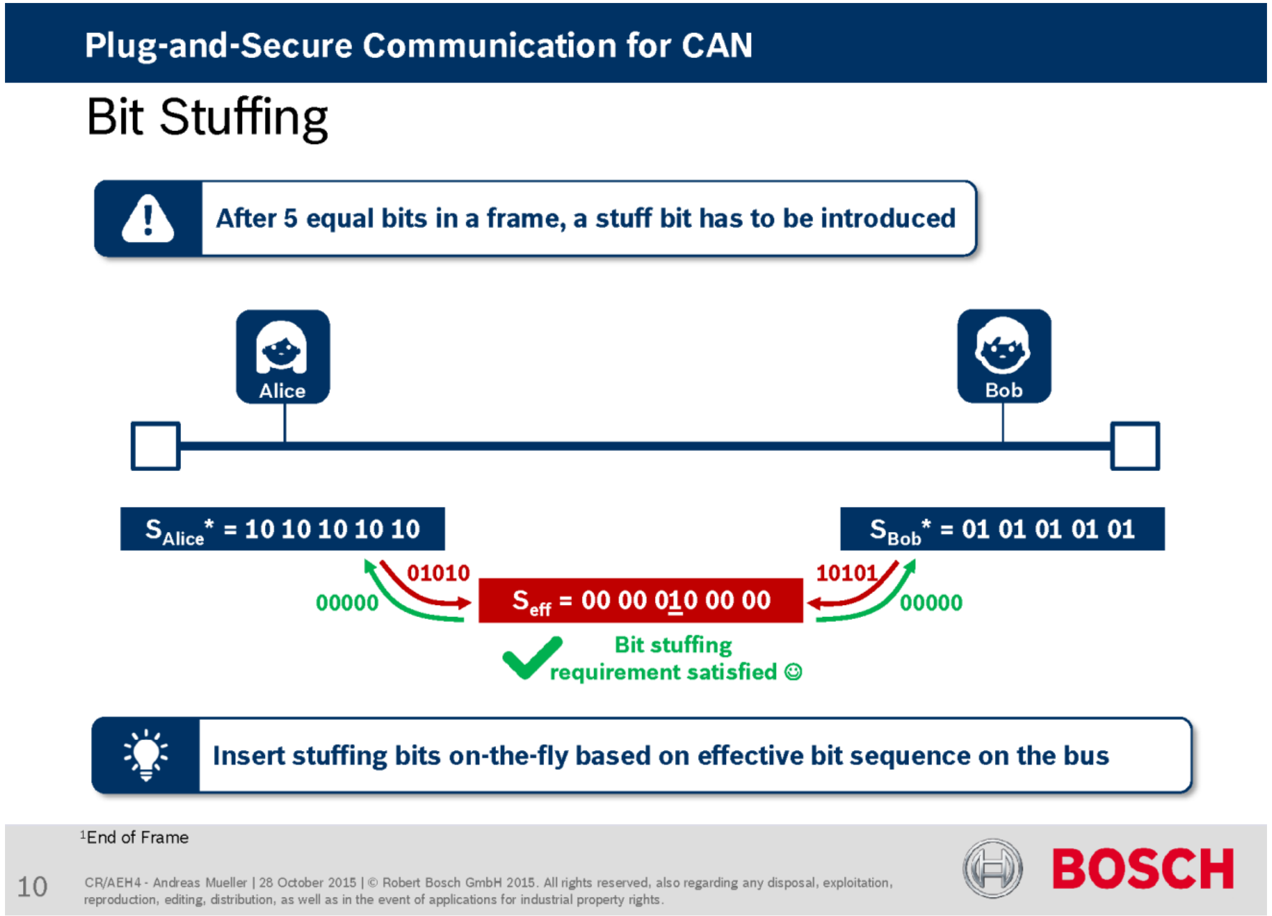
Inter-Flow Network Coding on CAN Bus

Courtesy of BOSCH



Inter-Flow Network Coding on CAN Bus

Courtesy of BOSCH



Inter-Flow Network Coding on CAN Bus

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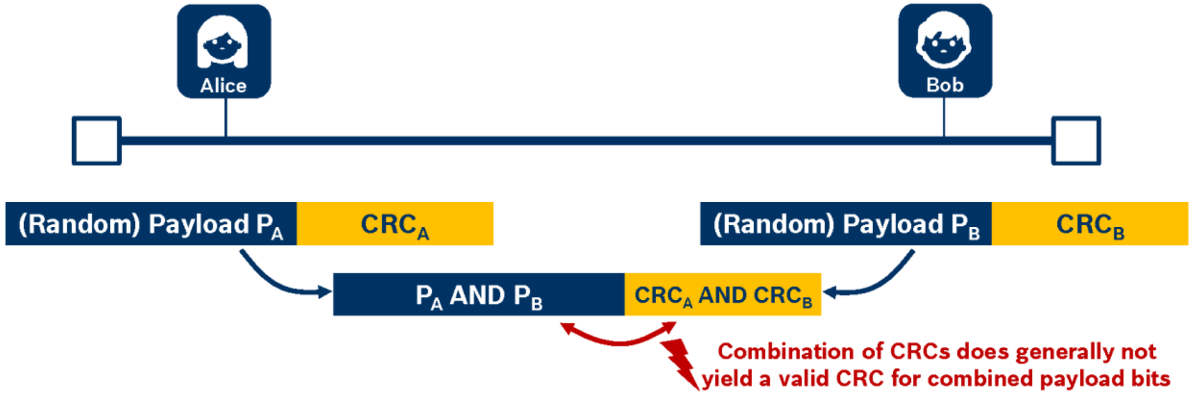
Plug-and-Secure Communication for CAN

CRC Check

Cyclic redundancy check field enables detection of transmission errors
→ Superimposed CRC fields ≠ correct CRC for superimposed payloads



Calculate CRC on-the-fly based on effective payload field on the bus

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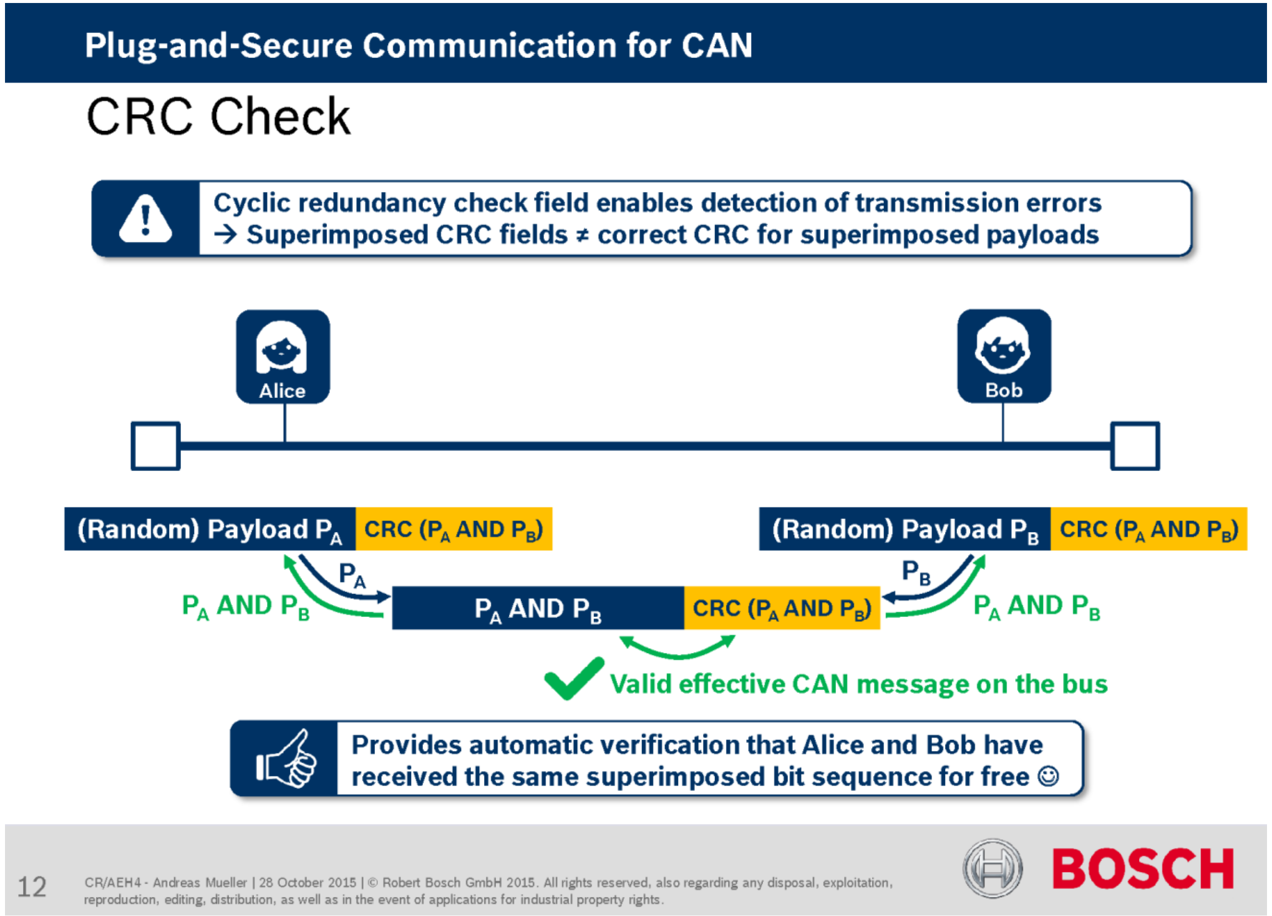
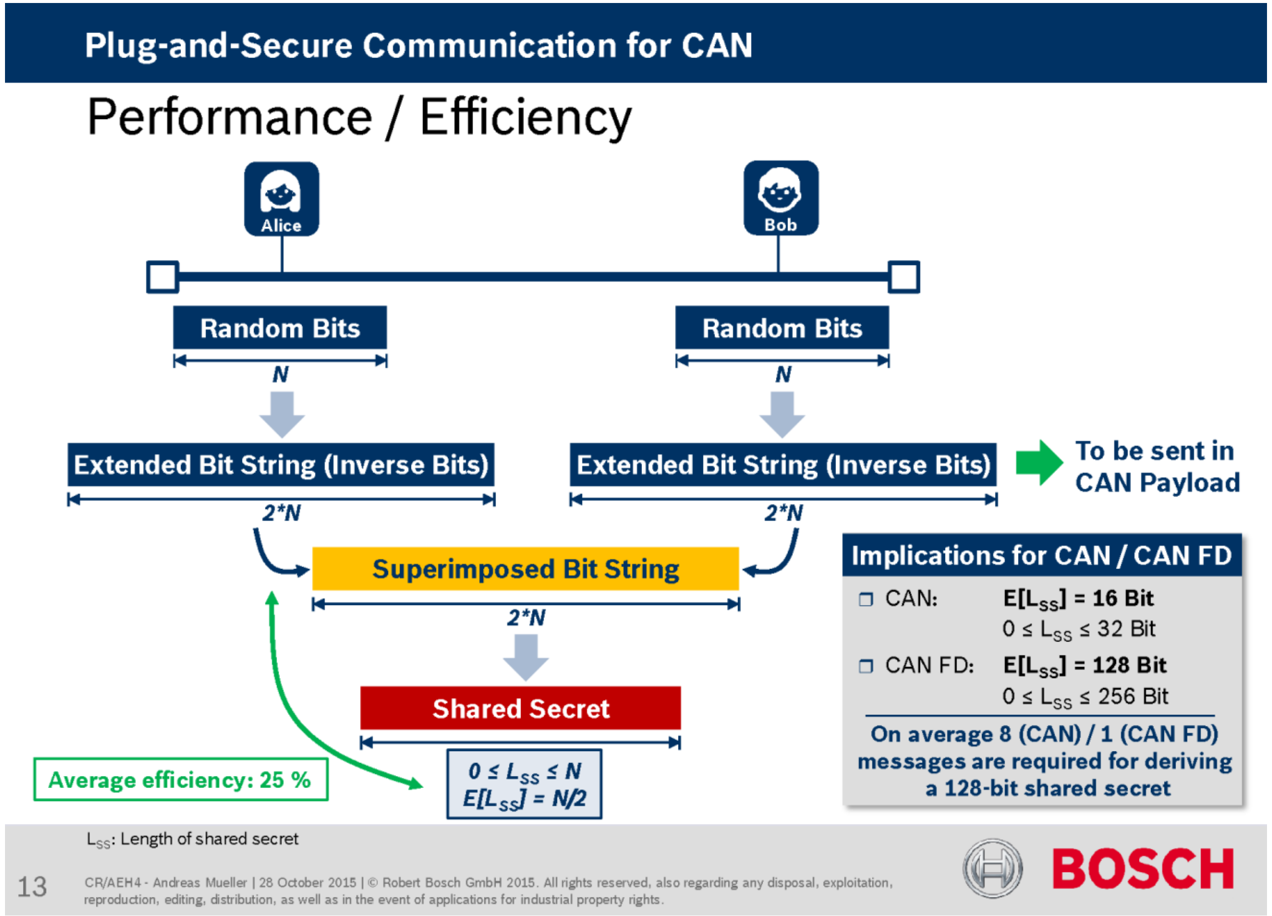
Inter-Flow Network Coding on CAN Bus

Courtesy of BOSCH



Inter-Flow Network Coding on CAN Bus

Courtesy of BOSCH



Inter-Flow Network Coding on CAN Bus
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Security Considerations

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Inter-Flow Network Coding on CAN Bus

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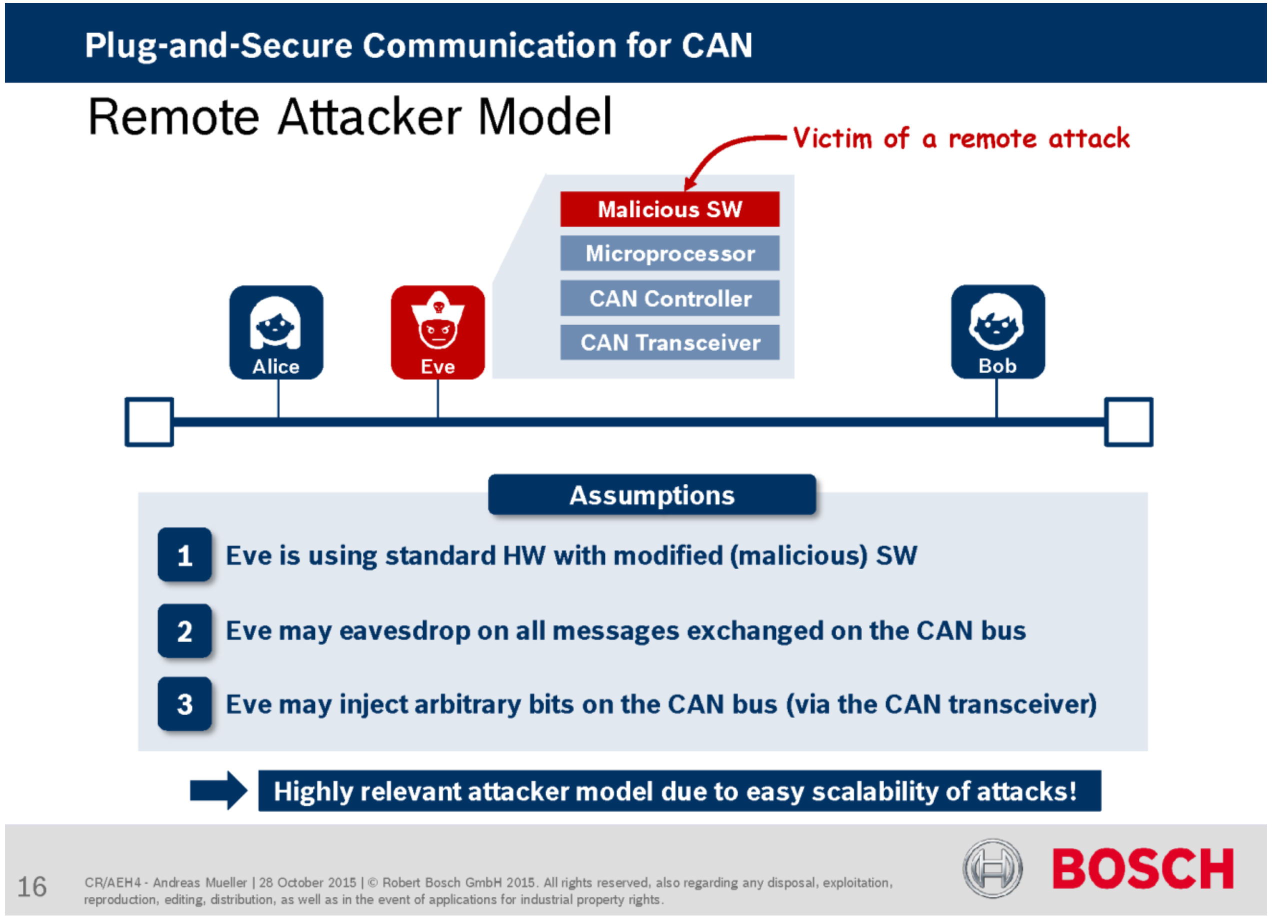
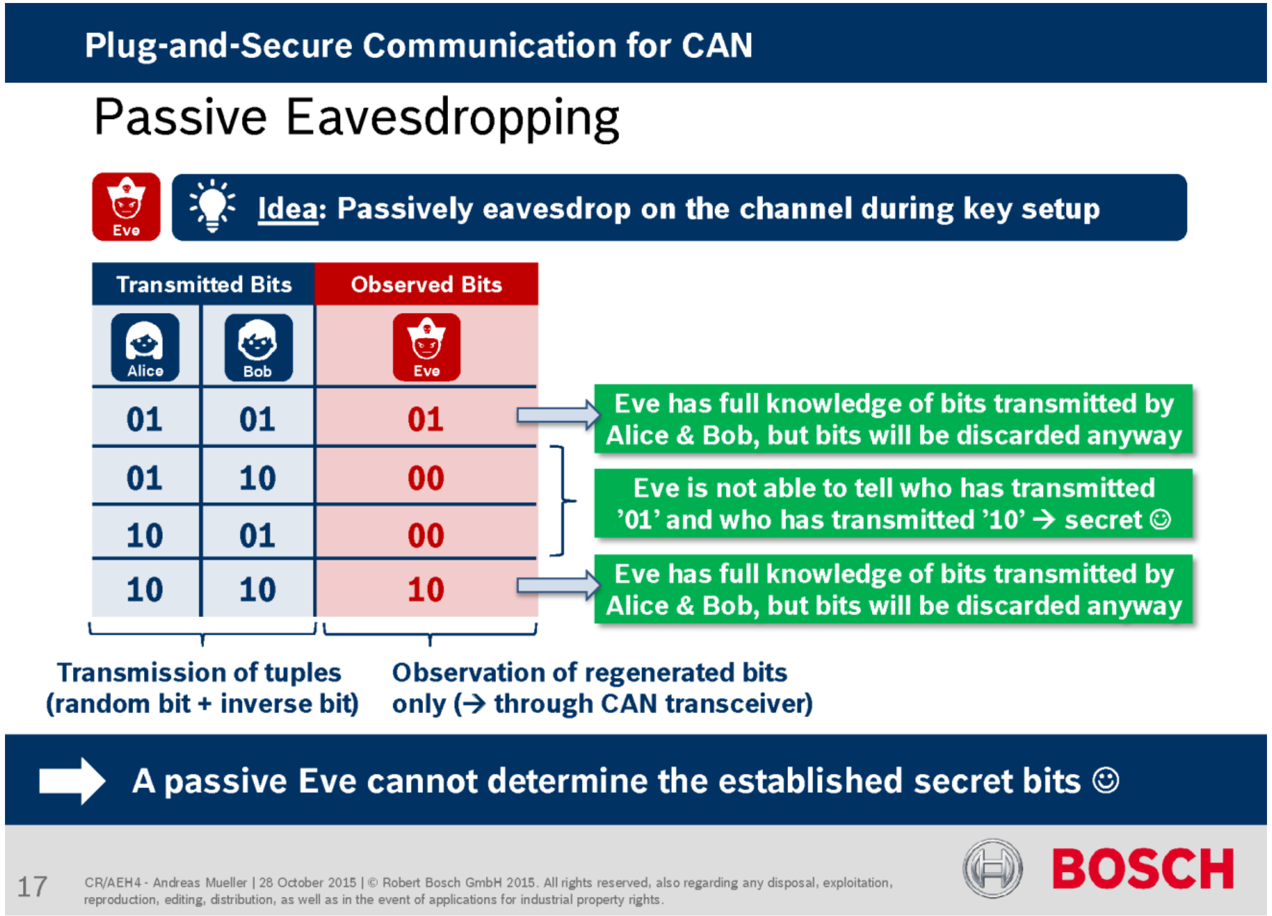


Inter-Flow Network Coding on CAN Bus

Courtesy of BOSCH



Inter-Flow Network Coding on CAN Bus

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Plug-and-Secure Communication for CAN

Active Attacks (I)

Eve

Idea: Actively interfere with key establishment procedure

By superimposing recessive bits

Transmitted Bits		Eve	Bus
Alice	Bob	Eve	CAN
0	0	1	0
0	1	1	0
1	1	1	1

No different from not transmitting at all → no impact ☺

By superimposing dominant bits

Transmitted Bits		Eve	Bus
Alice	Bob	Eve	CAN
01	01	00	00
01	10	00	00
?1	?0	01	00

Requires a closer look

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Inter-Flow Network Coding on CAN Bus

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Plug-and-Secure Communication for CAN

Active Attacks (II)

Eve

Idea: Actively interfere with key establishment procedure

By superimposing dominant bits

Transmitted Bits		Eve	Bus
Alice	Bob	Eve	CAN
01	01	00	00
01	10	00	00
?1	?0	01	00

Manageable

Alice and Bob wrongfully assume that they have transmitted different bits, even though it is not true
→ Derived keys are not identical
→ Solution: Perform final key verification

No problem

No impact → same situation as w/o interference

Good for us

If Eve sends a dominant bit, she cannot tell the status on the bus would have been w/o her

An active Eve can prevent a successful key establishment, but cannot determine or influence the established keys ☺

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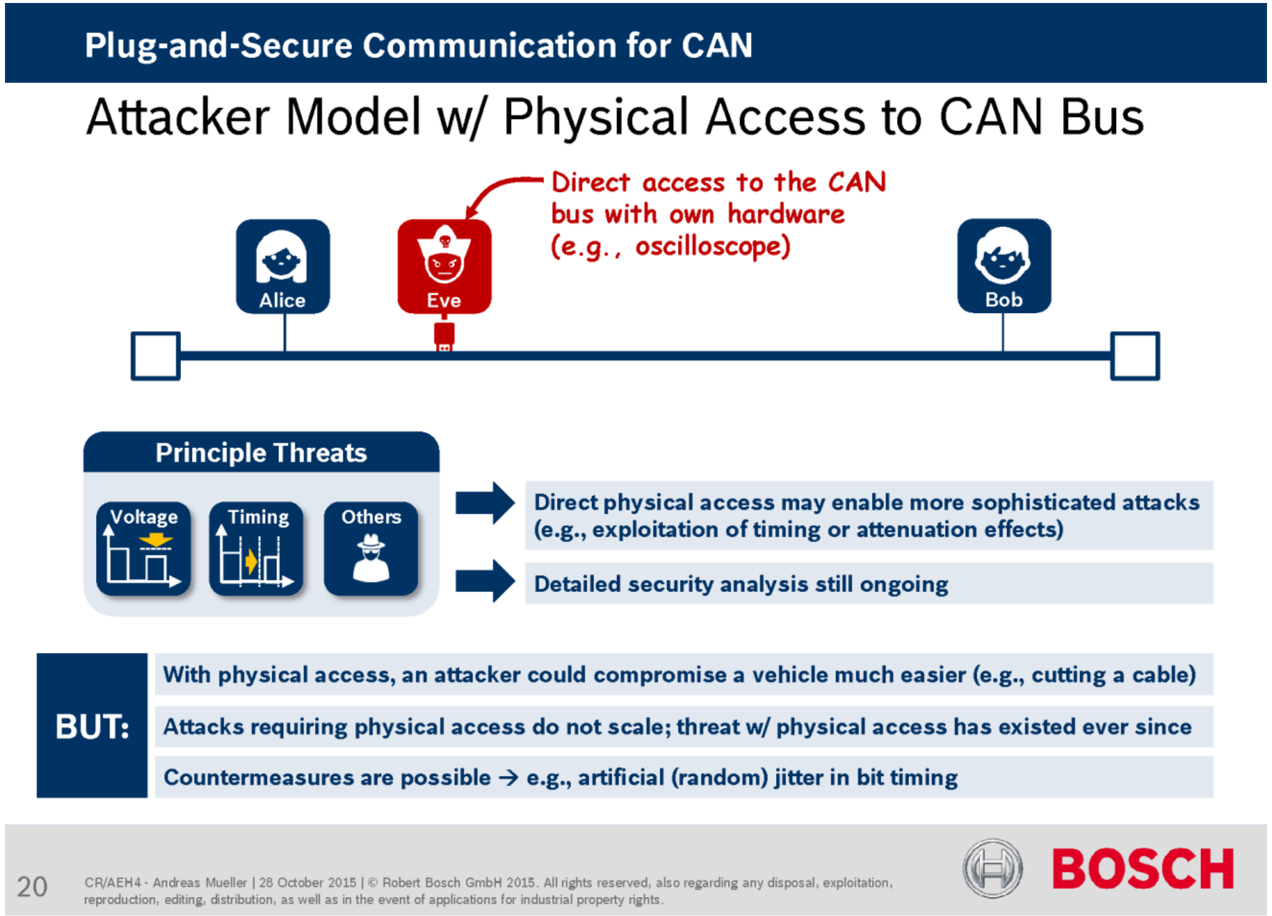
Inter-Flow Network Coding on CAN Bus

Courtesy of BOSCH



Inter-Flow Network Coding on CAN Bus
Courtesy of BOSCH

Plug-and-Secure Communication for CAN

Proof-of-Concept Demonstration

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Proof-of-Concept Demonstrator (I)

Alice Bob Eve

Portable demonstrator including Alice & Bob

Bus analyzer emulating attacker Eve

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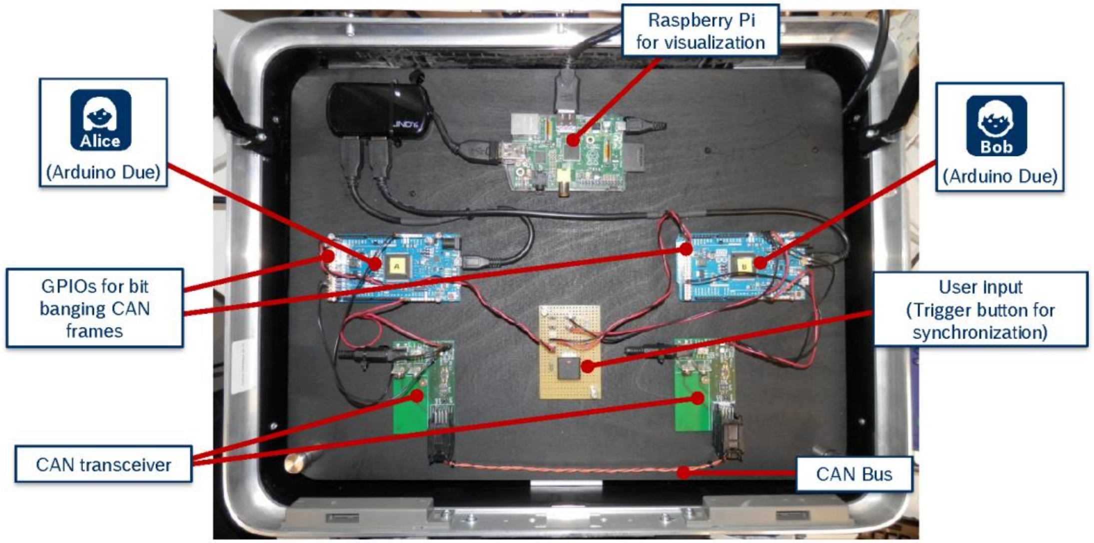
Proof-of-Concept Demonstrator (II)



- **Basic idea successfully demonstrated using off-the-shelf (maker) hardware**
- **100% standard compliant CAN frames on the bus → full backwards-compatibility**

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Inter-Flow Network Coding on CAN Bus

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Plug-and-Secure Communication for CAN

Conclusion

1. Security is getting more and more important in many domains
2. Distribution of cryptographic keys as a major challenge
3. PnS[1] for CAN as an innovative approach of very low complexity
4. Basic idea successfully demonstrated, fully backwards compatible
5. Major strengths: Remote / SW-based attacks, re-keying, wide applicability

Possible Extensions

LOCAL INTERCONNECT NETWORK

I2C BUS

Extension to other bus systems with similar PHY rather straightforward

Many Applications

Numerous applications in automotive, industrial & other CAN networks

Your Input

Interested?
→ Get in touch with us ☺

[1] Plug-and-Secure

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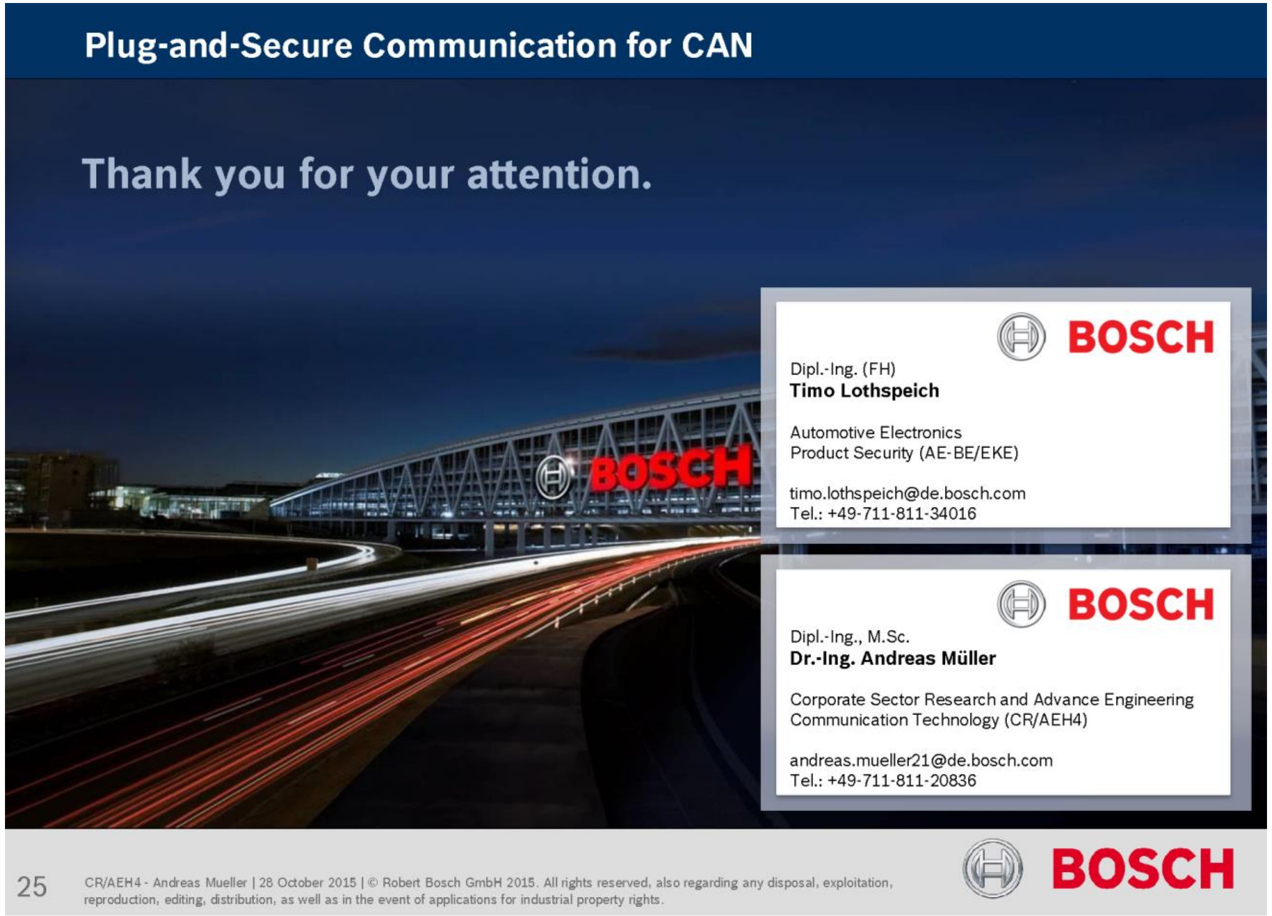
Inter-Flow Network Coding on CAN Bus
Courtesy of BOSCH



Summary Inter-Flow Network Coding

- Advantages
  - Easy to understand
  - Huge gains in theory

- Disadvantages
  - Requires signaling/planning
    - Not a huge problem in static networks, e.g. SDN controller
    - Huge problem for dynamic networks, more load and inefficient if not in time

- Real implementation (more than lab test run)
  - CATWOMAN in LINUX Kernel 3.10 onwards
  - BOSCH CAN Bus

Backup

Cautious View

Janus Heide, Morten V. Pedersen, Frank H.P. Fitzek, and Torben Larsen, **“Cautious view on network coding - from theory to practice,”** Journal of Communications and Networks (JCN), 2009

XOR operations

Simple XOR seems to be no problem with respect to computation

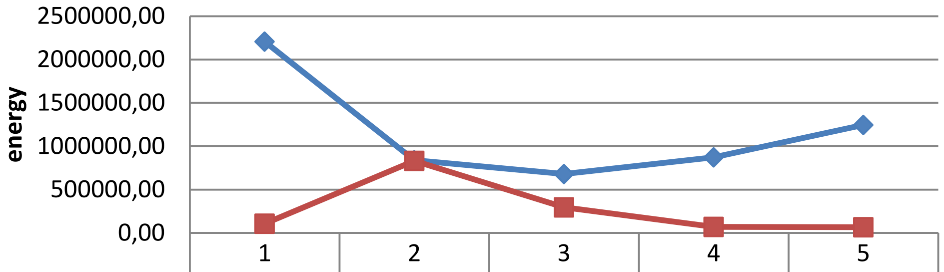
More energy used for the encoding vector to be transmitted than in the actual coding

POWER AND ENERGY LEVELS USED FOR NETWORK CODING ON THE MOBILE PHONE

state	power value [W]	energy value [J]	number of operations
coding	$0,593$	$4,789$	25000000
coding	$0,593$	$0,191 \cdot 10^{-6}$	1
idle	$0,041$	—	—

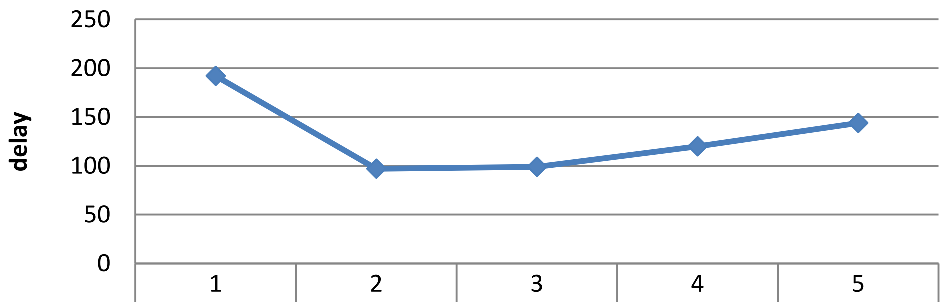
Wheel Example: Multi-dimension Alice and Bob

Energy Plot



	1	2	3	4	5
WLAN	2208153,60	837901,52	678419,28	872524,80	1244436,48
ideal	106905,60	832314,32	296358,48	70732,80	66631,68

Delay Plot

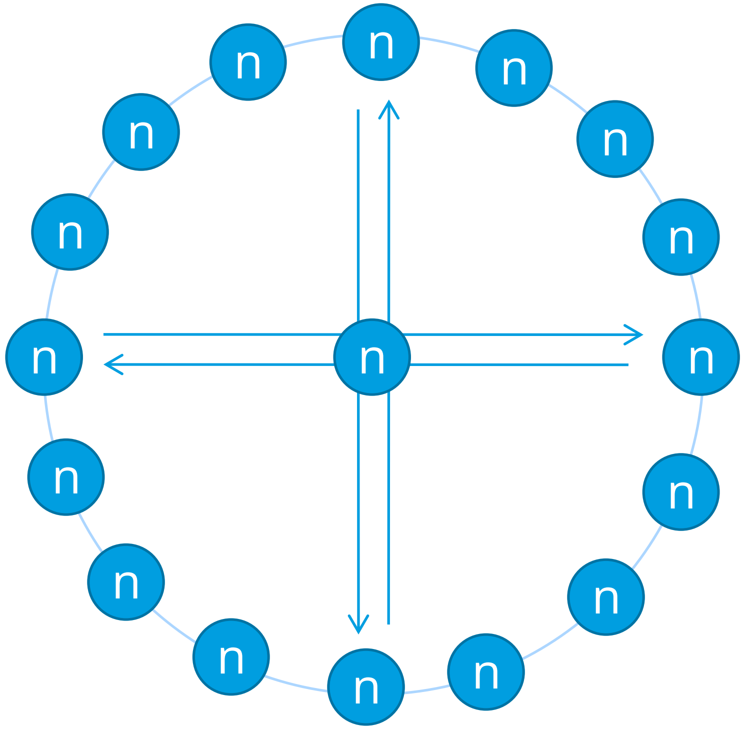


	1	2	3	4	5
slots	192	97	99	120	144

Scenario: Wheel

- 97 mobile devices in total
- 96 flows (one per cluster)
- Just relaying to exchange

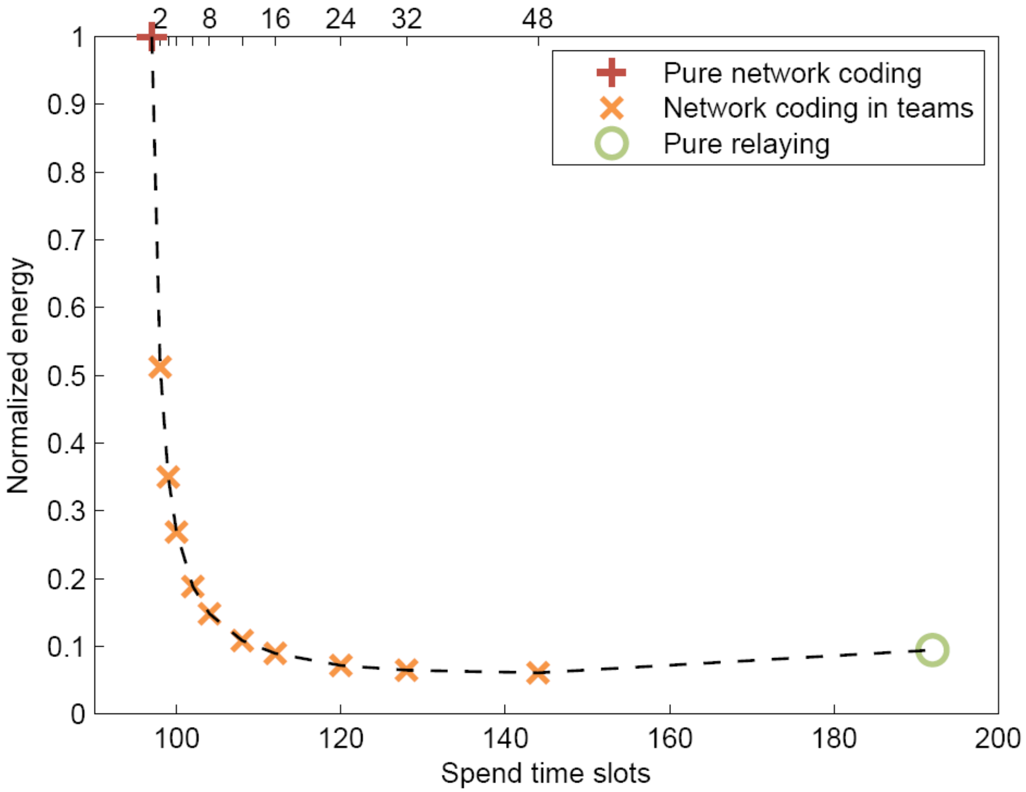
F number of flows
T number of teams



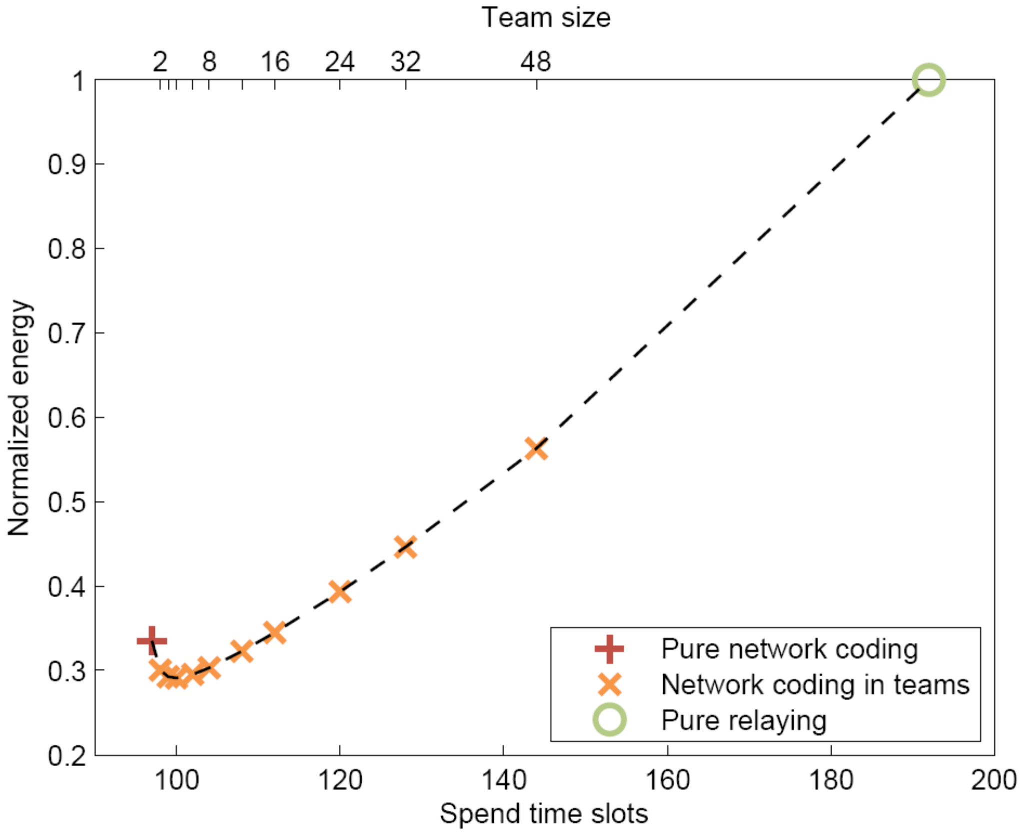
	sending	receiving	idle
Single node	1	F/T-1	F*(T-1)/T +T
Outer nodes	F	(F/T-1)F	(F(T-1)/T +T)F
Inner node	T	F	0
SUM netcod	**F+T**	**F^2/T**	**(F(T-1)/T +T)F**
SUM relay	**2F**	**2F**	**2F(F-1)**

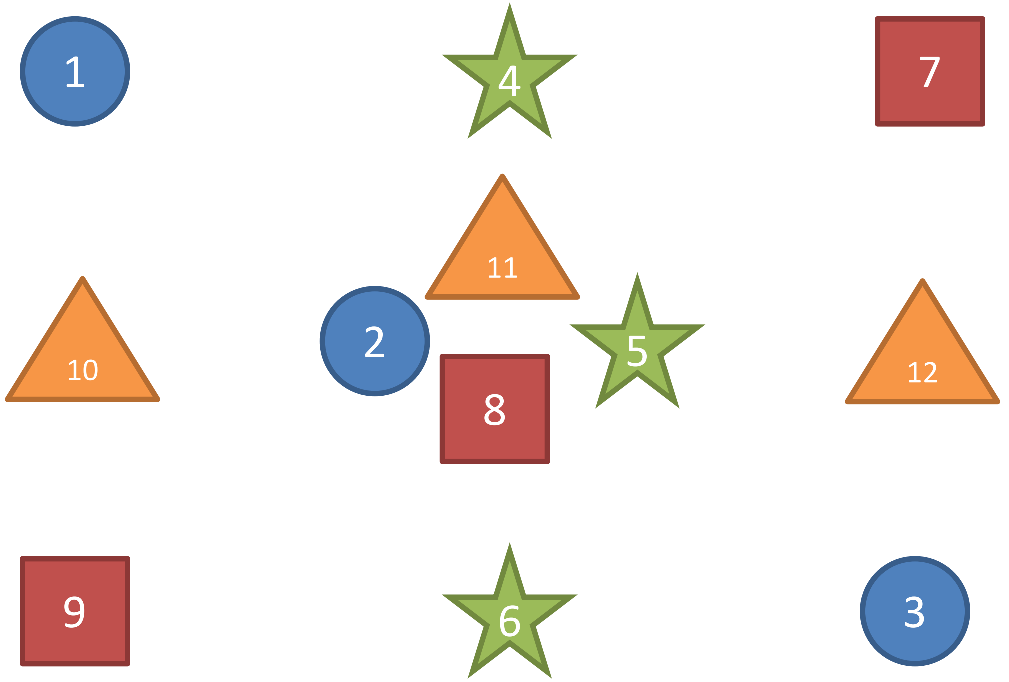
Wheel Example: Multi-dimension Alice and Bob

Without considering IDLE power value



With considering IDLE power value

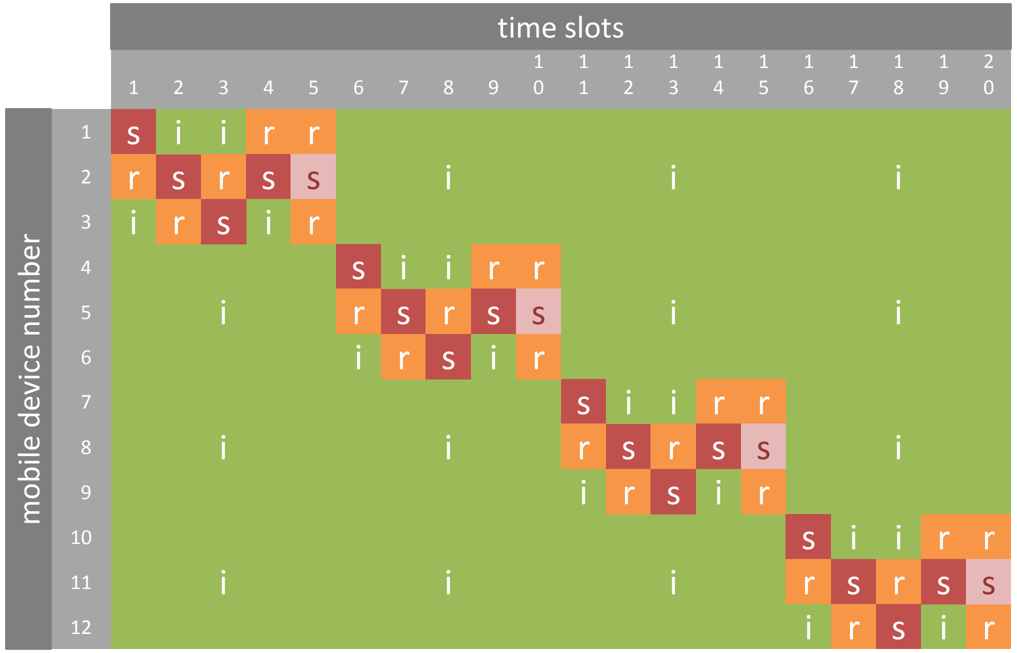




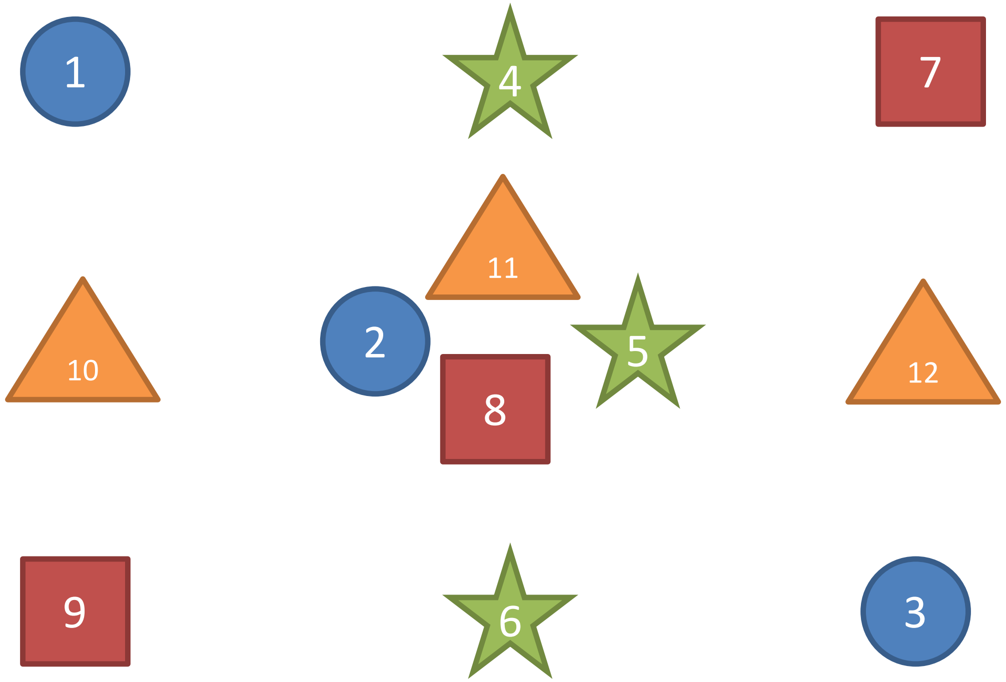
Scenario: Wheel++

- 12 mobile devices in total
- Four flows (one per cluster)
- Each device receives cellular input
- Just relaying to exchange

- i idle slot
- r receiving slot
- s sending unicast slot
- s broadcasting slot
- s broadcasting coded slot



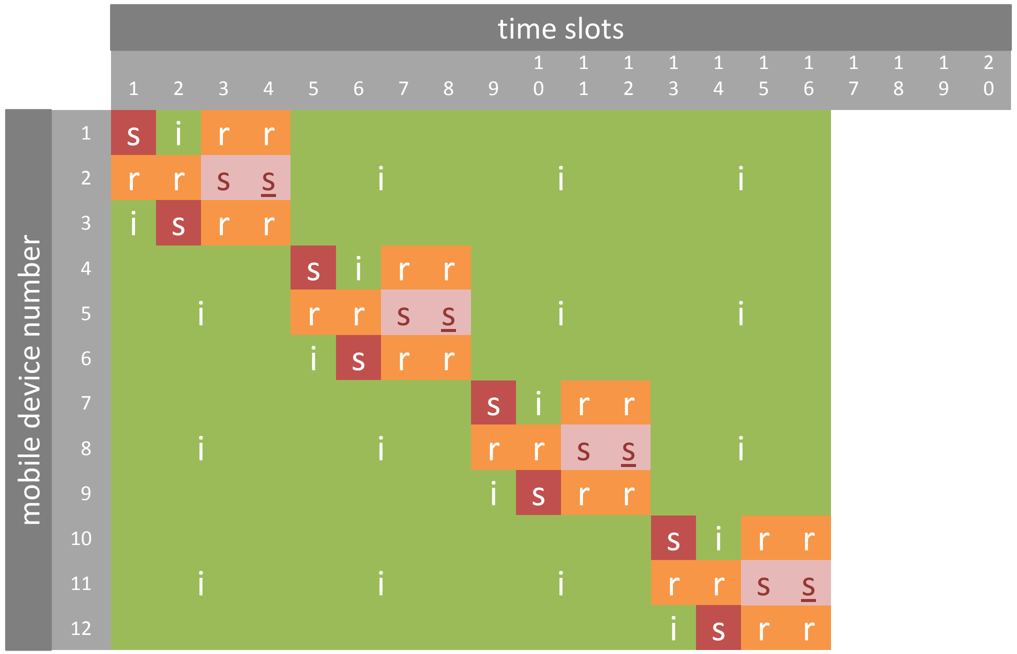
	sending	receiving	idle
One activity matrix	5	6	4
All activity matrixes	20	24	16
All idle matrixes	0	0	180
SUM	**20**	**24**	**196**



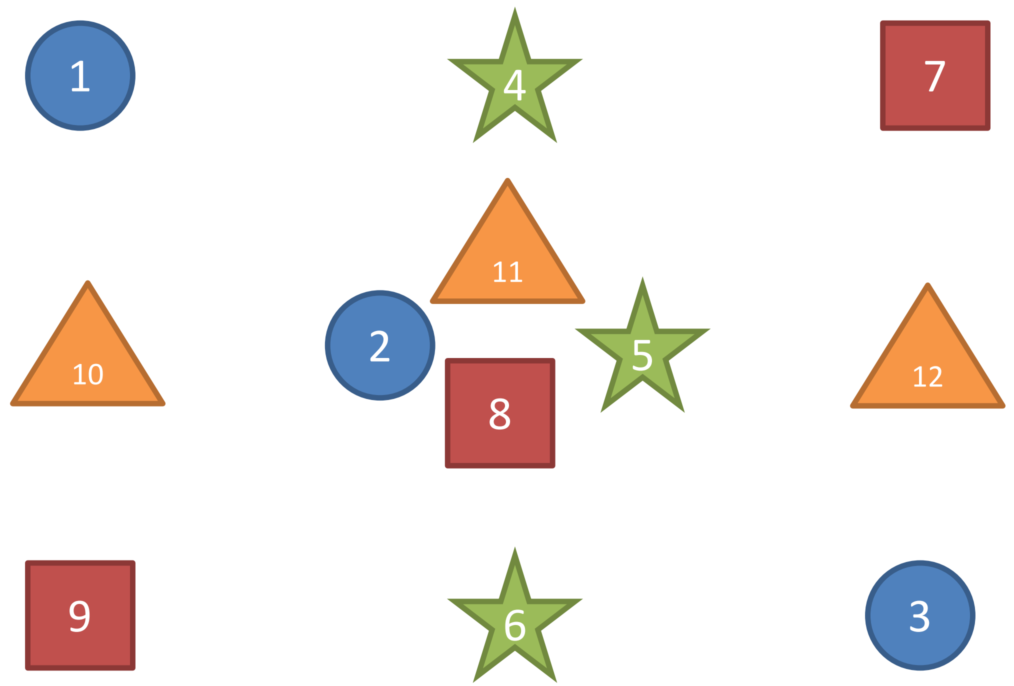
Scenario: Wheel++

- 12 mobile devices in total
- Four flows (one per cluster)
- Each device receives cellular input
- Network coding within each cluster

i idle slot
r receiving slot
s sending unicast slot
s broadcasting slot
s broadcasting coded slot



	sending	receiving	idle
One activity matrix	4	6	2
All activity matrixes	16	24	8
All idle matrixes	0	0	144
SUM	**16**	**24**	**152**



Scenario: Wheel++

- 12 mobile devices in total
- Four flows (one per cluster)
- Each device receives cellular input
- Network coding over all cluster
- Device 2 is doing the most work

i	idle slot
r	receiving slot
s	sending unicast slot
s	broadcasting slot
s	broadcasting coded slot

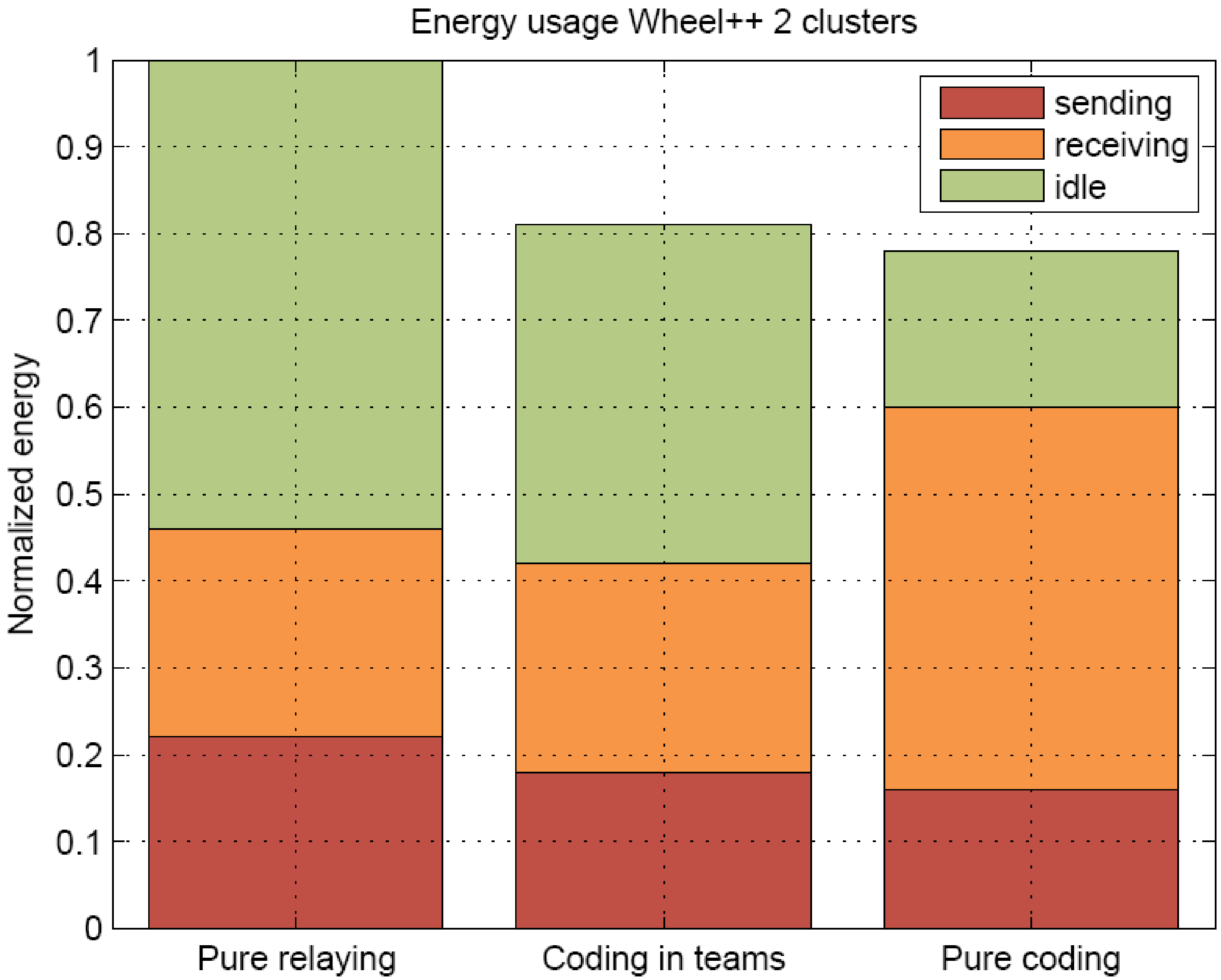
time slots

mobile device number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	r	i	i	i	s	i	r	r	r	r	r	r	r							
2	s	i	i	i	r	r	r	r	r	r	r	r	s							
3	r	i	i	i	i	s	r	r	r	r	r	r	r							
4	i	r	i	i	r	r	s	i	r	r	r	r	r							
5	i	s	i	i	i	i	r	r	i	i	i	i	i							
6	i	r	i	i	r	r	i	s	r	r	r	r	r							
7	i	i	r	i	r	r	r	r	s	i	r	r	r							
8	i	i	s	i	i	i	i	i	r	r	i	i	i							
9	i	i	r	i	r	r	r	r	i	s	r	r	r							
10	i	i	i	r	r	r	r	r	r	r	s	i	r							
11	i	i	i	s	i	i	i	i	i	i	r	r	i							
12	i	i	i	r	r	r	r	r	r	r	i	s	r							

Phase 1 Phase 2 Phase 3

	sending	receiving	idle
Phase 1	4	8	36
Phase 2	8	62	26
Phase 3	1	8	3
SUM	**13**	**78**	**65**

Results

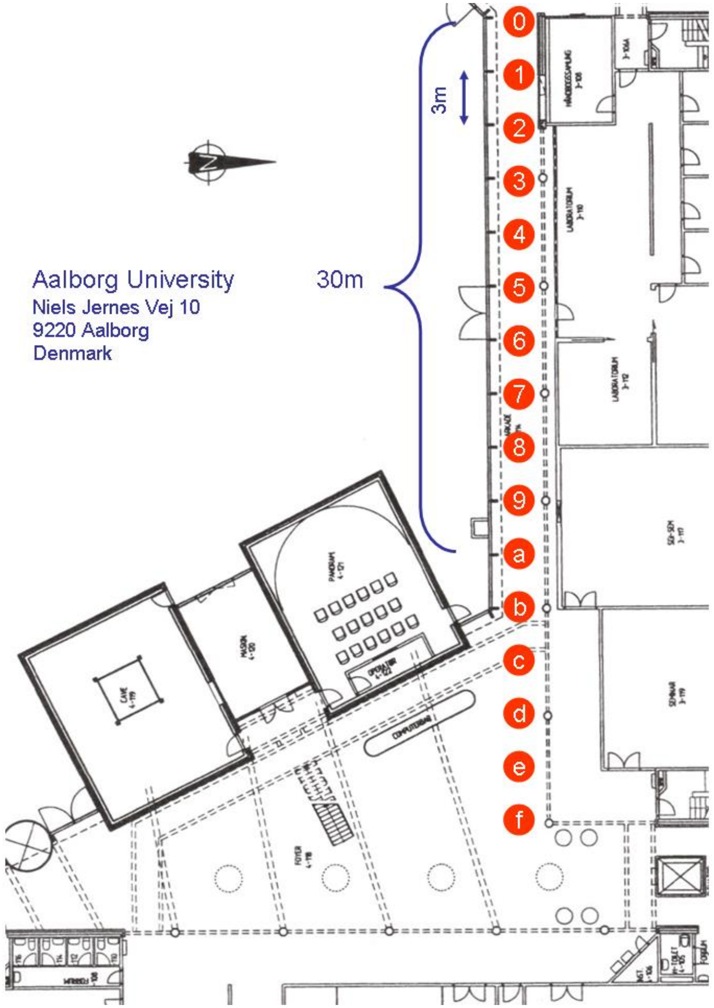


Energy usage Wheel++ 2 clusters
Normalized energy
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
sending
receiving
idle
Pure relaying
Coding in teams
Pure coding

Energy and Channel Measurements: Point to point

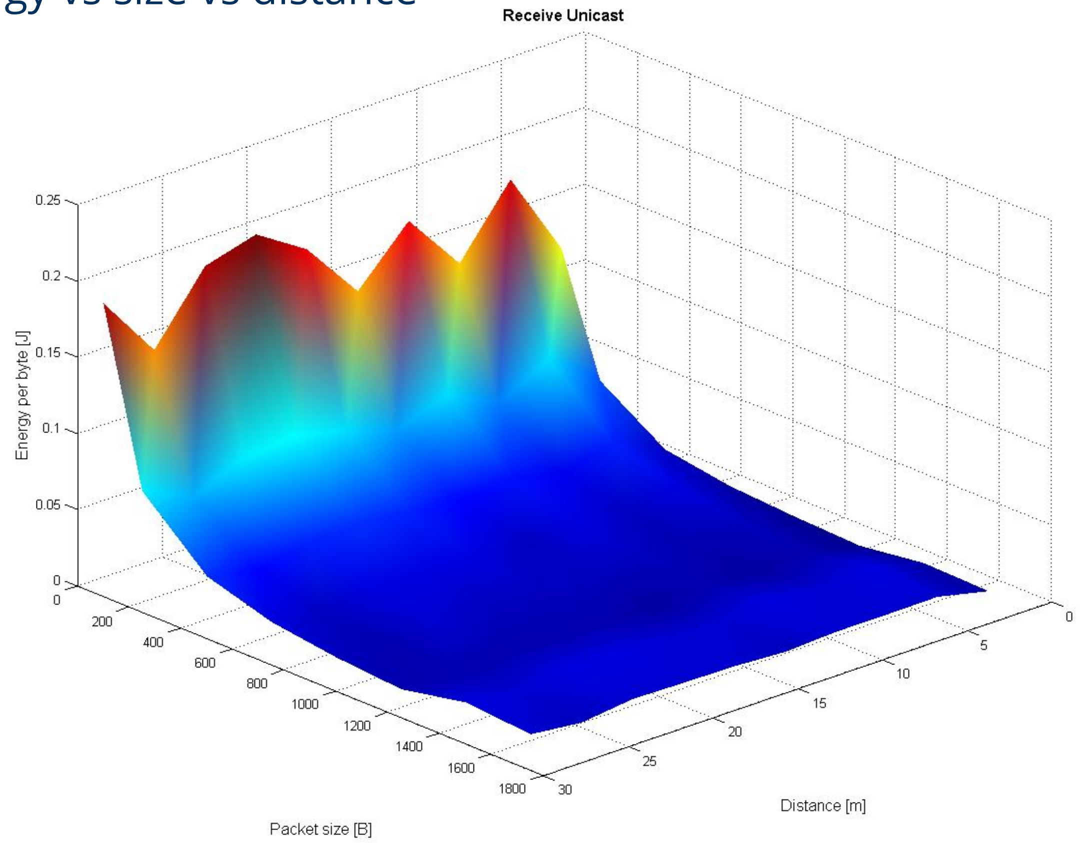
M.V. Petersen and G.P. Perrucci and F.H.P. Fitzek. **Energy and Link Measurements for Mobile Phones using IEEE802.11b/g.** 2008. in *The 4th International Workshop on Wireless Network Measurements (WiNMEE 2008) - in conjunction with WiOpt 2008*. Berlin, Germany.

Measurement Campaign for NC

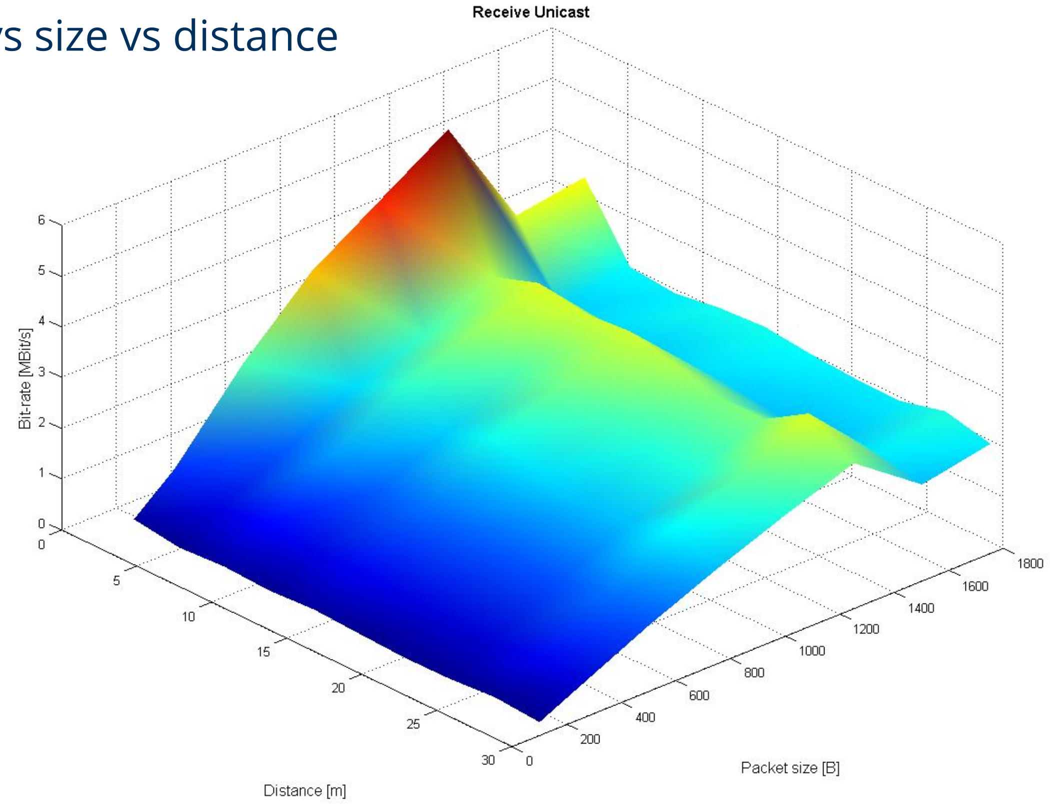


Unicast Results

Energy vs size vs distance



Data rate vs size vs distance



- •Small packets have higher energy per bit ratios due to the MAC overhead
- •Small increase for packets larger than MTU size

- •Larger data rates for small distances
- •Small decrease after MTU sizes