

Netzwerkkodierung in Theorie und Praxis

Praktische Anwendungen der Netzwerkkodierung

Professor Dr.-Ing. Dr. h.c. Frank H.P. Fitzek

M.Sc. Juan Cabrera

Deutsche Telekom Chair of Communication Networks (ComNets)



Netzwerkkodierungstheorie

Professor Dr.-Ing. Eduard Jorswieck

Dipl.-Ing. Johannes Richter

Theoretische Nachrichtentechnik



Lecture / Exercise Dates - tinyurl.com/zooafld

**TECHNISCHE
UNIVERSITÄT
DRESDEN**

Chair Research Teaching News

Course Schedule Modules Lectures Student Theses

Practical Implementations of Network Coding

Lecturer: Professor Frank Fitzek Assistant: M.Sc. Juan Cabrera

Overview

This course introduces the students to the challenges and approaches of the state of the art implementations of network coding. The course is taught not just through lectures, but also with hands-on exercises using the KODDO software library.

The initial lectures refresh the knowledge of the students of the theoretical background of network coding, e.g., the min-cut max-flow of a network; inter-flow network coding, and intra-flow Random Linear Network Coding (RLNC). The student is then introduced to the state of the art software library KODDO and the advanced implementations of network coding such as systematic, sparse, tunable sparse, sliding window, etc. The course also covers the benefits of network coding in distributed software applications. By the end of the course, the student will be introduced to advanced applications of network coding, e.g., Coded TCP, MORE, FULCRUM.

The exercises will teach the students how to use sockets in python as well as the python bindings of the KODDO software library for implementing unicast and broadcast communication applications.

Time Schedule

Lectures: Wednesdays 9:20 – 10:50
 Exercises: Thursdays (**Odd weeks**) 14:50 – 16:20

Show	10	entries	Search:
Date	Type	Room	Topic
04.Apr.2016 16:40-18:10	L1	GÖR/0127/U	Presentation of the chair; Organisation of the course; 5G Intro; Butterfly; min cut max flow.
06.Apr.2016	L2	VMB/0E02/U	Inter Flow NC; Index Coding; Zick Zack Coding; CATWOMAN
11.Apr.2016 16:40-18:10	L3	GÖR/0127/U	Analog Inter Flow Network Coding
13.Apr.2016	L4	VMB/0E02/U	Random Linear Network Coding (Basics)
14.Apr.2016	E1	GÖR/0229/U	UDP transmissions with python sockets. Unicasts and Broadcasts.
20.Apr.2016	L5	VMB/0E02/U	KODO
27.Apr.2016	L6	VMB/0E02/U	RLNC advanced (sparse, tunable)
28.Apr.2016	E2	GÖR/0229/U	

ComNets
 Deutsche Telekom Chair of Communication Networks

Latest News

- February 19th, 2016 Wirtschaftswoche & Handelsblatt report on research of ComNets & 5G - Prof. Fitzek head and center of European Research: [Wirtschaftswoche & Handelsblatt](#)
- January 8th, 2016 New open position at the chair: [Research Fellow](#)
- January 7th, 2016 Deutsche Telekom announces collaboration and sponsorship of the "Deutsche Telekom Chair for Communication Networks" and becomes an industrial partner of the 5G Lab Germany. [Press Release](#)

Tweets by @ComNets_TUD

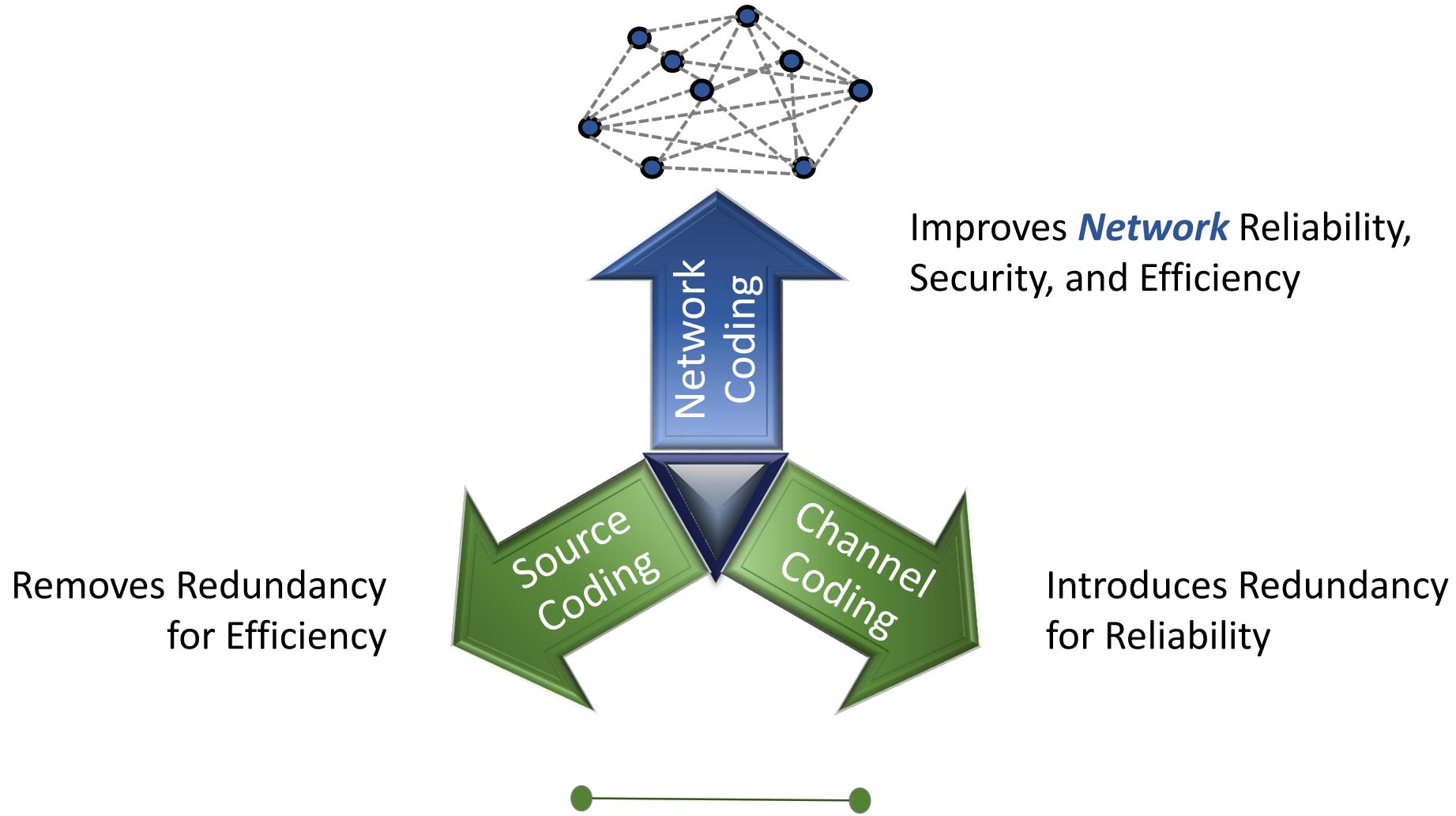
- ComNets Chair at TUD Retweeted C. Bettstetter @bettstetter Workshop on #5G mobile networks and tactile Internet hosted by @frankfitzek and team in Dresden on June 10, 2016. [itg.lkn.ei.tum.de/doku.php?id=te...](#)
- ComNets Chair at TUD Retweeted Frank Fitzek @frankfitzek Keynote at NOSSDAV/MoVid: [mmsys2016.itec.aau.at/keynote-5g-ena...](#) #tactileinternet #5g @5g_lab @ComNets_TUD
- ComNets Chair at TUD @ComNets_TUD #haec #openstack working. What is better than late night programming with success killing a problem we were fighting for months #victory

- Here all information for the lecture and the exercise can be found.
- Slides
- Links
 - Steinwurf
 - Python
 - KODOMARK (google play)

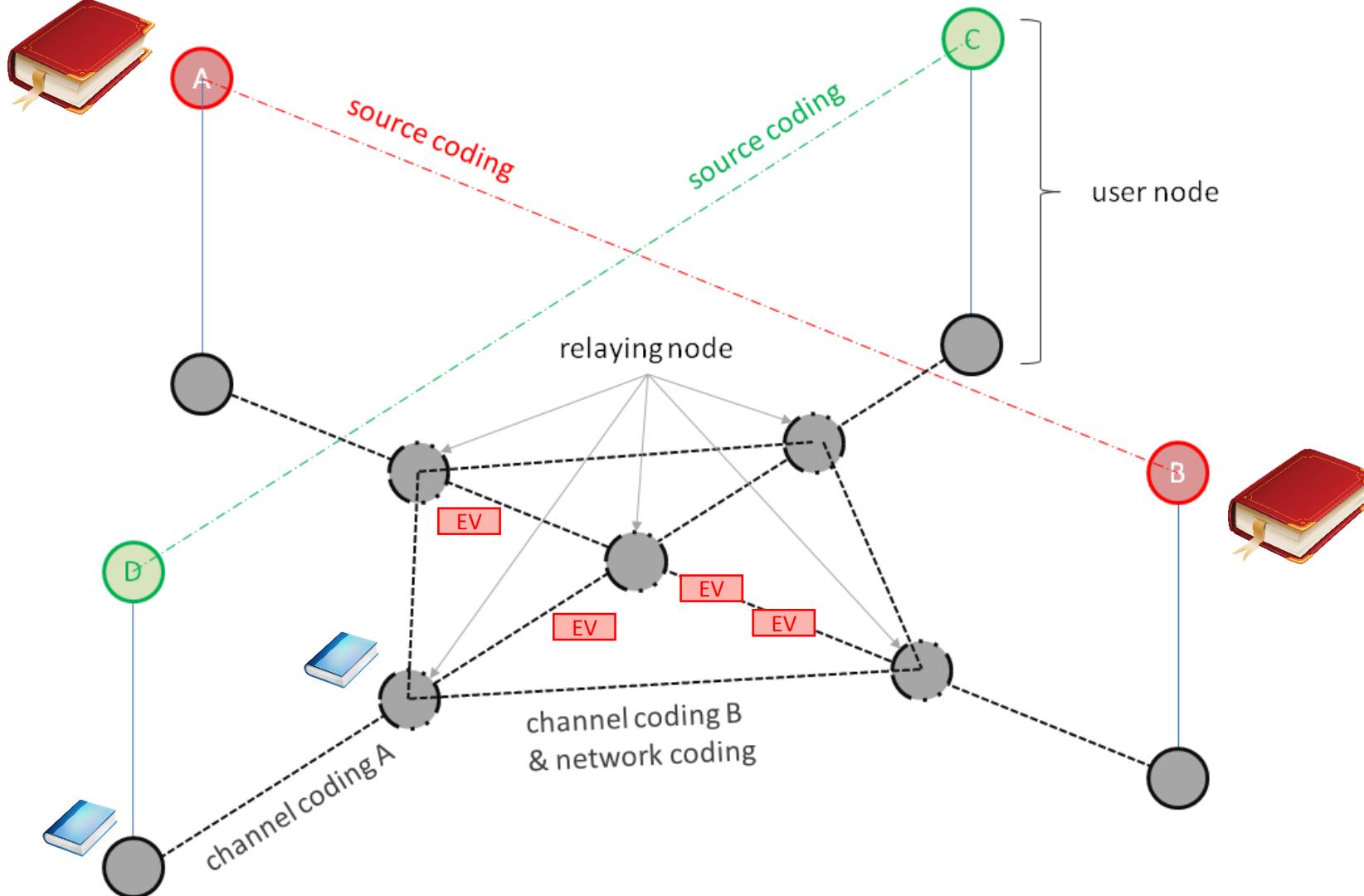
Please check every week!

Channel & Source Coding vs. Network Coding

Comparison of Coding Approaches



Comparison of Coding Approaches



Wireless Network Examples

Exploiting the broadcast nature of the wireless medium

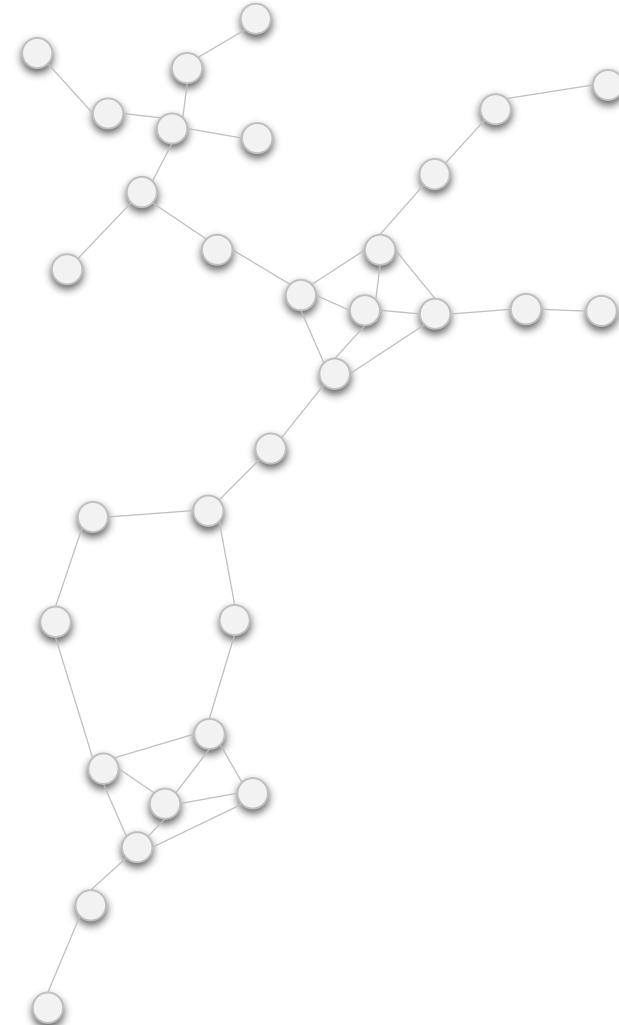


It is not about butterflies ...

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.

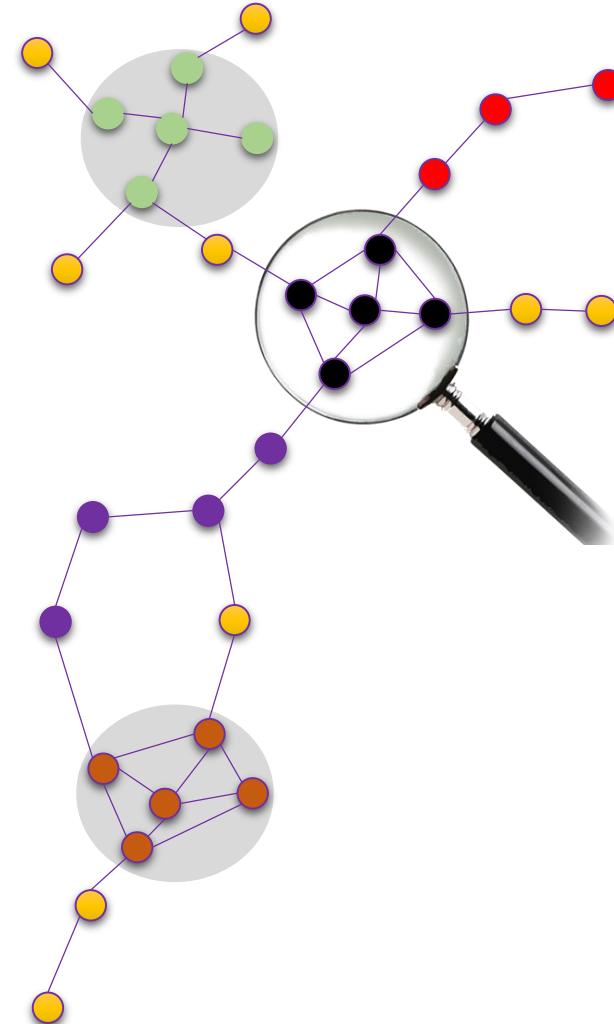
General Network Topologies and Sub-Nets

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



General Network Topologies and Sub-Nets

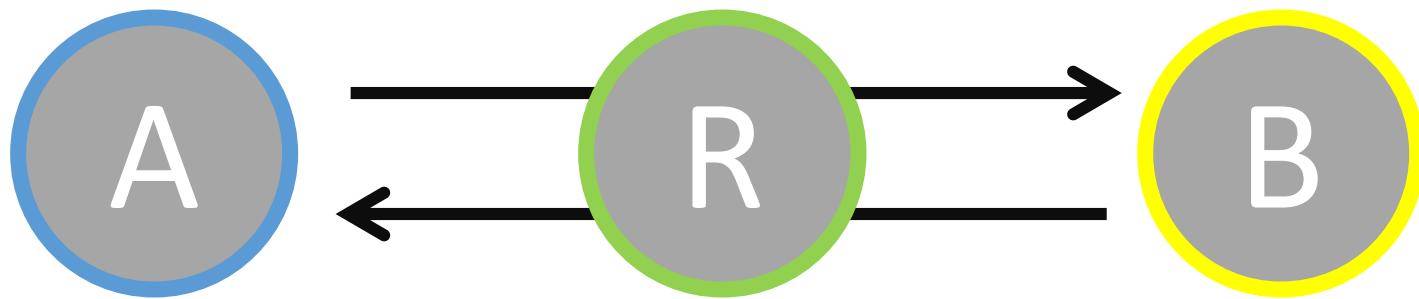
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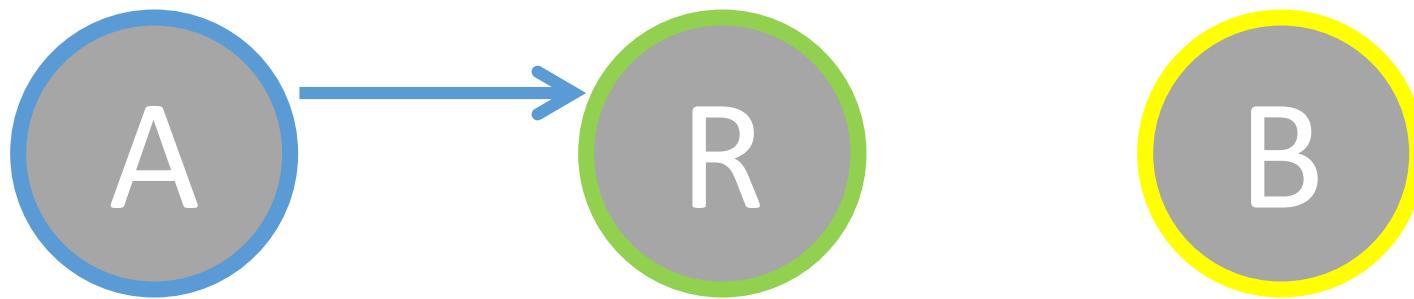
Alice and Bob –The two way relay

Early VTC paper by Ericsson

Alice and Bob



Alice and Bob: Forwarding



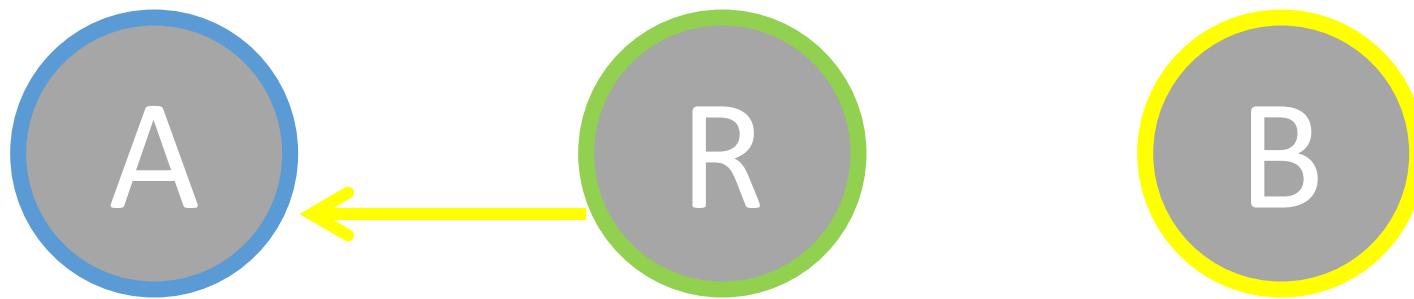
Alice and Bob: Forwarding



Alice and Bob: Forwarding

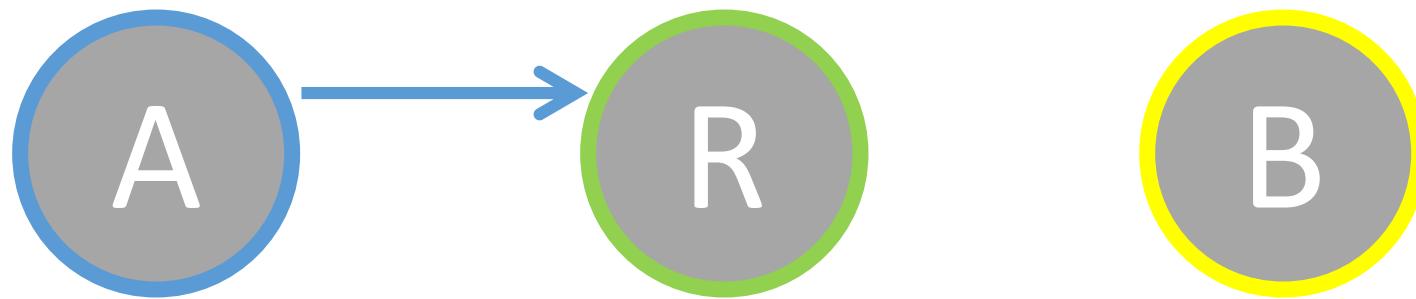


Alice and Bob: Forwarding



4 time slots for exchange

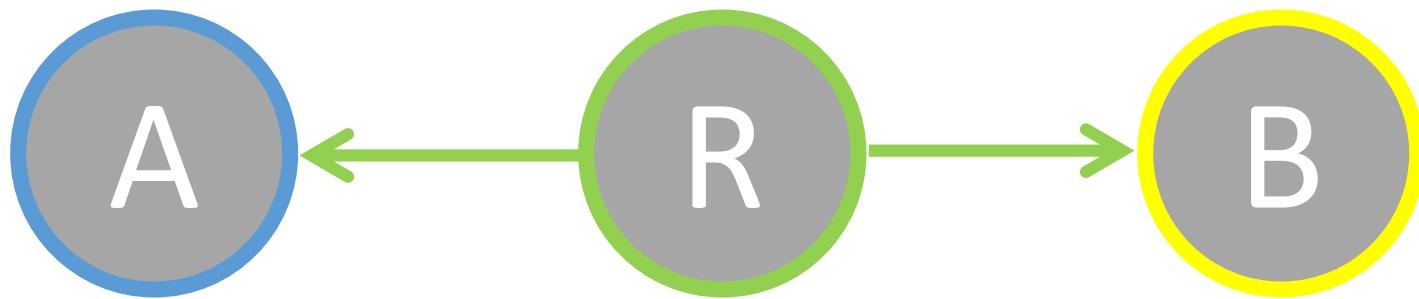
Alice and Bob: Network Coding



Alice and Bob: Network Coding



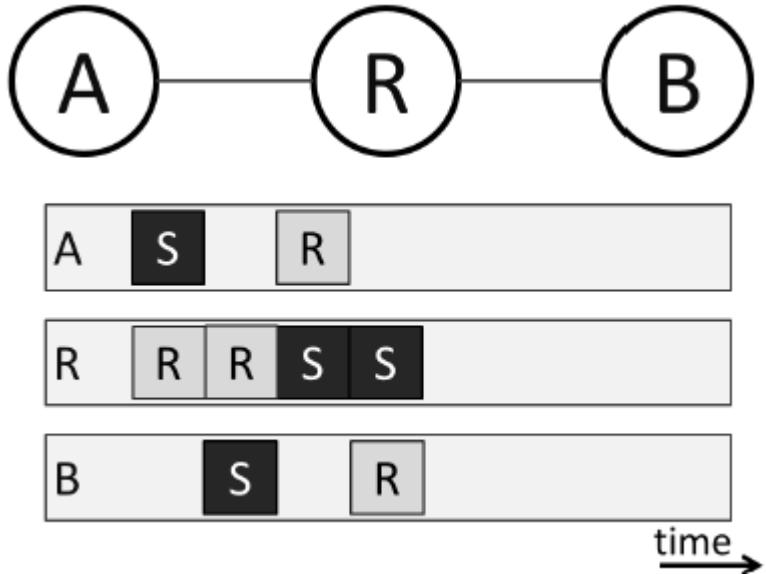
Alice and Bob: Network Coding



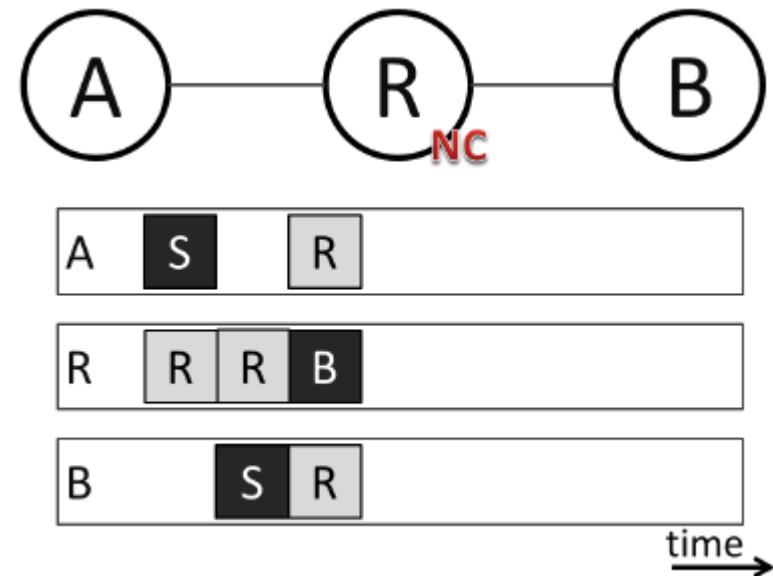
3 time slots for exchange

Alice and Bob: Activity Chart

w/o NC

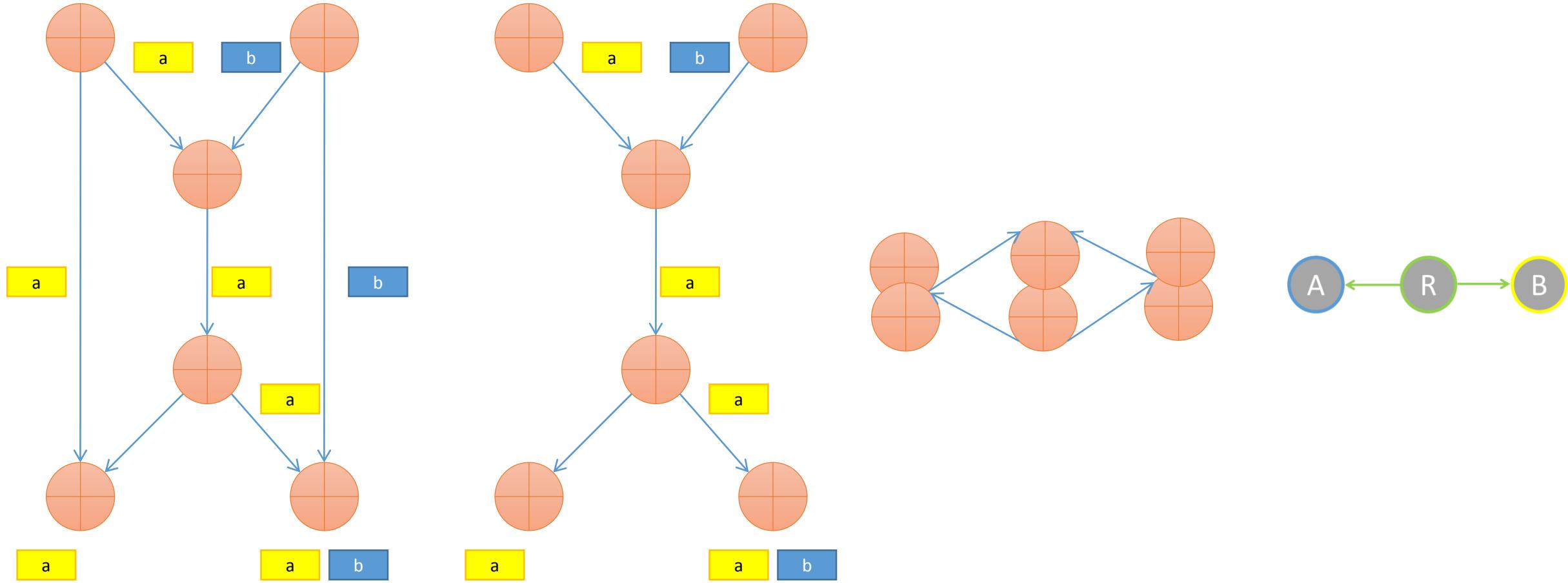


with NC



Gain = 33%

Butterfly == Alice and Bob

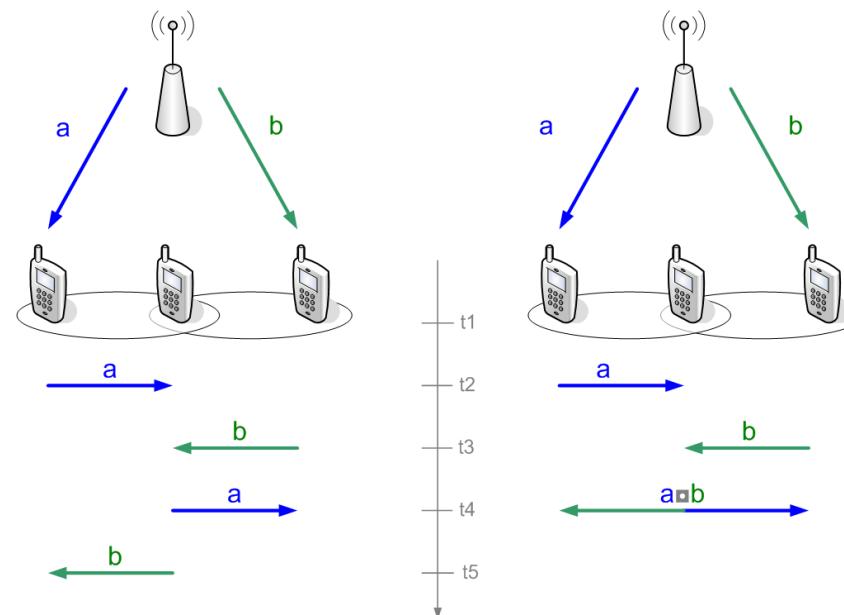


Network Coding: Magic XOR

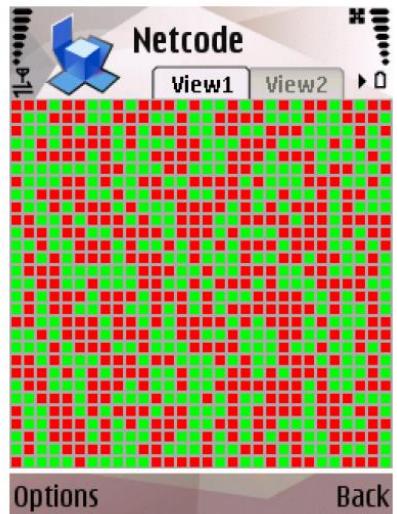
M.V. Pedersen and F.H.P. Fitzek and T. Larsen. **Implementation and Performance Evaluation of Network Coding for Cooperative Mobile Devices.** 2008. in *IEEE International Conference on Communications (ICC 2008) - CoCoNet Workshop.*

Alice and Bob: Symbian60

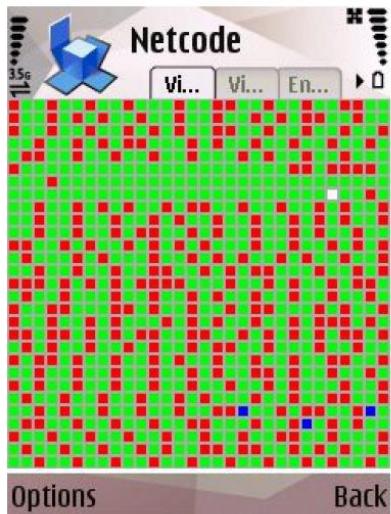
- Our starting point
- Simple scenario
- Seeding of packet a and b is crucial
 - Fairness
 - Performance
- Forms of NC
 - XOR in the air (COPE)
- Implementation on S60



Alice and Bob: Symbian60

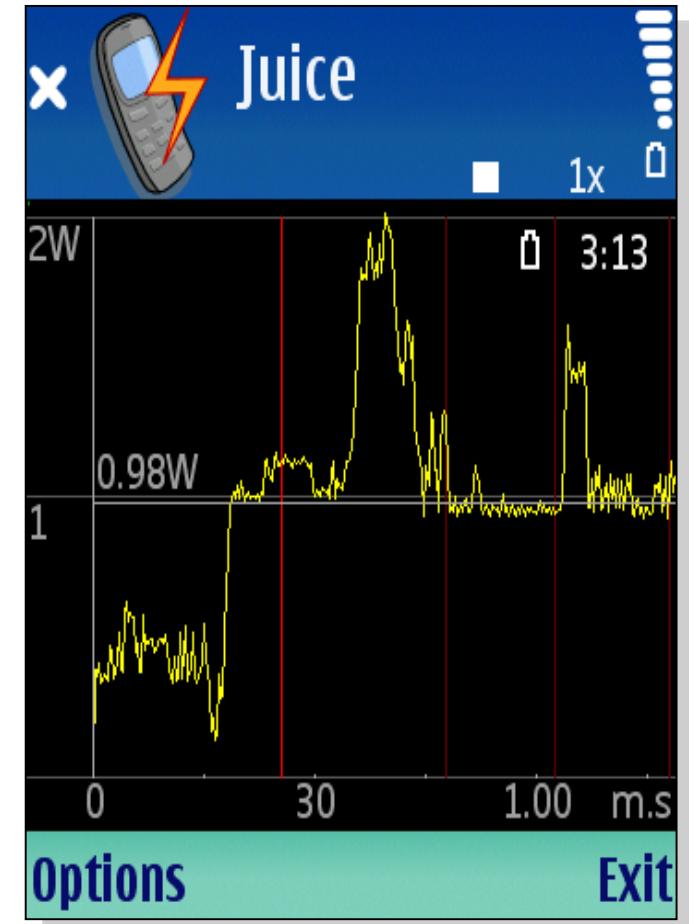
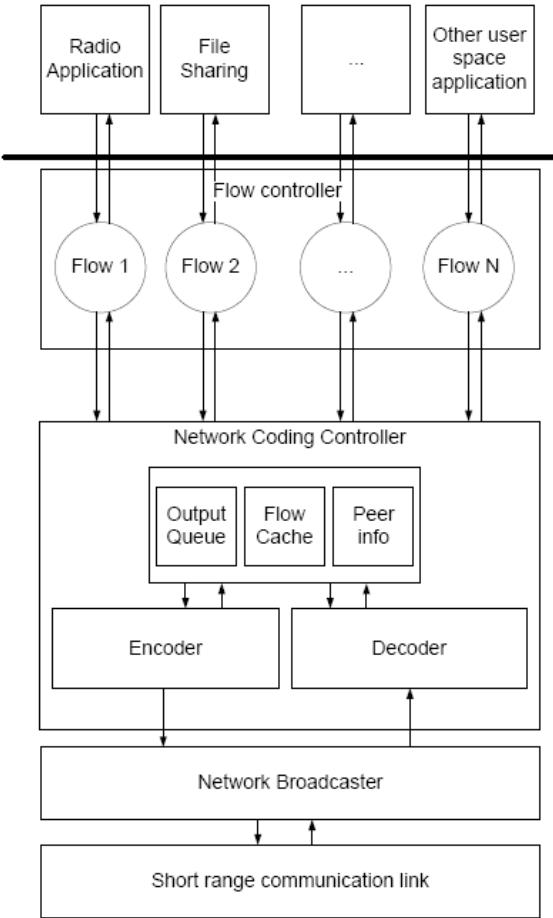


(a)

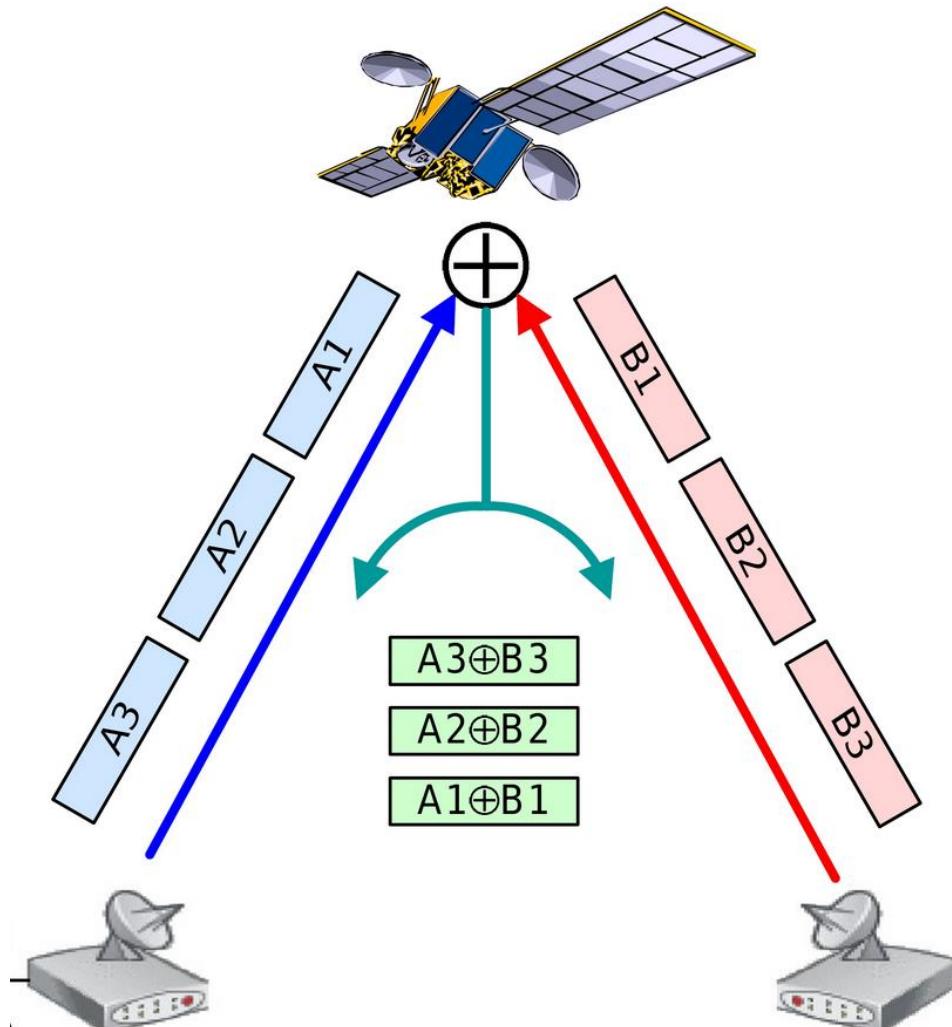


(b)

Lessons learned: It is important to create coding potential!



Alice and Bob: Satellite Communication

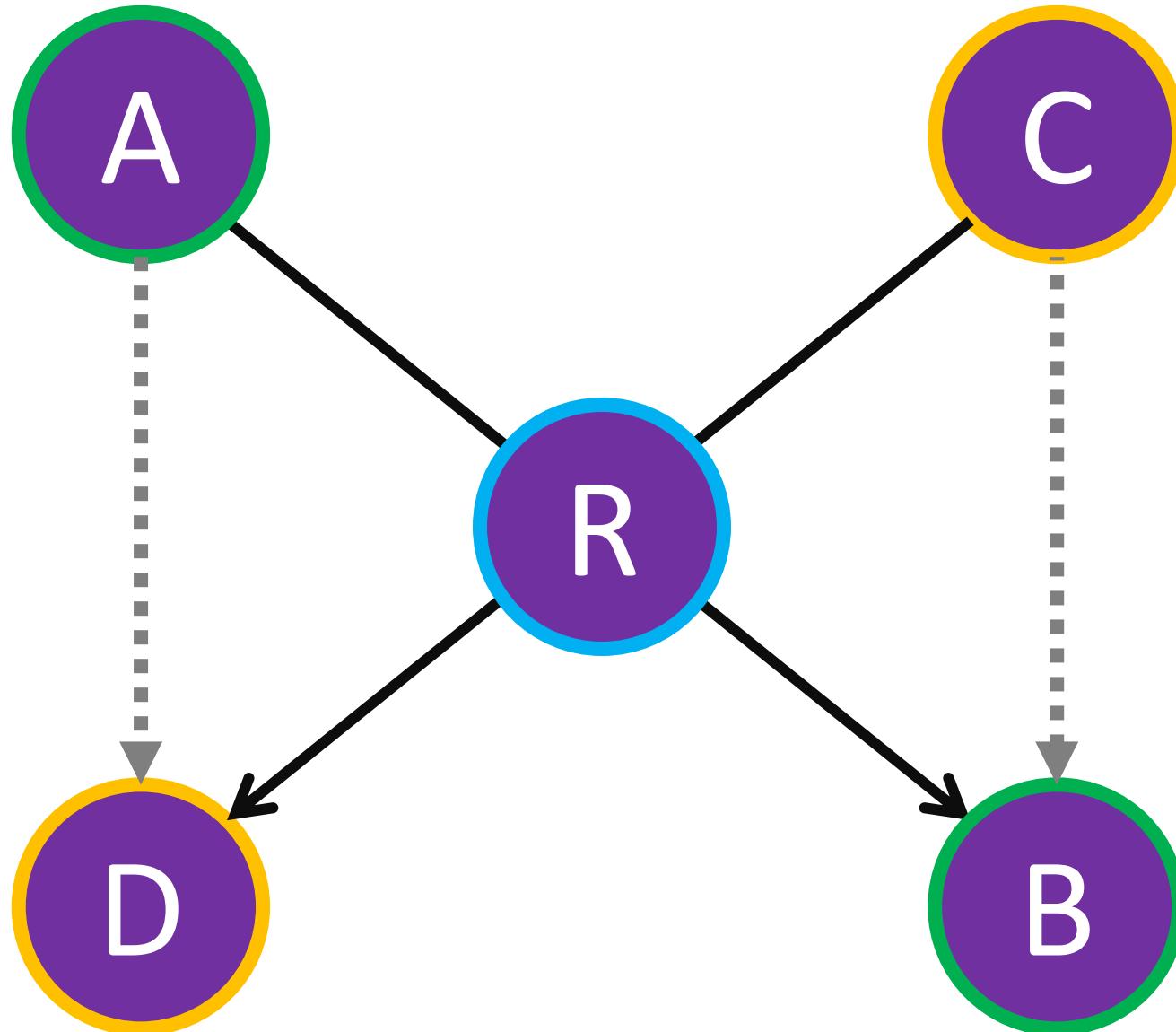


http://www.dlr.de/kn/Portaldata/27/Resources/images/projekte/NEXT-Network_coded_interconnection_of_computer_networks_via_satellite.jpg

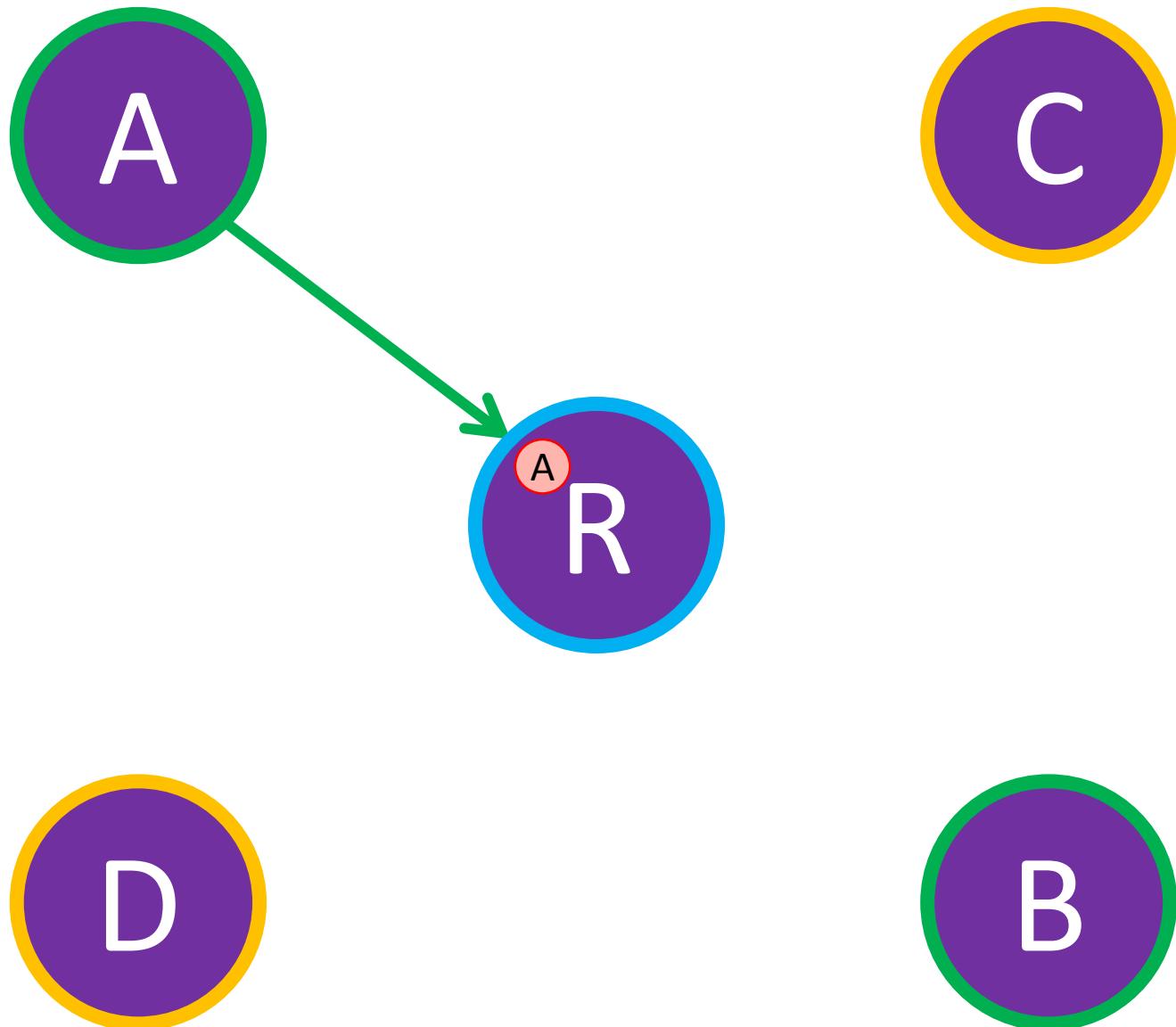
The X-Topology

Introducing the concept of overhearing

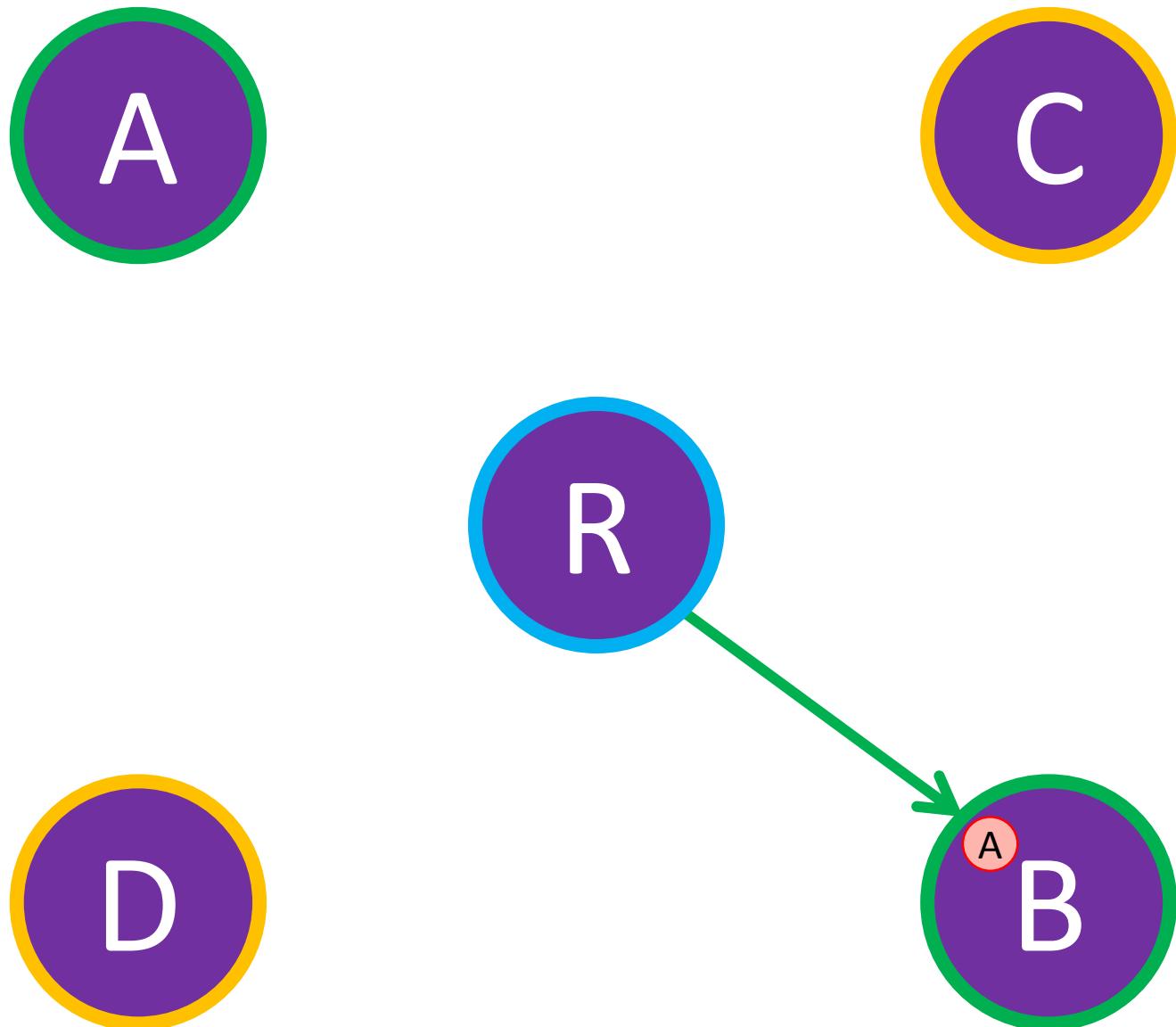
X Topology with Overhearing



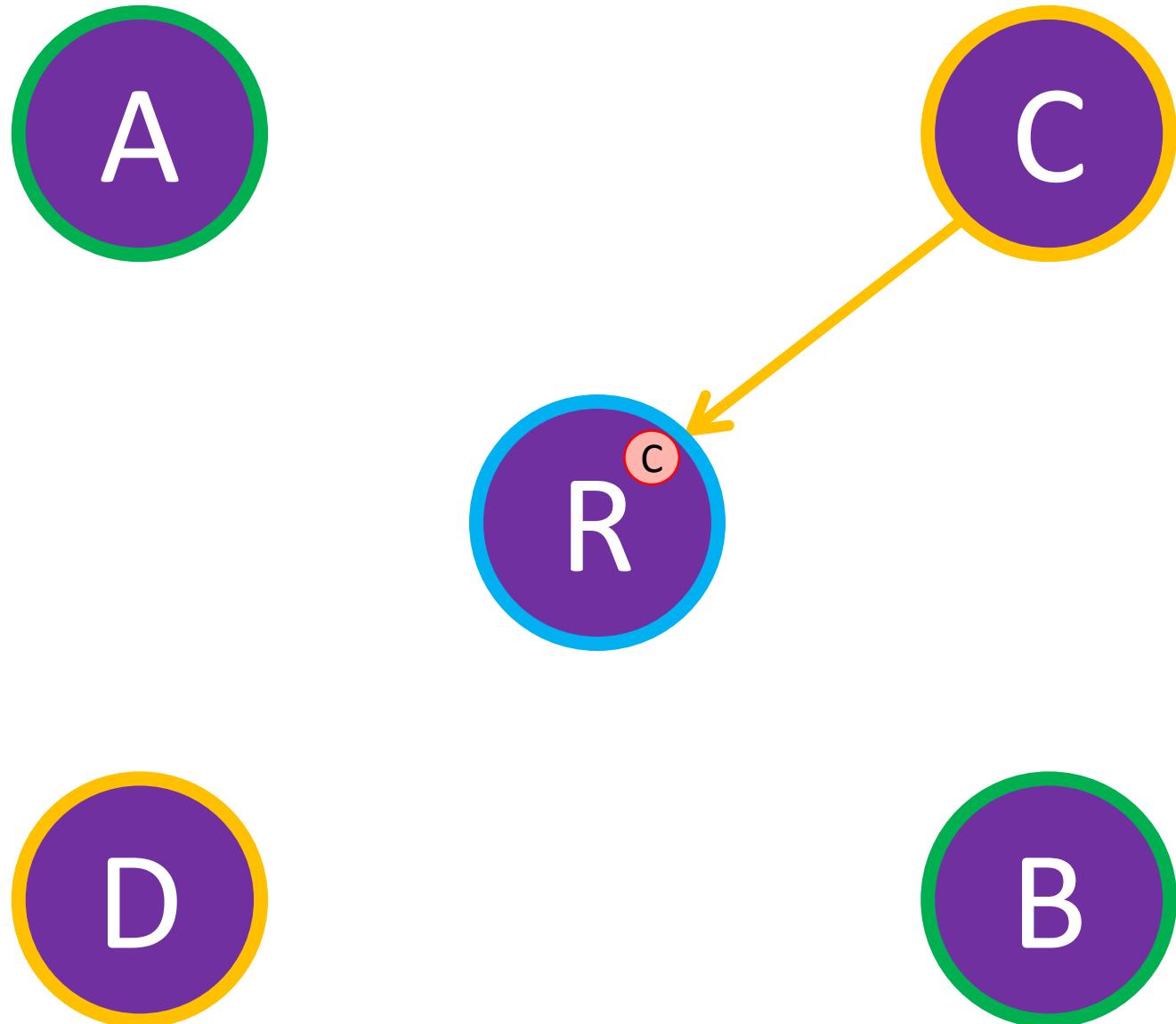
X Topology: SoA



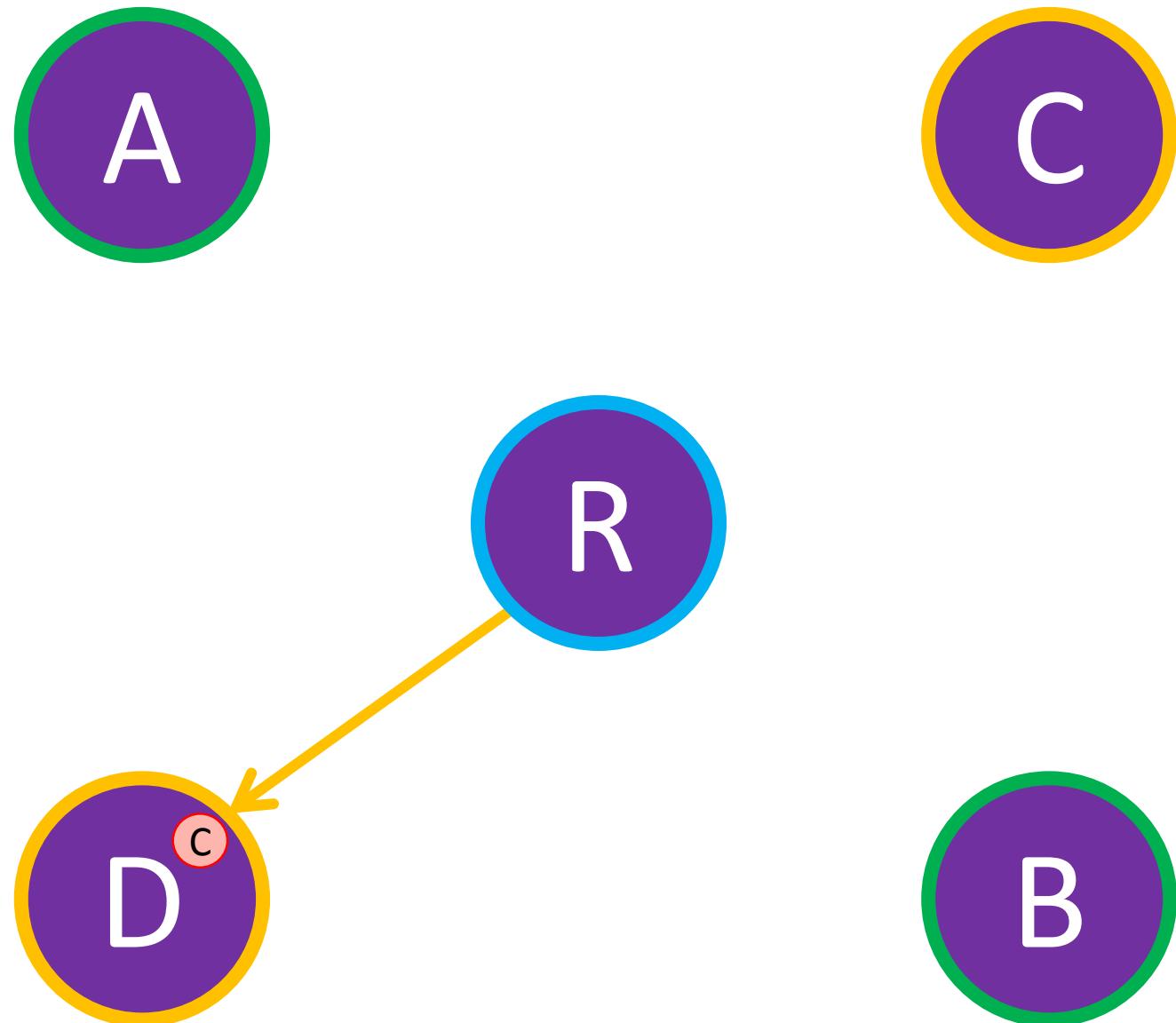
X Topology: SoA



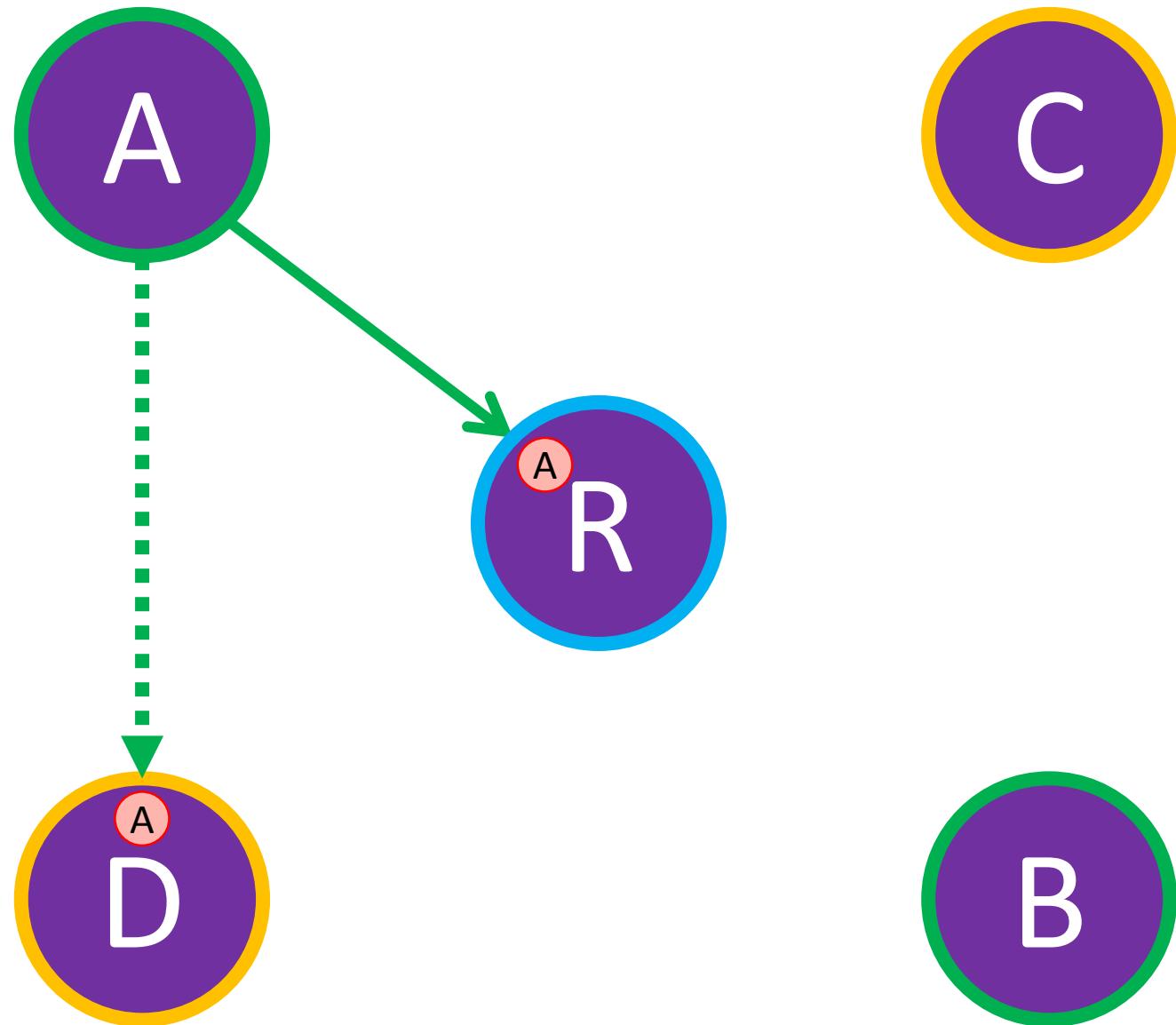
X Topology: SoA



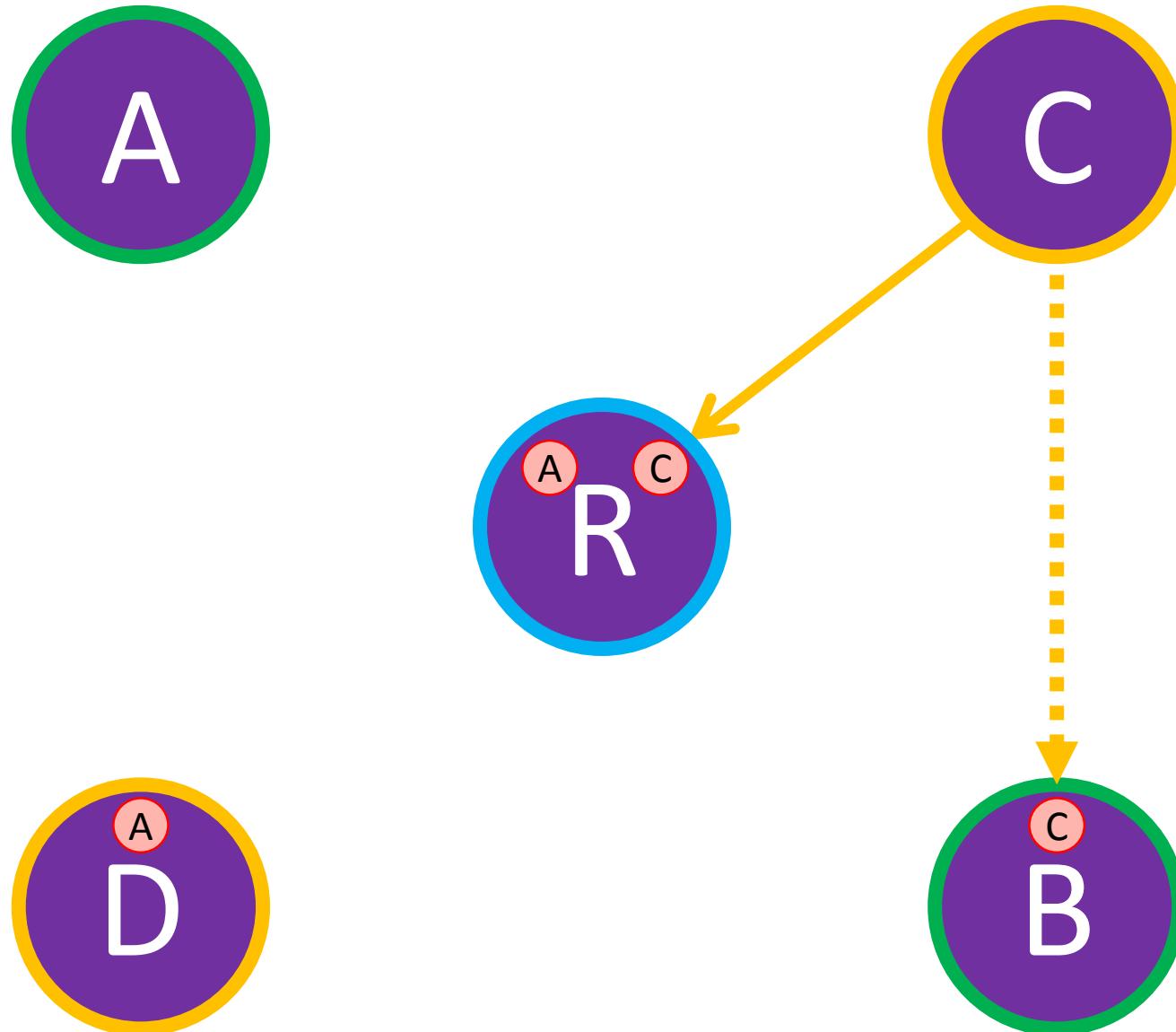
X Topology: SoA



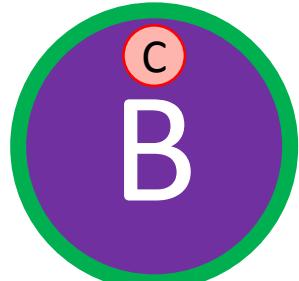
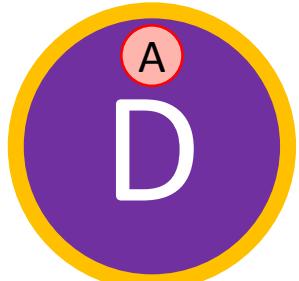
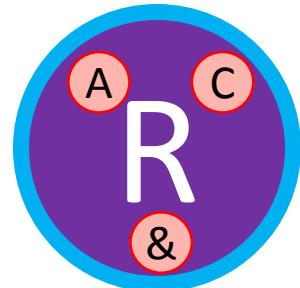
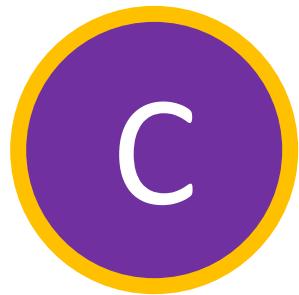
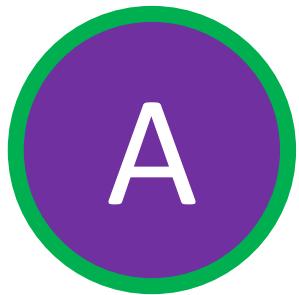
X Topology with Overhearing



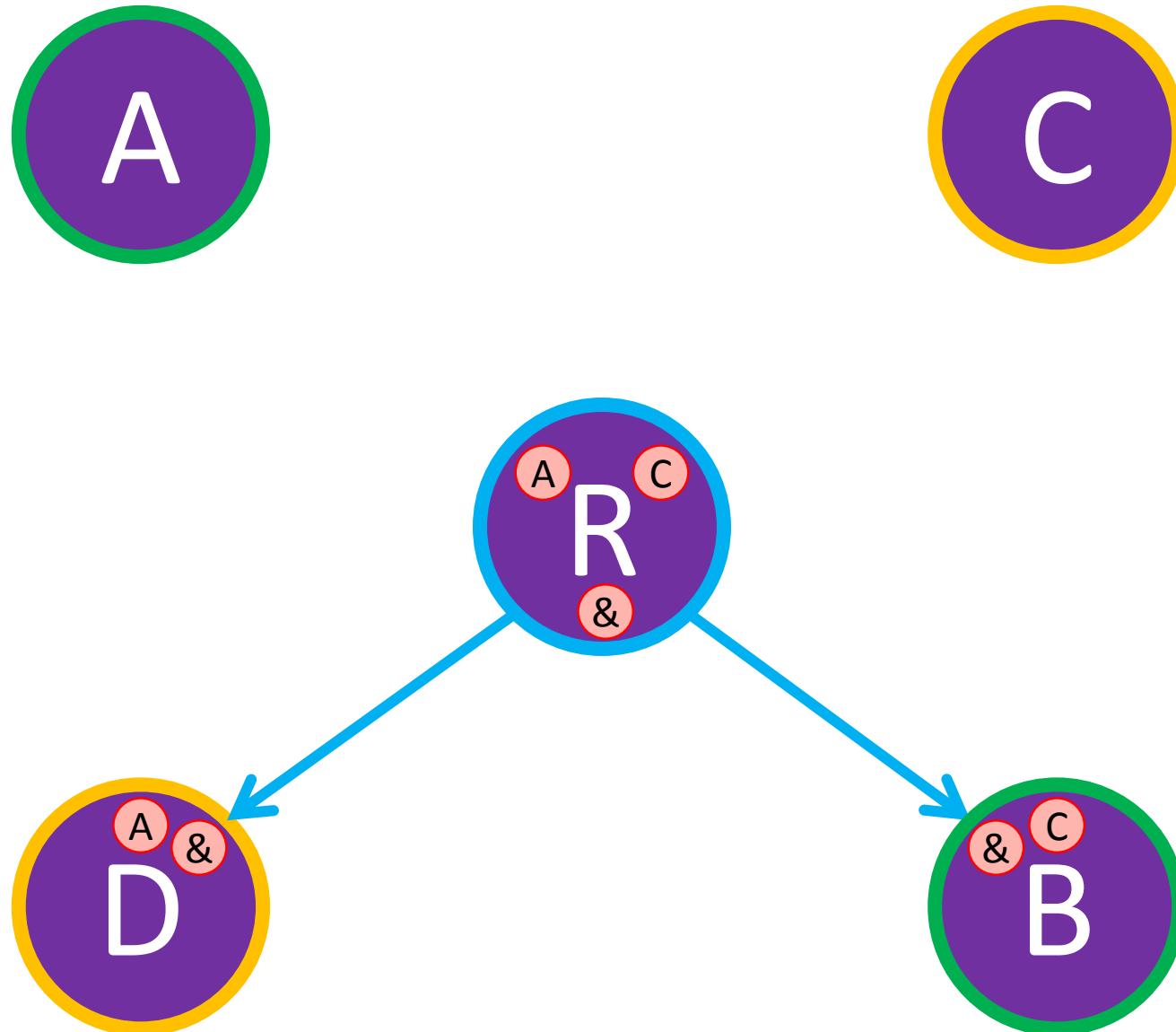
X Topology with Overhearing



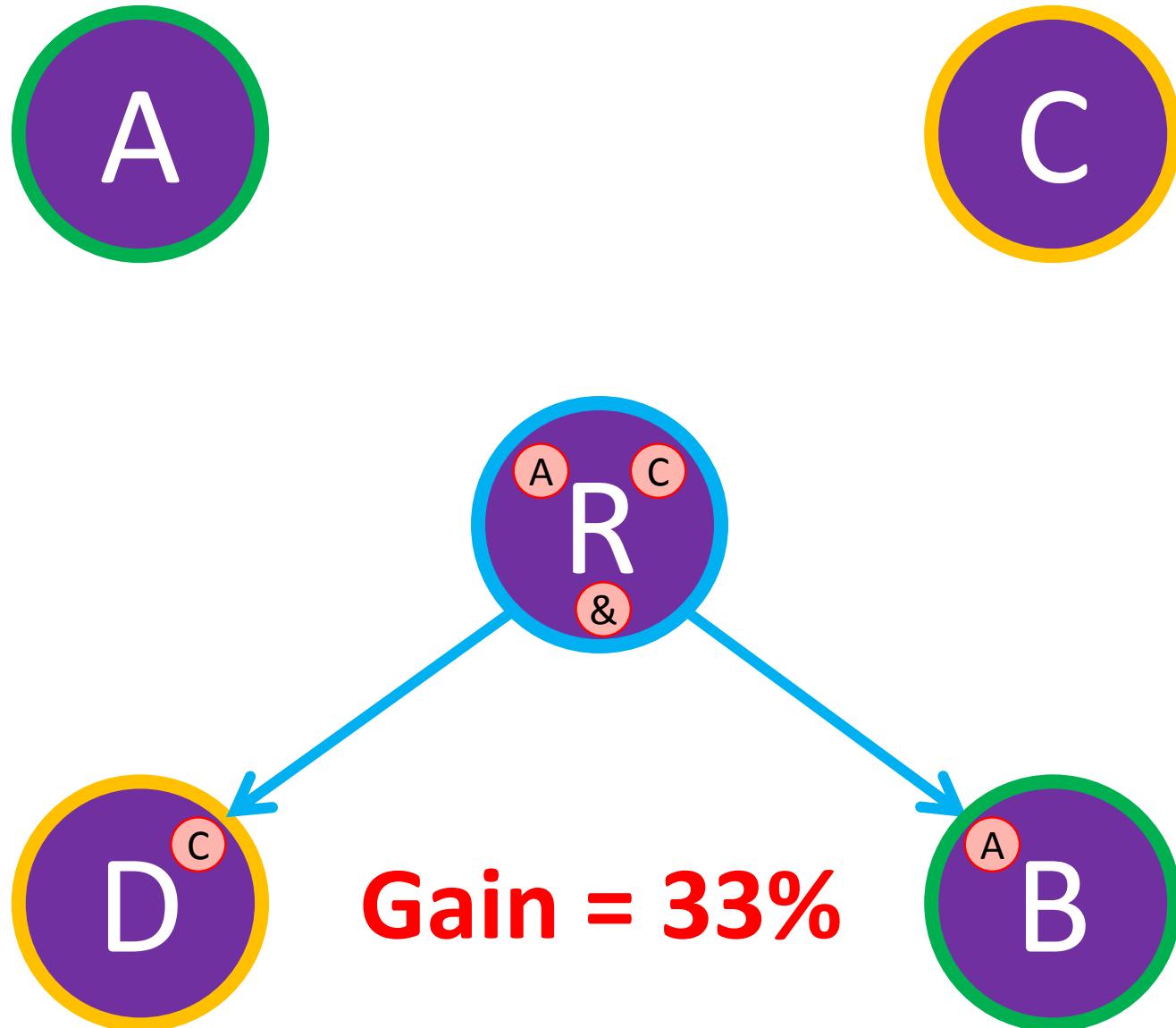
X Topology with Overhearing



X Topology with Overhearing

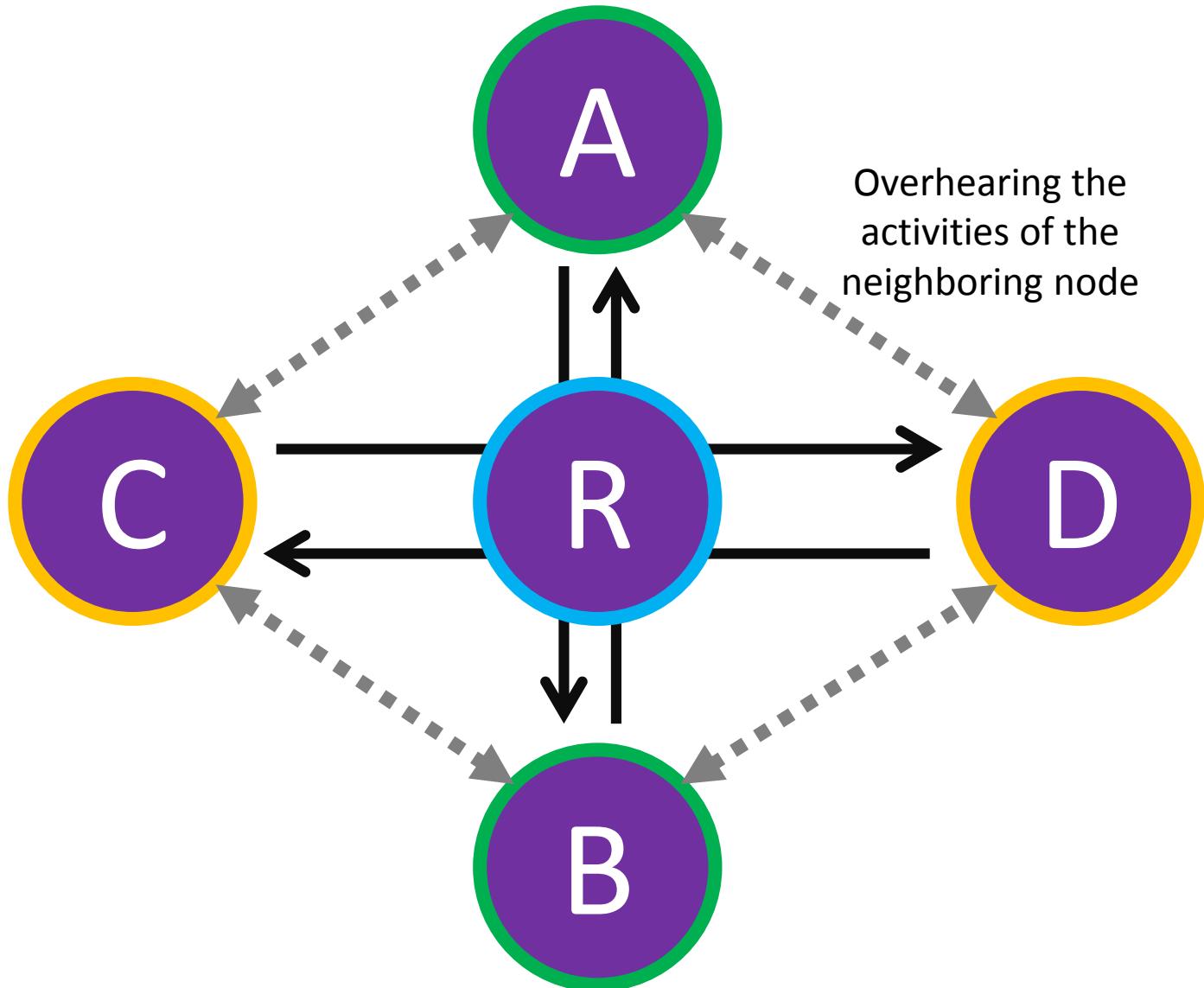


X Topology with Overhearing

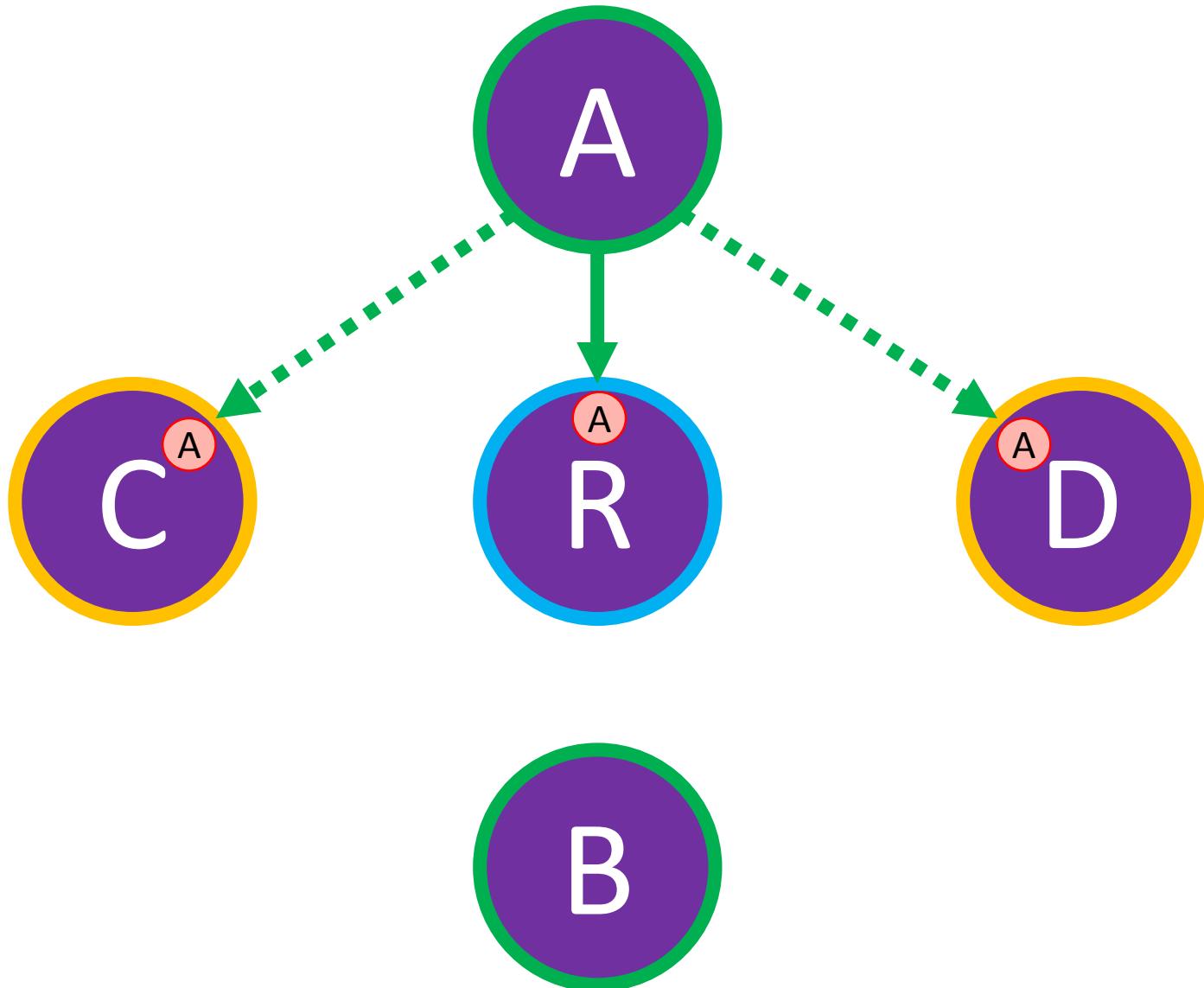


The Cross Topology

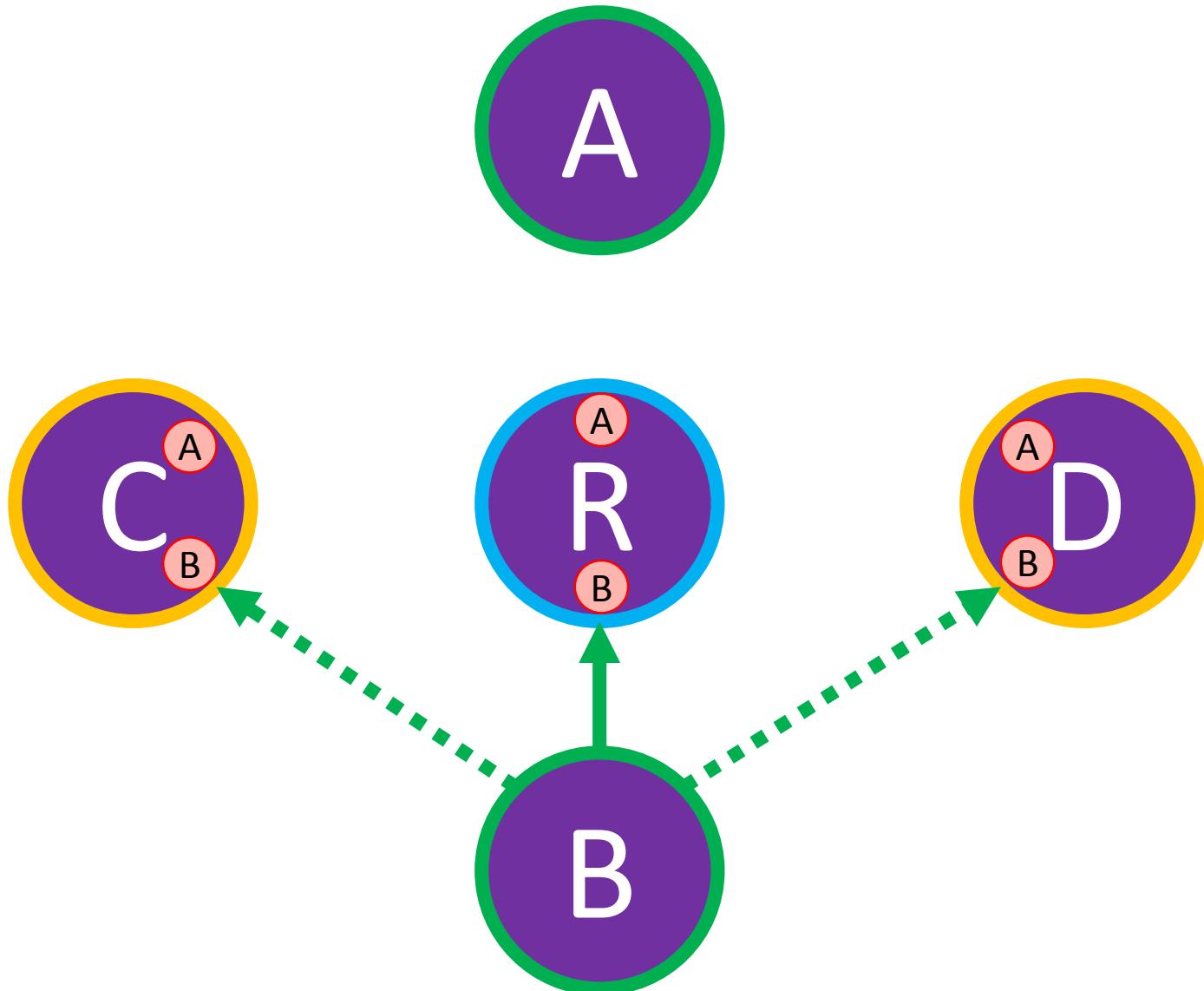
Cross Topology with Overhearing



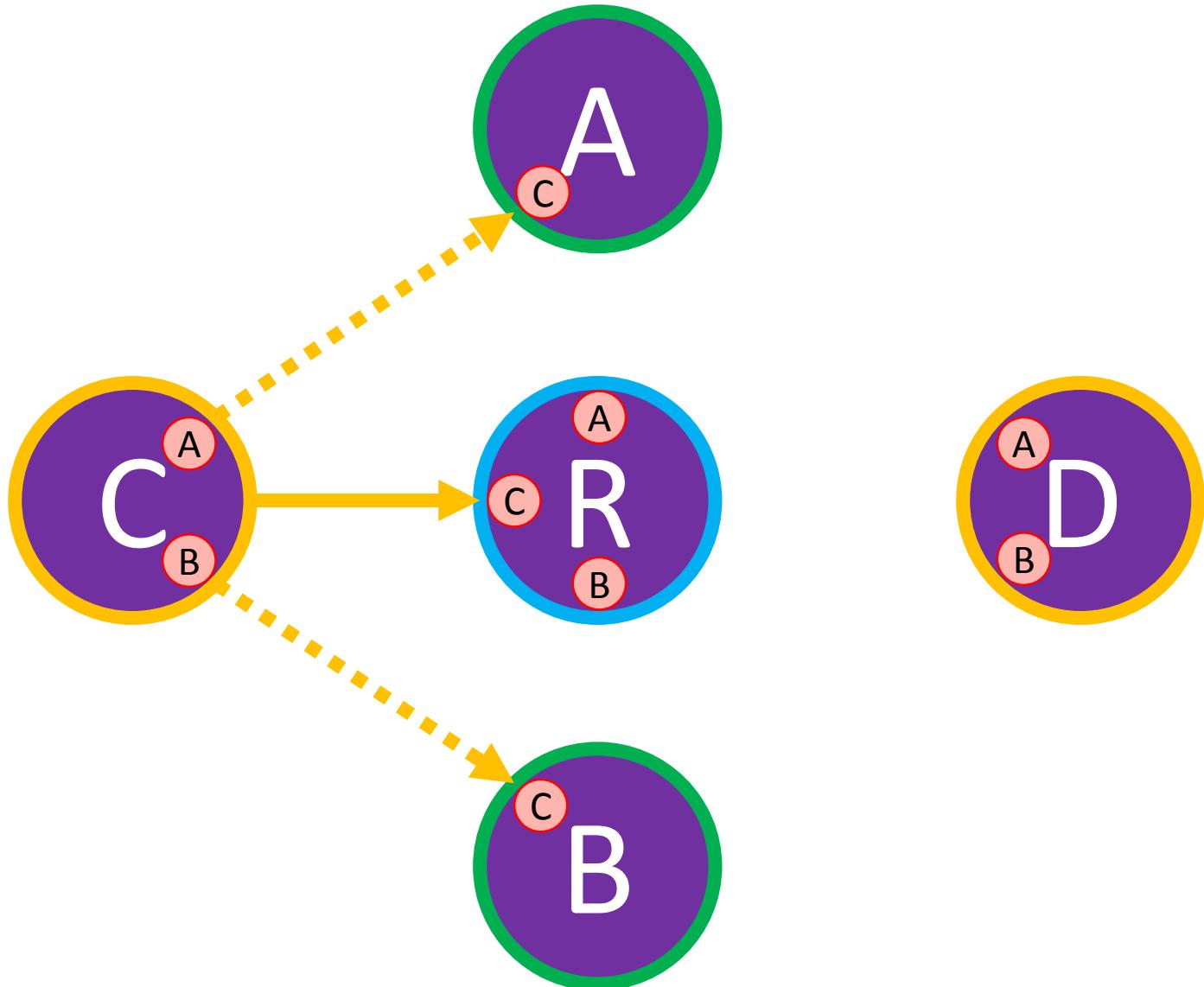
Cross Topology with Overhearing 1/5



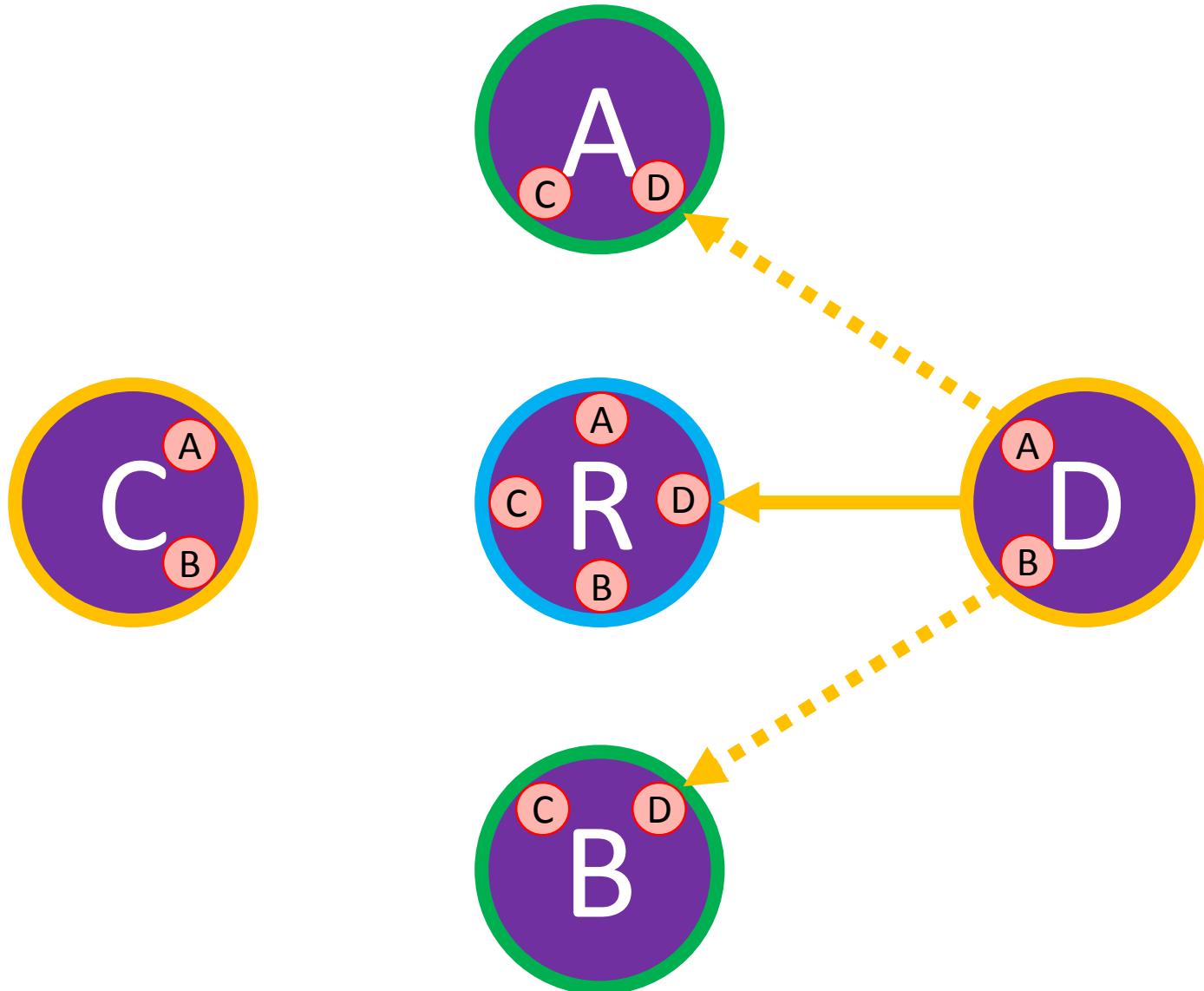
Cross Topology with Overhearing 2/5



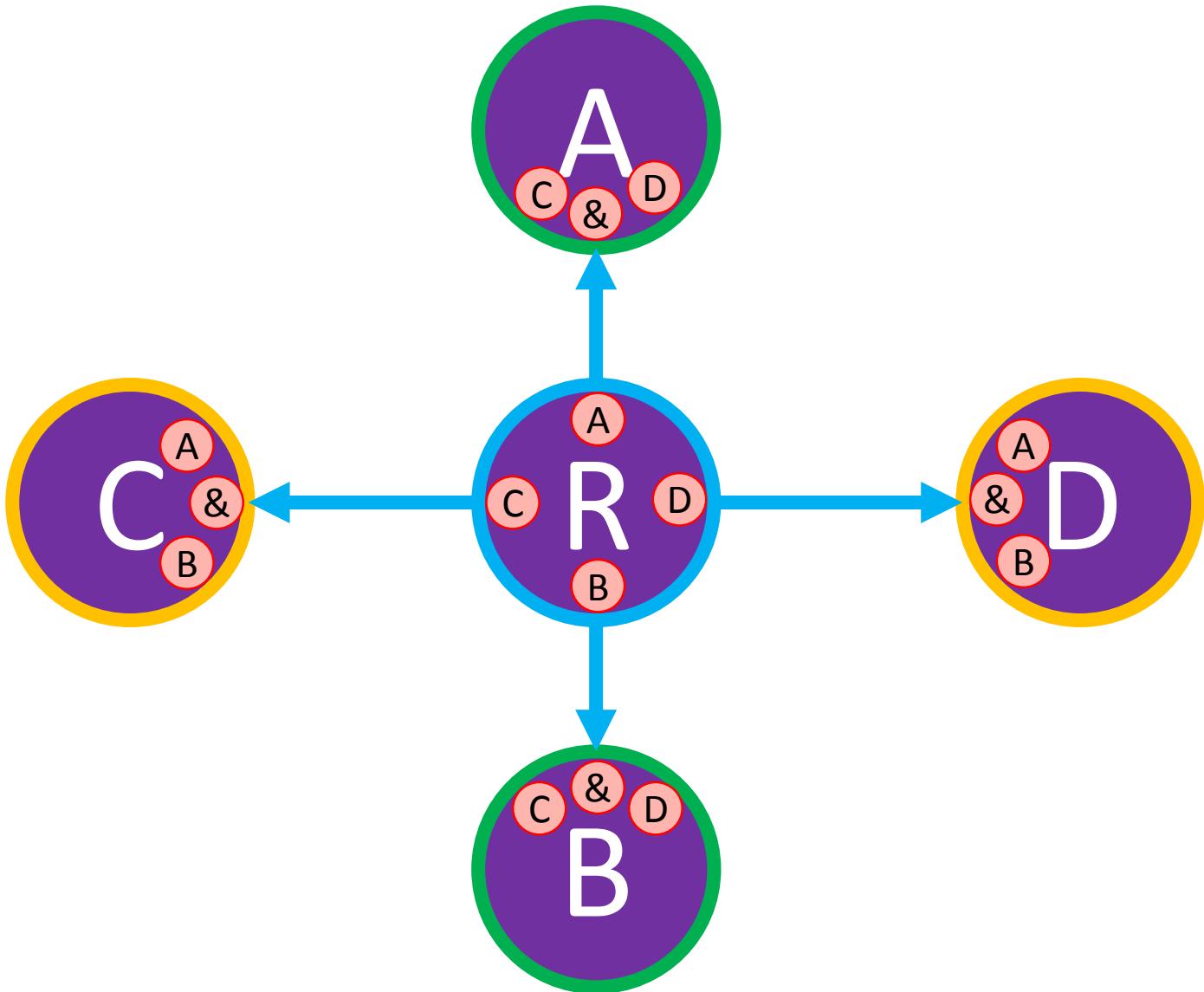
Cross Topology with Overhearing 3/5



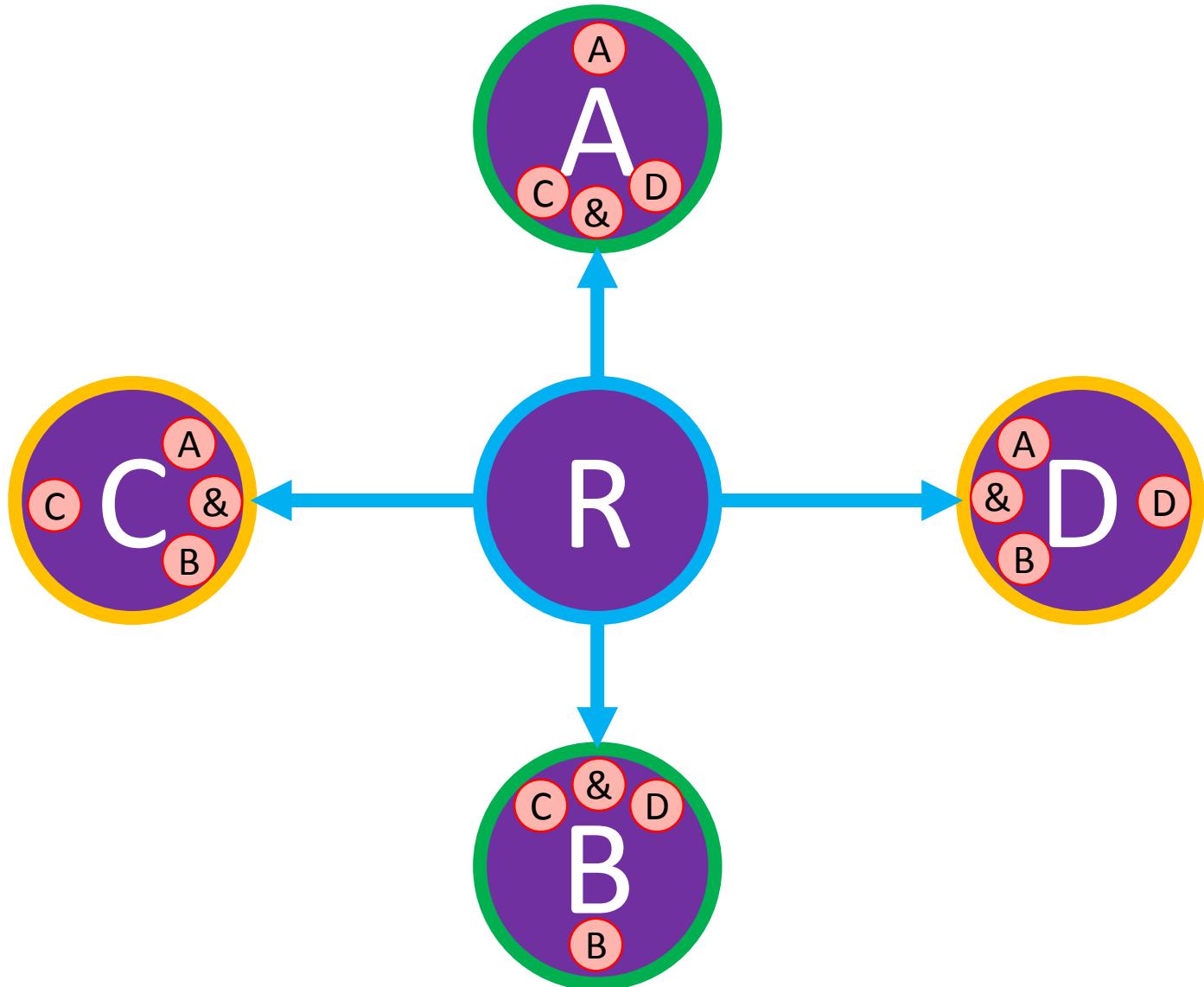
Cross Topology with Overhearing 4/5



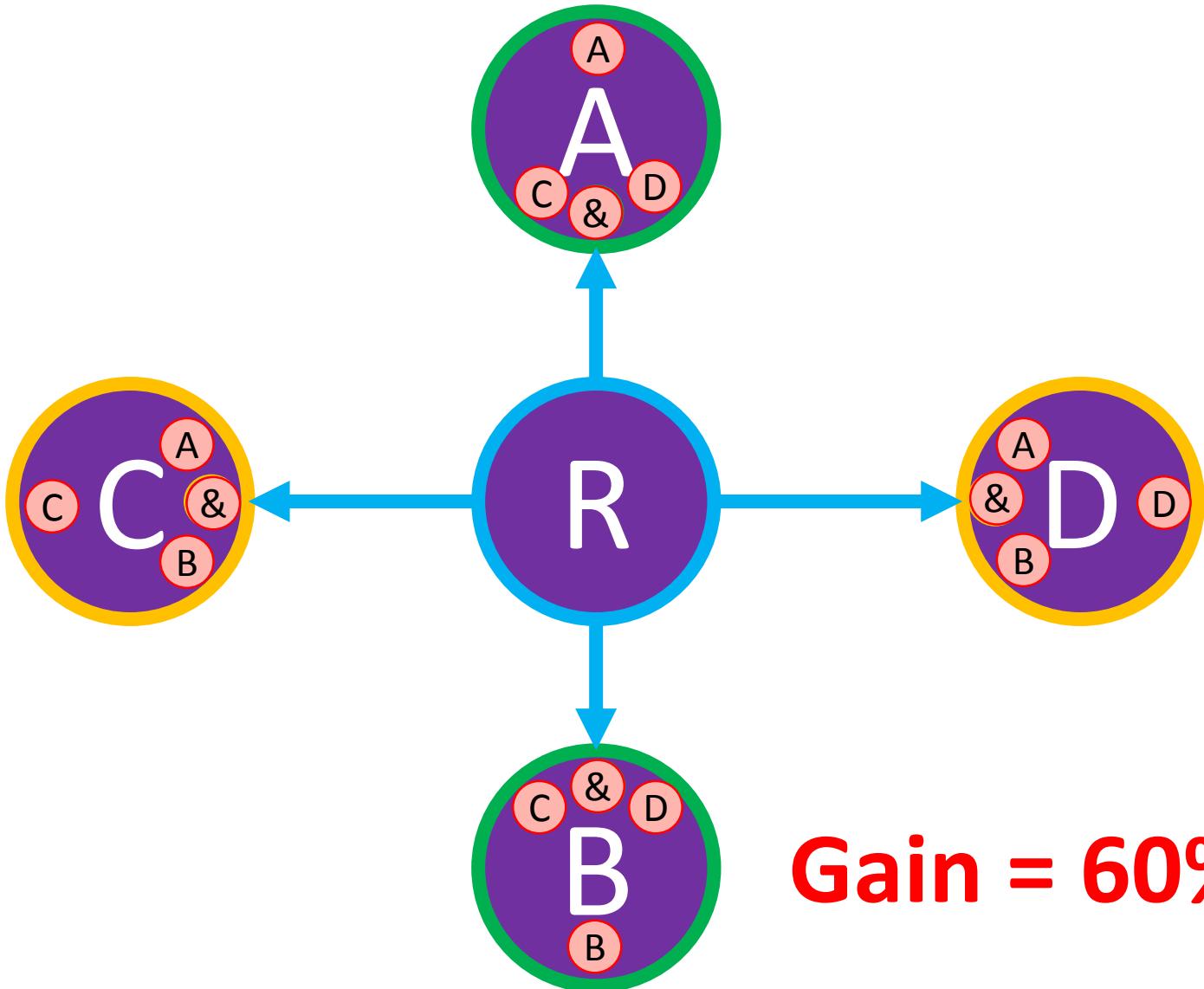
Cross Topology with Overhearing 5/5



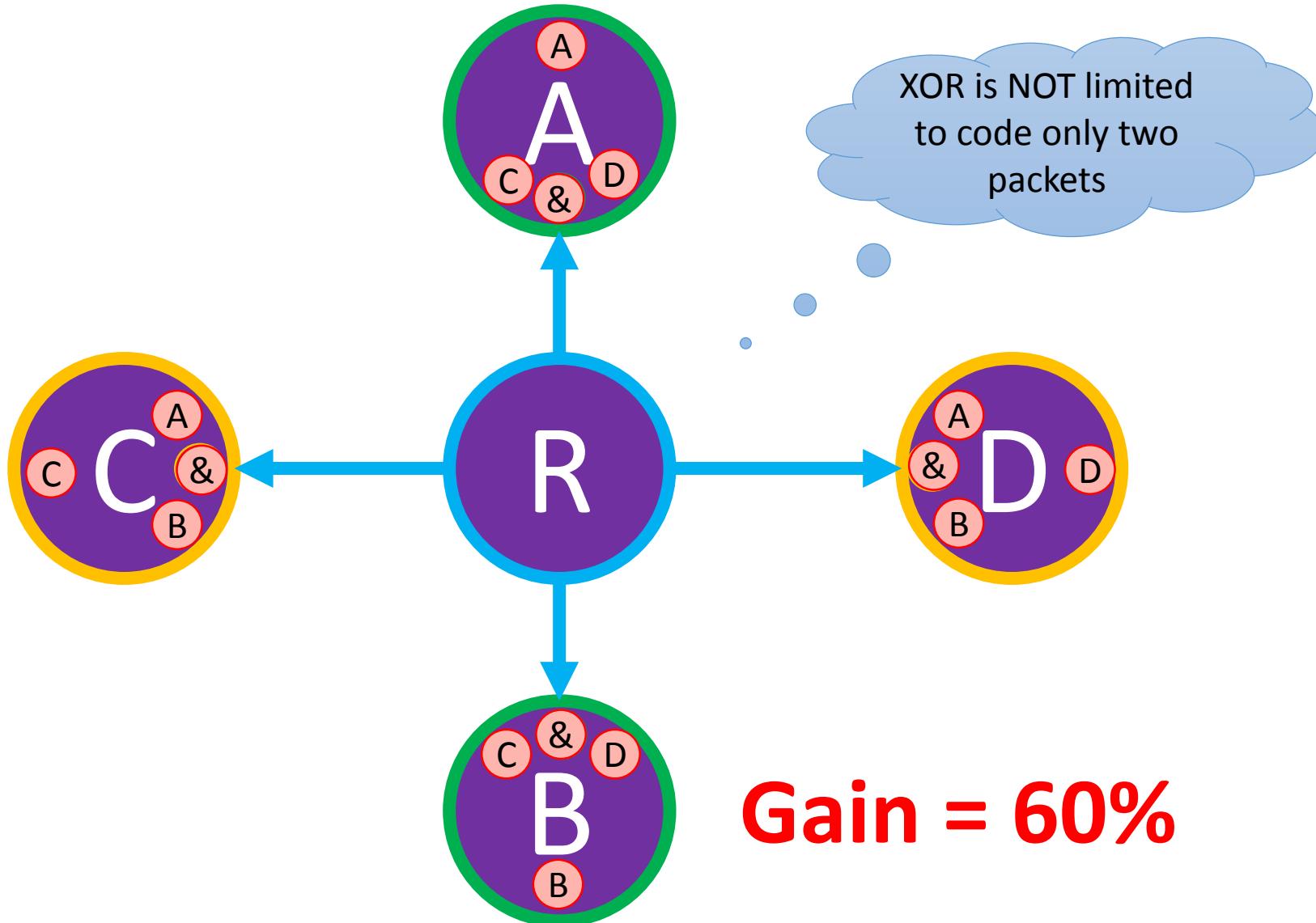
Cross Topology with Overhearing 1/2



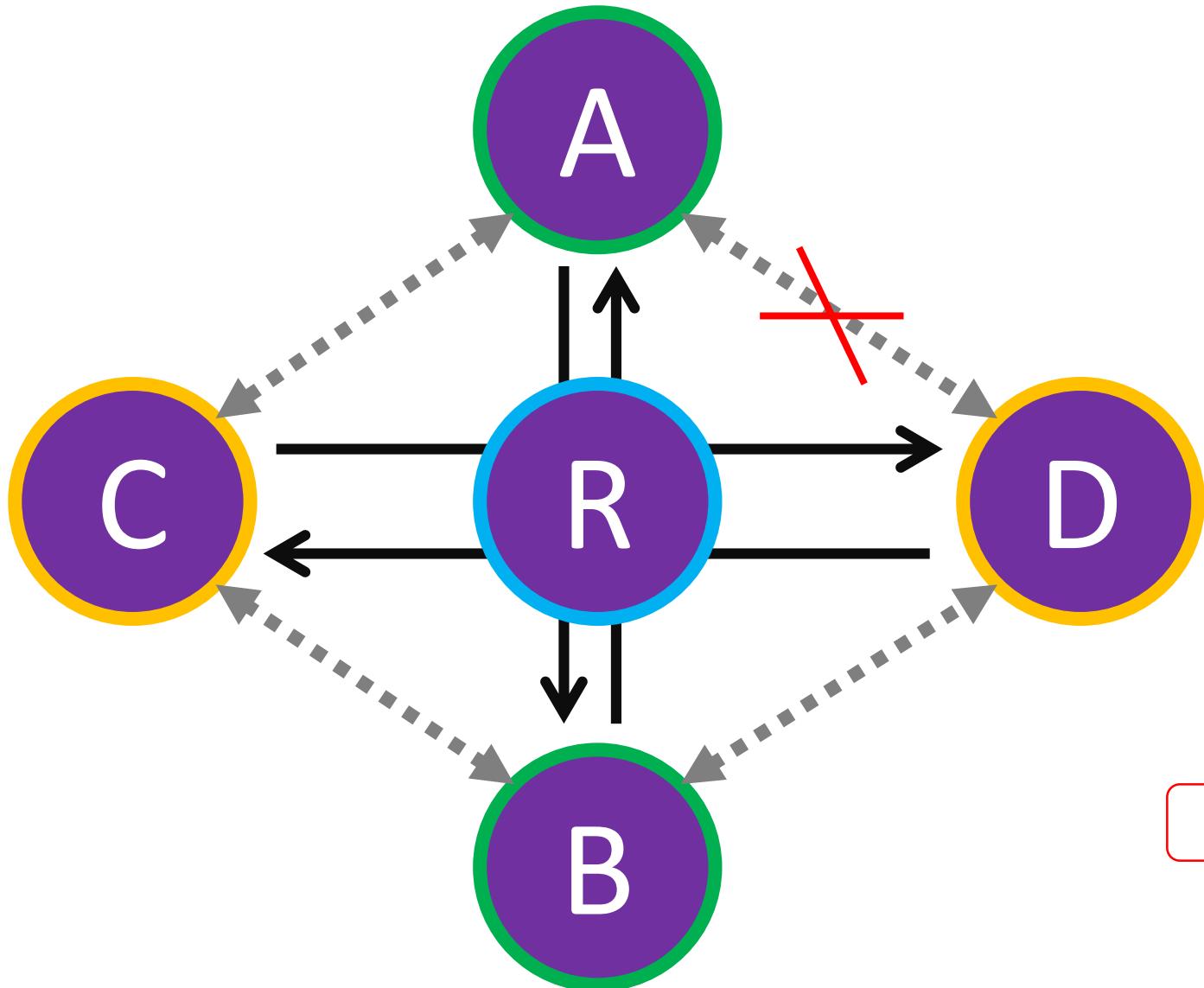
Cross Topology with Overhearing 2/2



Cross Topology with Overhearing 2/2



Cross Topology with Overhearing Problems



Hint: CORE protocol

Pro

- No delay
- Low complexity
- Easy integration with commercial solutions
- Some ideas are used in ANALOG network coding

Cons

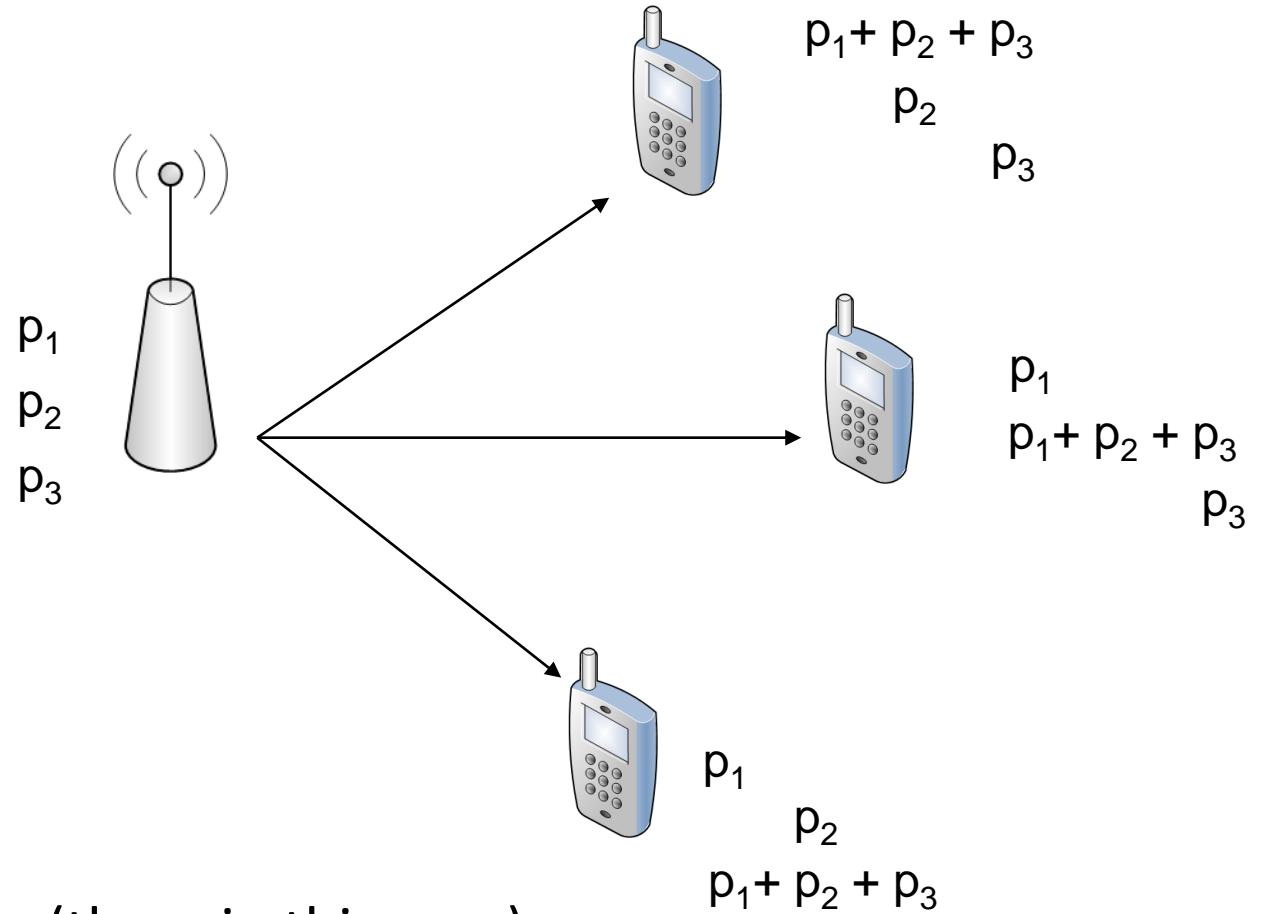
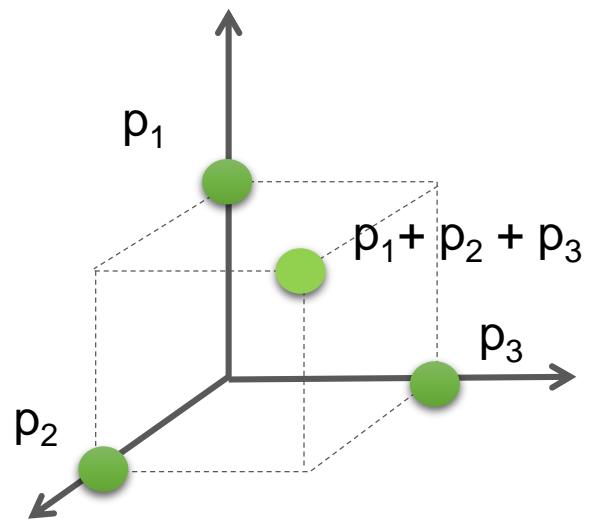
- Planning and book keeping needed
- Certain traffic characteristics are beneficial in mesh networks
- Symmetric traffic allows for more coding potential

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

Initial Phase
 $N=1000 ; J=10$



Recover 1

Recover 2

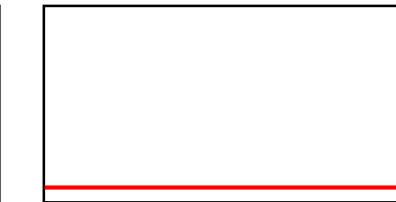
Initial Phase
 $N=1000 ; J=1000$



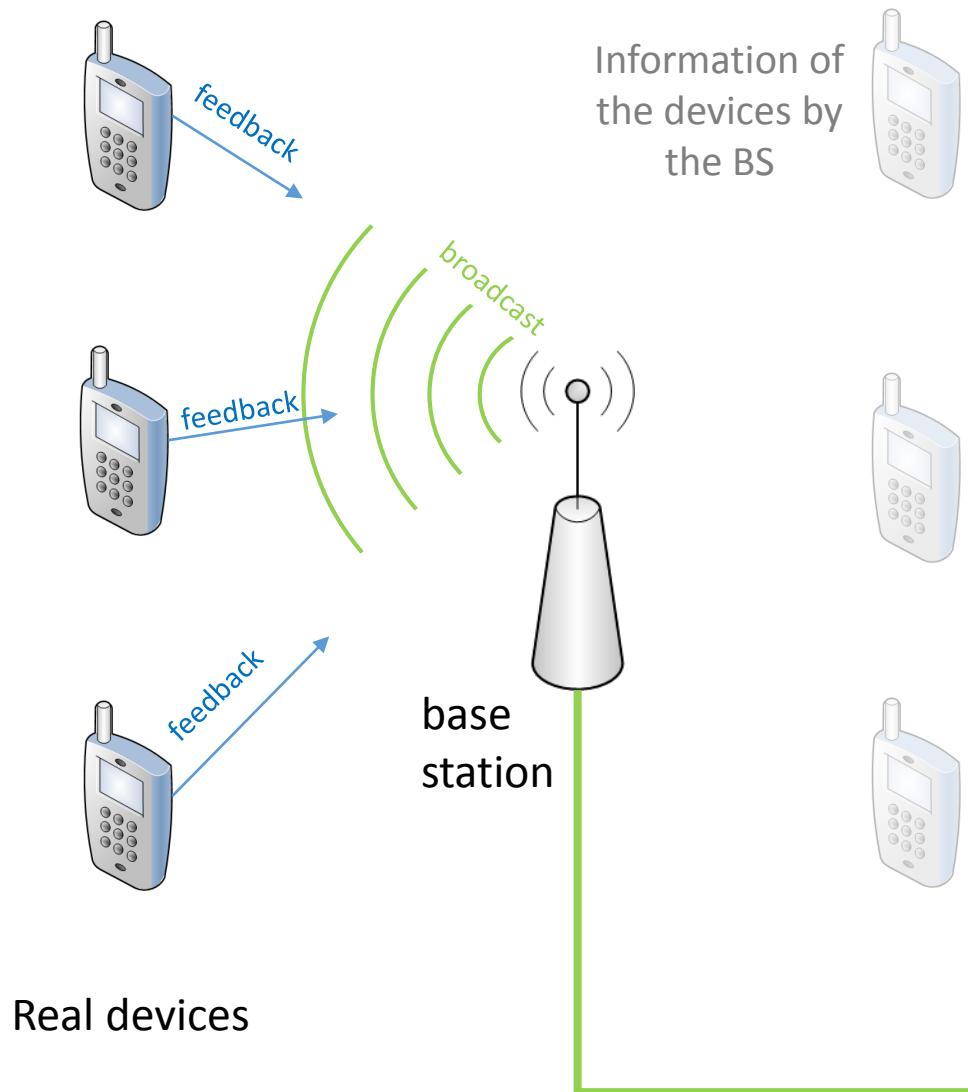
Recover 1

Recover 2

Recover 3



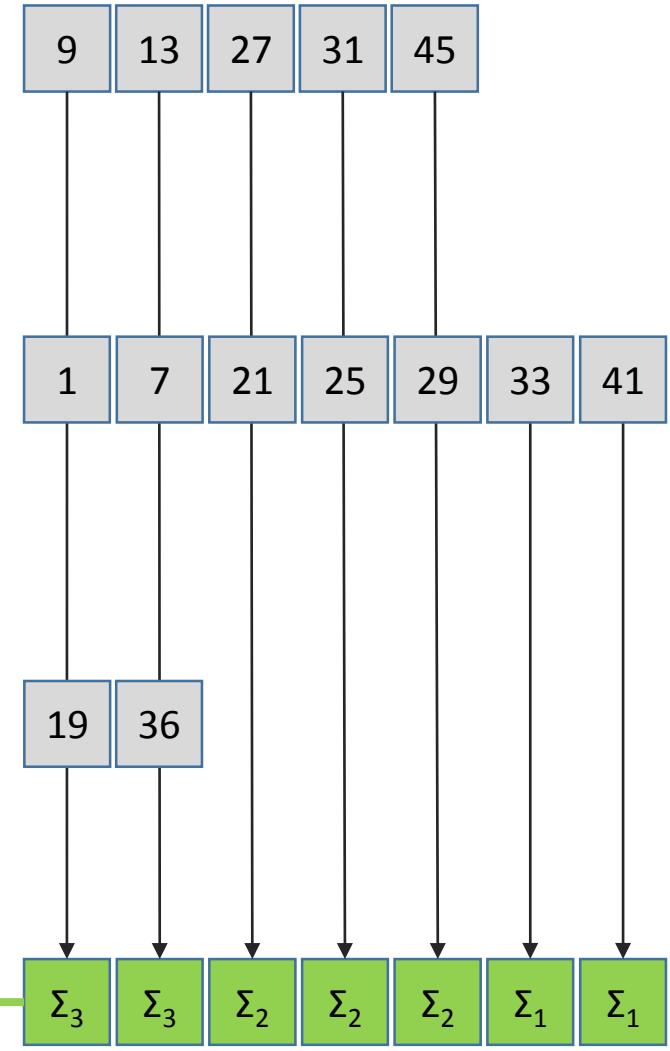
Index Coding



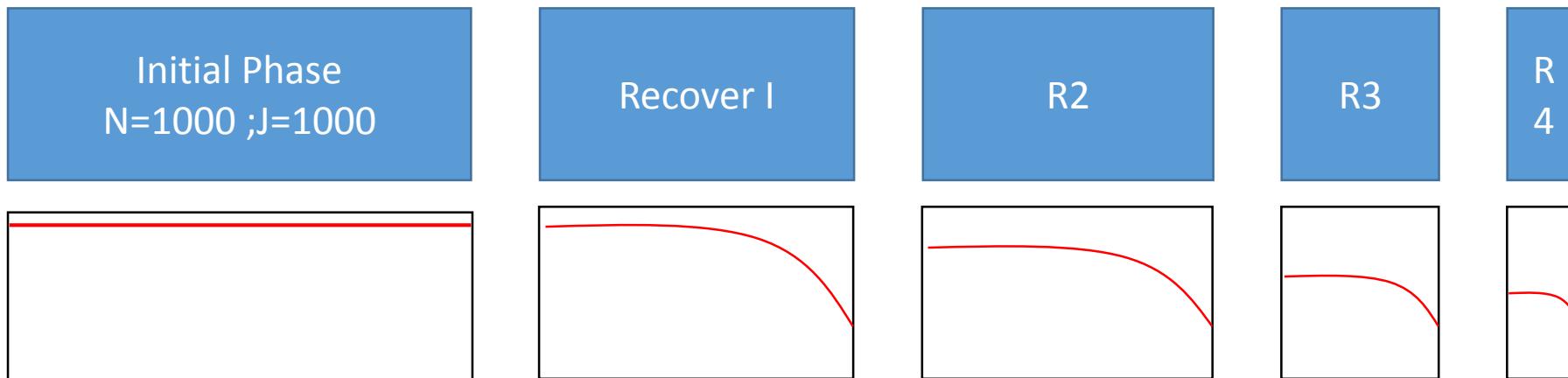
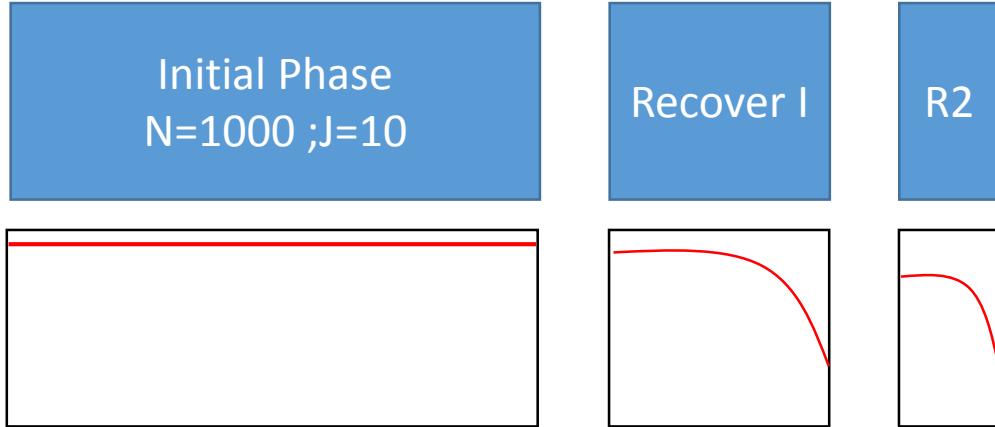
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31	32	33	34	35
36	37	38	39	40	41	42
43	44	45	46	47	48	49

1	2	3	4	5	6	7
8	9	10	11	12	13	14
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43	44	45	46	47	48	49

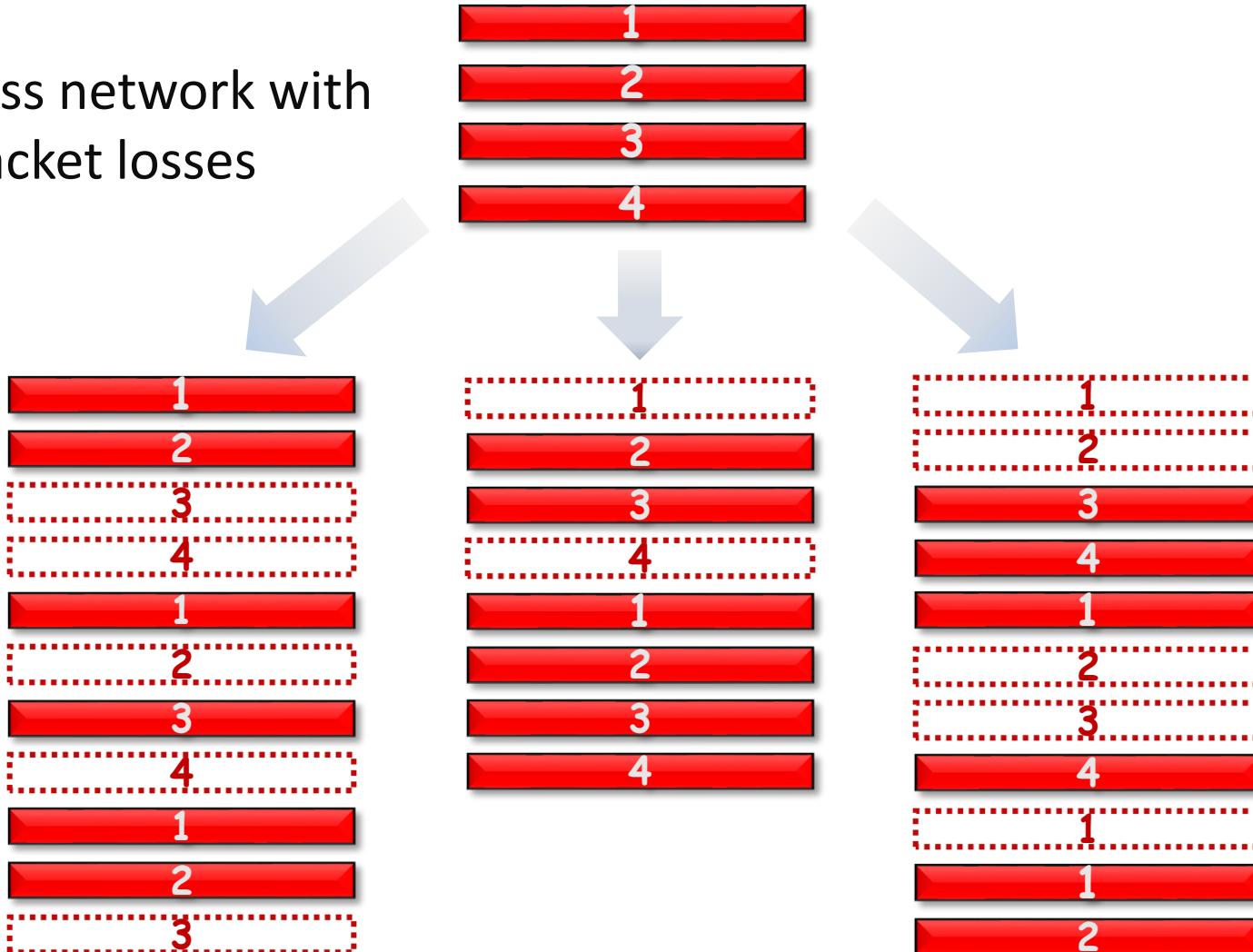


Index Coding



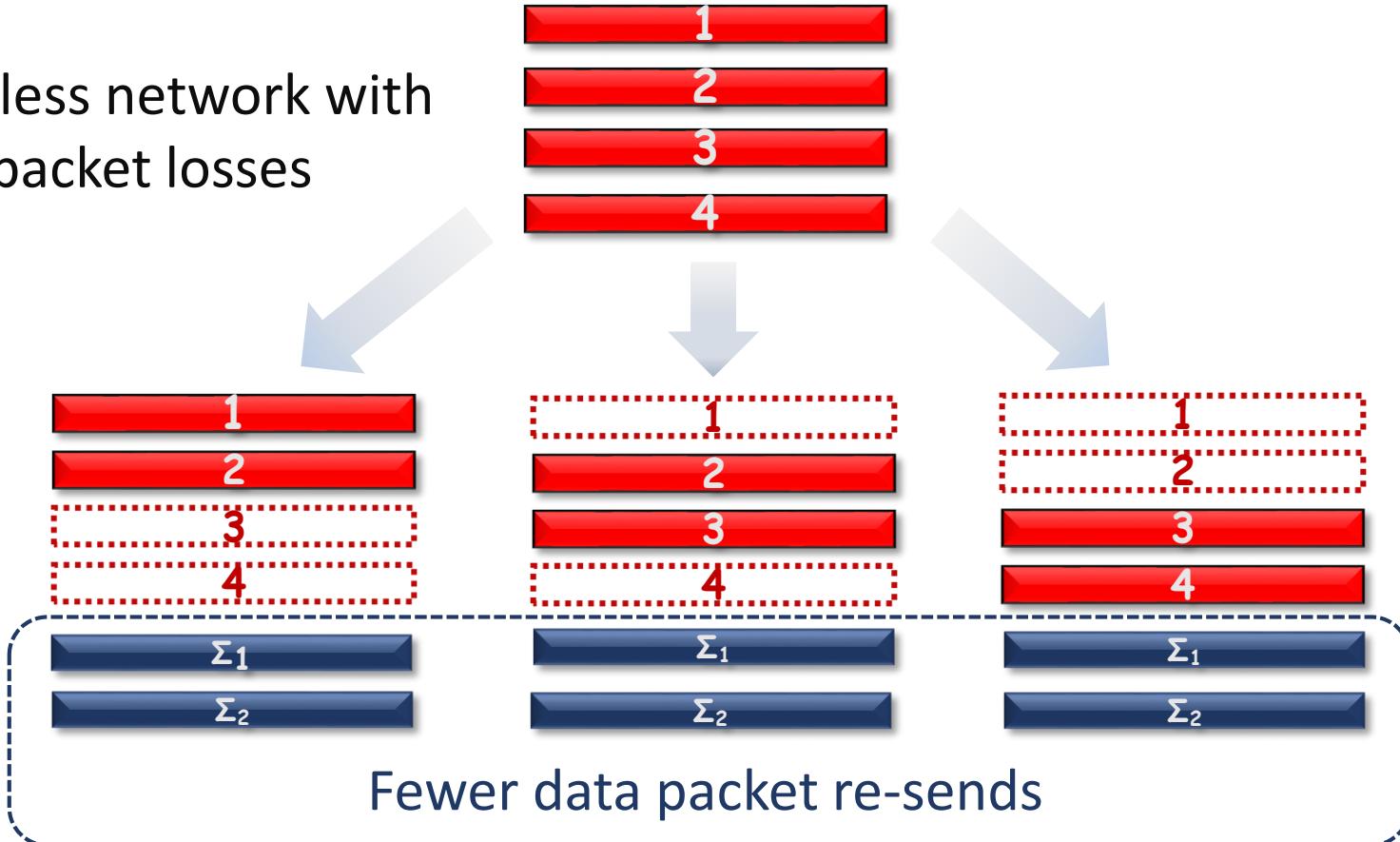
Broadcast Example

Wireless network with
packet losses



Broadcast Example

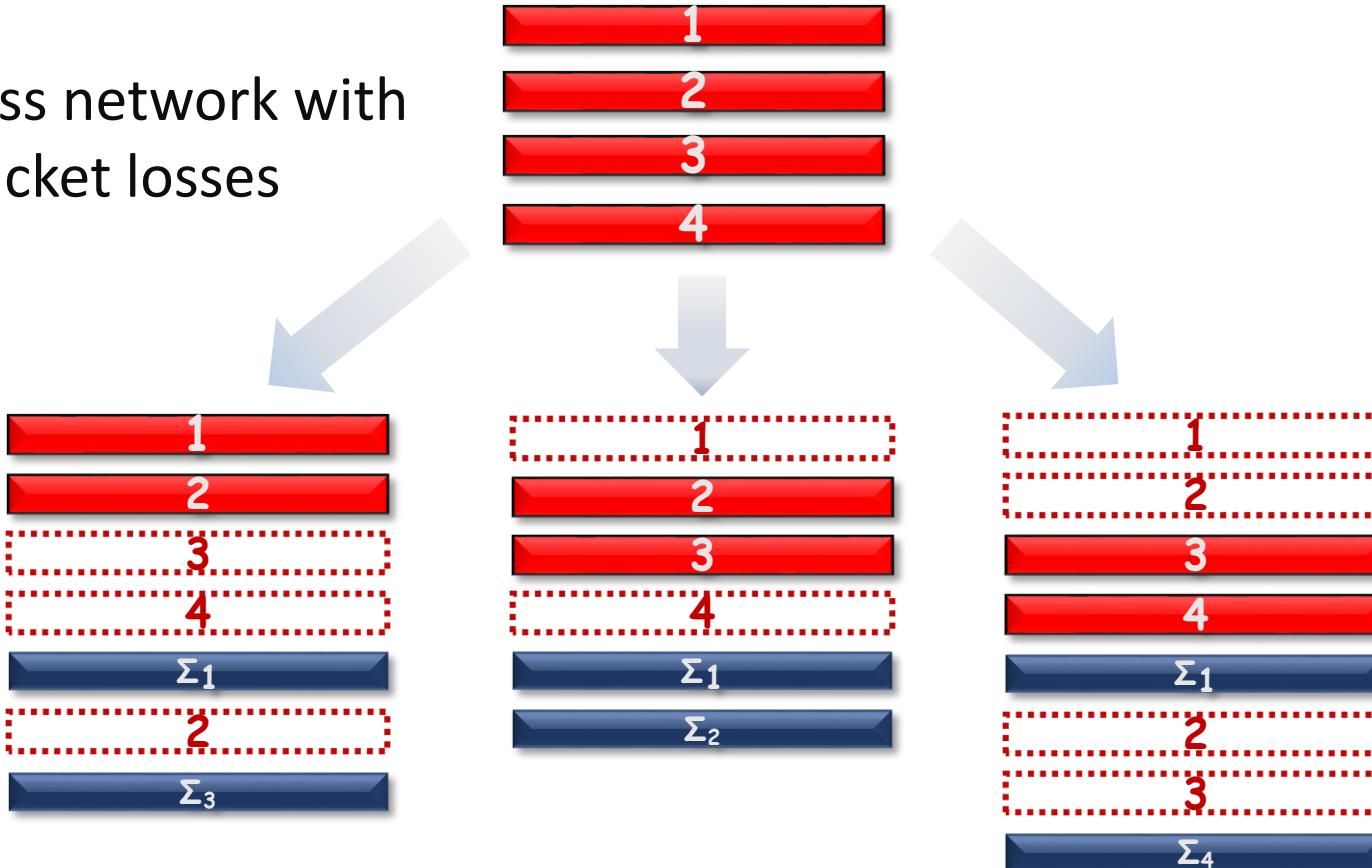
Wireless network with
packet losses



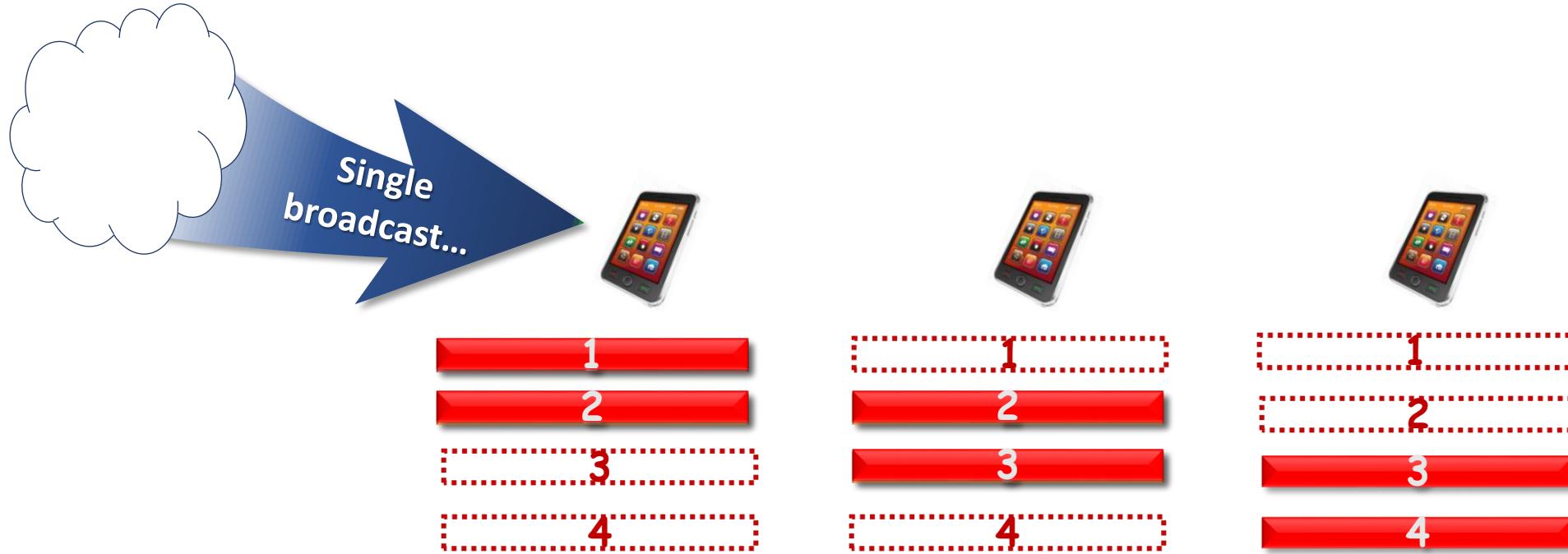
Broadcast Example

Wireless network with
packet losses

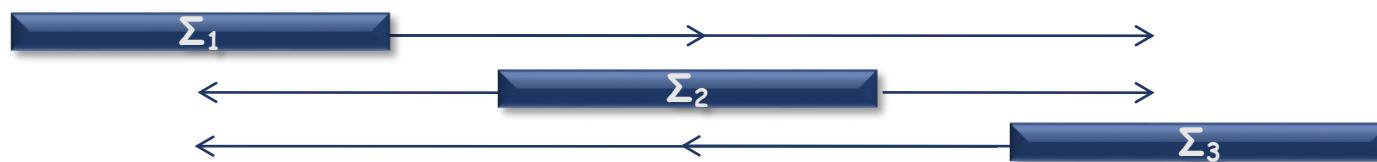
Same errors as before ...



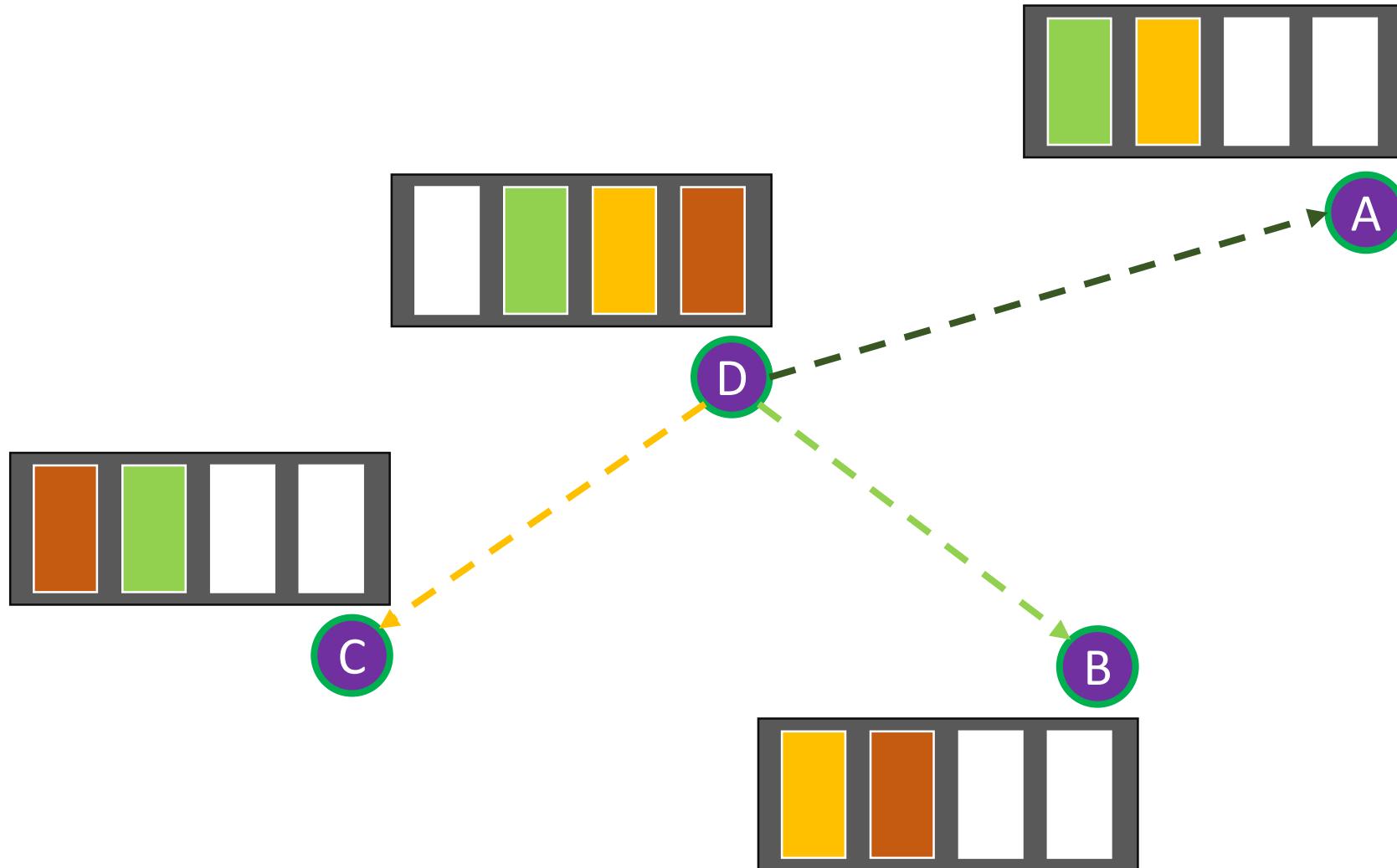
Broadcast Example: Cooperative Advantage



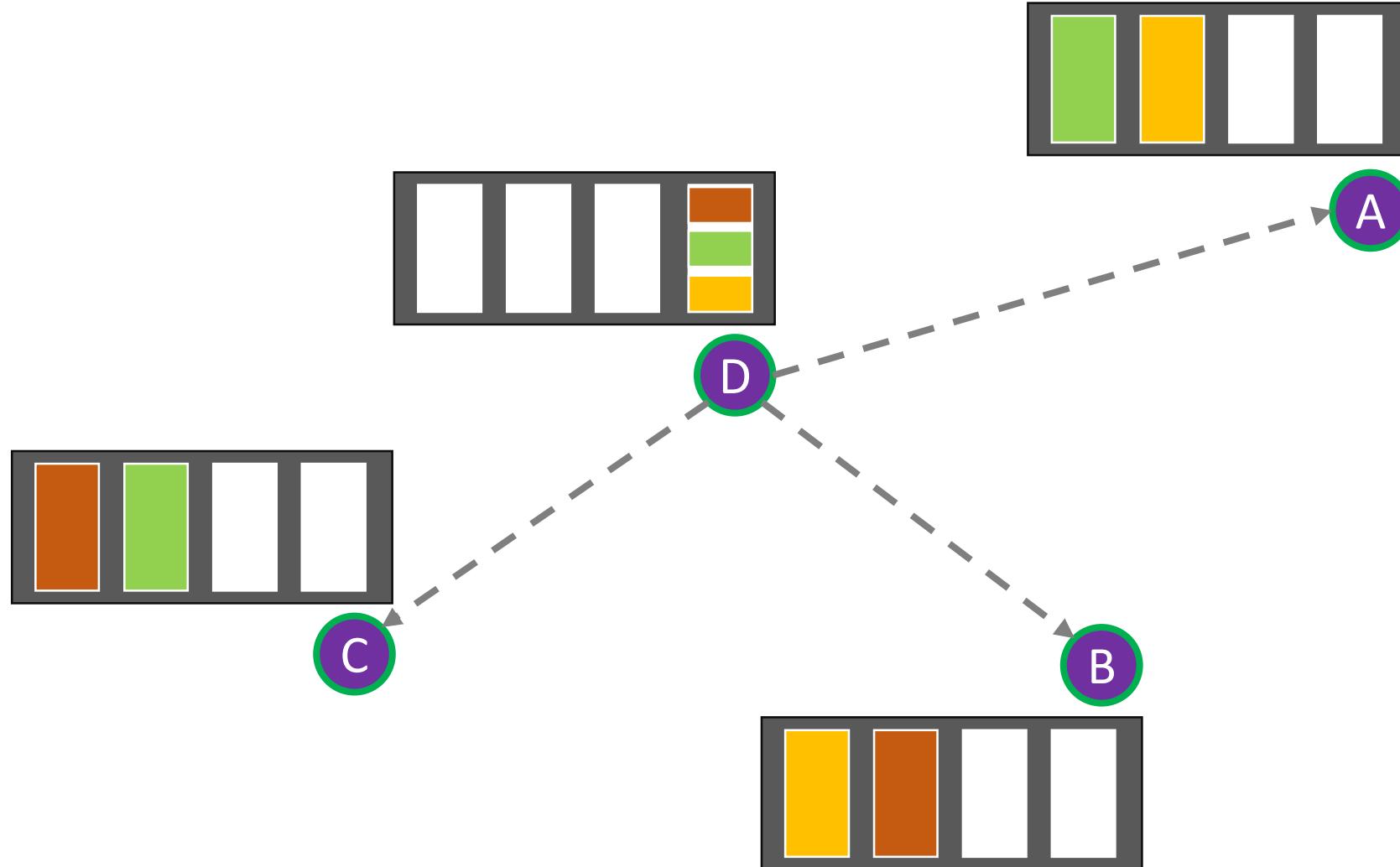
...and peers share missing data



w/o Coding

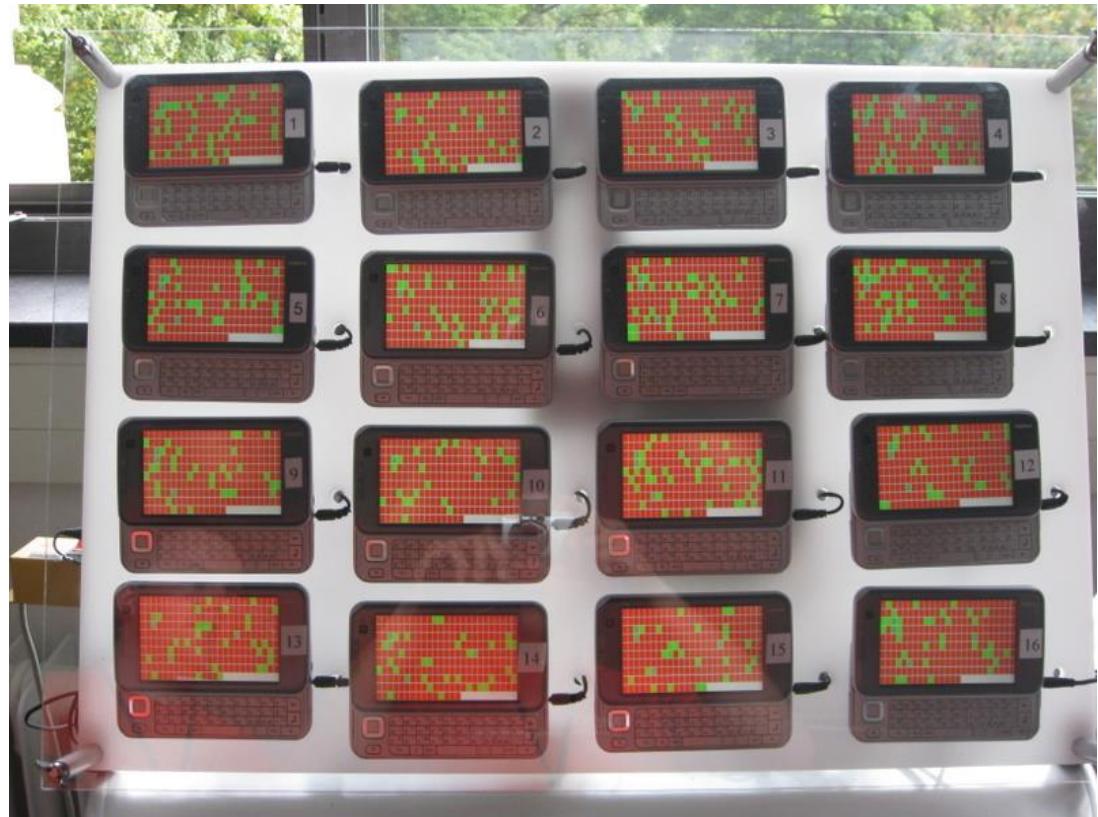


w Coding



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
- Enriching teaching activities



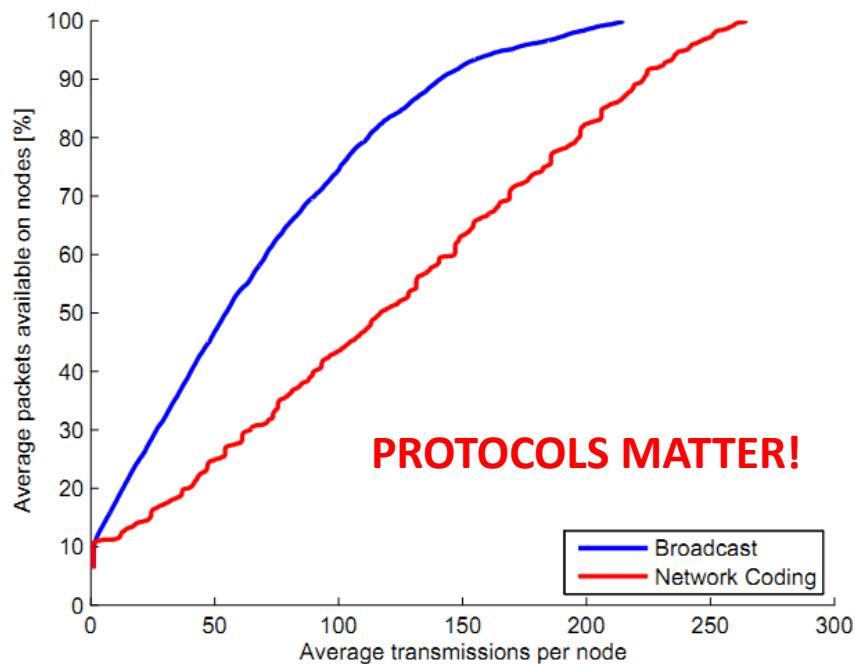
N810 Implementation COPE



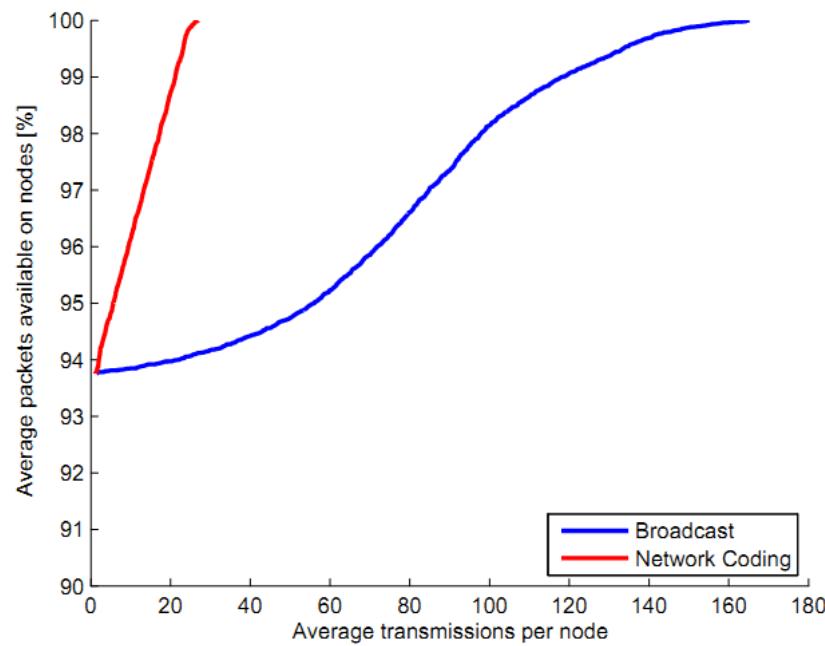
<https://www.youtube.com/watch?v=VZYLSSyZaEO8>

Results: N810

**Disjoint Starting Phase:
(no duplicates on beginning)**



**Random Starting phase:
(duplicates are possible)**





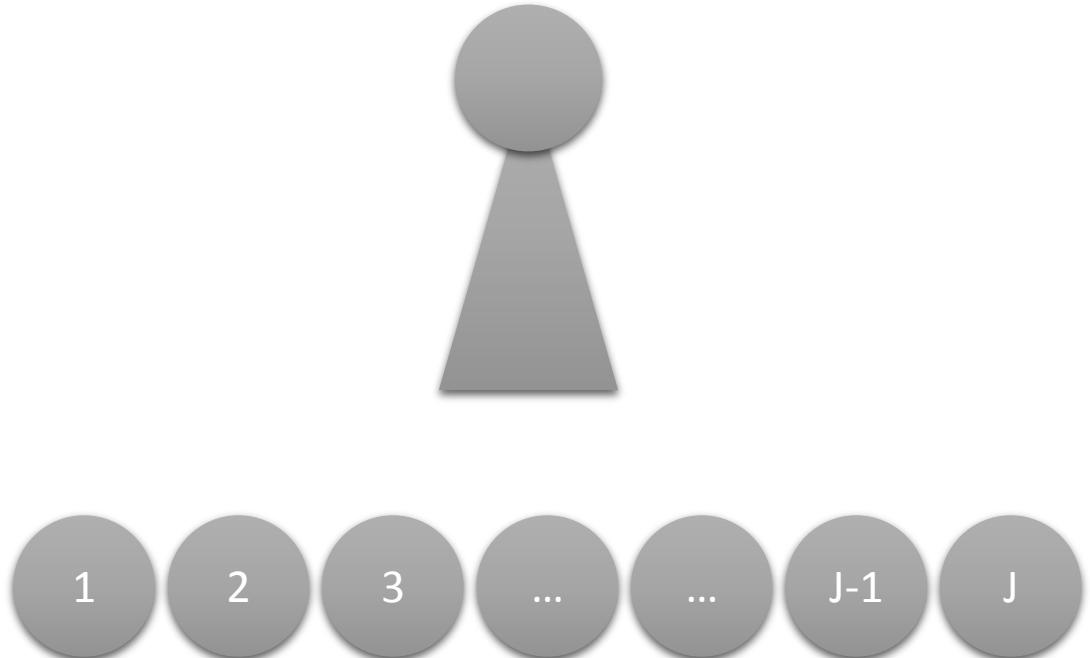
Digital Zig Zag Coding



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

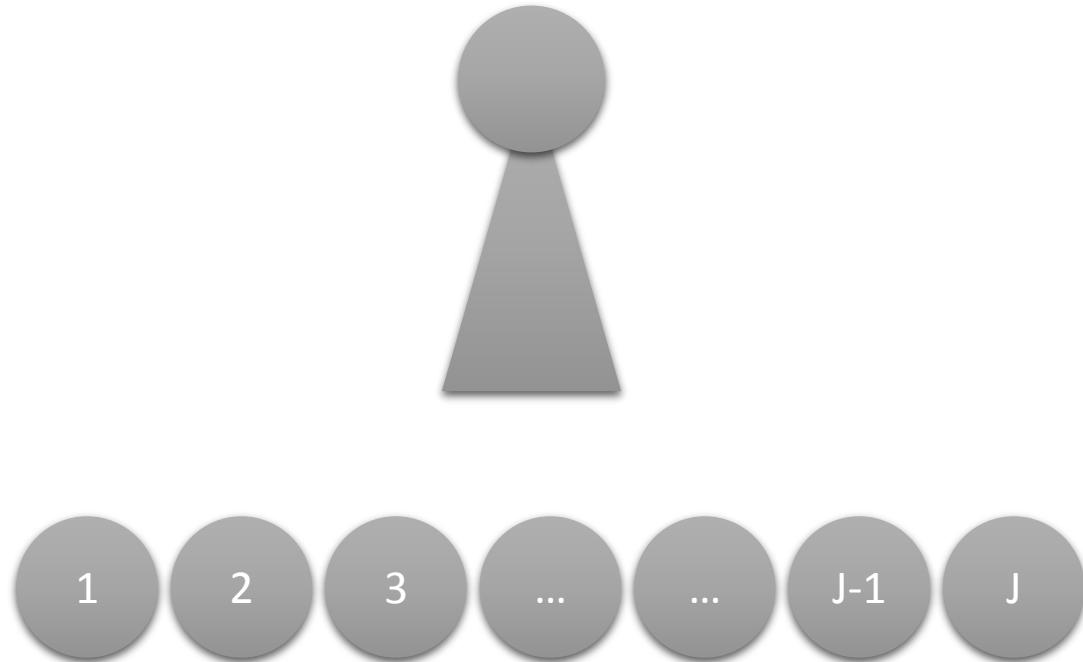


Architecture and Example

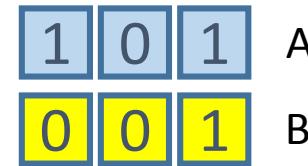
1	0	1
0	0	1

A
B

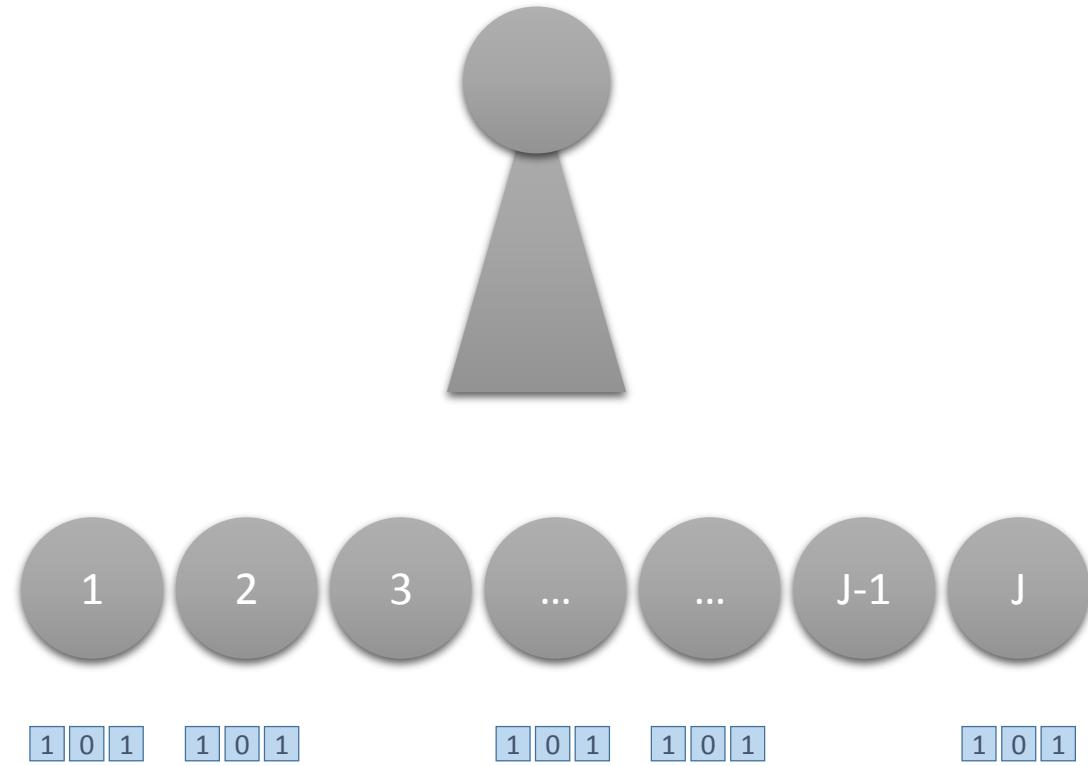
- Assuming one node broadcasts information to several nodes over error-prone medium
- All nodes are interested in the same content
- Assuming we have only two messages A and B with three bits of information each (to make it easy)



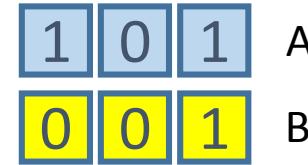
Architecture and Example



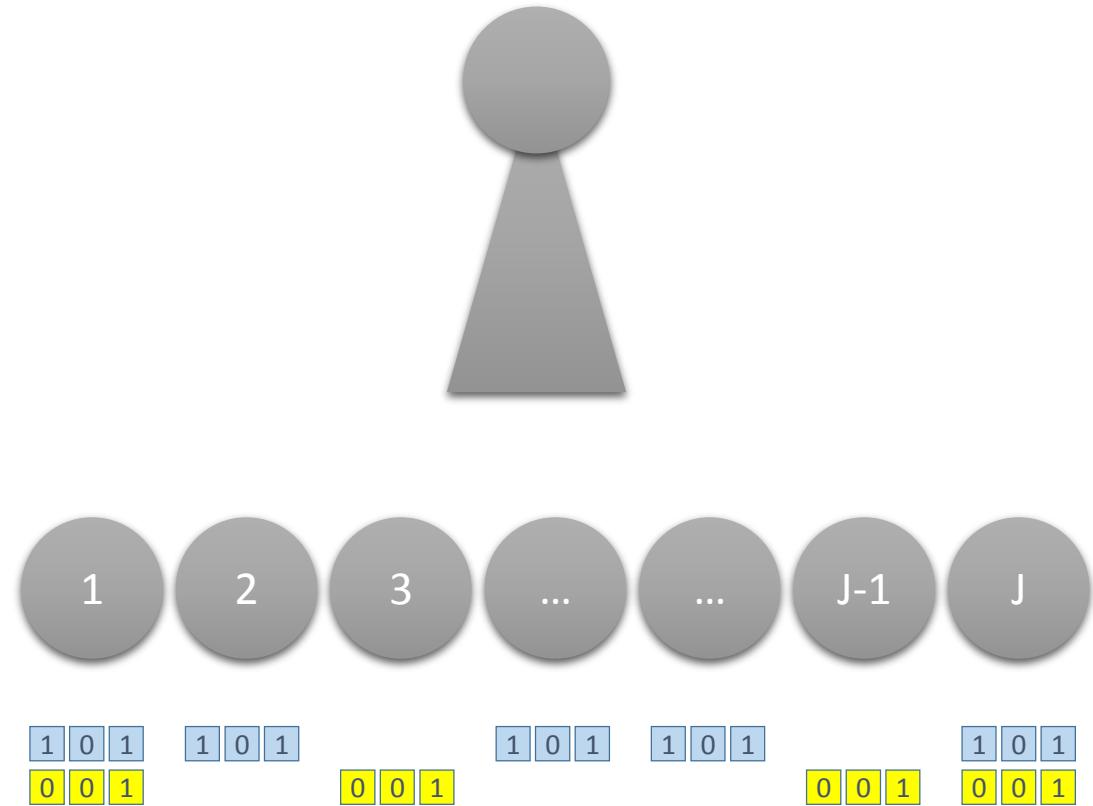
- Assuming one node broadcasts information to several nodes over error-prone medium
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Architecture and Example



- 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)

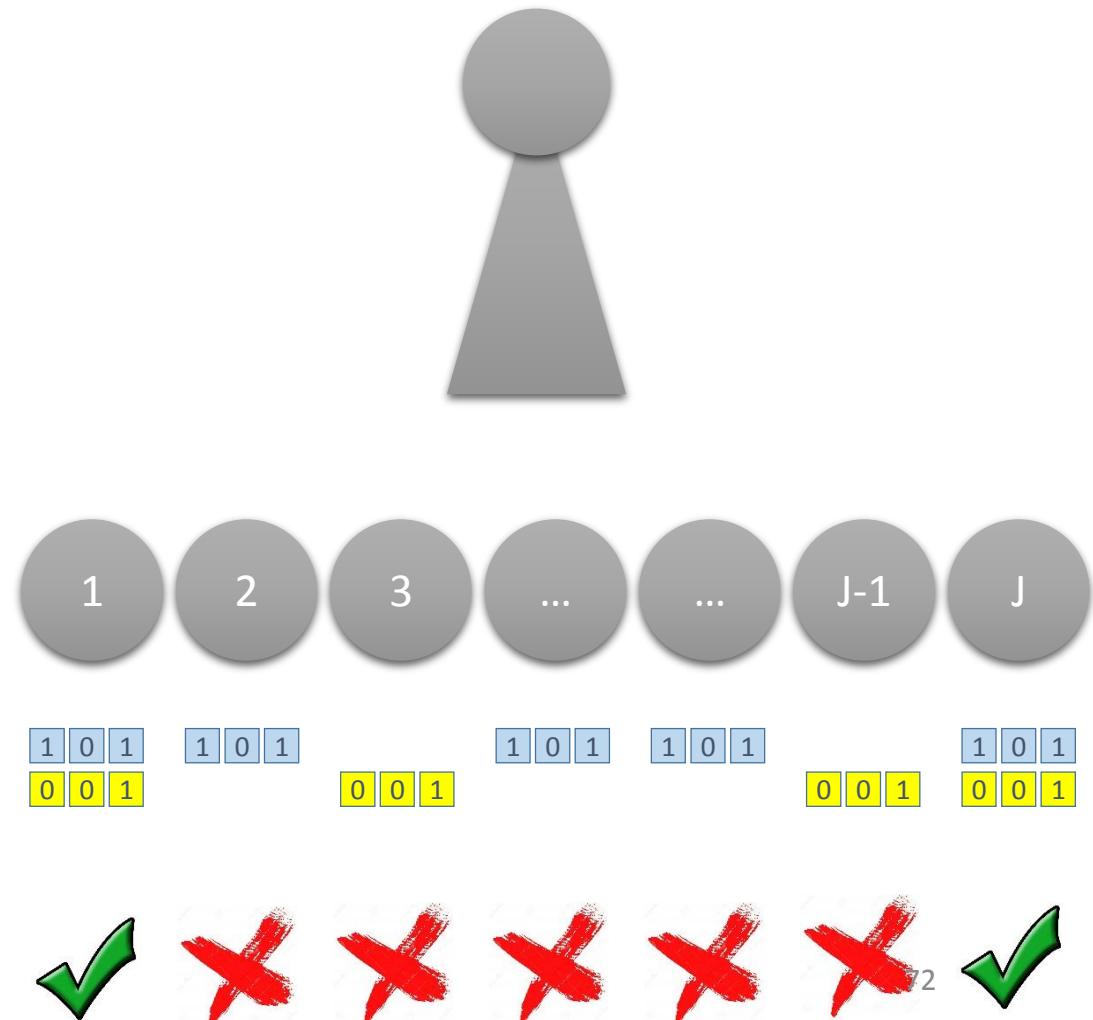


Architecture and Example

1	0	1
0	0	1

A
B

- 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
0	0	1
1	0	0

Original packet A

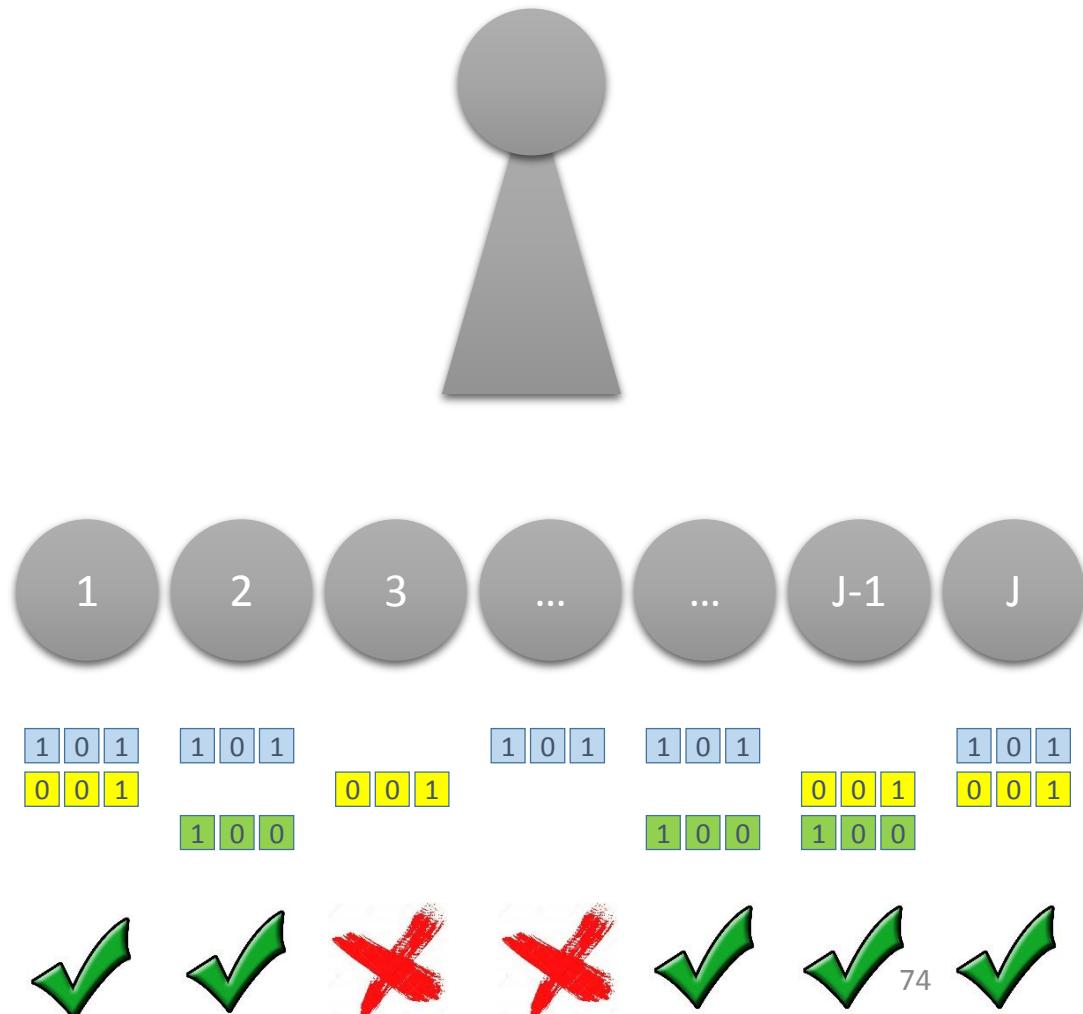
Original packet B

Coded packet $A \oplus B$

Architecture and Example

		A
		B
		XOR coded

- 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 $A \oplus B^*2$

Legend:



Bit with value x from packet A



Bit with value x from packet B

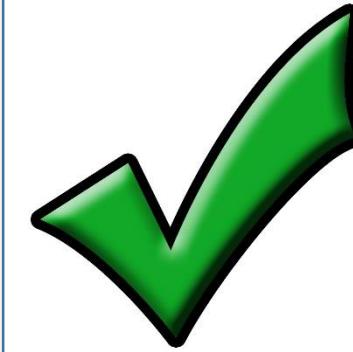


Coded bit with value x from packet A and packet B

Decoding 1

Original packet A

1	0	1
0	0	1



Original packet B

Decoding 2

Original packet A

1	0	1
1	0	0

Coded packet $A \oplus B$

Decoding 2

Original packet A

1	0	1
---	---	---

Coded packet $A \oplus B$

1	0	0
---	---	---

1	0	1
0	0	1

Simple reading & XOR



Decoding 3

Coded packet $A \oplus B^* 2$

0	1	1	1
0	0	1	

Original packet B

Original packet A

Original packet B

Decoding 3

Coded packet $A \oplus B^* 2$

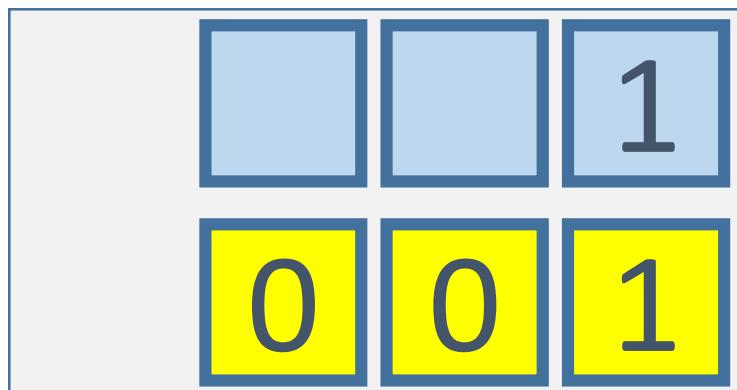
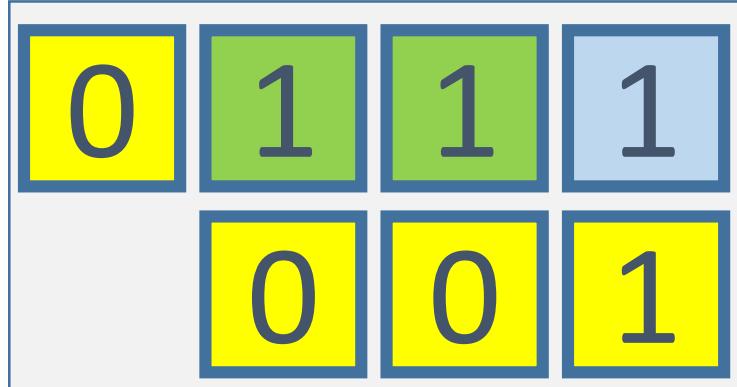
0	1	1	1
0	0	1	

Original packet B

Original packet A

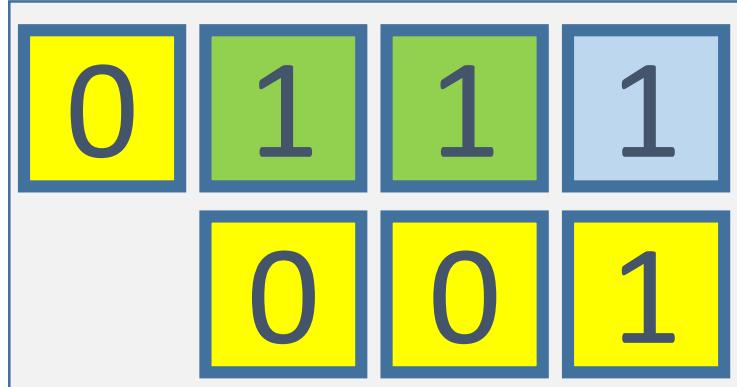
Original packet B

Decoding 3

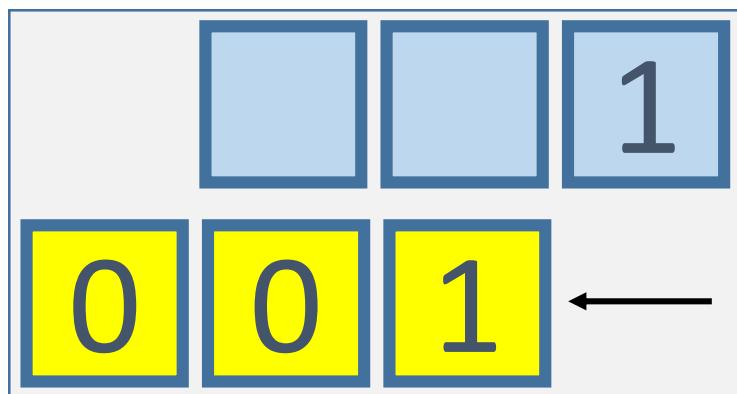


Simple reading

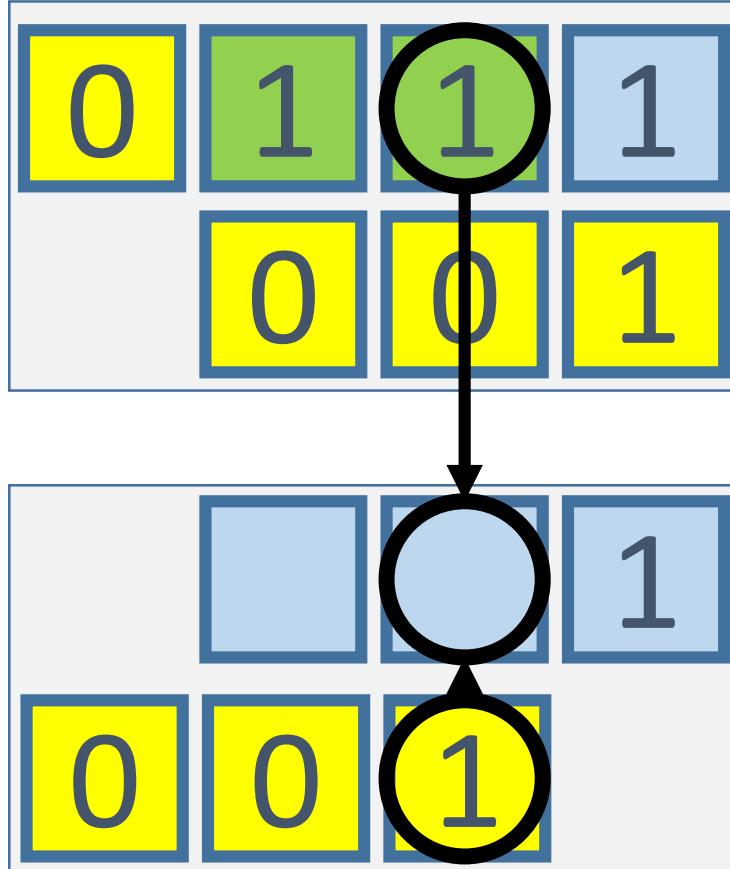
Decoding 3



Restore old shift

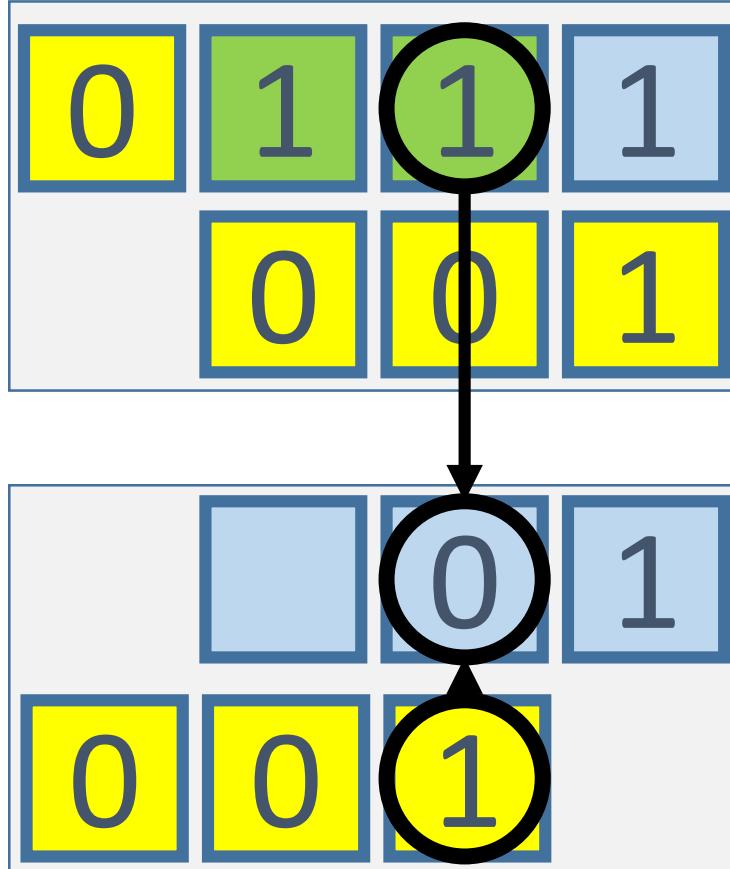


Decoding 3



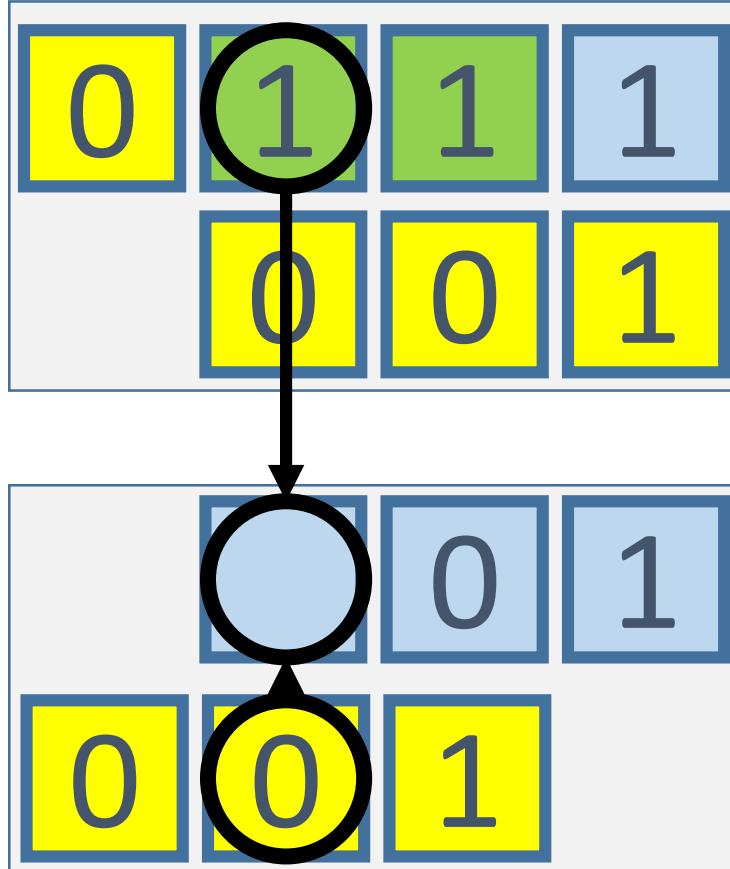
XOR: $1 \oplus 1$

Decoding 3



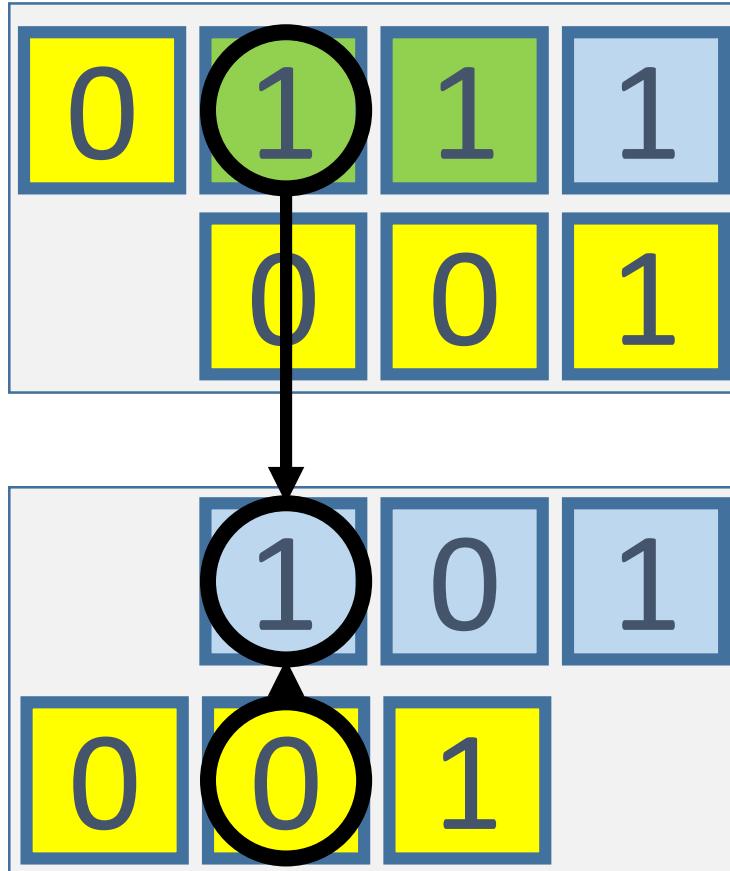
$$\text{XOR: } 1 \oplus 1 = 0$$

Decoding 3



XOR: $1 \oplus 0$

Decoding 3



$$\text{XOR: } 1 \oplus 0 = 1$$



Decoding 4

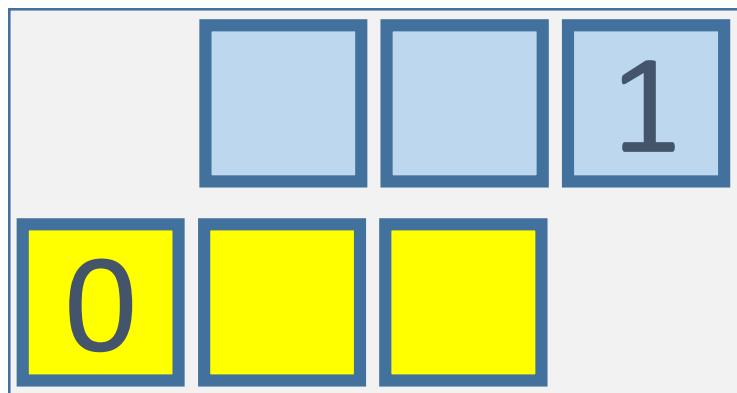
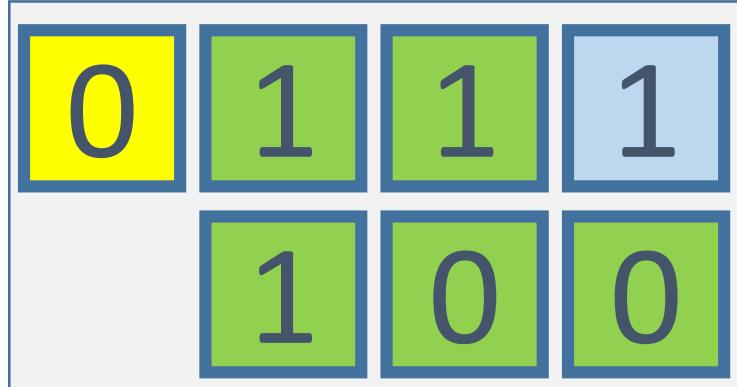
Coded packet $A \oplus B^* 2$

0	1	1	1
	1	0	0

Coded packet $A \oplus B$

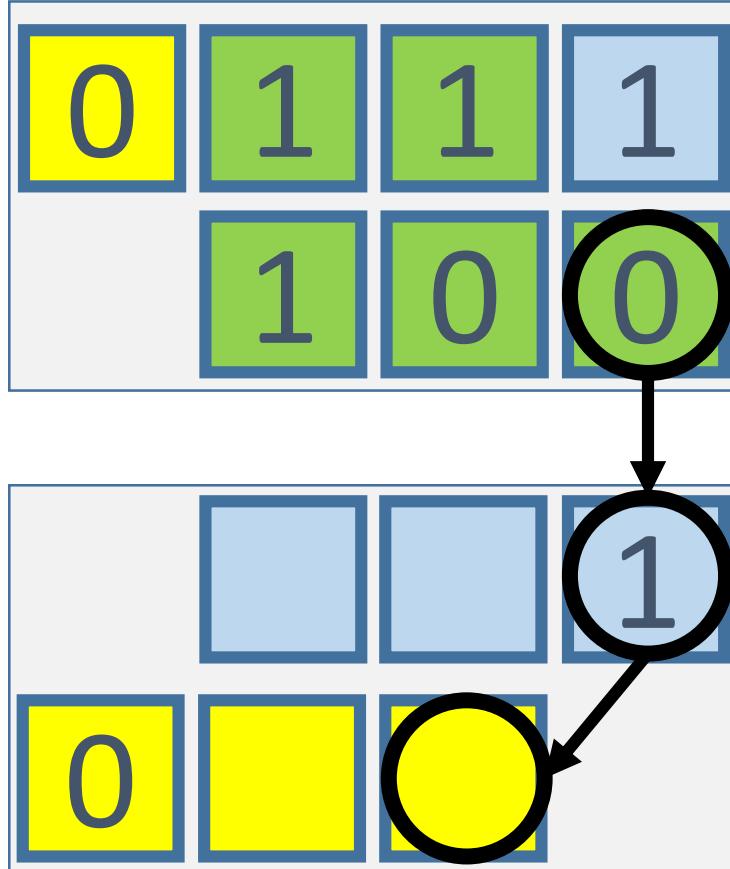
	1	0	0

Decoding 4



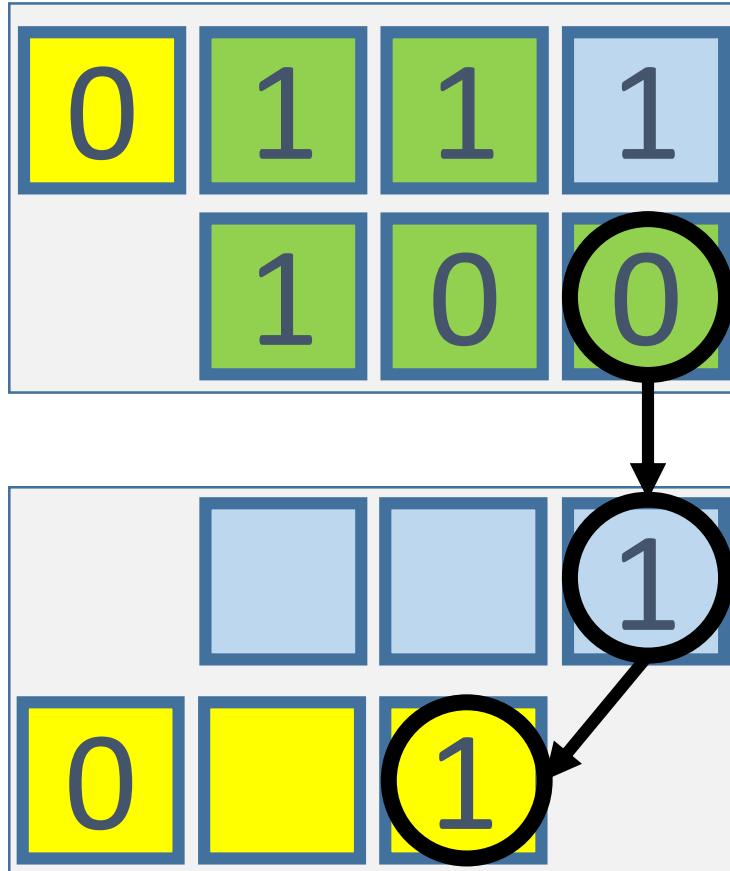
Simple reading

Decoding 4



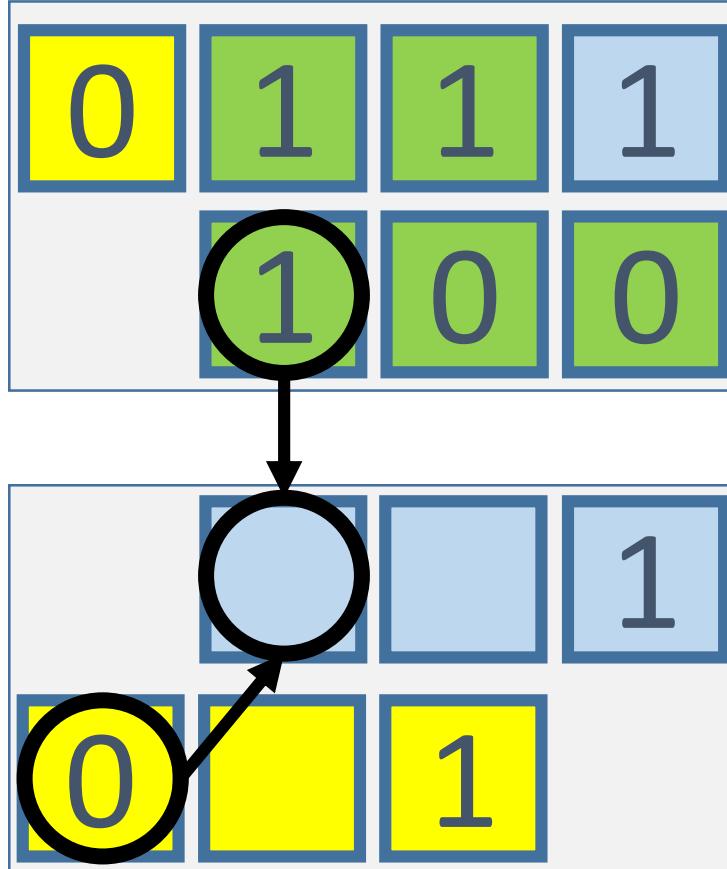
XOR: $0 \oplus 1$

Decoding 4



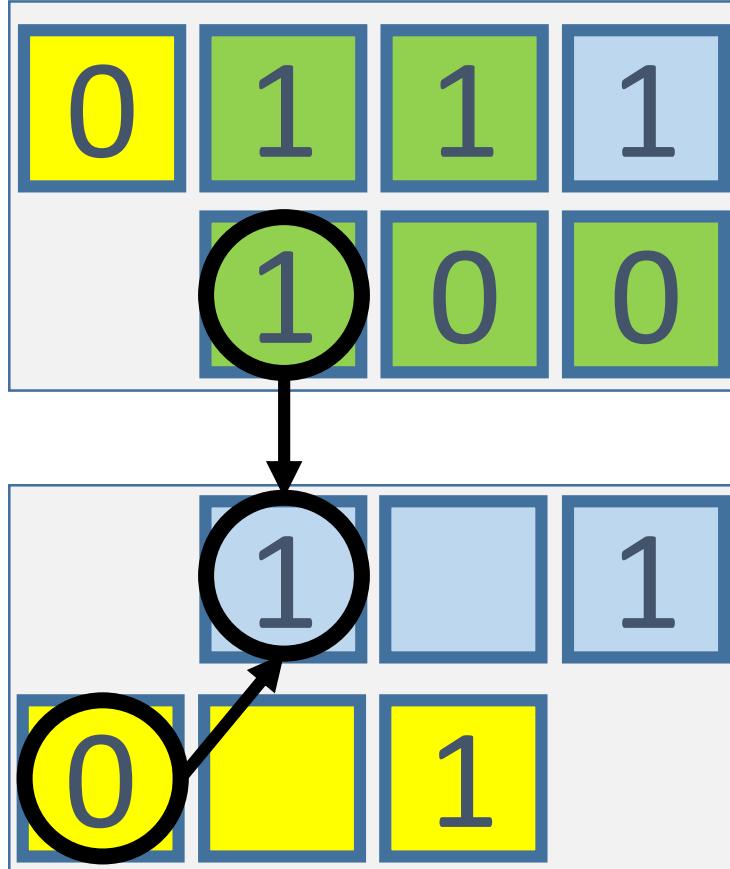
XOR: $0 \oplus 1$

Decoding 4



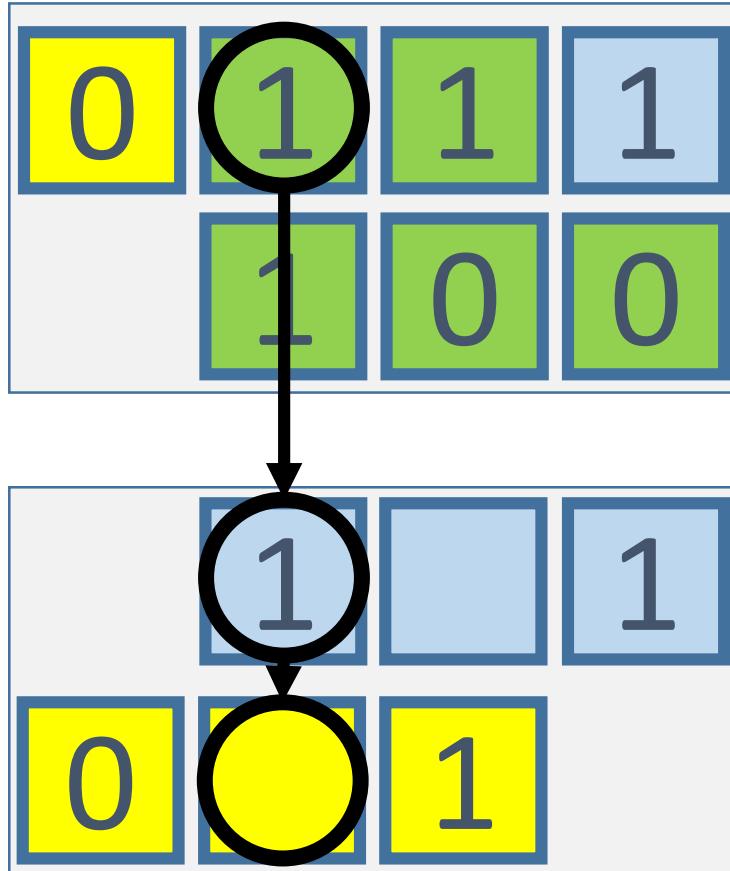
XOR: $1 \oplus 0$

Decoding 4



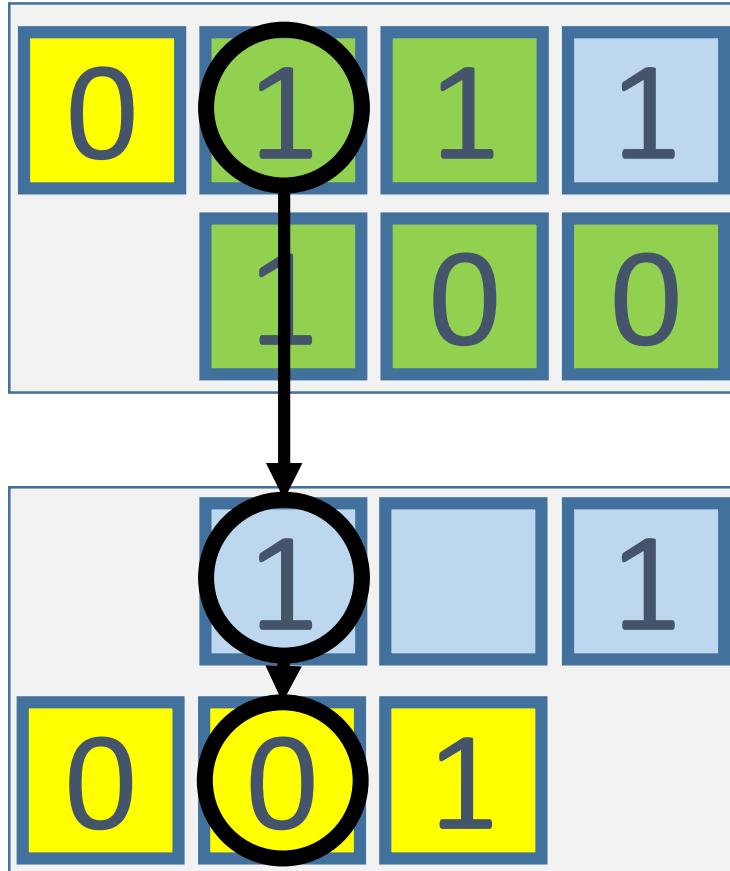
$$\text{XOR: } 1 \oplus 0 = 1$$

Decoding 4



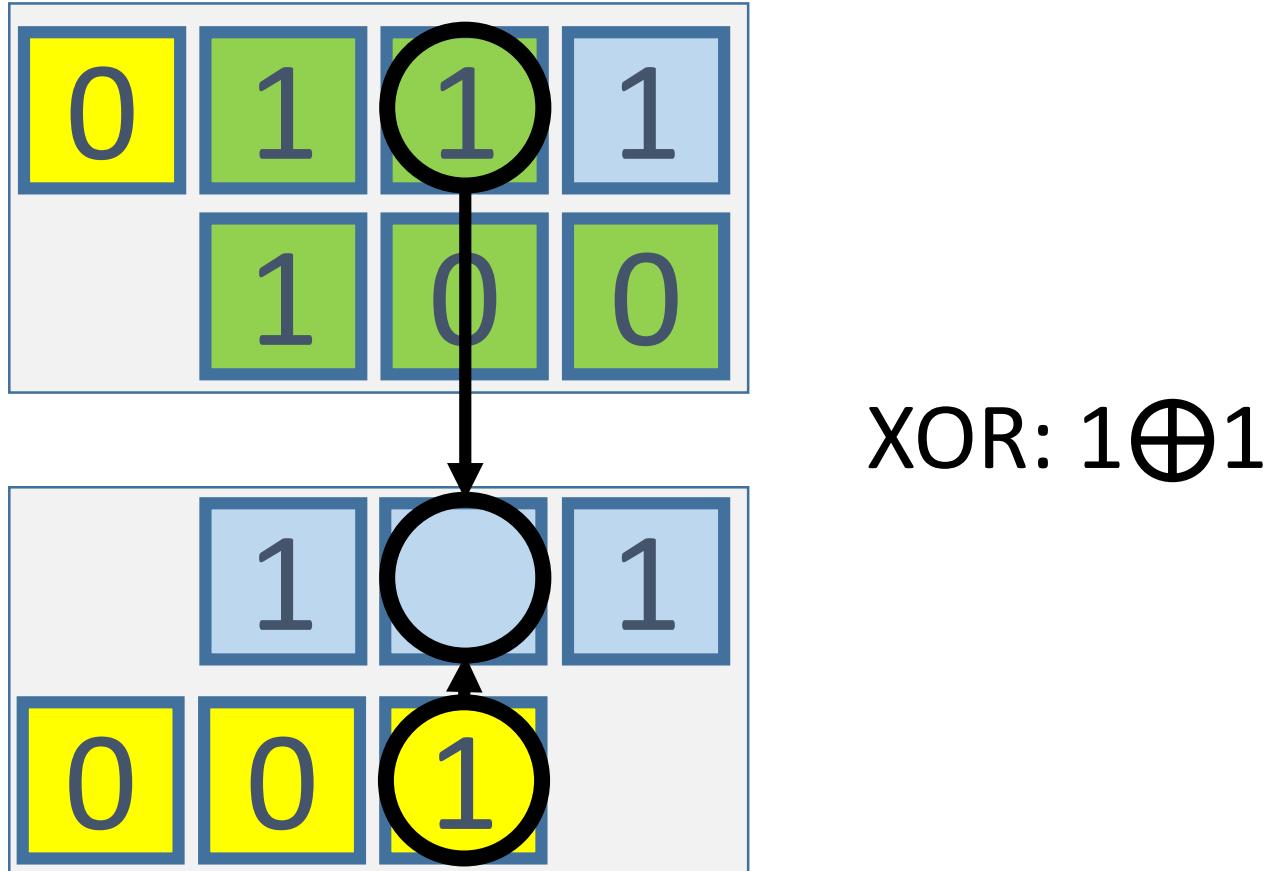
XOR: $1 \oplus 1$

Decoding 4

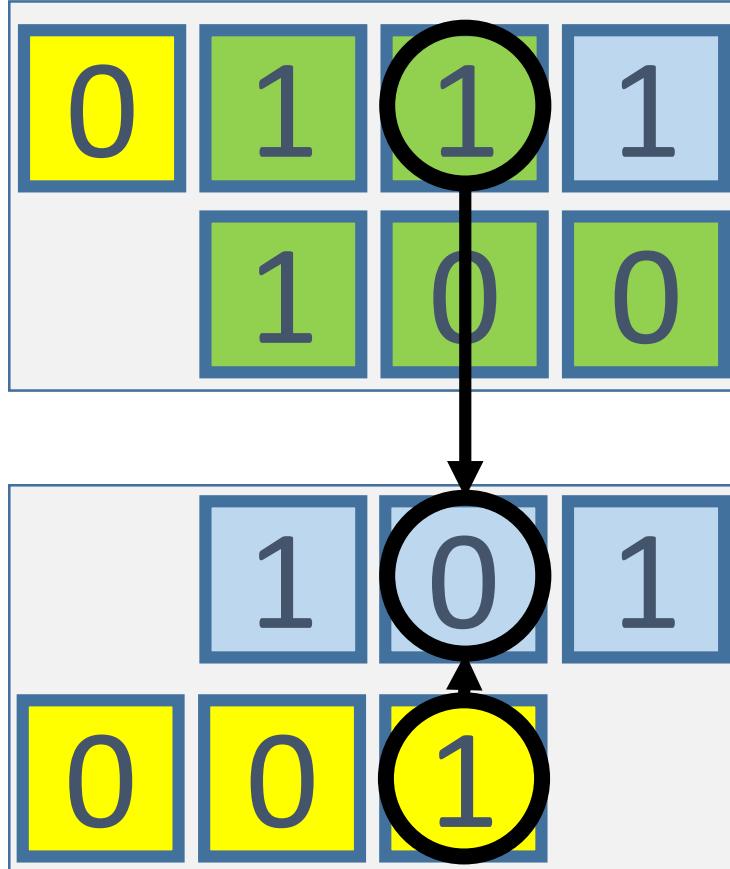


$$\text{XOR: } 1 \oplus 1 = 0$$

Decoding 4



Decoding 4



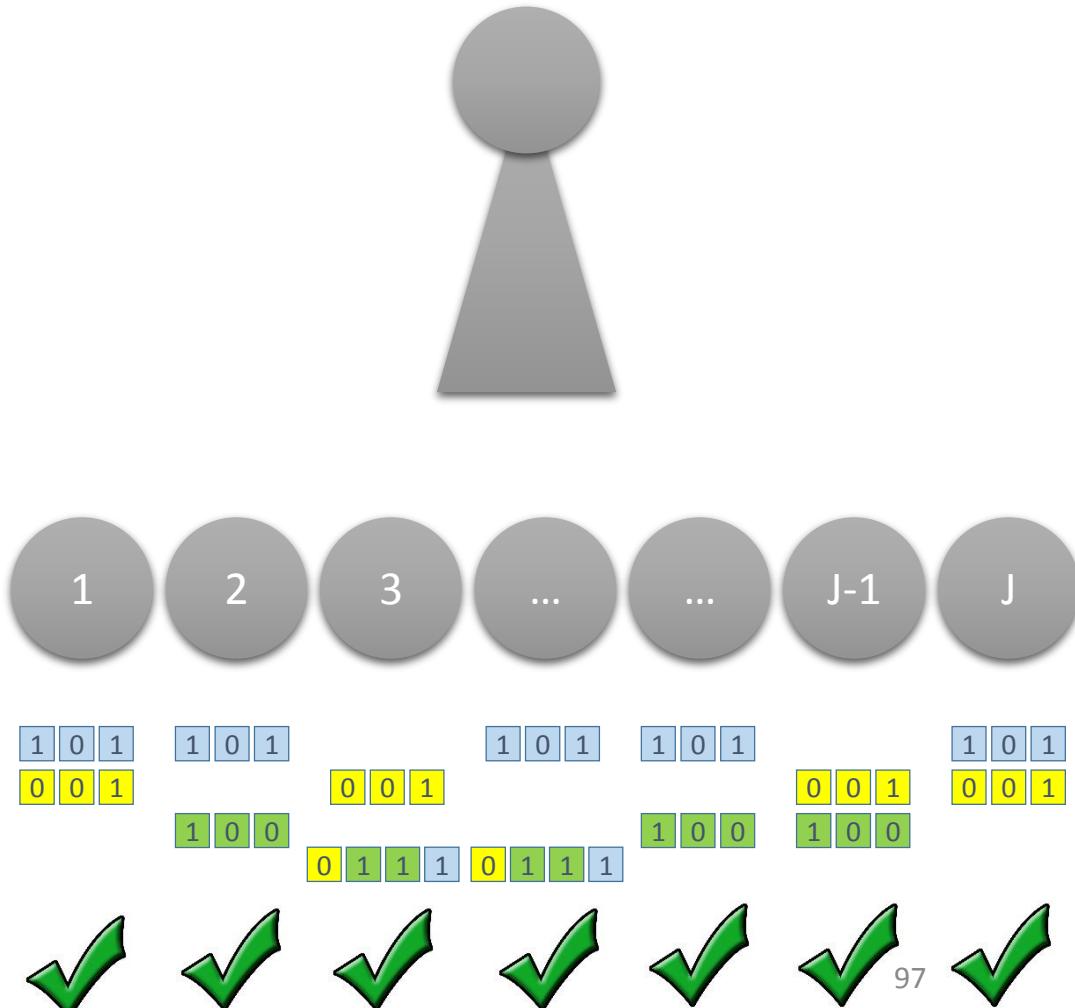
$$\text{XOR: } 1 \oplus 1 = 0$$



Architecture and Example

			A
			B
			XOR coded

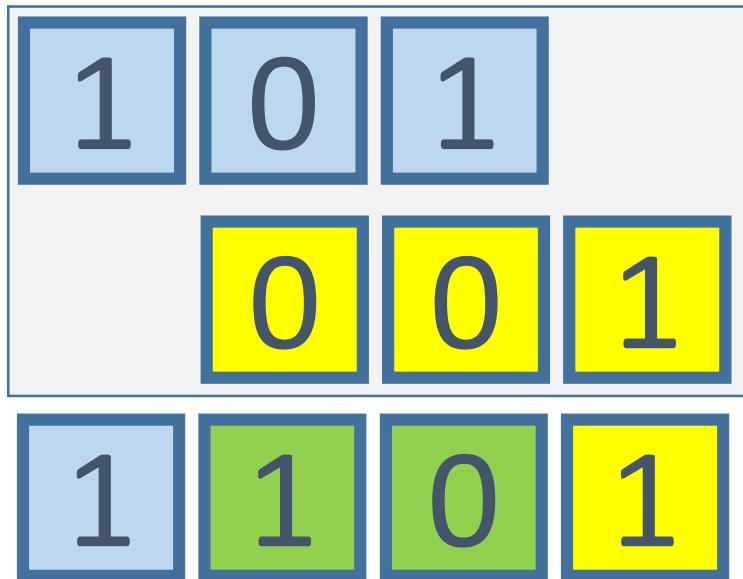
- Assuming one node broadcasting information to several nodes over error-prone medium
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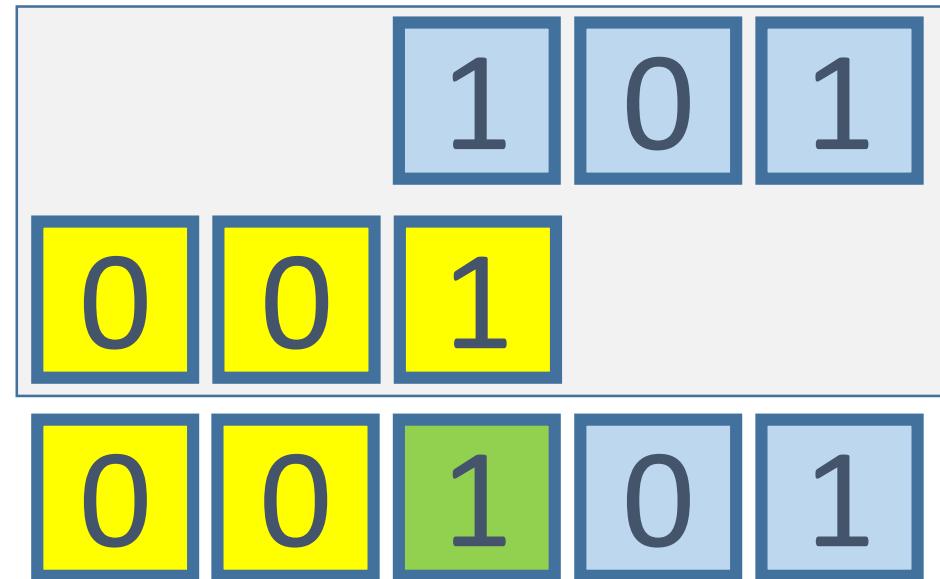
Overhead consideration

- For packets with B bits and S shift bits, the overhead O is simply S/B

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)

Network Coding in the ISO/OSI Context

Where is network coding located?

Application Layer

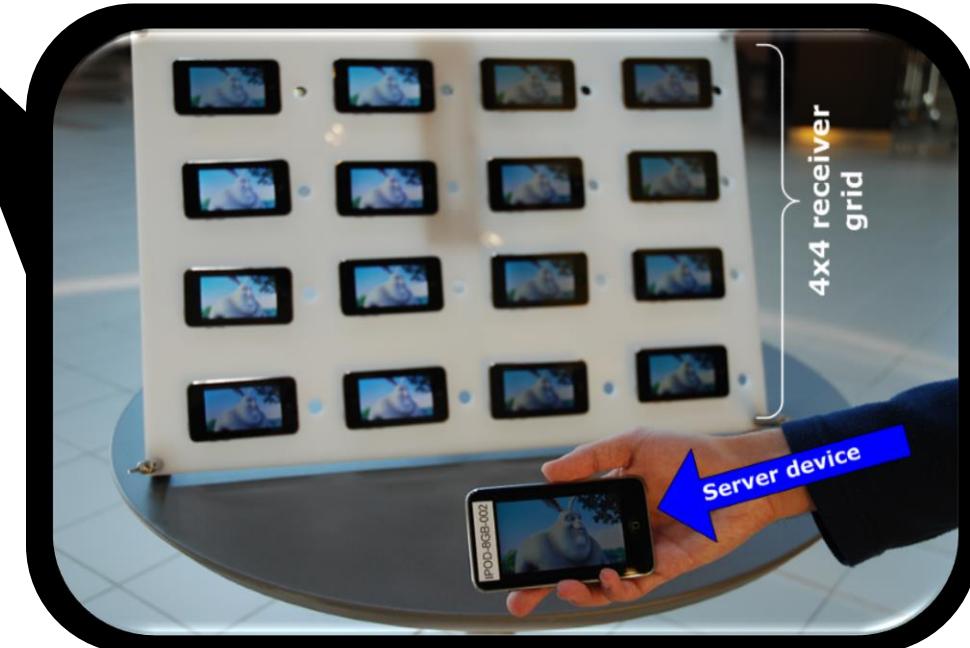
Transport Layer

Network Layer

Data Link Layer

Physical Layer

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



Where is network coding located?

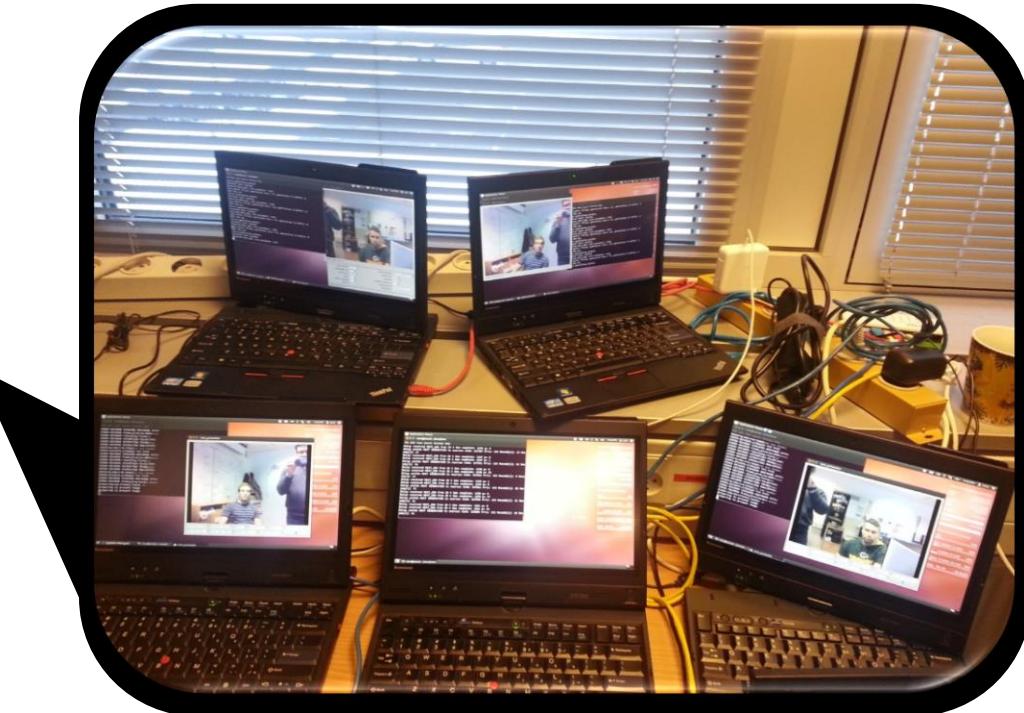
Application Layer

Transport Layer

Network Layer

Data Link Layer

Physical Layer



Where is network coding located?

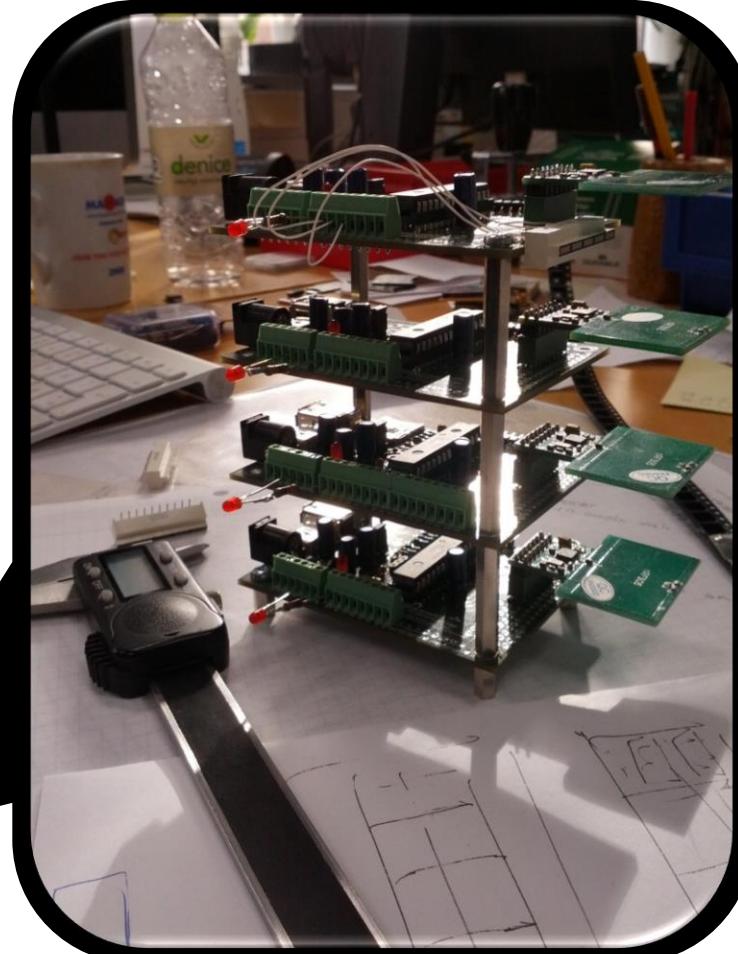
Application Layer

Transport Layer

Network Layer

Data Link Layer

Physical Layer



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

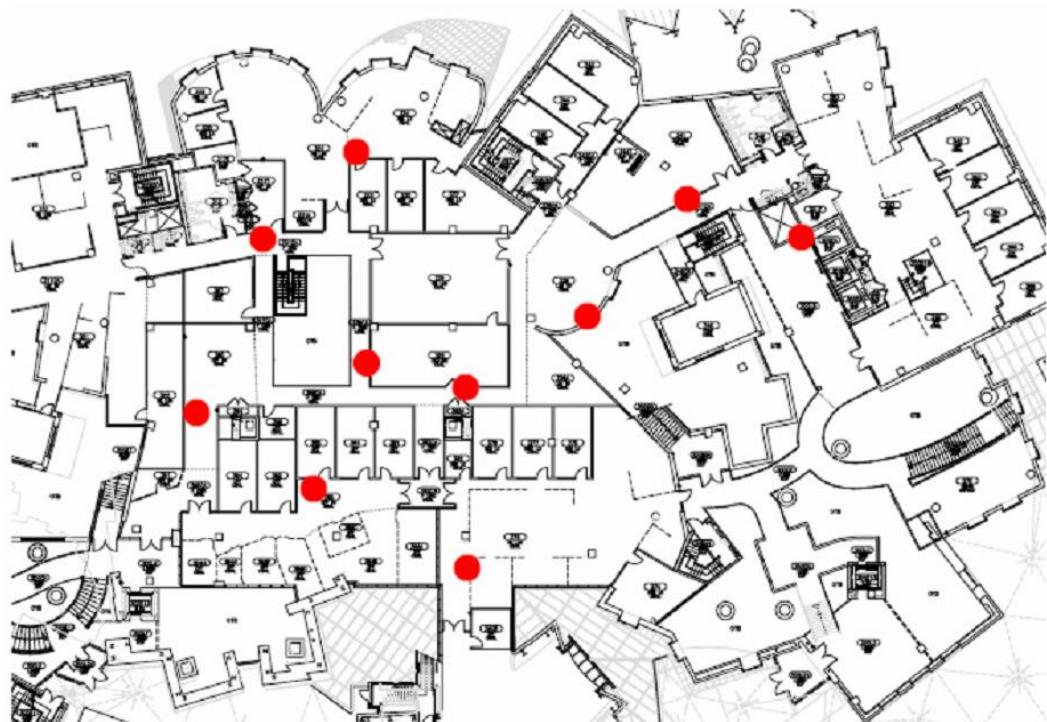


Figure 7—Node locations for one floor of the testbed.

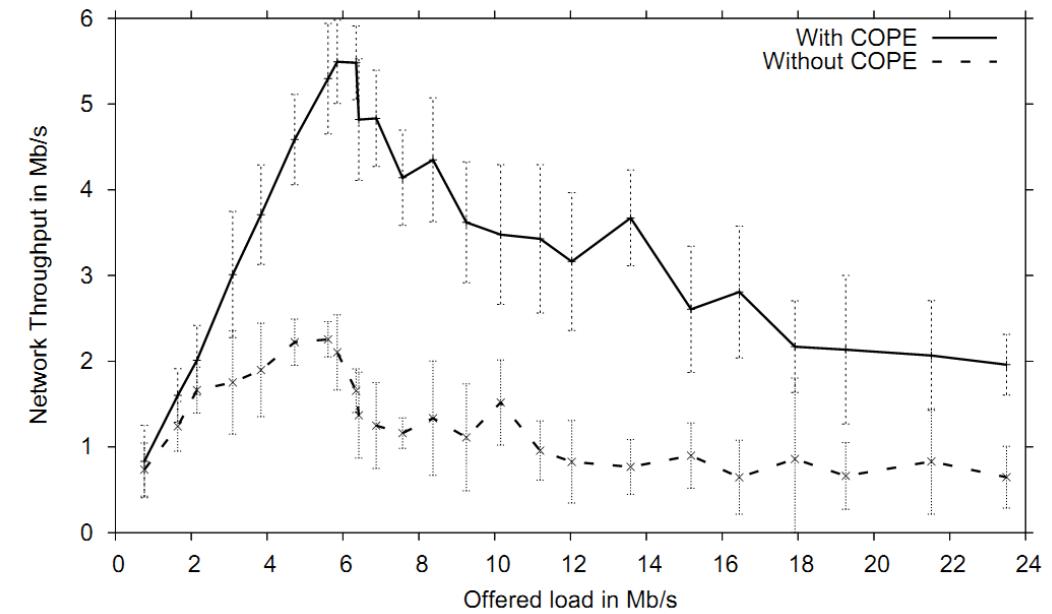


Figure 12—COPE can provide a several-fold (3-4x) increase in the throughput of wireless Ad hoc networks. Results are for UDP flows with randomly picked source-destination pairs, Poisson arrivals, and heavy-tail size distribution.

- 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

Wireless Mesh



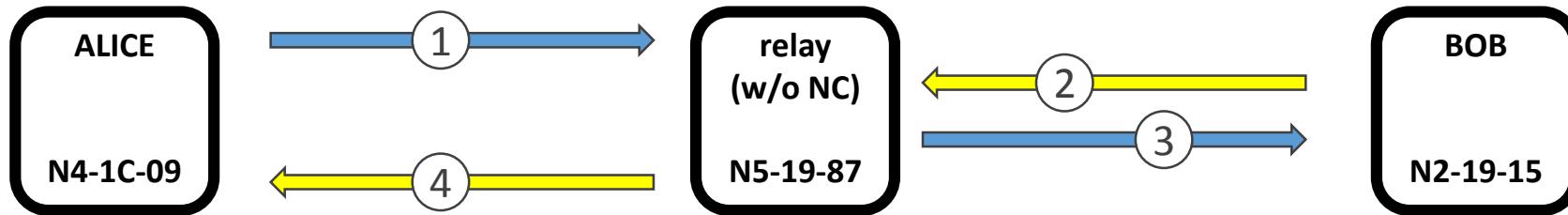
Foto: Torsten Proß, Jeibmann Photographik

CATWOMAN (2011)

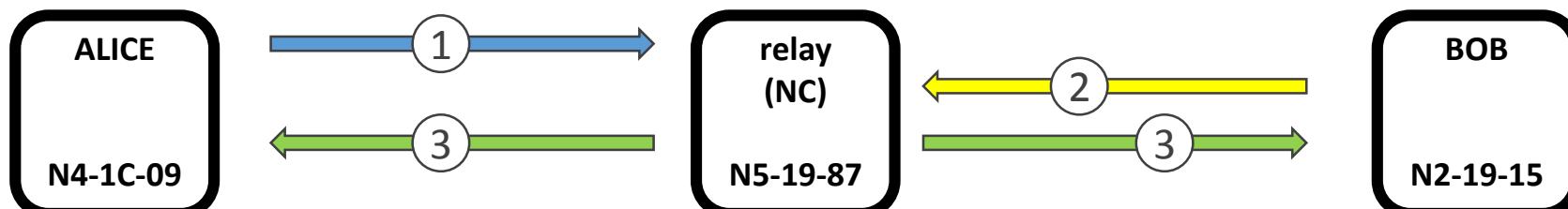
- Multihop network based on BATMAN routing (draft RFC)
- Implementation of network coding on real WiFi access points
- Multi hop
- Part of Linux Kernel 3.10



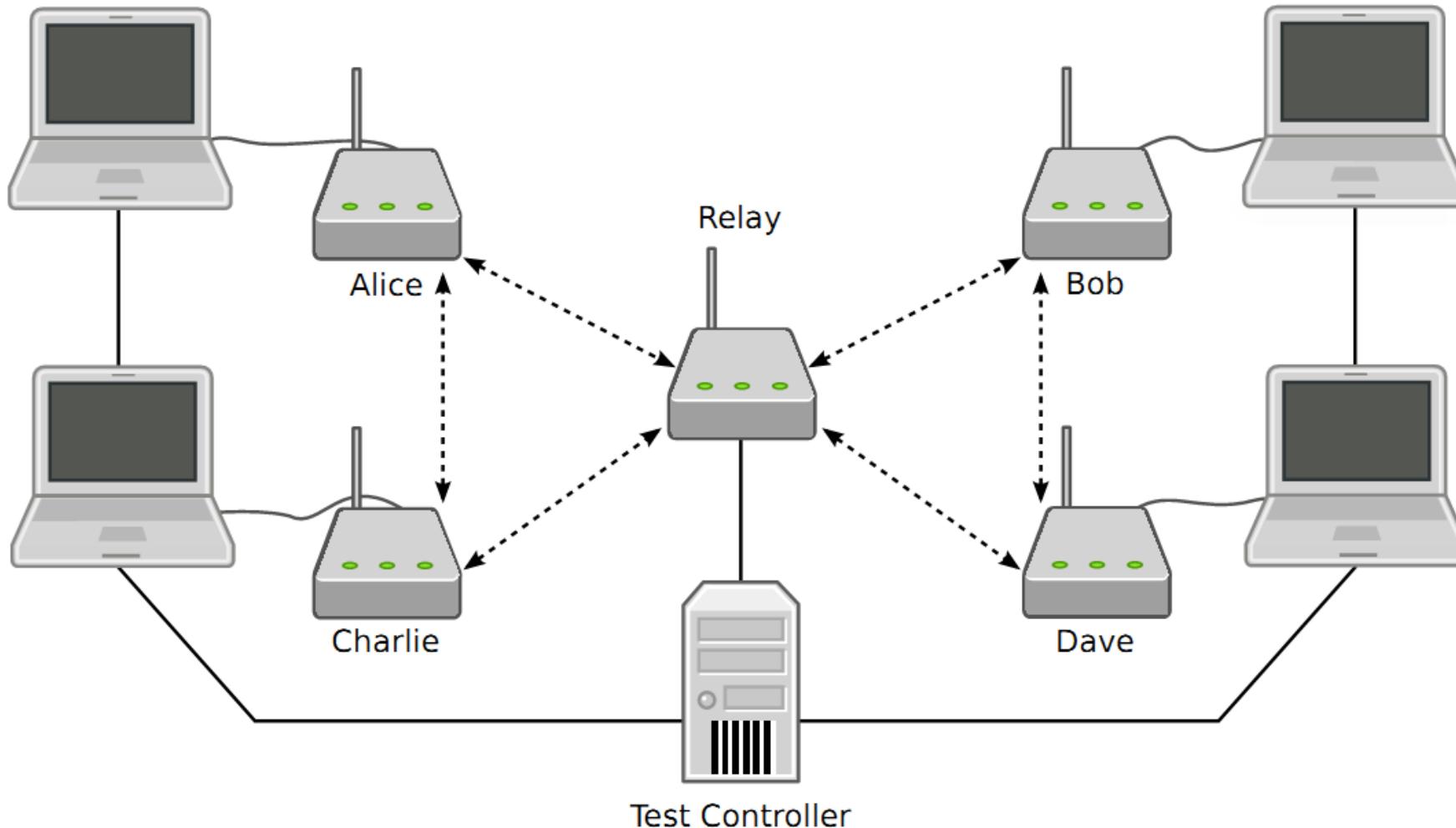
CATWOMAN: Scenarios under Investigation



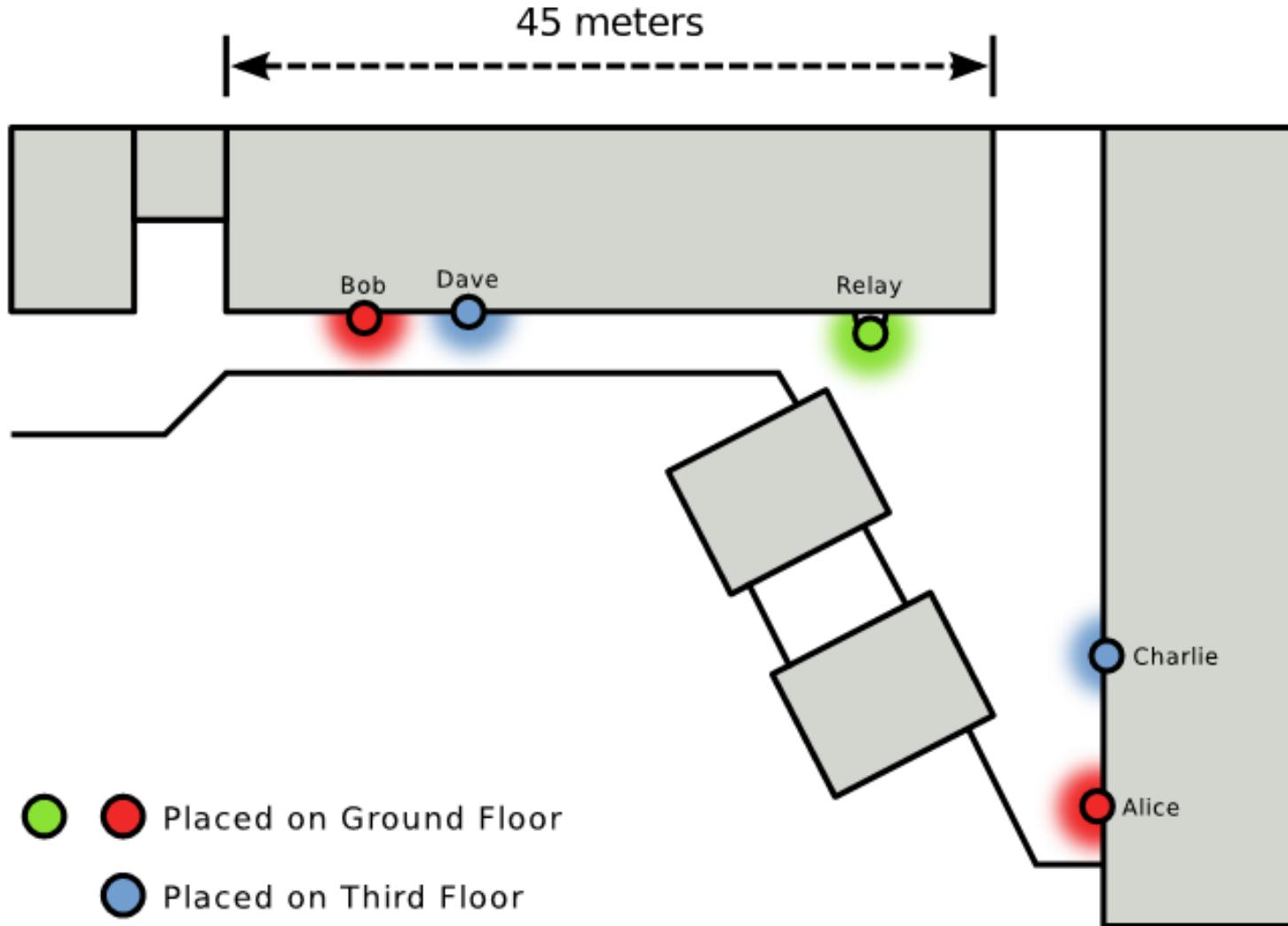
- First Alice & Bob
- Later arbitrary networks



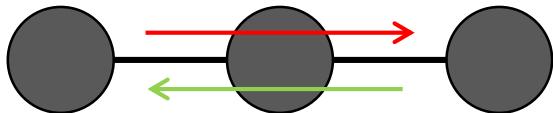
CATWOMAN: Testbed



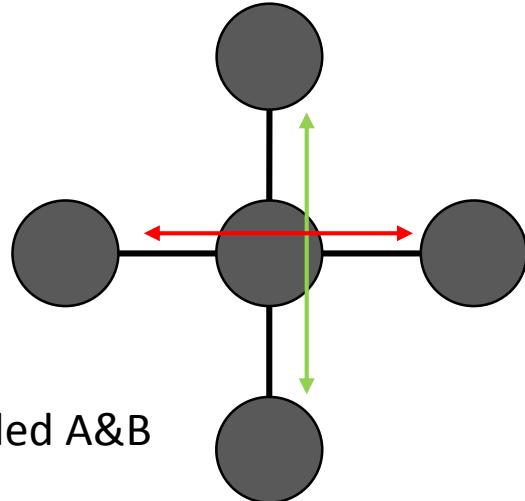
CATWOMAN: Testbed Placement



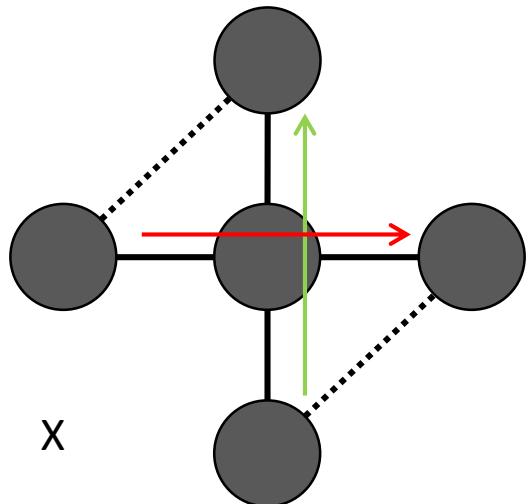
CATWOMAN Topologies



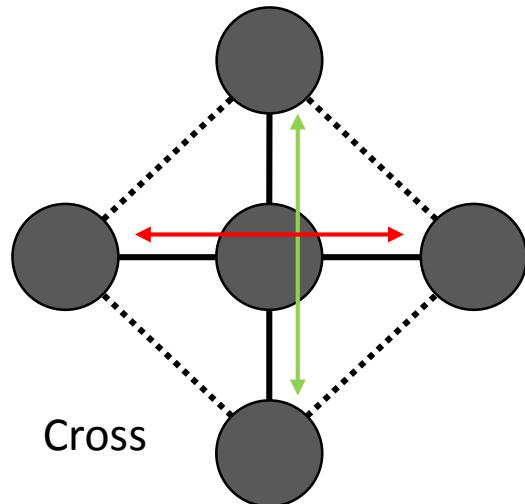
Alice and Bob



Extended A&B



X



Cross

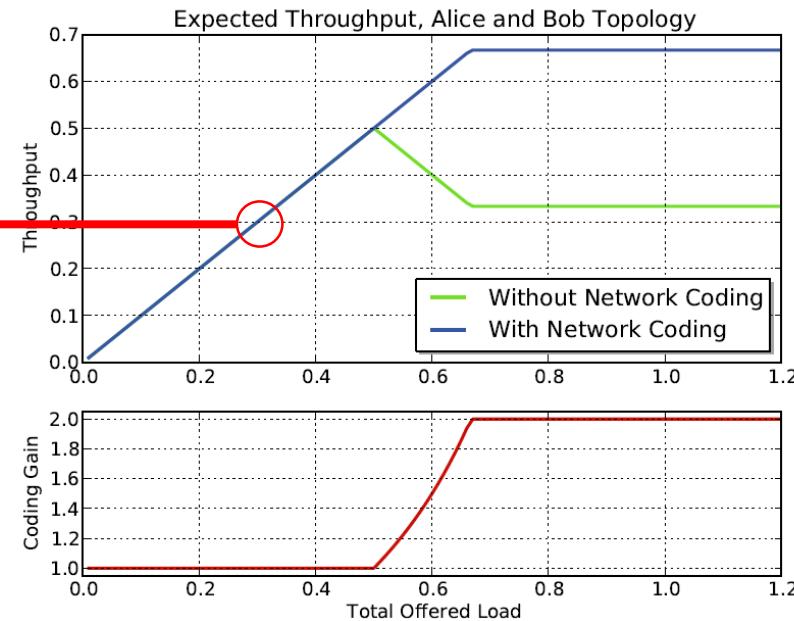
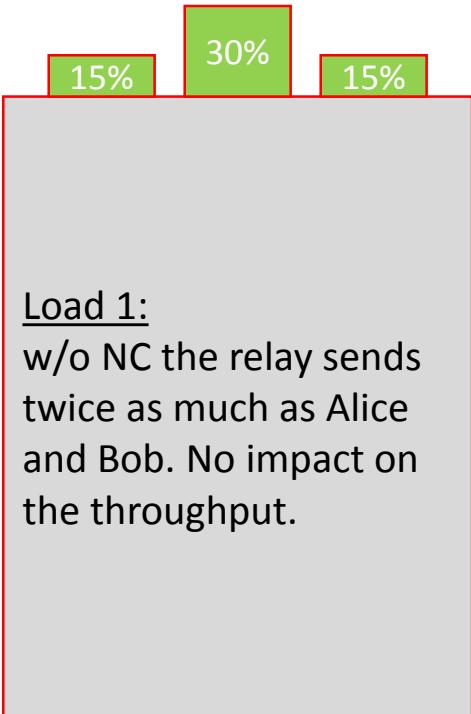
- Throughput [bit/s]
 - Bandwidth used
- Losses [%]
- Energy [J]
 - Activity level on send, receive, idle
 - CPU load
- Delay [s]

Model for Alice and Bob (symmetric TRAFFIC)

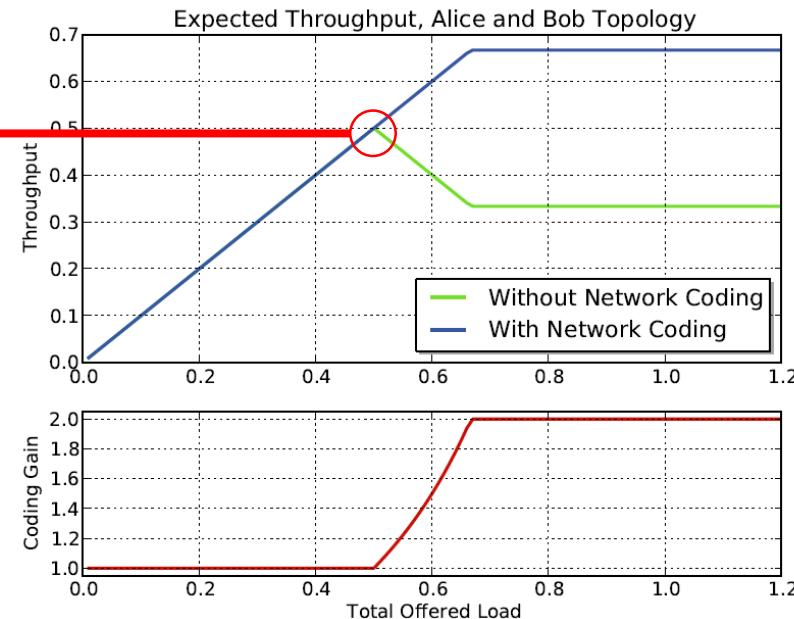
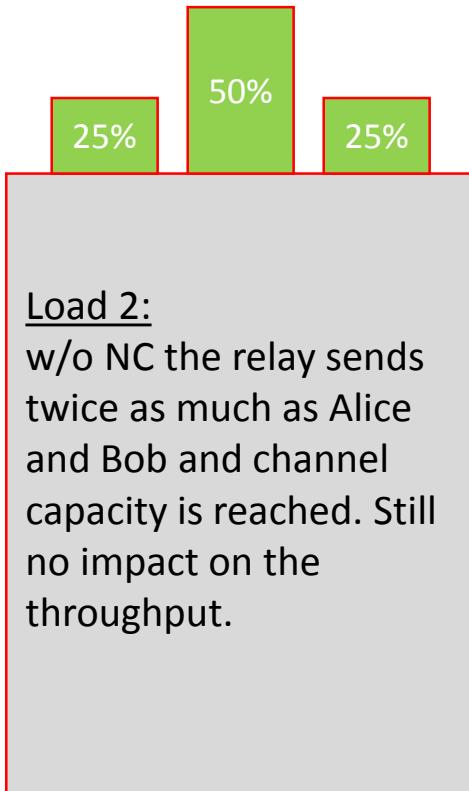
Assumption

- 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

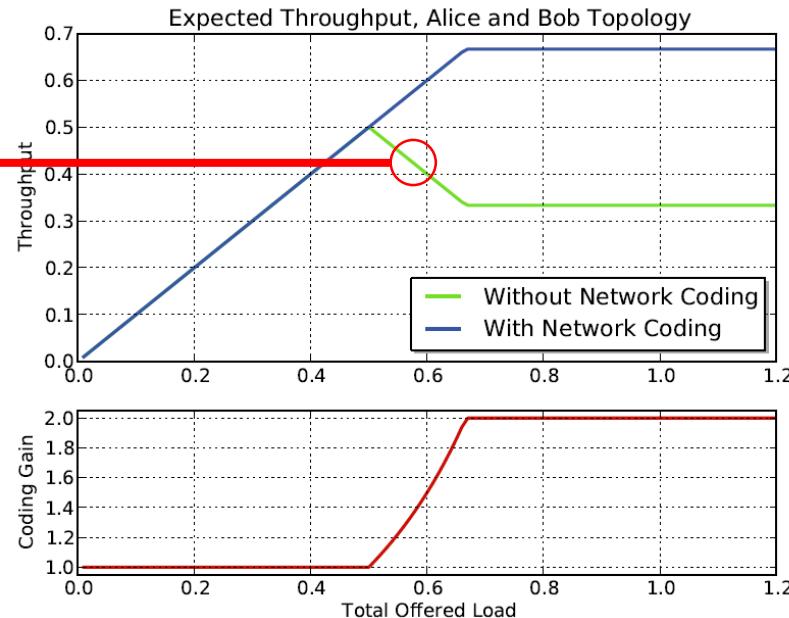
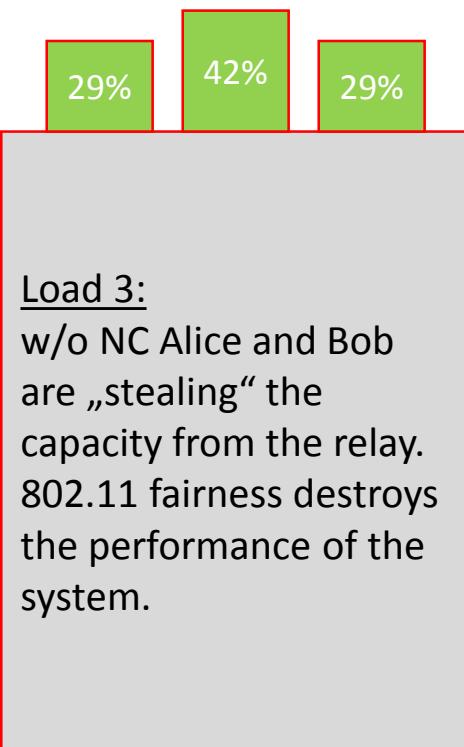
Throughput Model



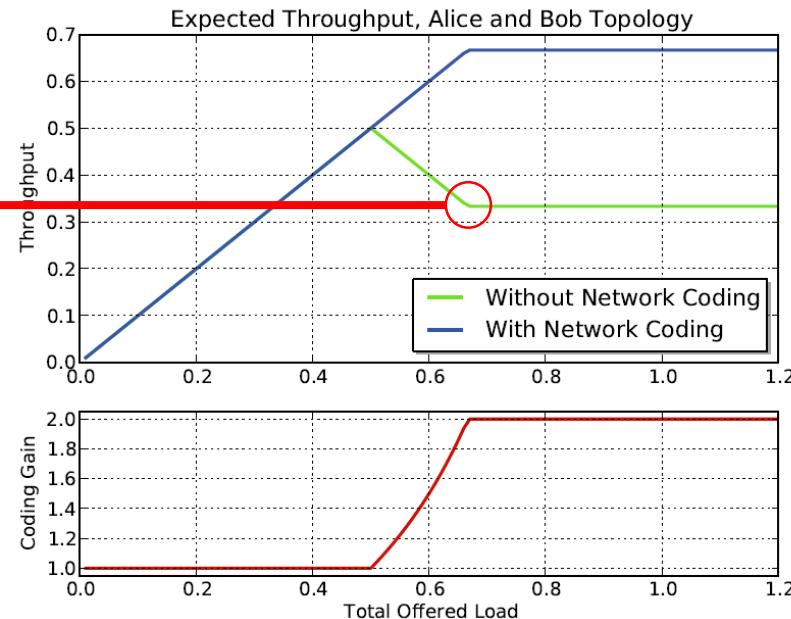
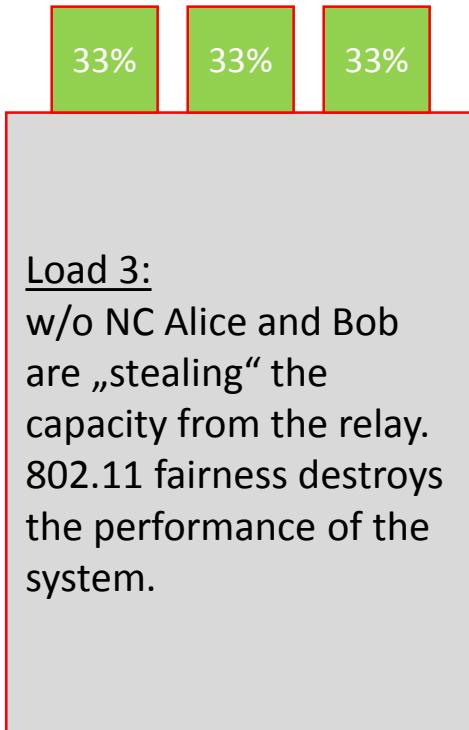
Throughput Model



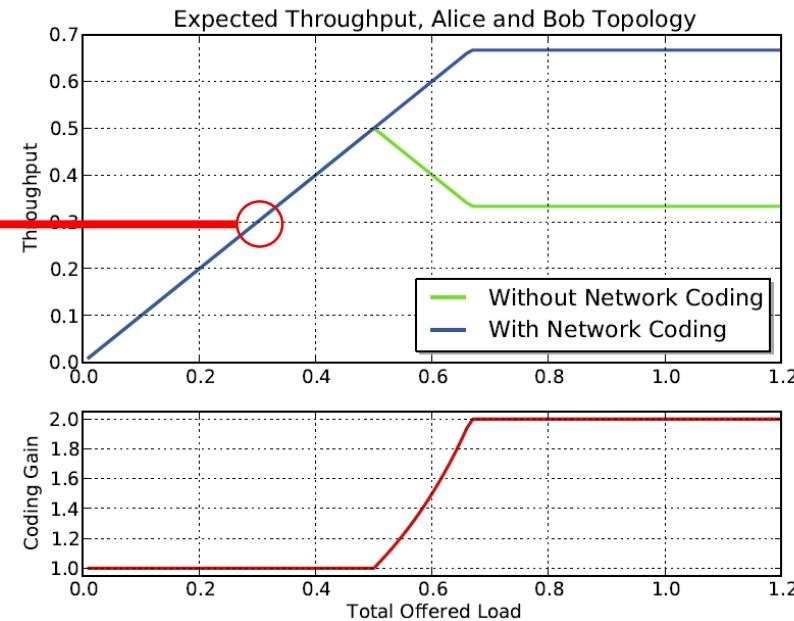
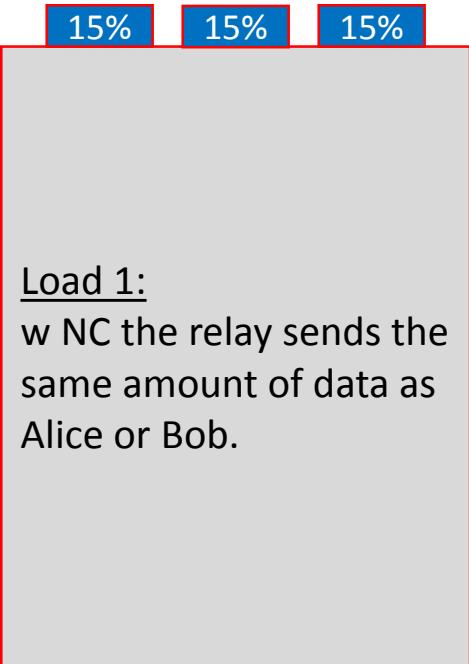
Throughput Model



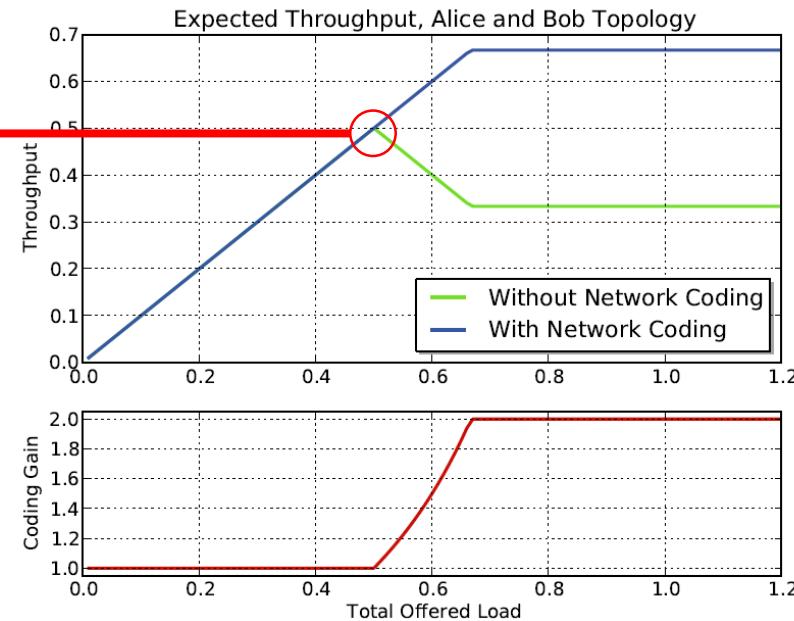
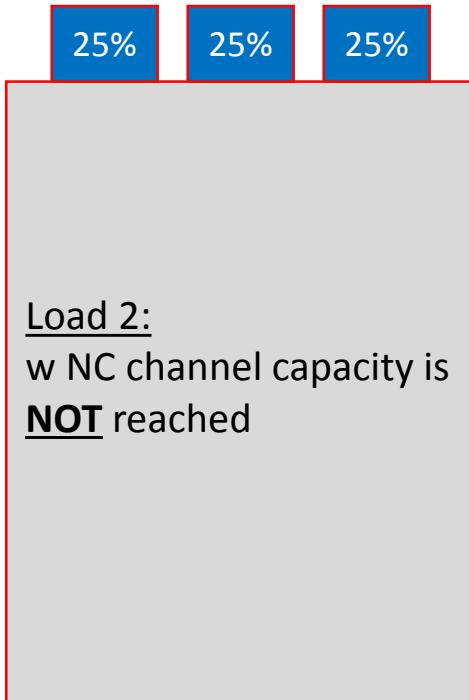
Throughput Model



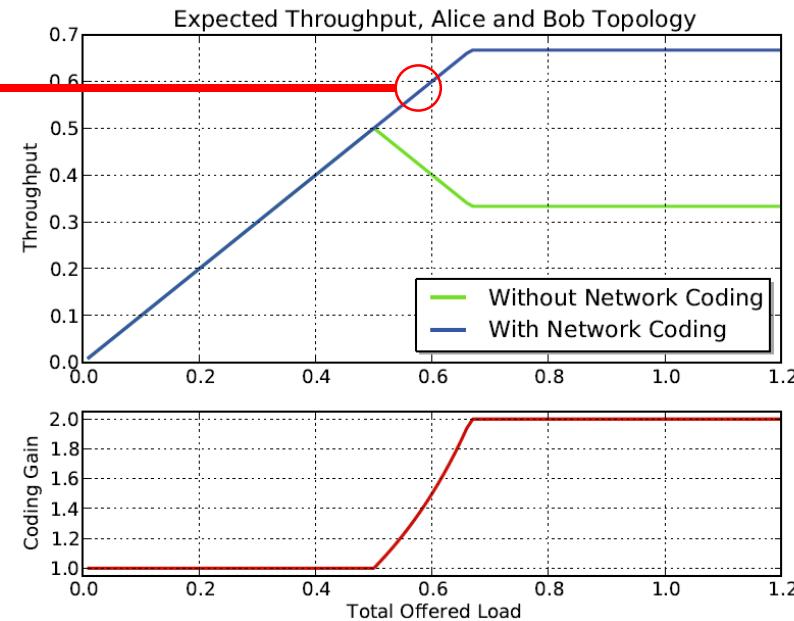
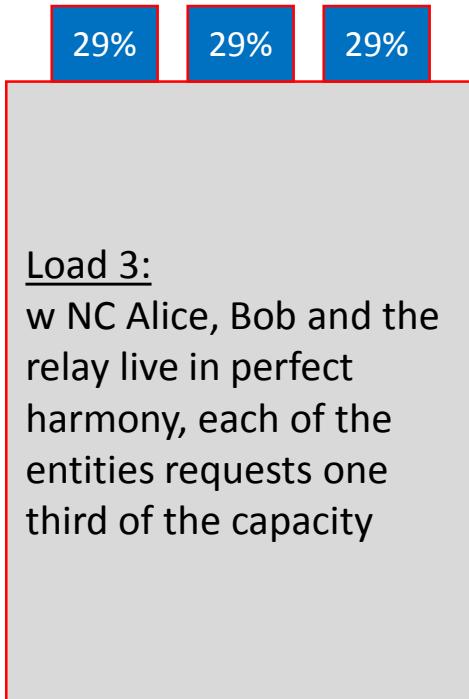
Throughput Model



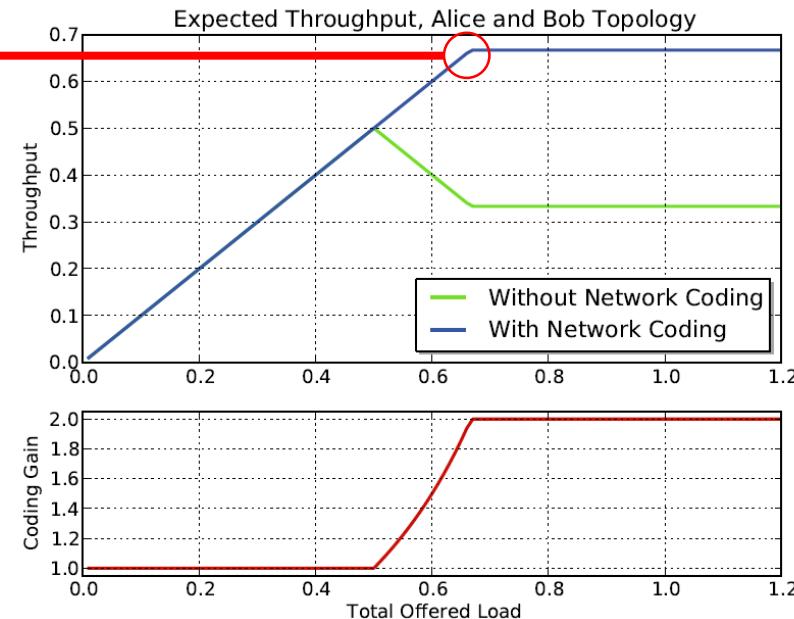
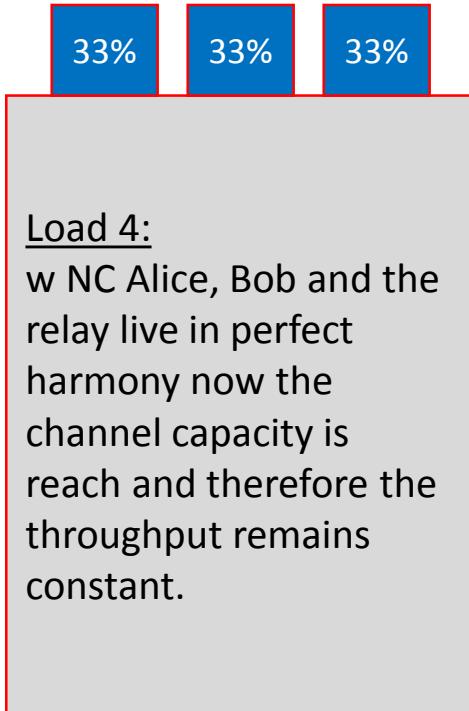
Throughput Model



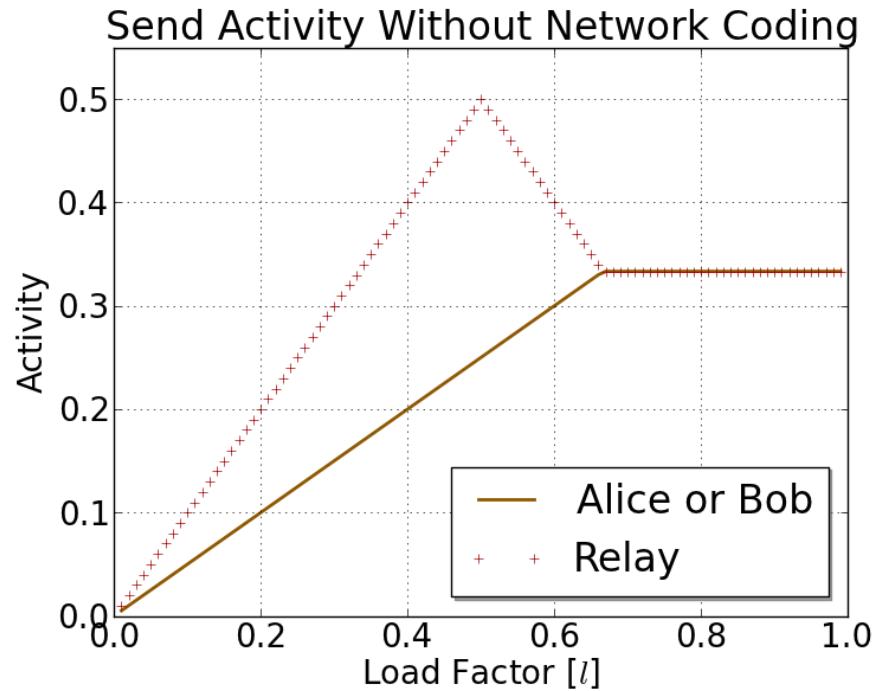
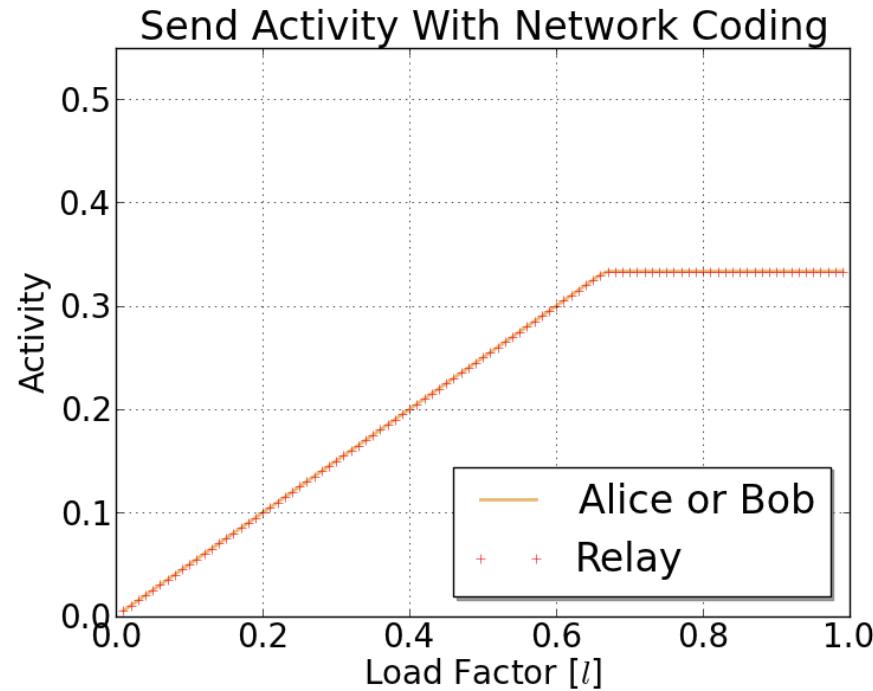
Throughput Model



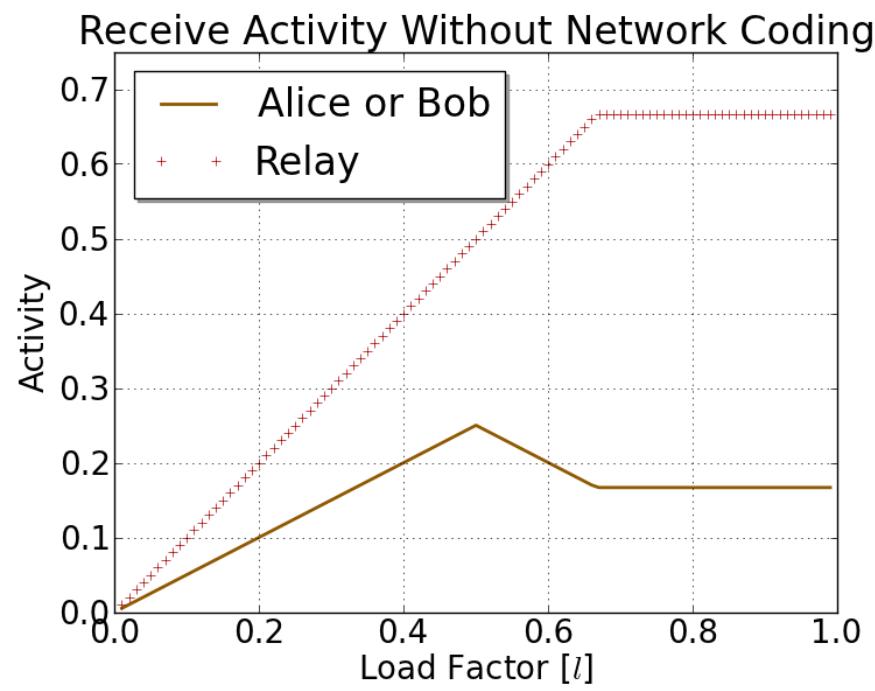
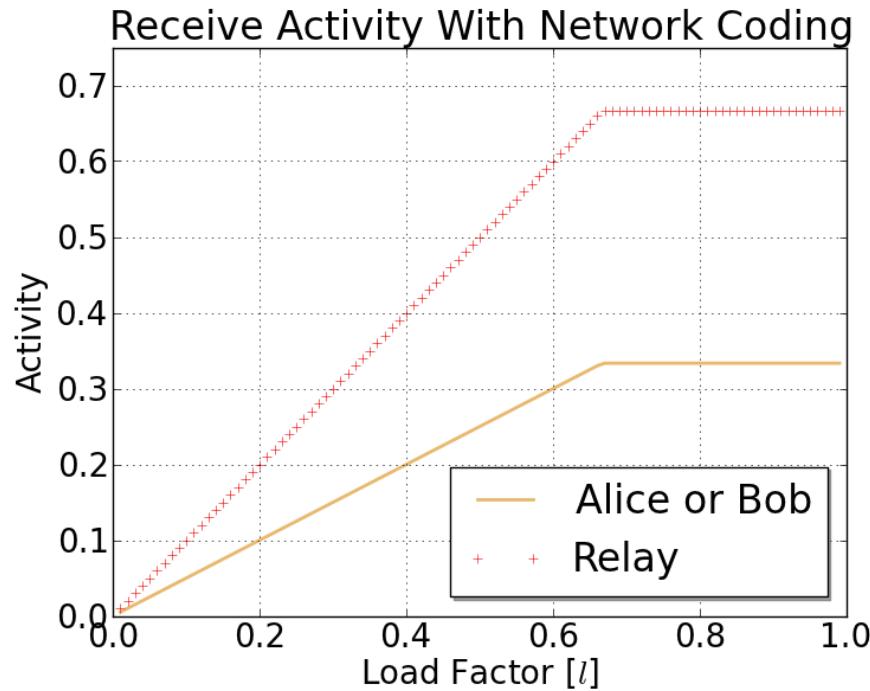
Throughput Model



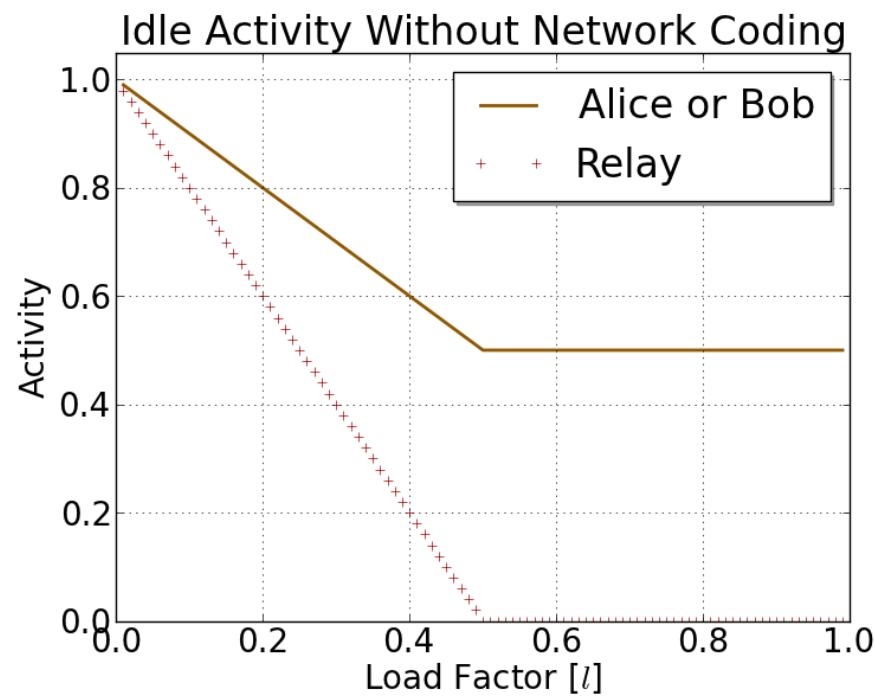
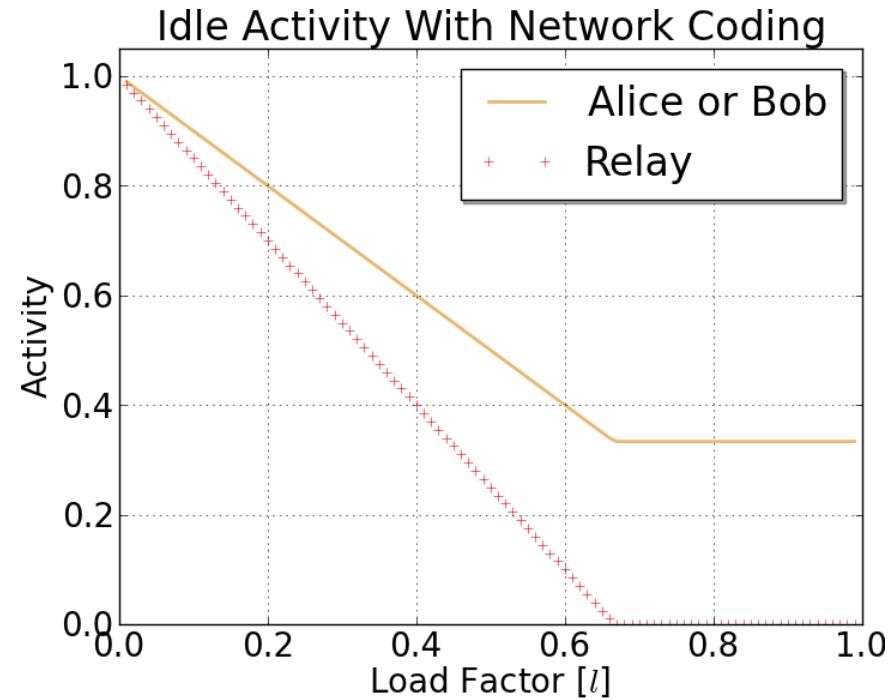
Send Activity Model



Receive Activity Model



Idle Activity Model



Activity Model

		Phase	I	II	III
		Load $[l]$	0-0.5	0.5-0.6	0.6-1.0
Send $[\alpha_s]$	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 $[\alpha_r]$	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

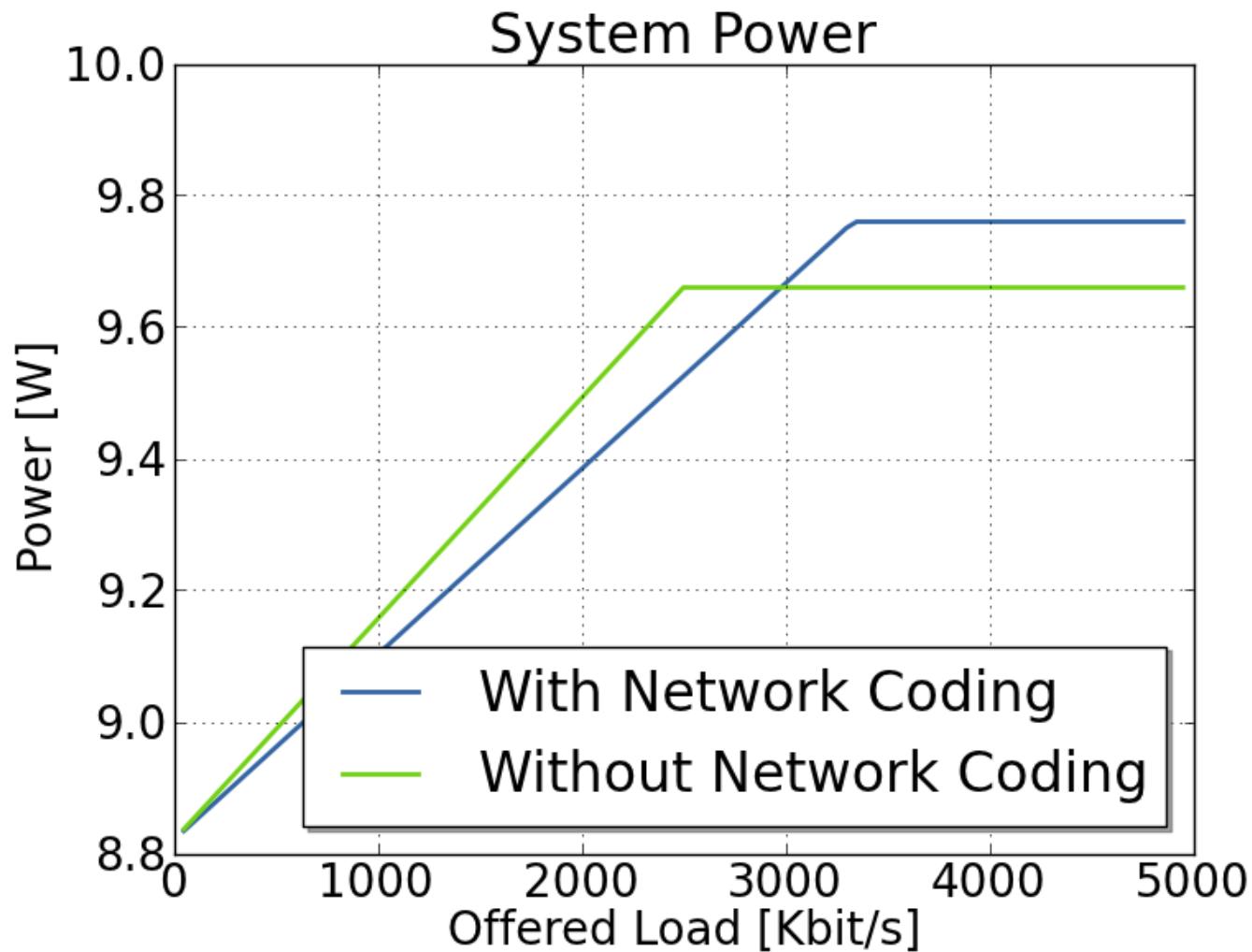
- In order to derive total power we sum up the product of the activity a and power level P of the individual states.

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

Power Model

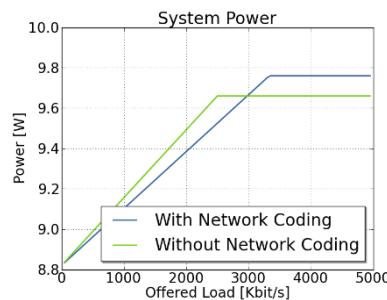
- Out of our measurements for WHITEBOX we derive:
 - Total power level sending: $P_{\text{send}} = 3.48 \text{ W}$
 - Total power level receiving: $P_{\text{send}} = 3.24 \text{ W}$
 - Total power level idle: $P_{\text{send}} = 2.94 \text{ W}$
- Later we assume a maximum capacity of the channel of 4.9 Mbit/s

Power Rate Model

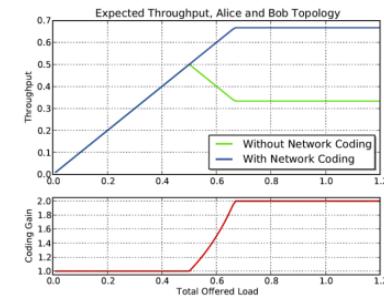


Energy Model

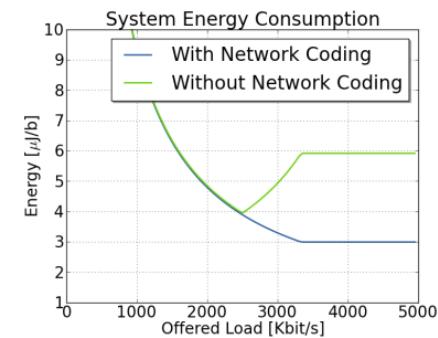
- $Energy = Power * Time$
- $Energy \text{ per bit} = \frac{Power}{Throughput} = \frac{Joule}{bit}$



:



=



power

throughput

energy/bit

Energy Model

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

