Review on the Model for Alice and Bob (symmetric TRAFFIC)

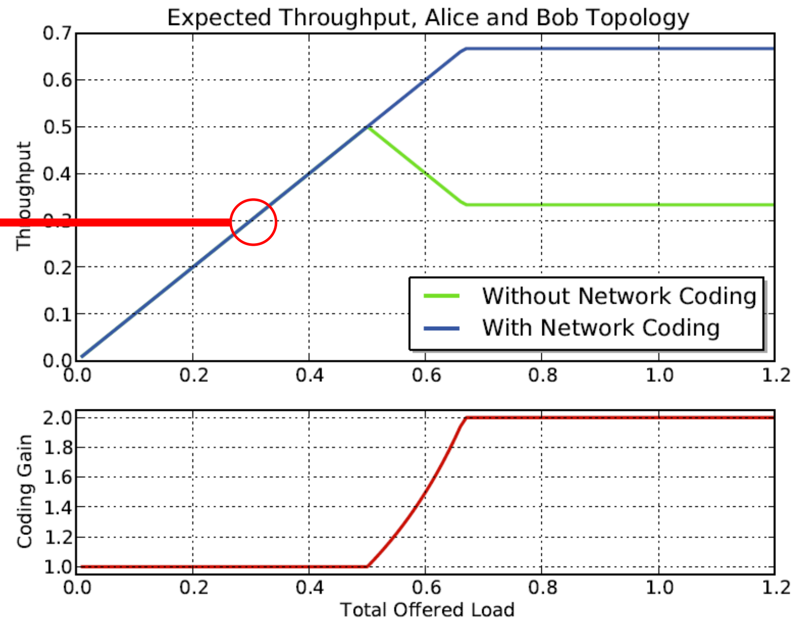
Assumption

- 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

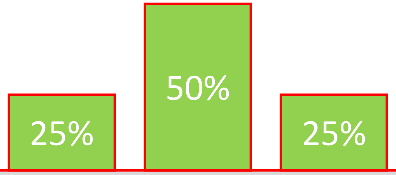
Throughput Model

15% 30% 15%

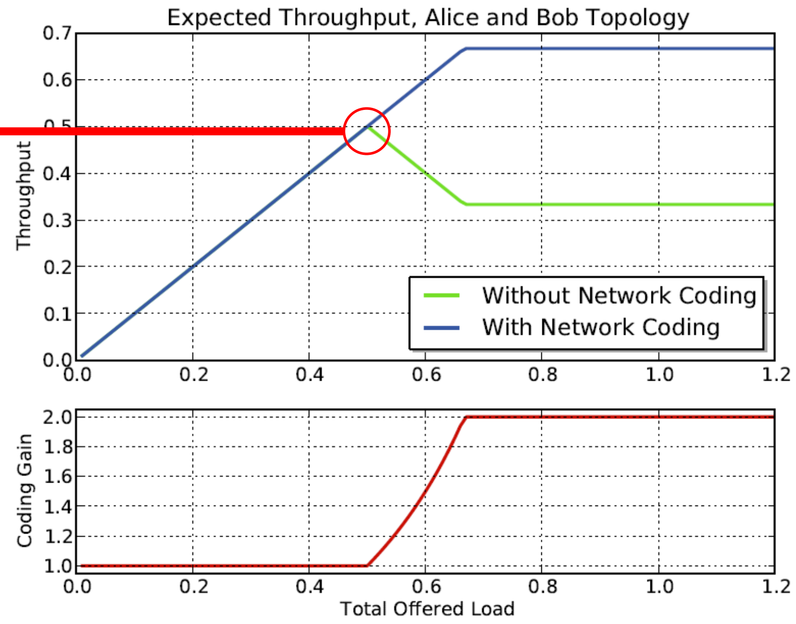
Load 1:
w/o NC the relay sends twice as much as Alice and Bob. No impact on the throughput.



Throughput Model



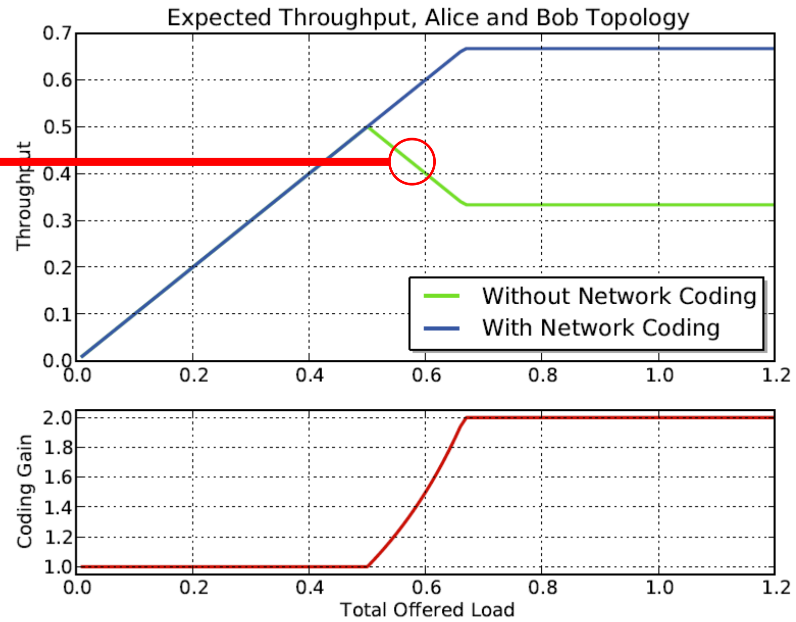
<u>Load 2:</u>
w/o NC the relay sends twice as much as Alice and Bob and channel capacity is reached. Still no impact on the throughput.



Throughput Model

29% 42% 29%

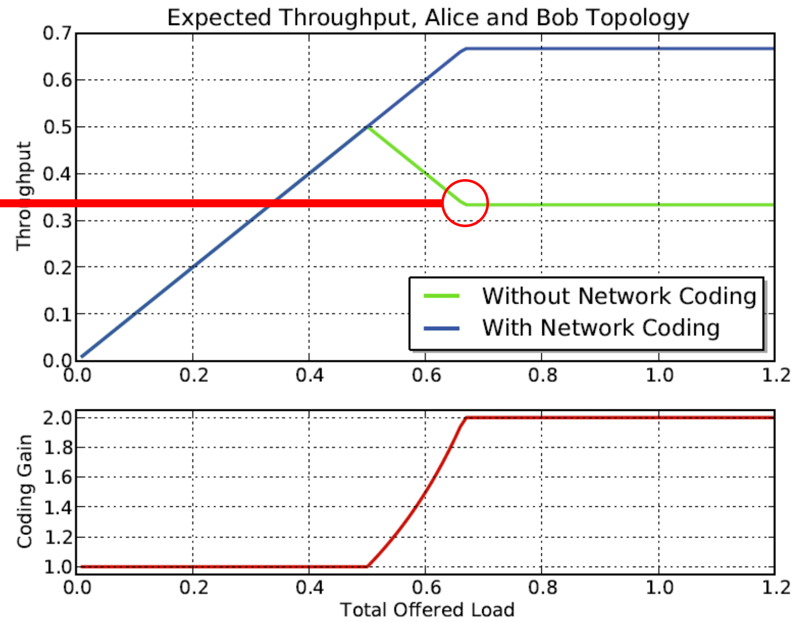
Load 3:
w/o NC Alice and Bob are „stealing“ the capacity from the relay. 802.11 fairness destroys the performance of the system.



Throughput Model

33% 33% 33%

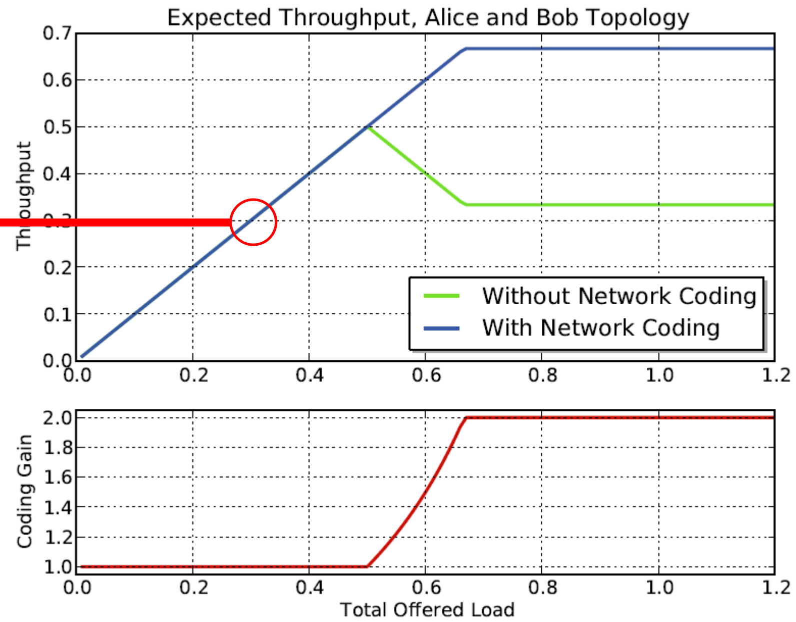
Load 3:
w/o NC Alice and Bob are „stealing“ the capacity from the relay. 802.11 fairness destroys the performance of the system.



Throughput Model

15% 15% 15%

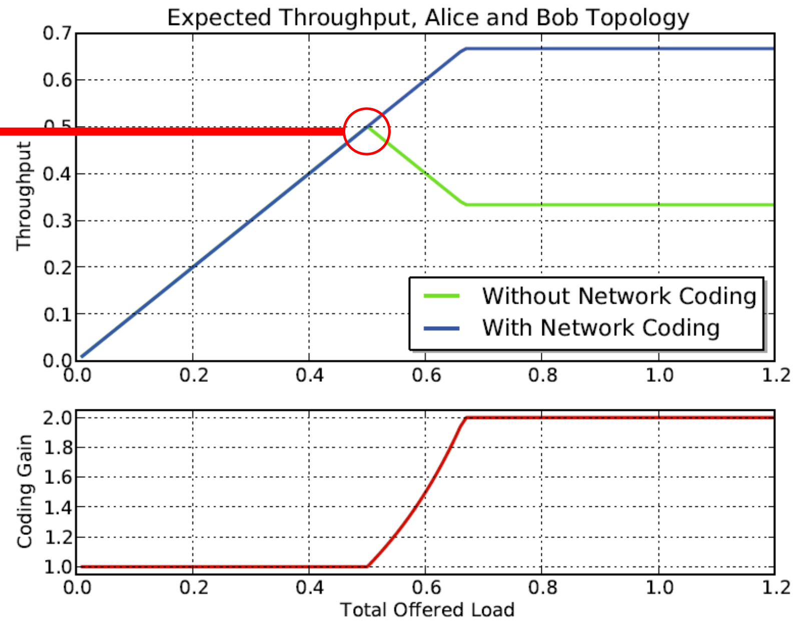
Load 1:
w NC the relay sends the same amount of data as Alice or Bob.



Throughput Model

25% 25% 25%

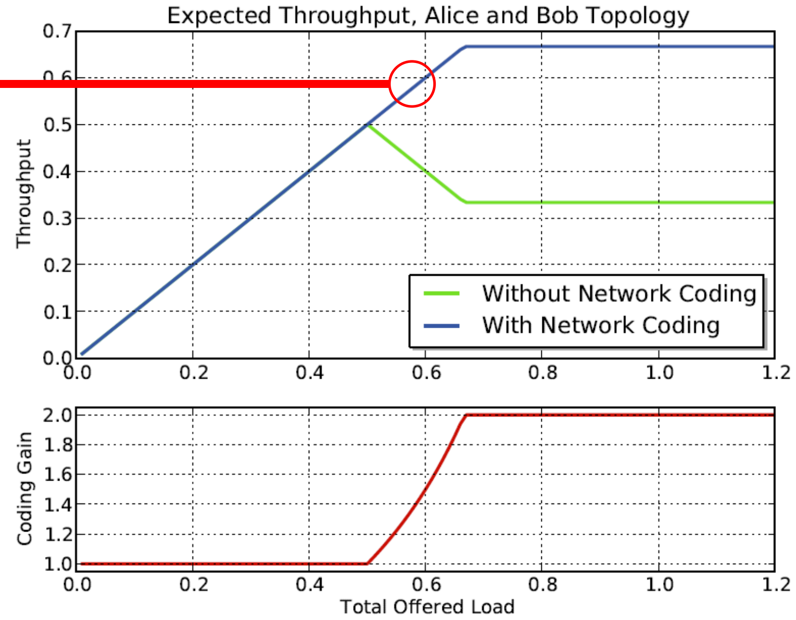
Load 2:
w NC channel capacity is
NOT reached



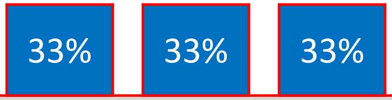
Throughput Model

29% 29% 29%

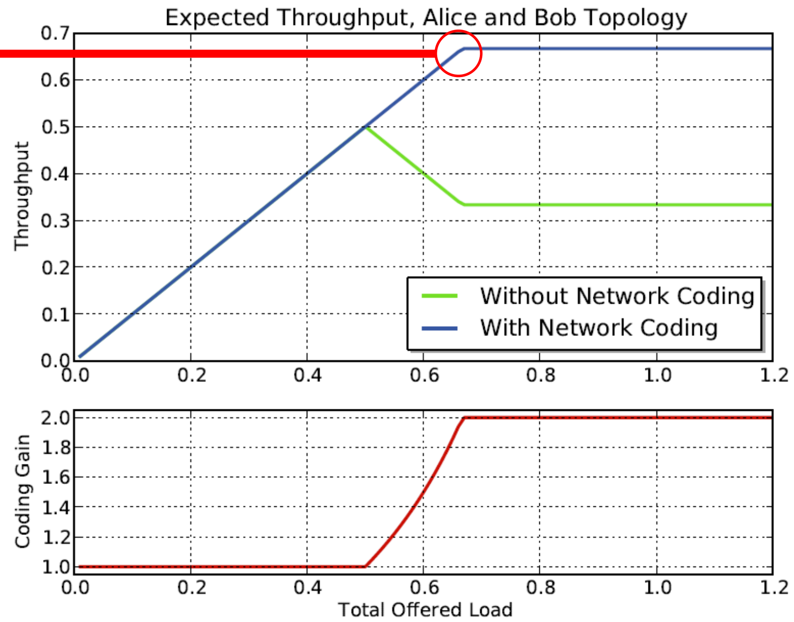
Load 3:
w NC Alice, Bob and the relay live in perfect harmony, each of the entities requests one third of the capacity



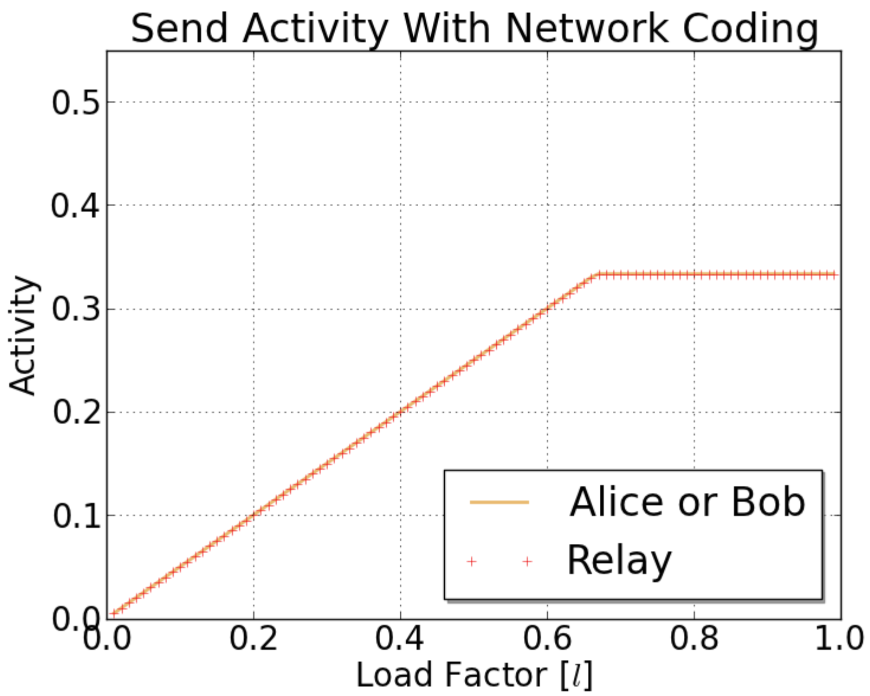
Throughput Model

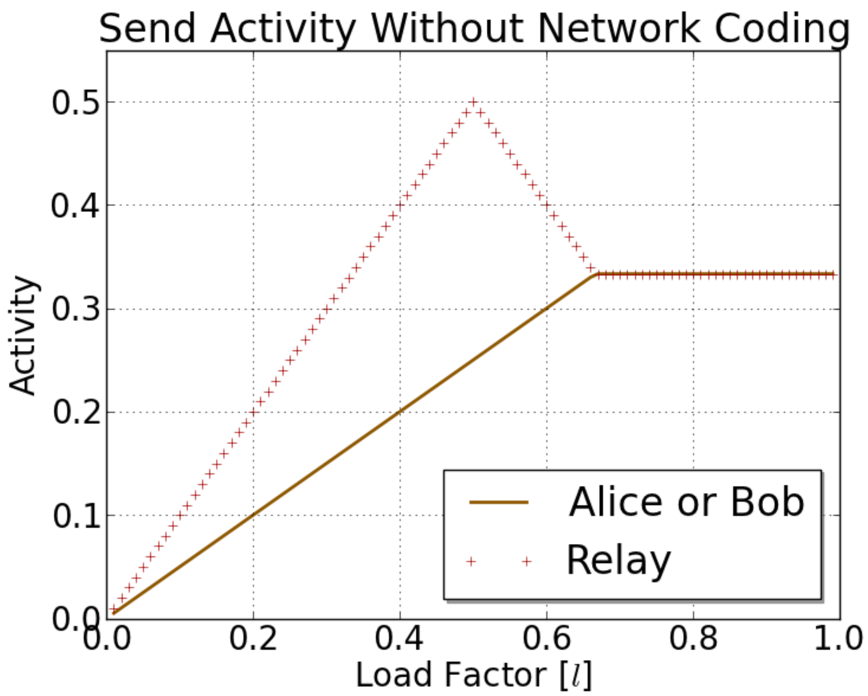


Load 4:
w NC Alice, Bob and the relay live in perfect harmony now the channel capacity is reach and therefore the throughput remains constant.

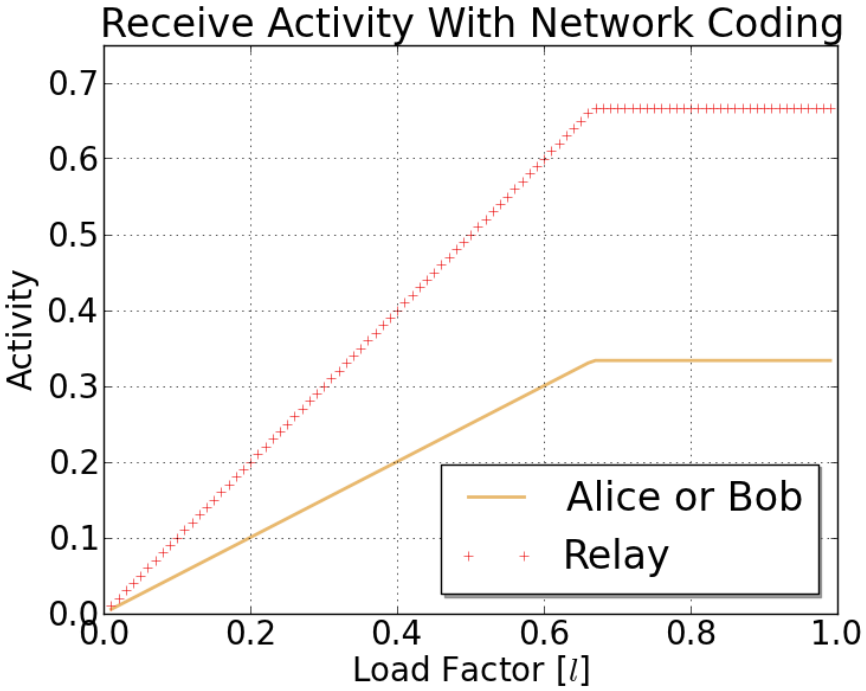


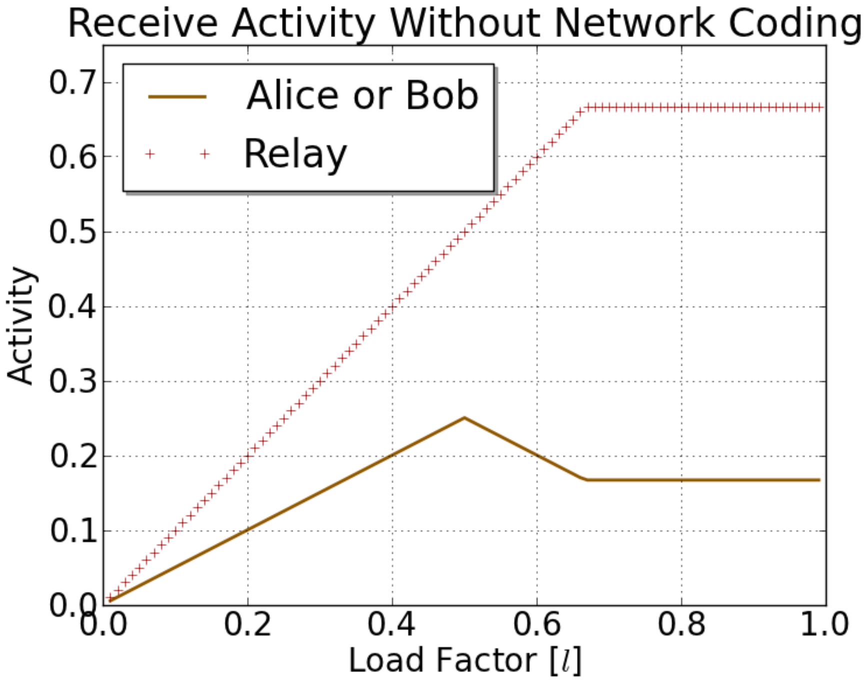
Send Activity Model



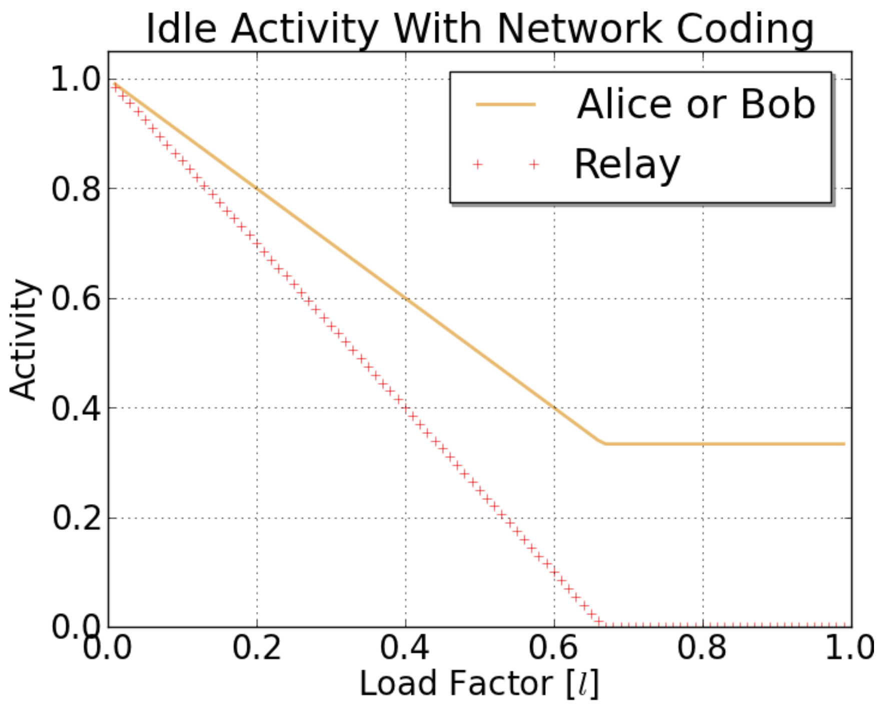


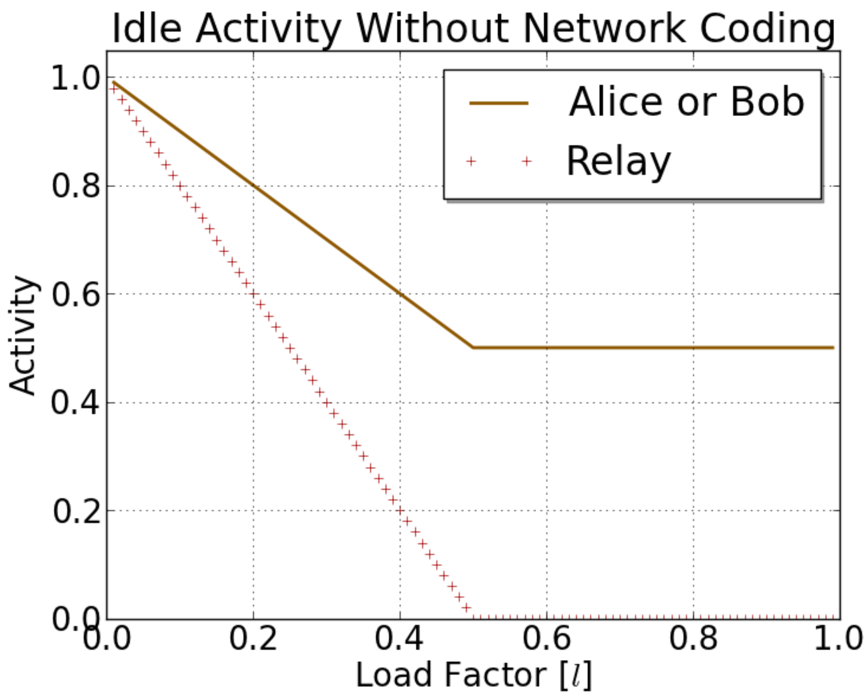
Receive Activity Model





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 $[\alpha_s]$	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.

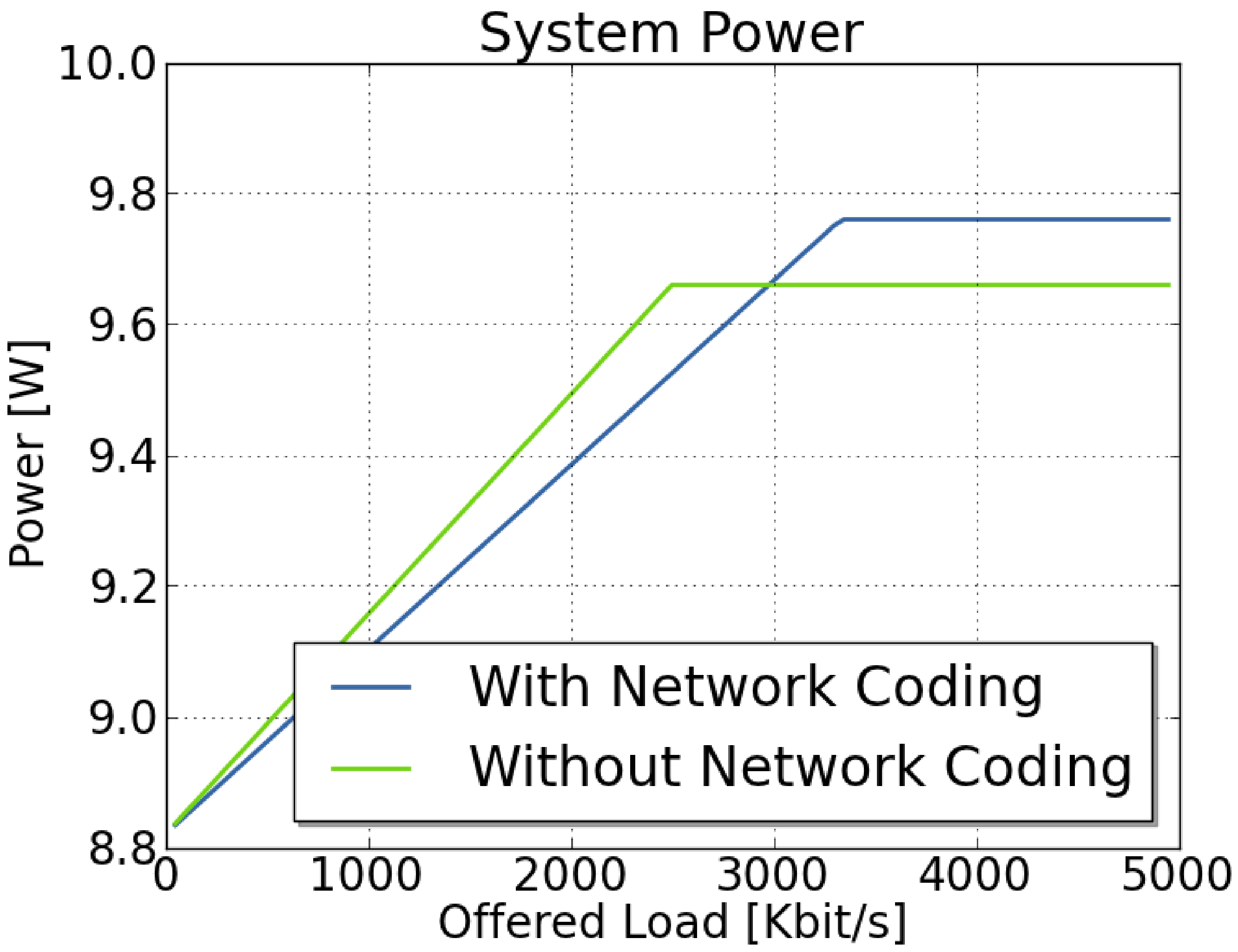
$$P_{total} = P_r * a_r + P_s * a_s + P_i * a_i$$

Power Model

- Out of our measurements for WHITEBOX we derive:
  - Total power level sending: $P_{send} = 3.48$ W
  - Total power level receiving: $P_{send} = 3.24$ W
  - Total power level idle: $P_{send} = 2.94$ W

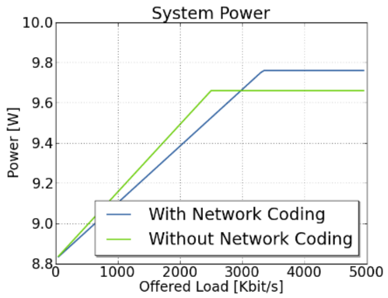
- Later we assume a maxium capacity of the channel of 4.9 Mbit/s

Power Rate Model



Energy Model

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



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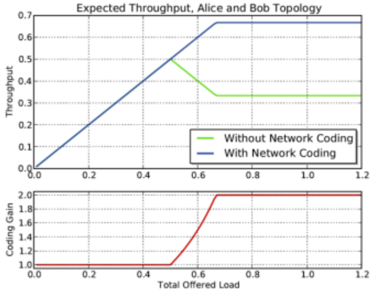

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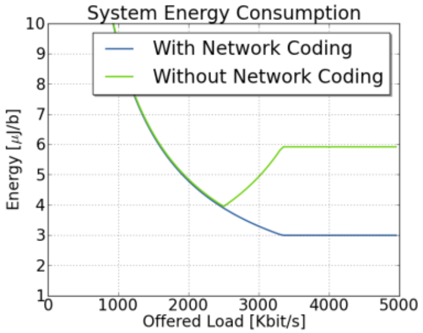
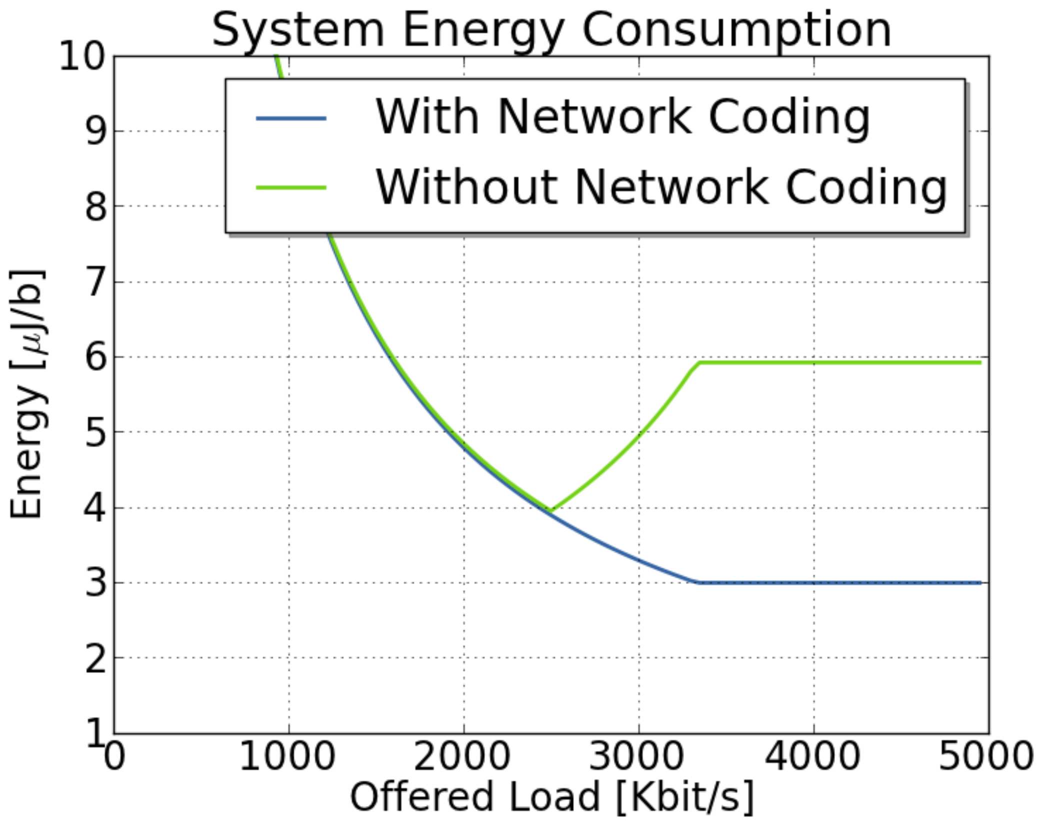


power throughput energy/bit

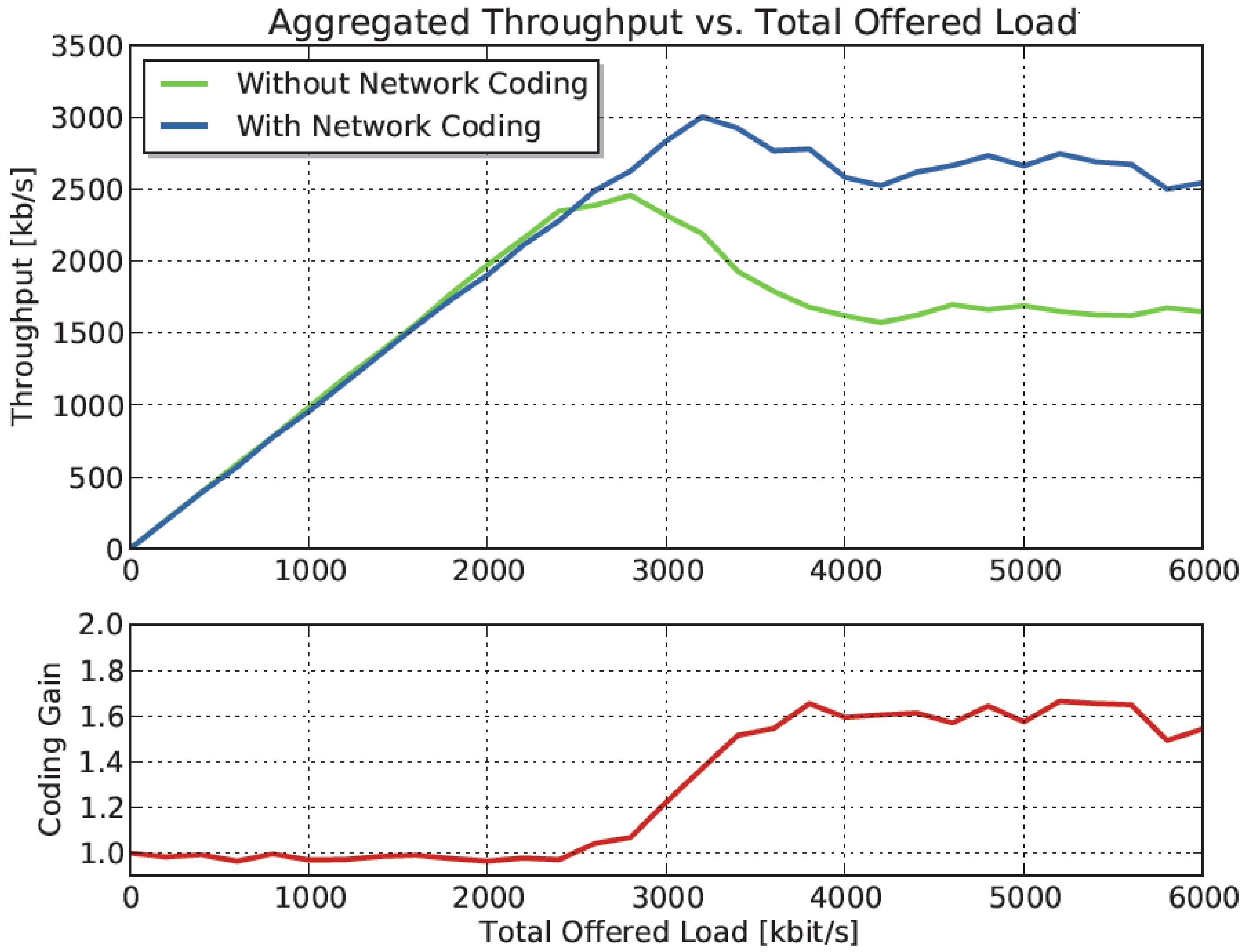
Energy Model

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



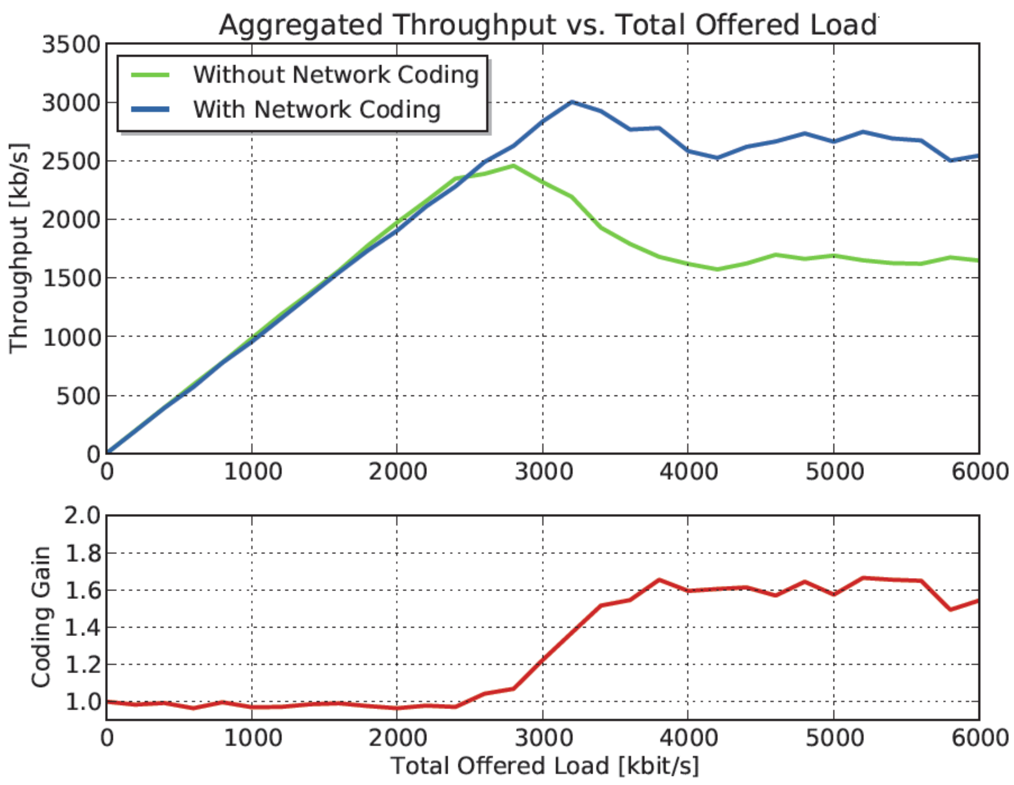
CATWOMAN Measurement Results

CATWOMAN: Results

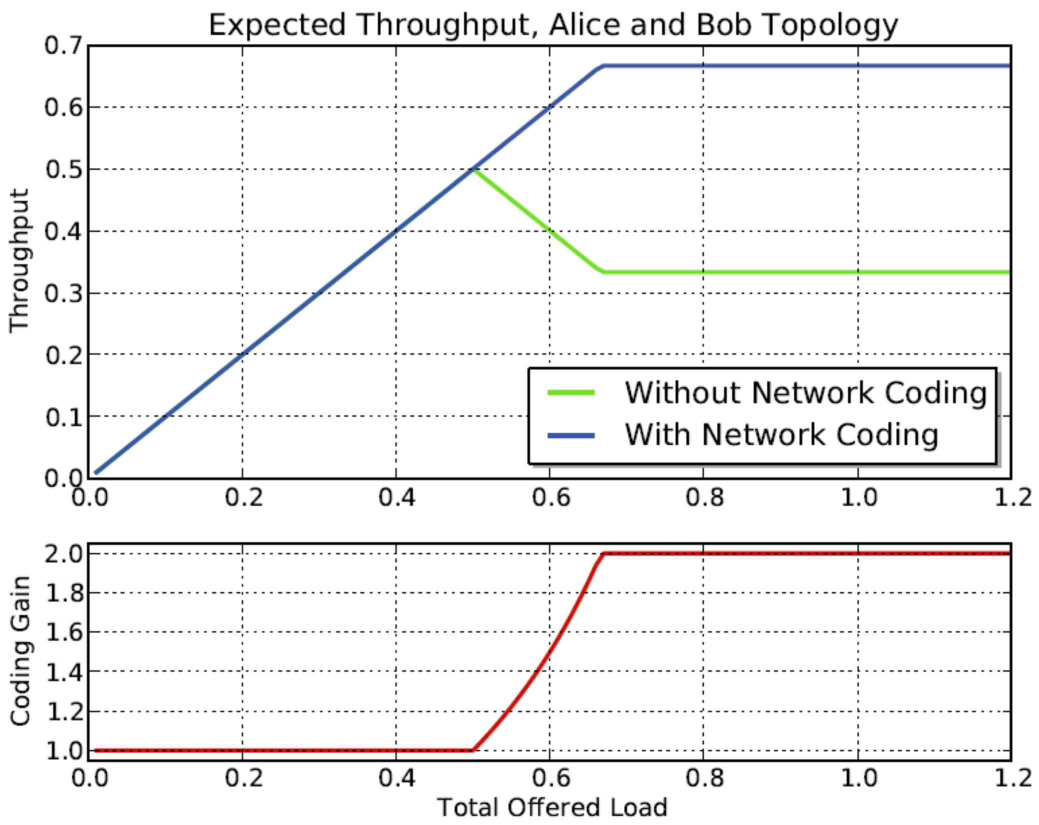


CATWOMAN: Comparison

Measurements



Analytical work

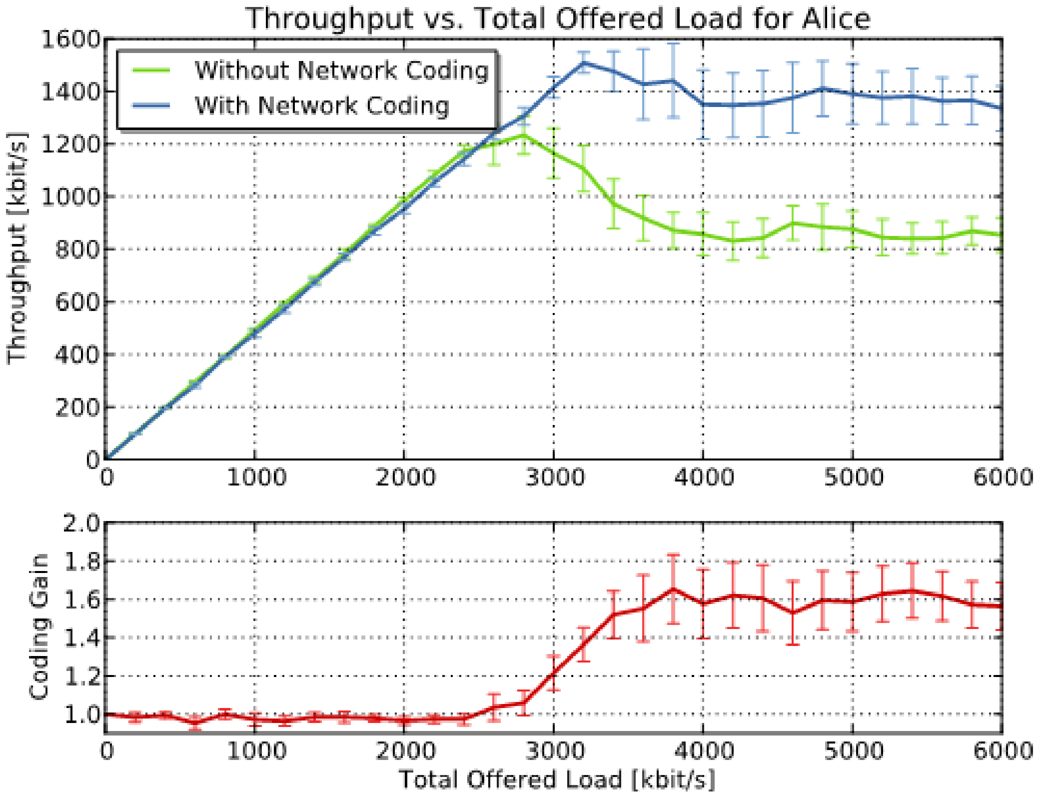


Discussion

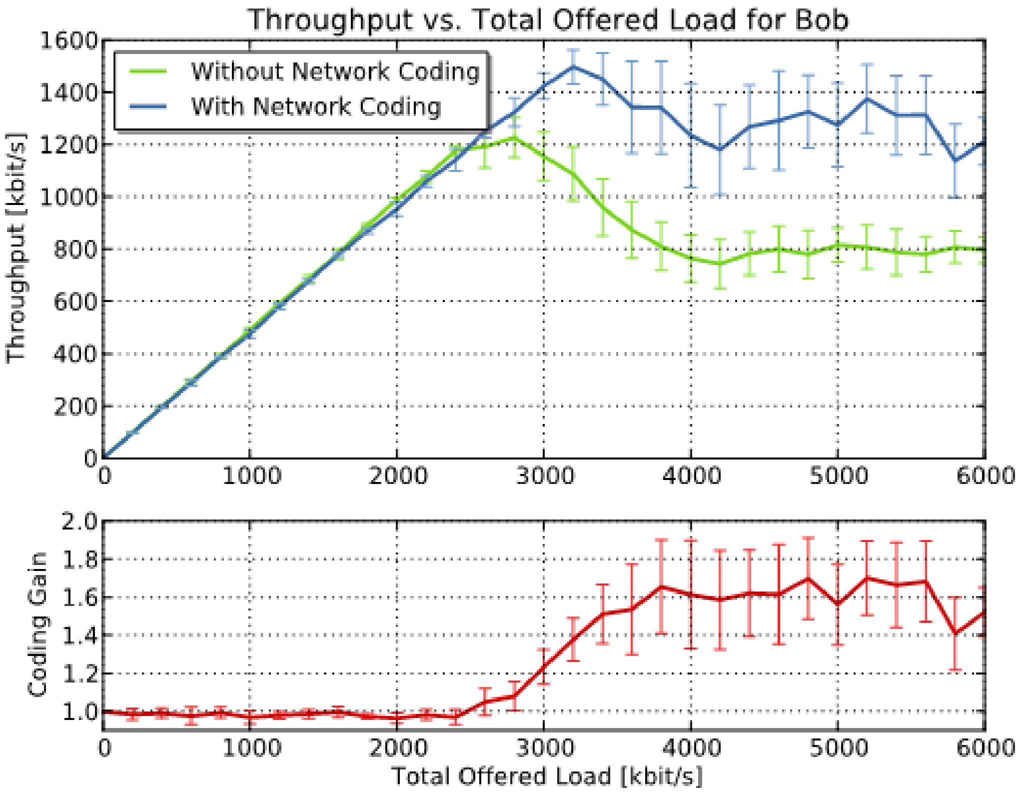
- Results fit nicely
- But
  - The coding gain is with 1.6 lower than expected with 2.0
  - The throughput of NC is not stable after reaching its maximum
- Why?

CATWOMAN: Results

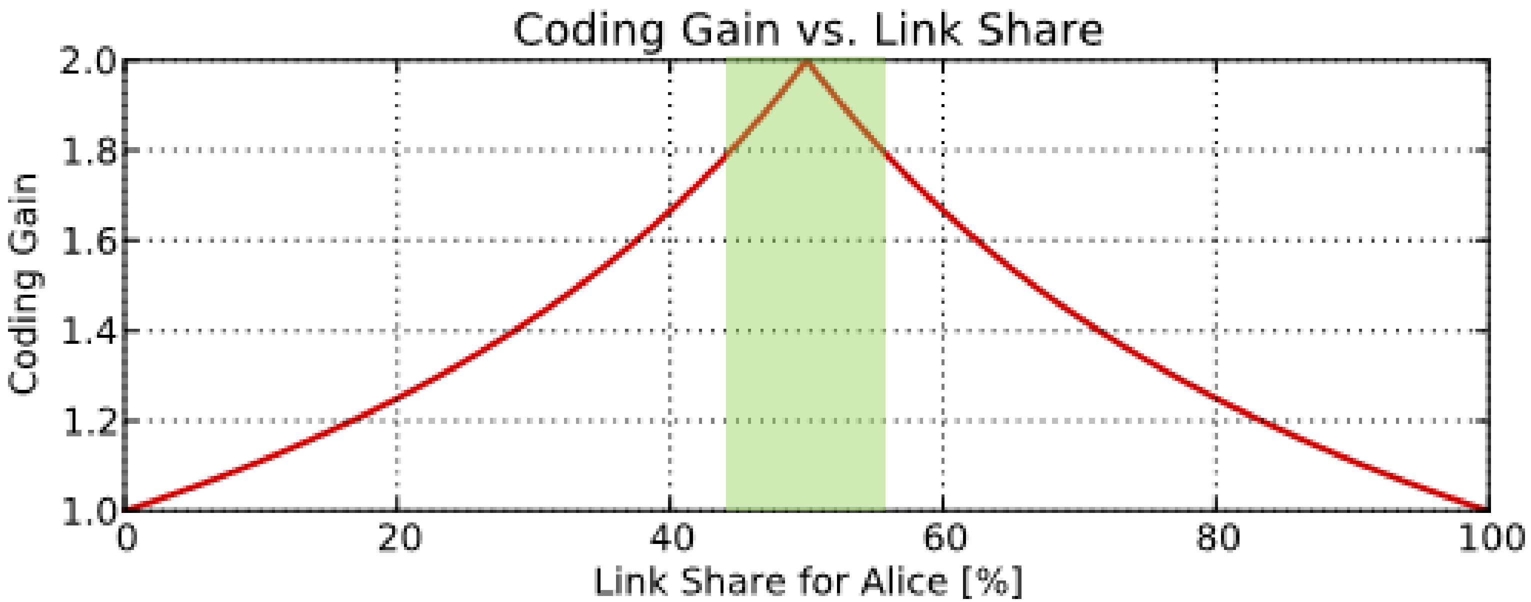
Alice



Bob

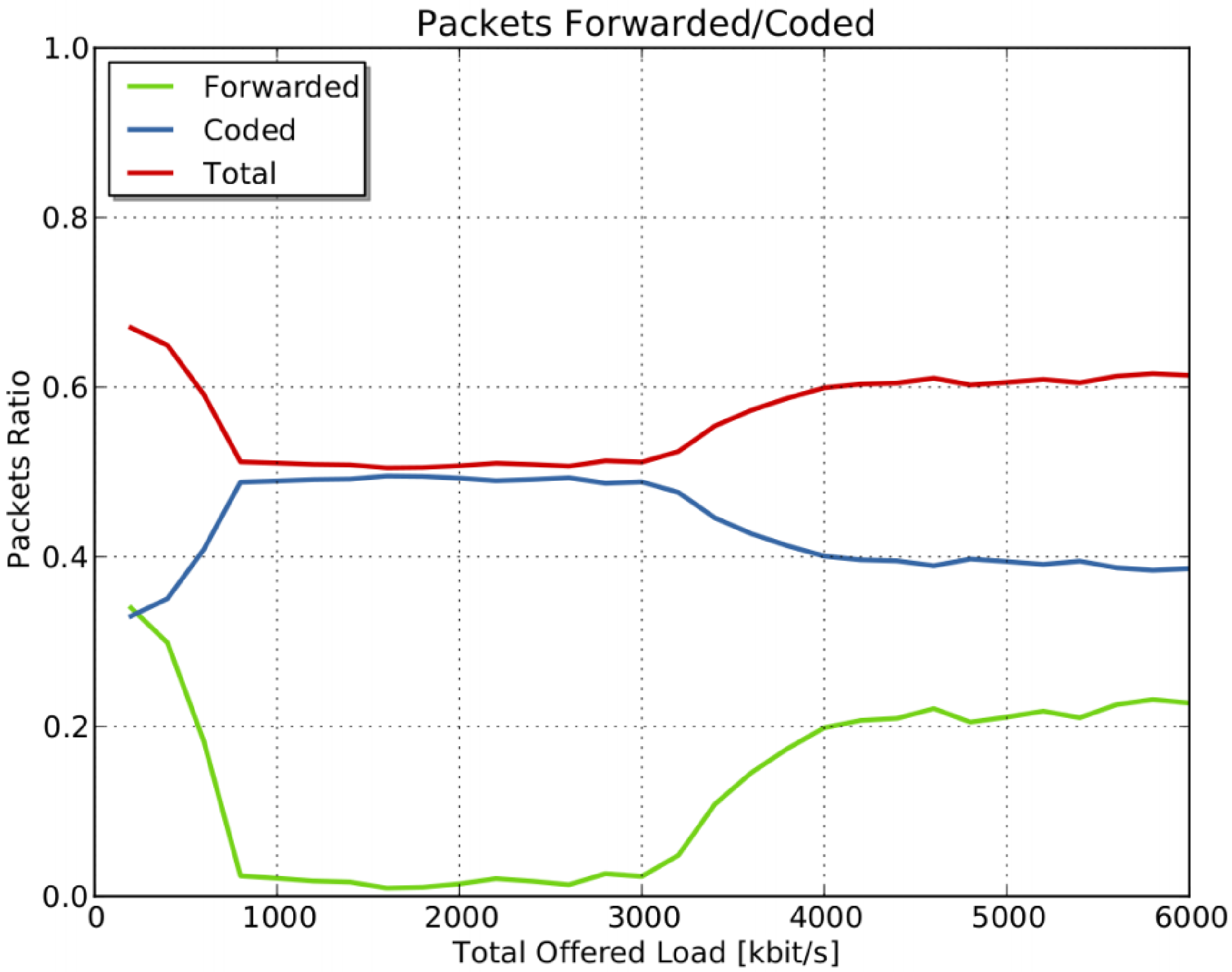


CATWOMAN: Results

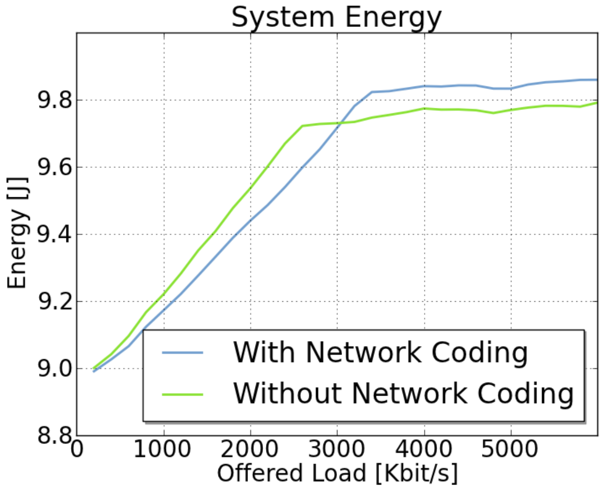


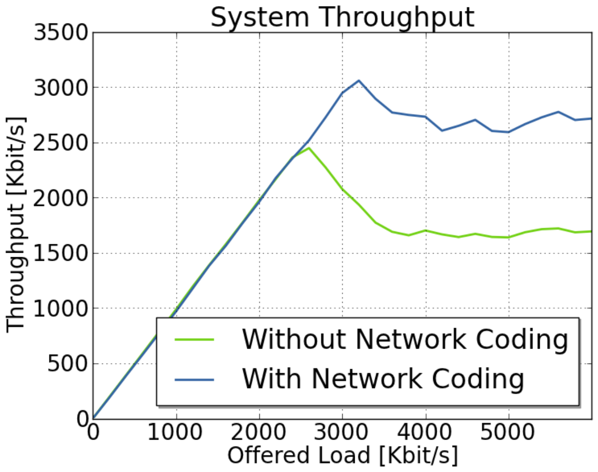
$$g_C = \frac{N}{N \cdot x + N((1-x) - x)} = \frac{1}{1-x}, \qquad 0 \leq x \leq 0.5.$$

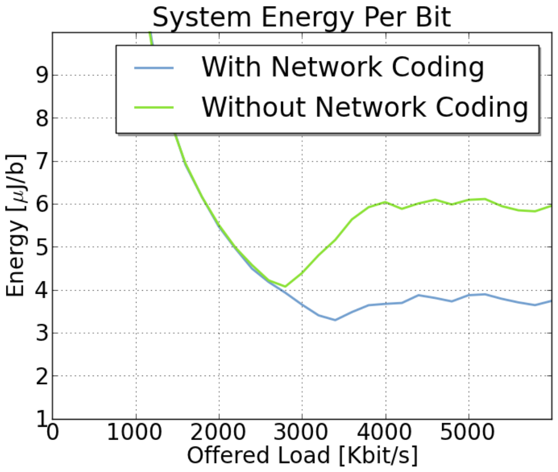
CATWOMAN: Results



First Measurement Result





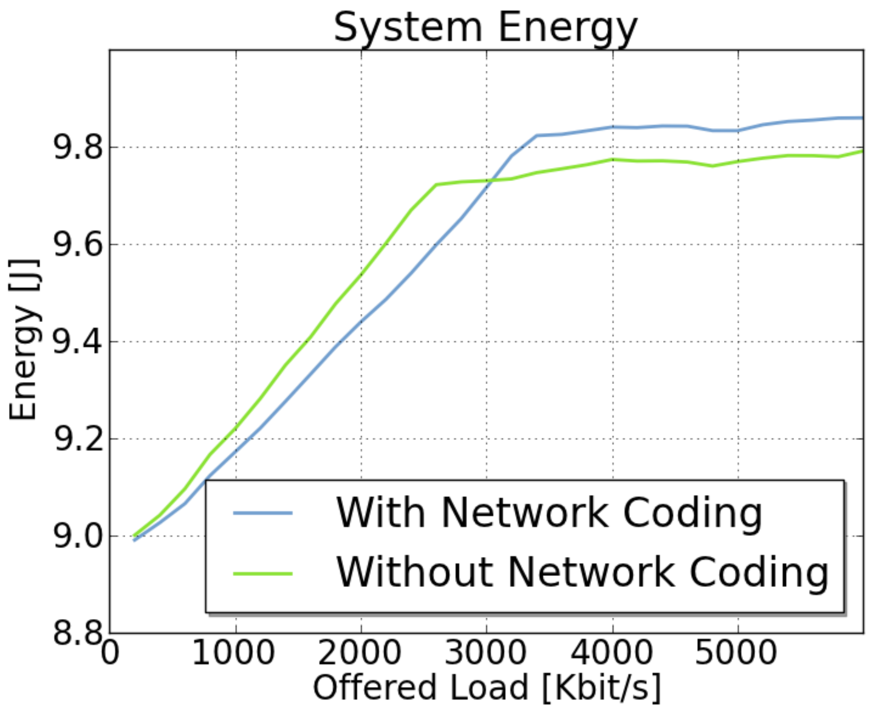


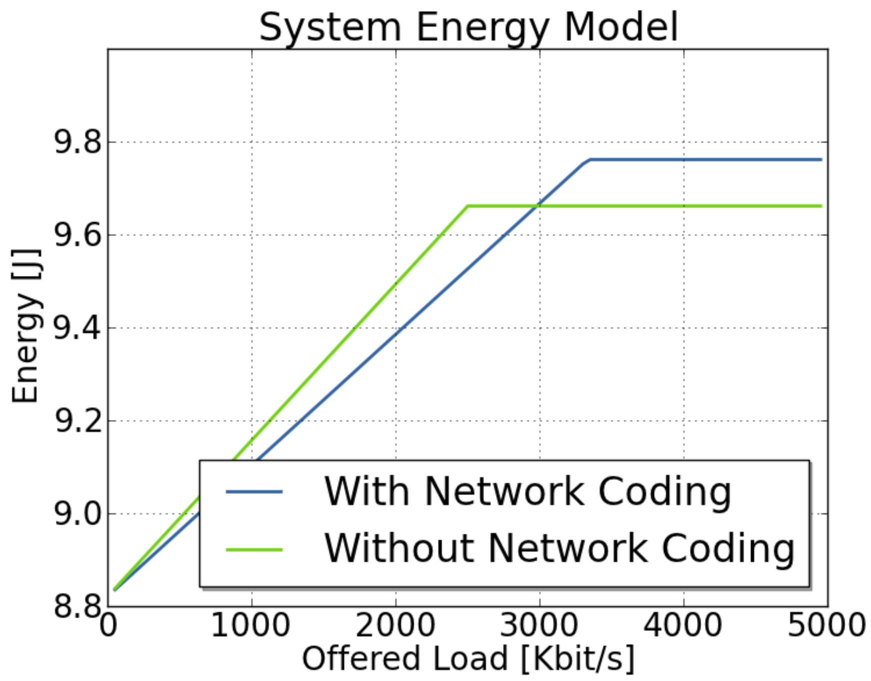
power

throughput

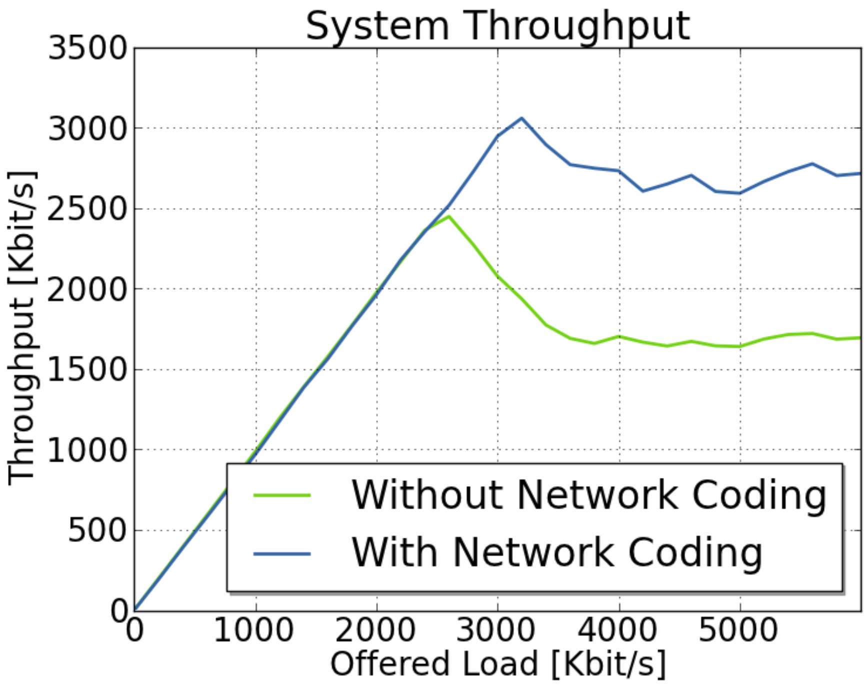
energy/bit

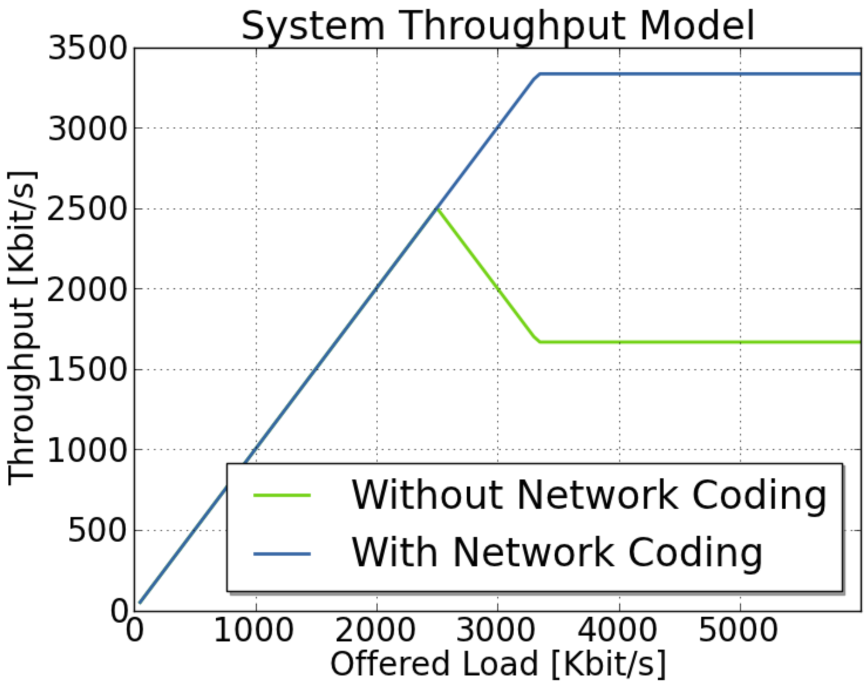
Comparion: Energy



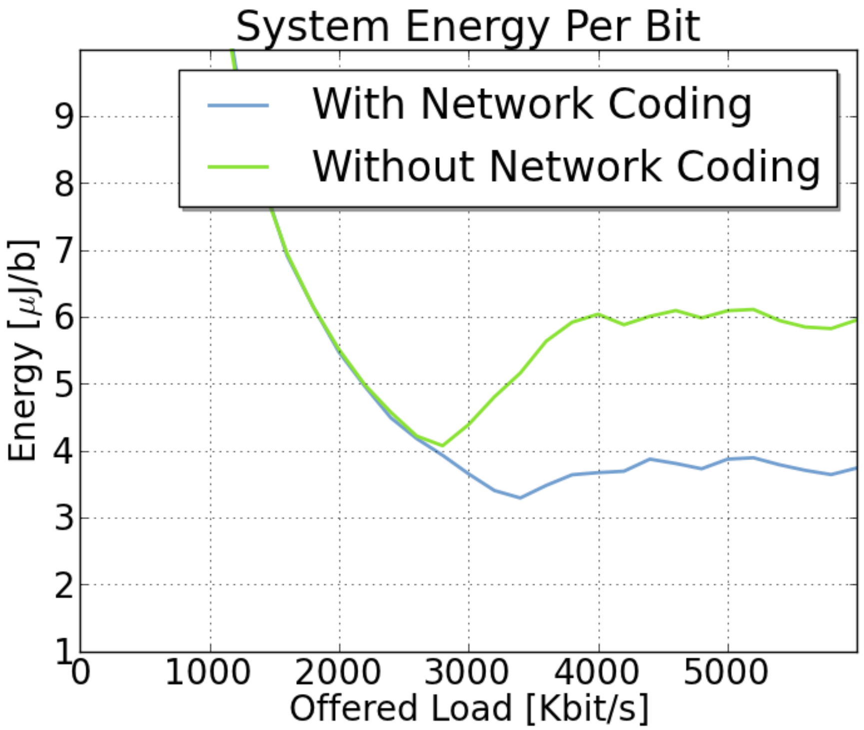


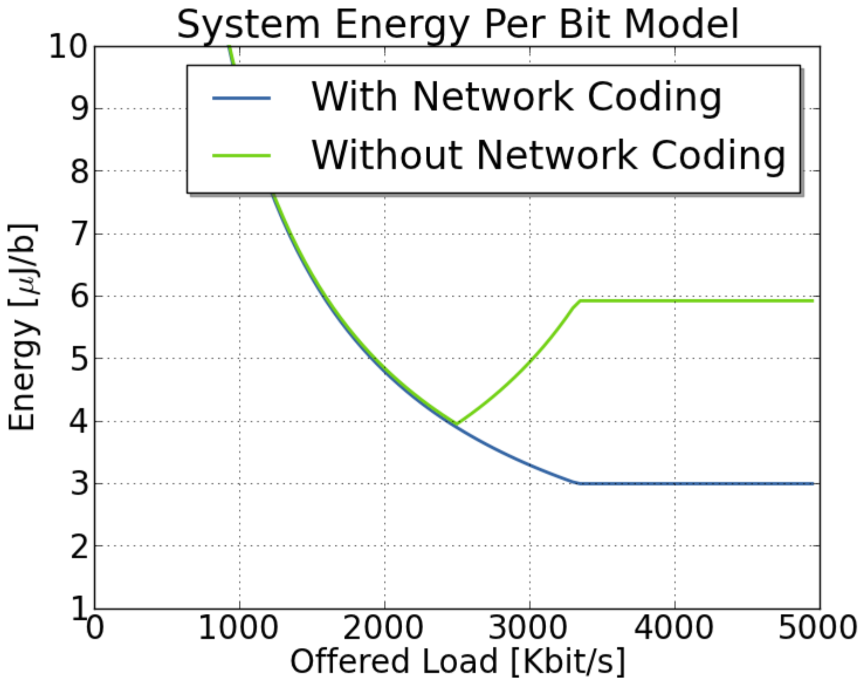
Comparion: Throughput





Comparion: Energy Per Bit





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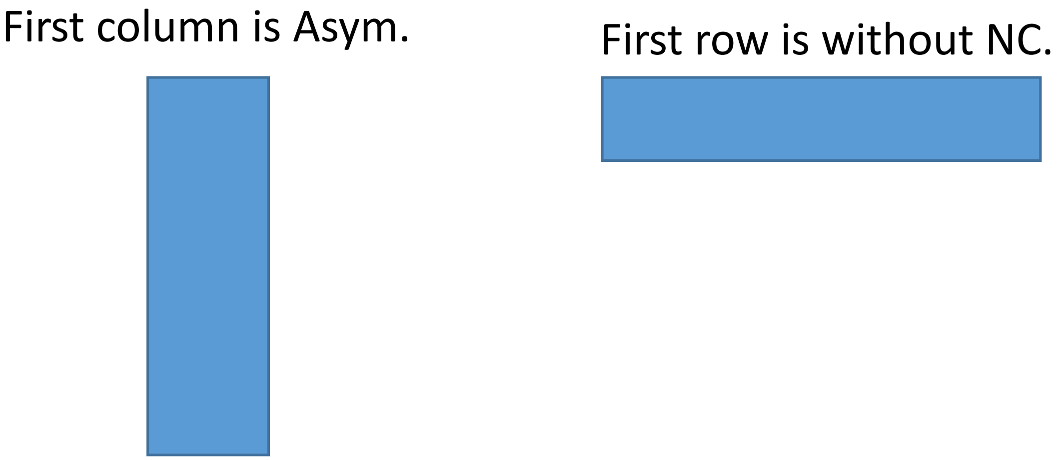
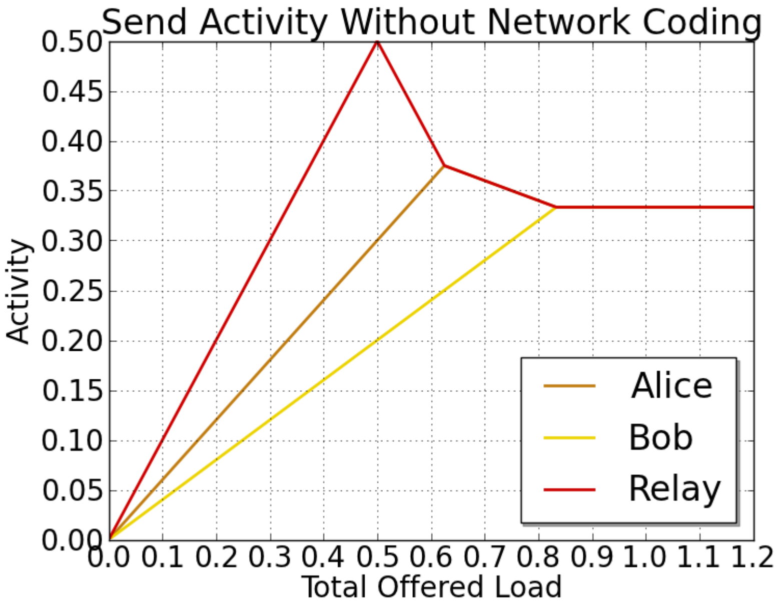
Model for Alice and Bob (symmetric TRAFFIC)

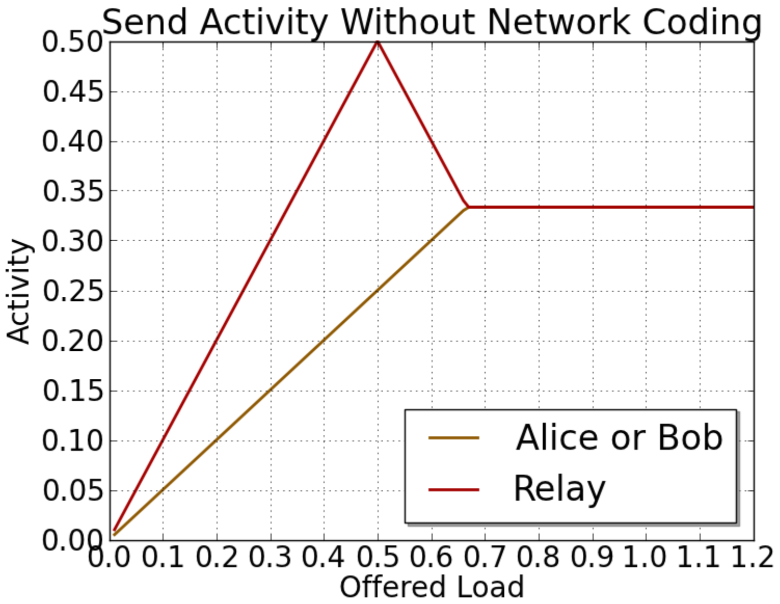
General Note

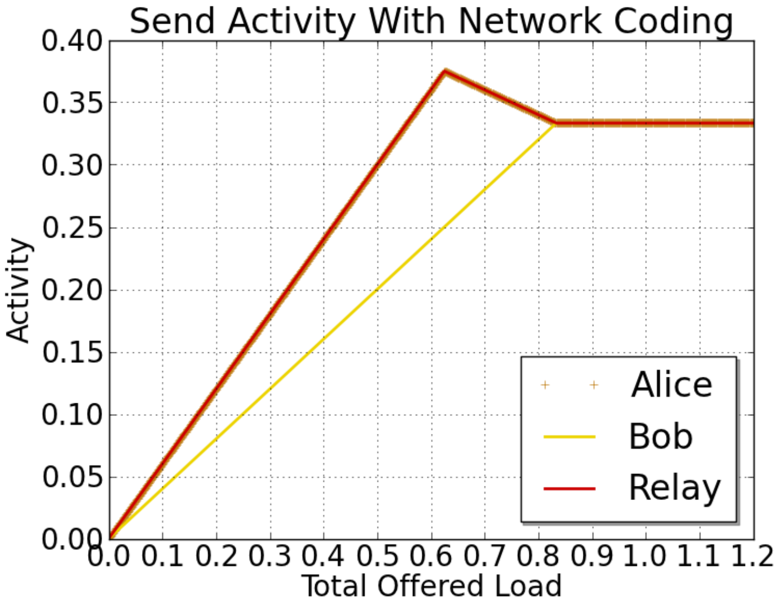
- Figure organization:

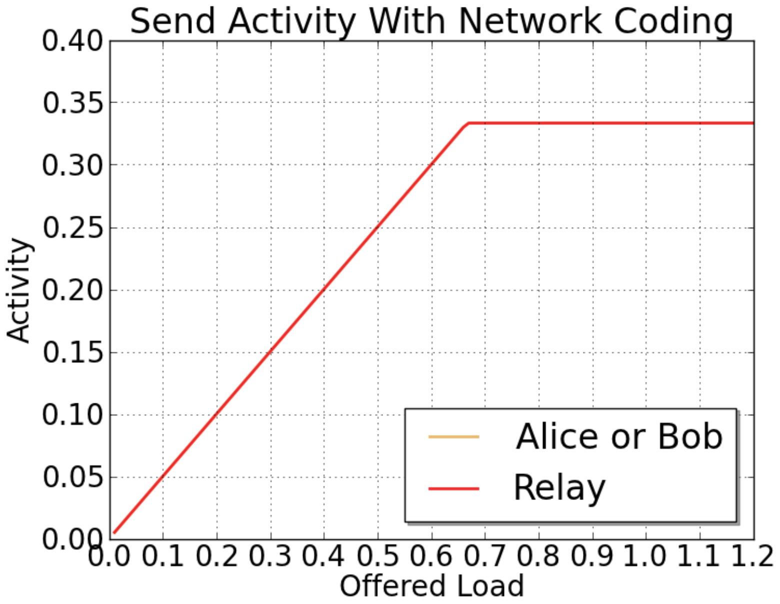


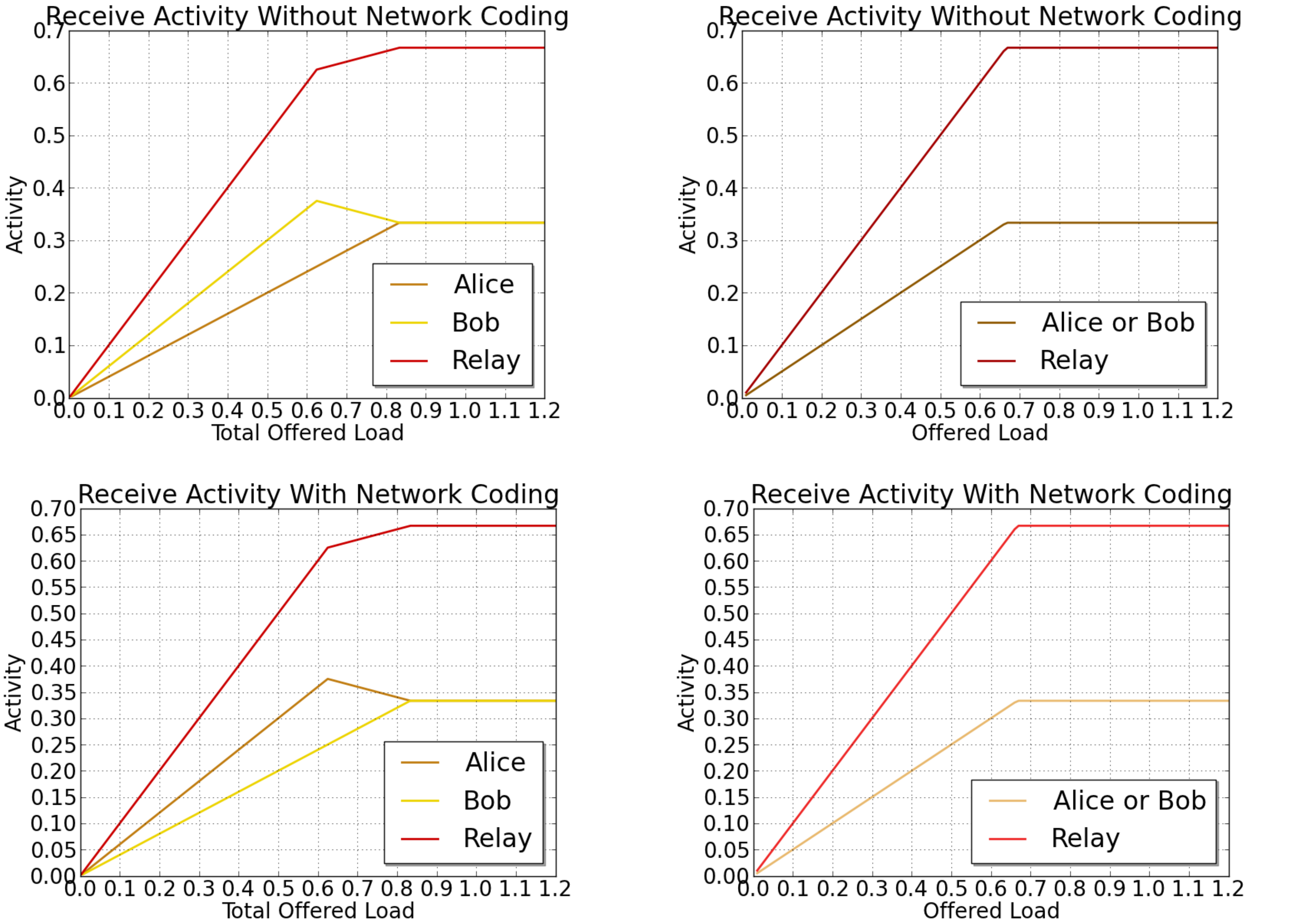
- Asymmetric with link share of 60%(A)/40%(B)


Send Activity Without Network Coding
Activity
Total Offered Load
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2
Alice
Bob
Relay


Send Activity Without Network Coding
Activity
Offered Load
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2
Alice or Bob
Relay


Send Activity With Network Coding
Activity
Total Offered Load
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2
Alice
Bob
Relay


Send Activity With Network Coding
Activity
Offered Load
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2
Alice or Bob
Relay


Receive Activity Without Network Coding
Activity
Total Offered Load
Alice
Bob
Relay
Receive Activity Without Network Coding
Activity
Offered Load
Alice or Bob
Relay
Receive Activity With Network Coding
Activity
Total Offered Load
Alice
Bob
Relay
Receive Activity With Network Coding
Activity
Offered Load
Alice or Bob
Relay

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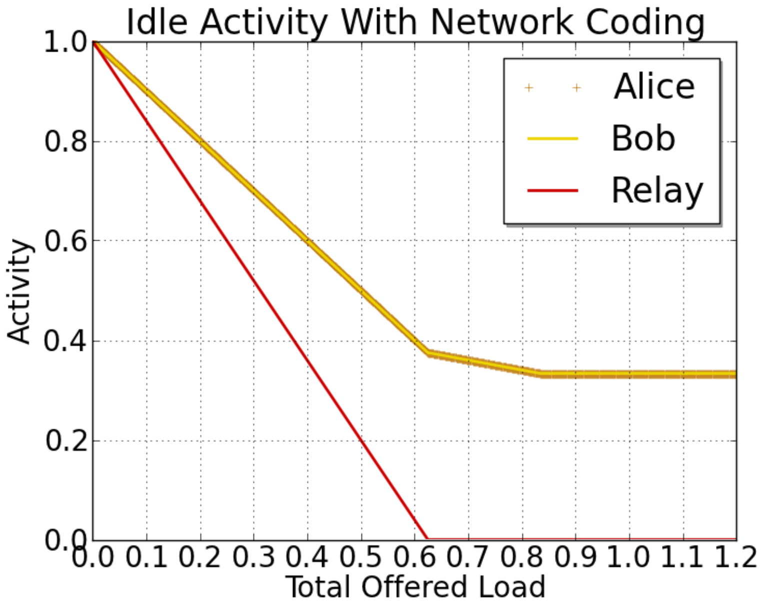
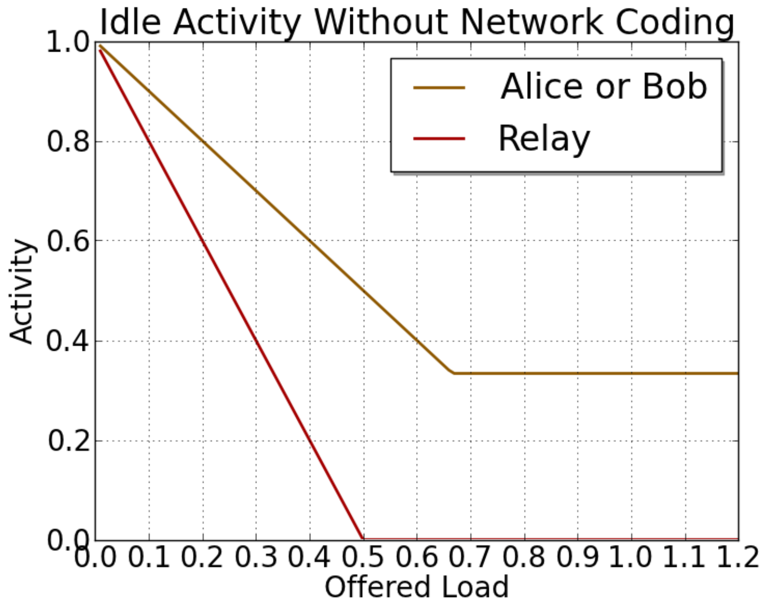
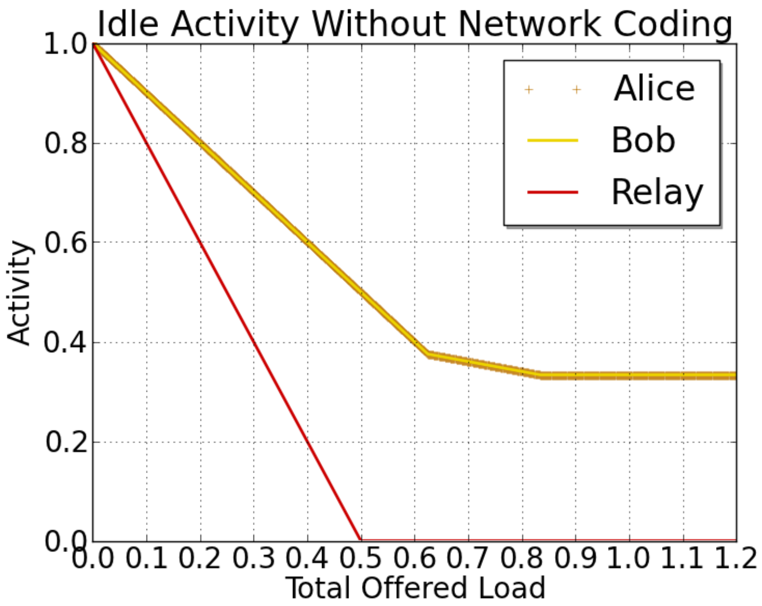
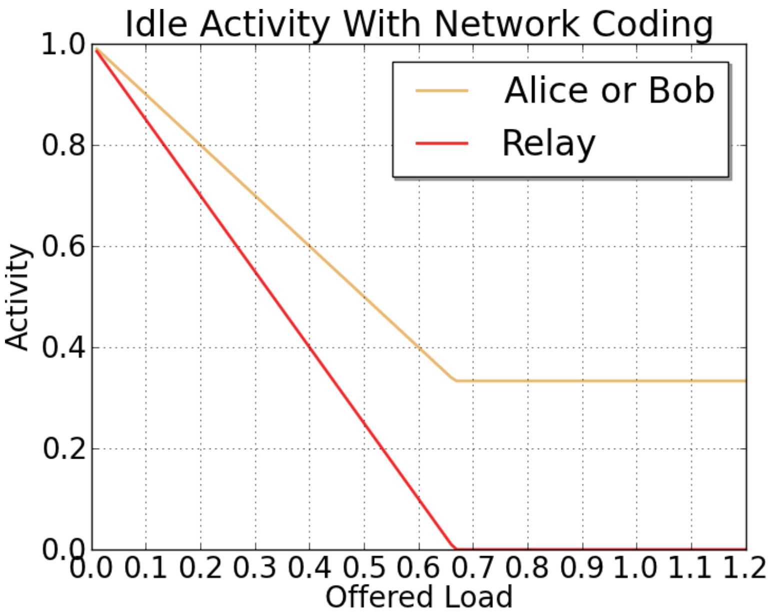
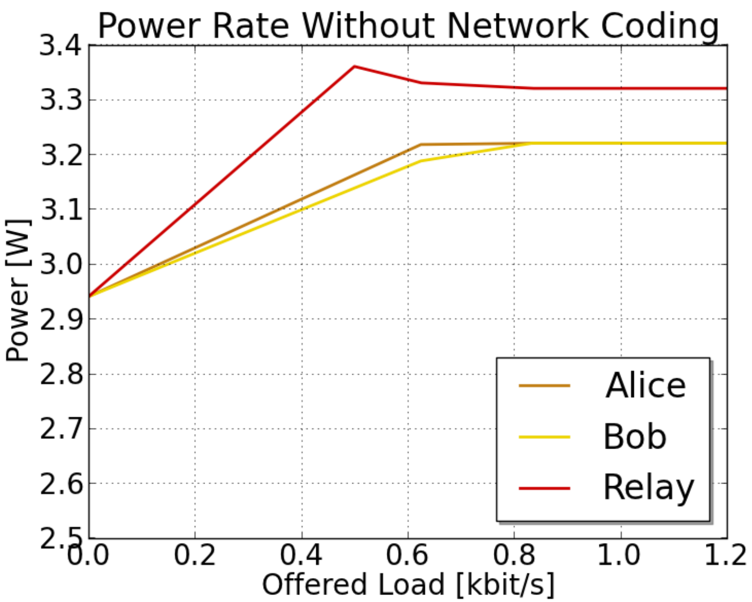
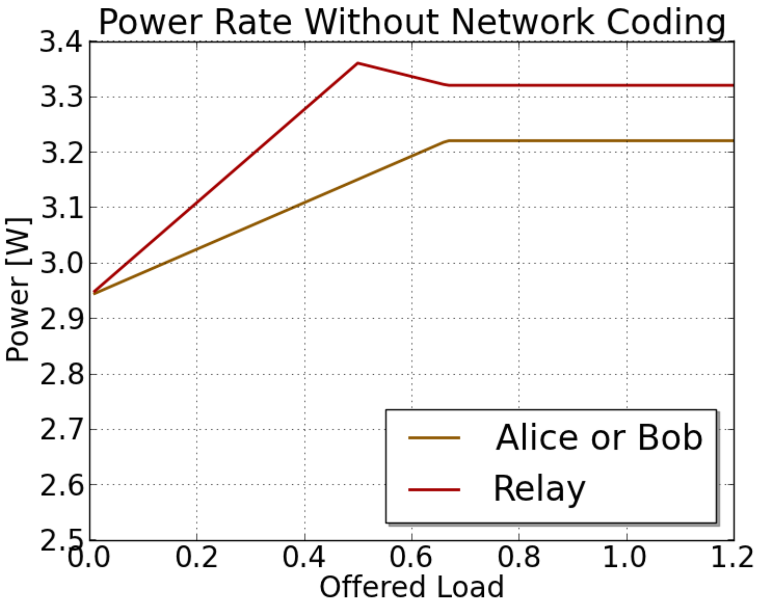


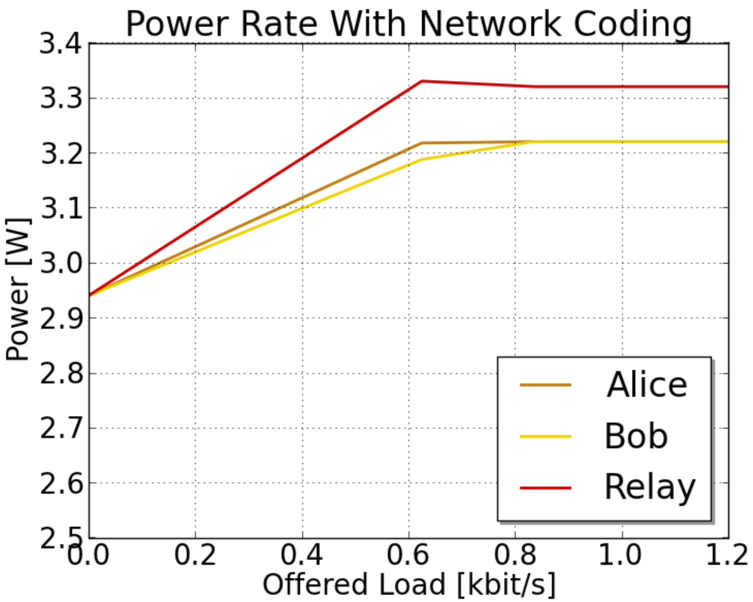


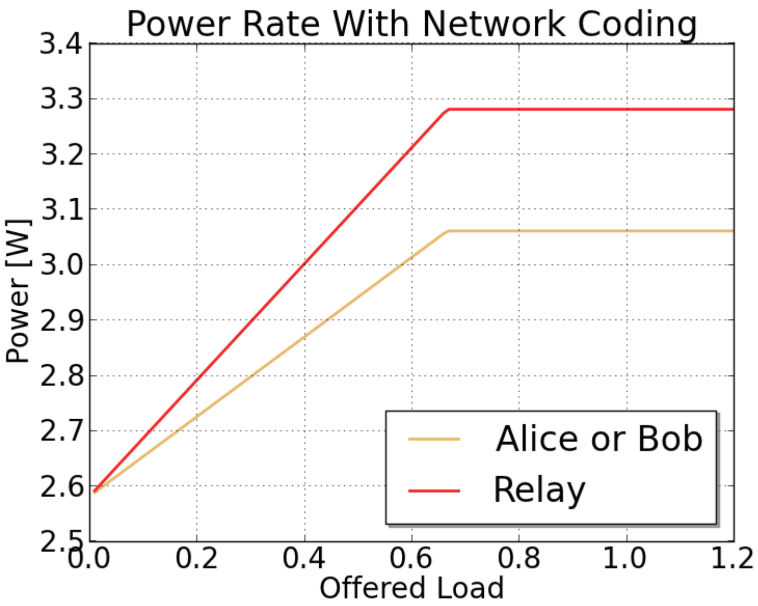


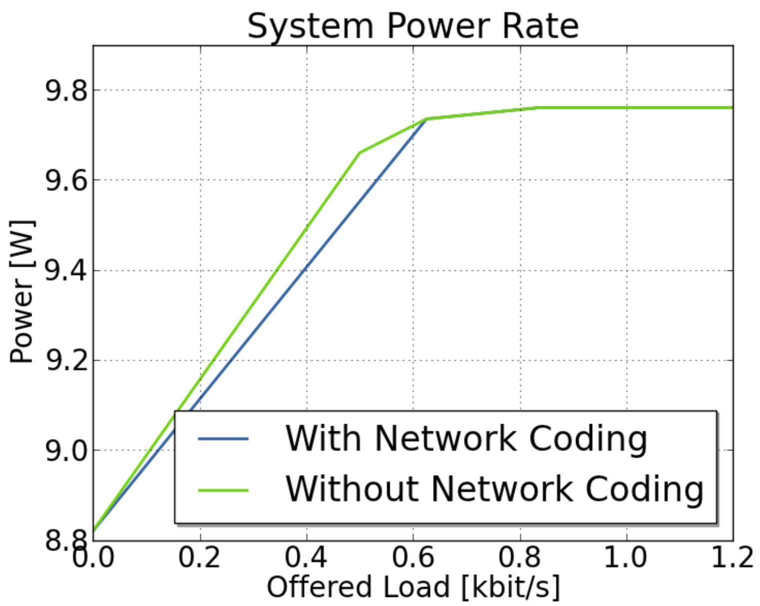



Power Rate Without Network Coding
Power [W]
Offered Load [kbit/s]
Alice
Bob
Relay

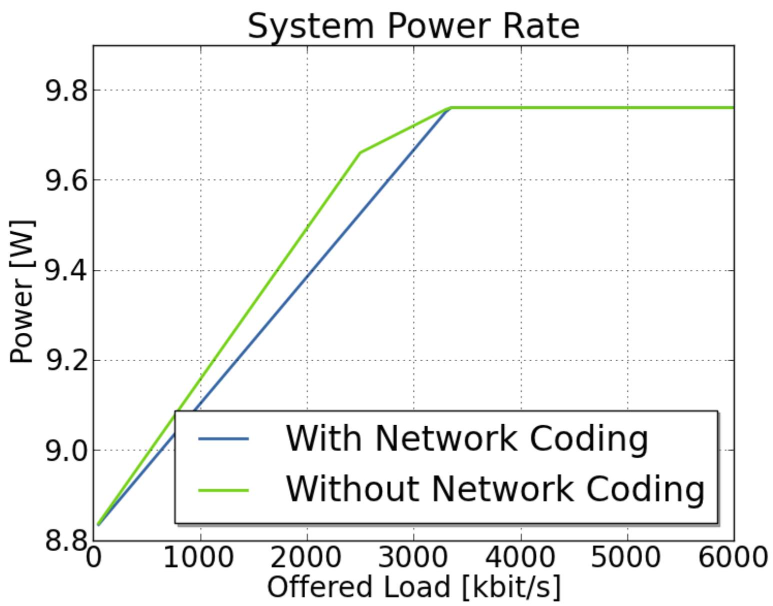

Power Rate Without Network Coding
Power [W]
Offered Load
Alice or Bob
Relay


Power Rate With Network Coding
Power [W]
Offered Load [kbit/s]
Alice
Bob
Relay


Power Rate With Network Coding
Power [W]
Offered Load
Alice or Bob
Relay



System Power Rate
Power [W]
Offered Load [kbit/s]
With Network Coding
Without Network Coding

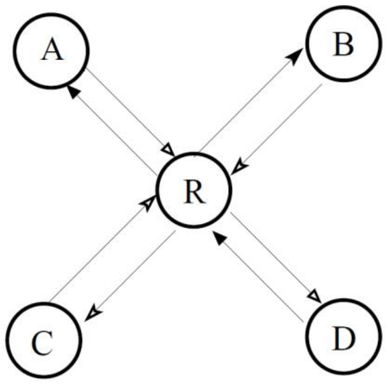


System Power Rate
Power [W]
Offered Load [kbit/s]
With Network Coding
Without Network Coding

Model for THE CROSS (symmetric TRAFFIC)

Cross Forwarding

pure relaying



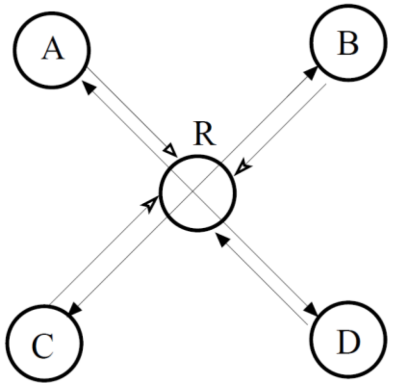
R	r	r	r	r	s	s	s	s
A	s	i	i	i	r	i	i	i
B	i	s	i	i	i	r	i	i
C	i	i	s	i	i	i	r	i
D	i	i	i	s	i	i	i	r

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

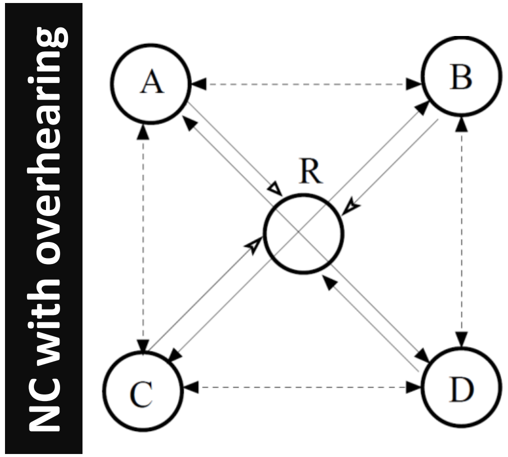


R	r	r	r	r	s	s
A	s	i	i	i	r	i
B	i	s	i	i	i	r
C	i	i	s	i	i	r
D	i	i	i	s	r	i

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

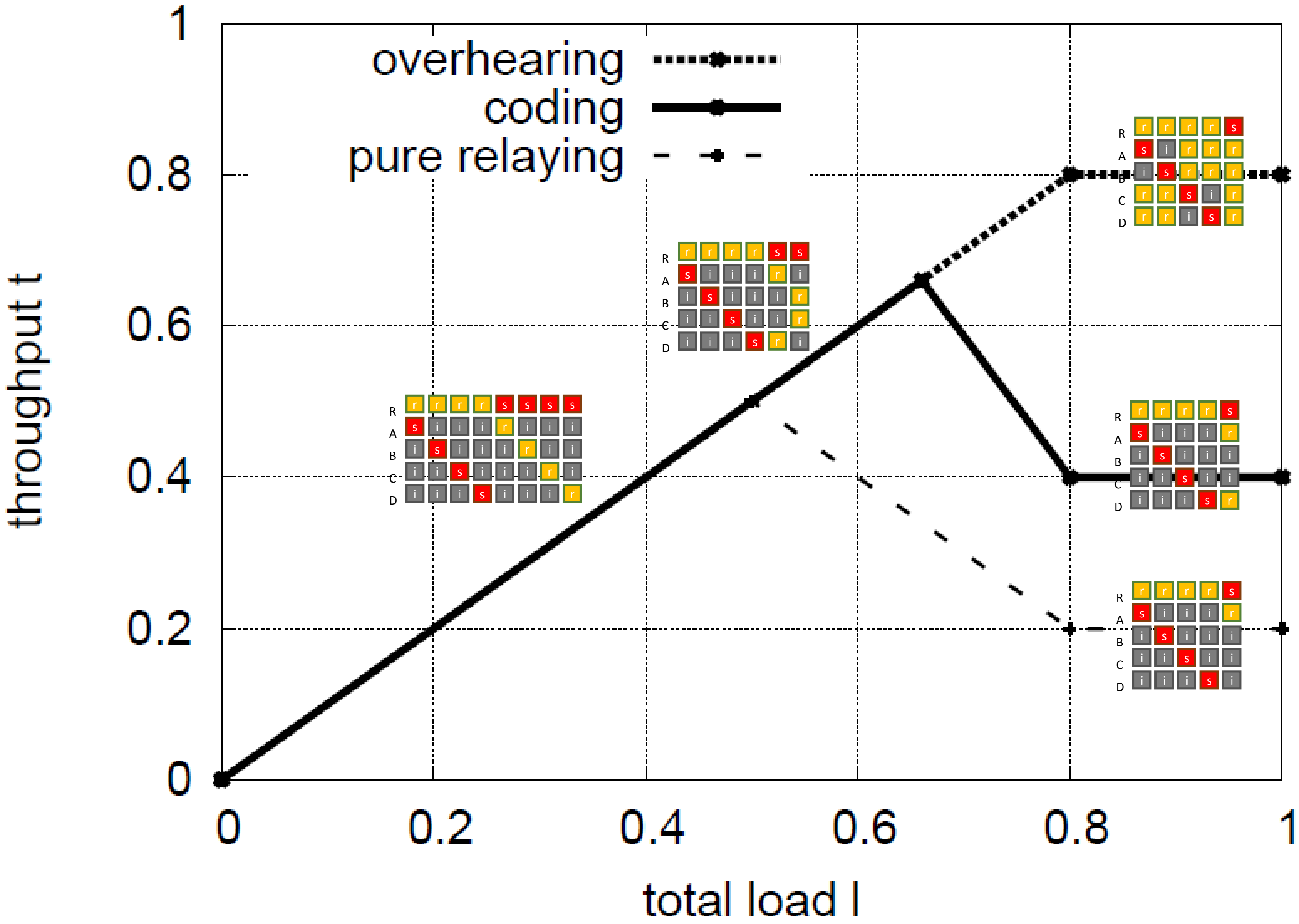
XOR Network Coding with overhearing



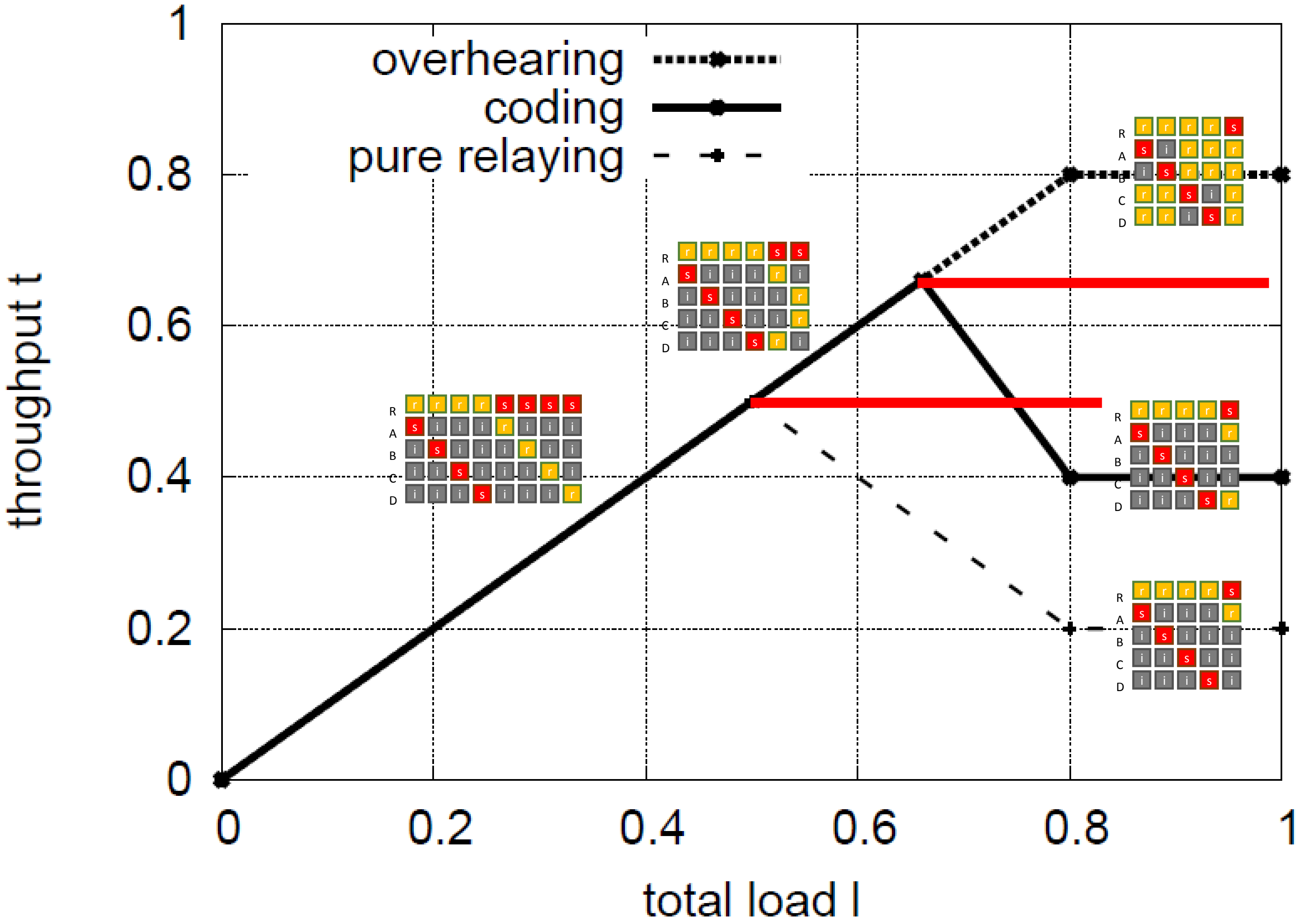
R	r	r	r	r	s
A	s	r	r	i	r
B	r	s	i	r	r
C	r	i	s	r	r
D	i	r	r	s	r

- 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

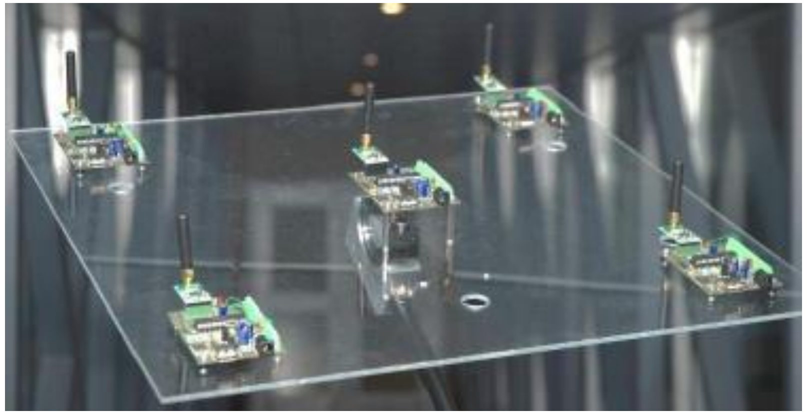


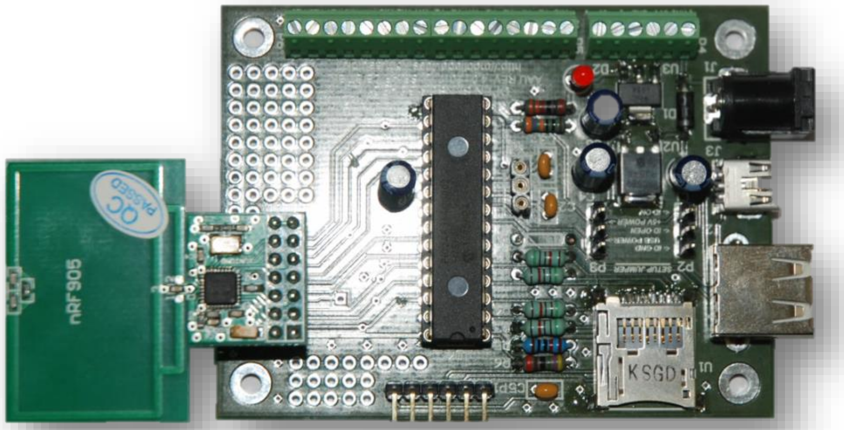
The Cross (MAC)

- Hardware
- 16bit PIC24 microprocessor
- nRF905 transceiver (433 MHz, 50 kbps)

- Software
- MAC-Protocol: A CSMA/CA design
- Network Coding: A simple XOR design [COPE06]

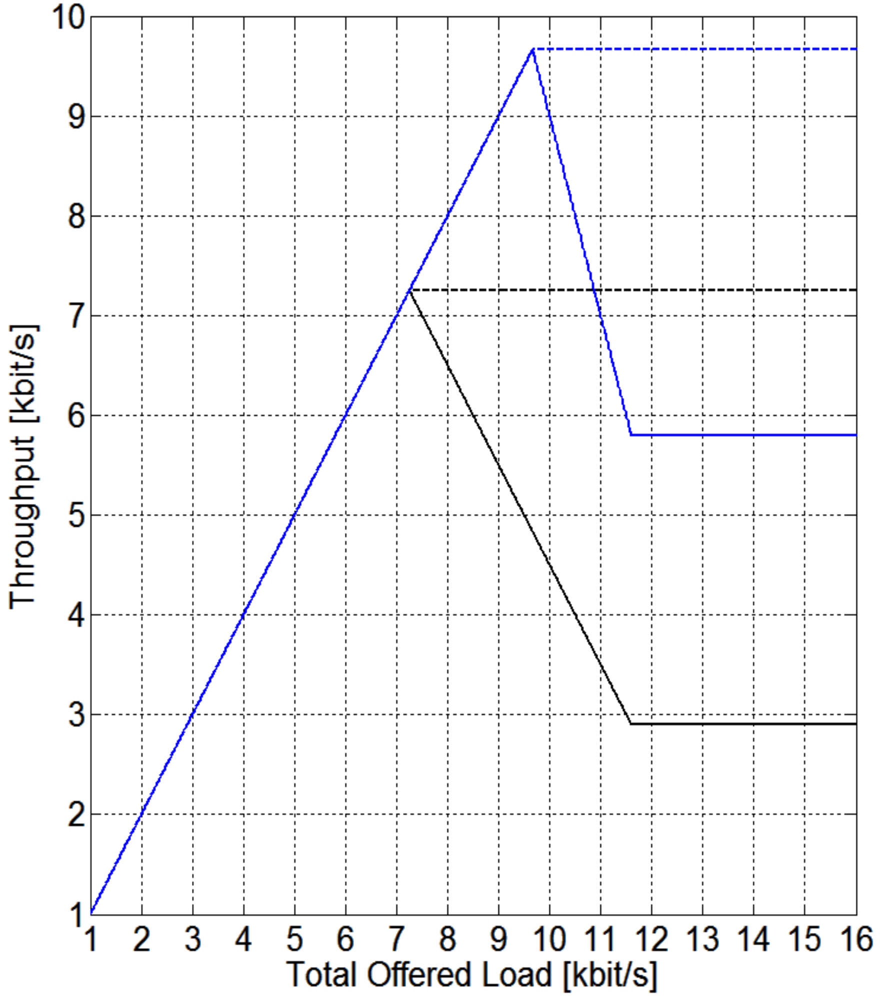
- Capability
- Easy access to the software
- Full control of both HW and SW



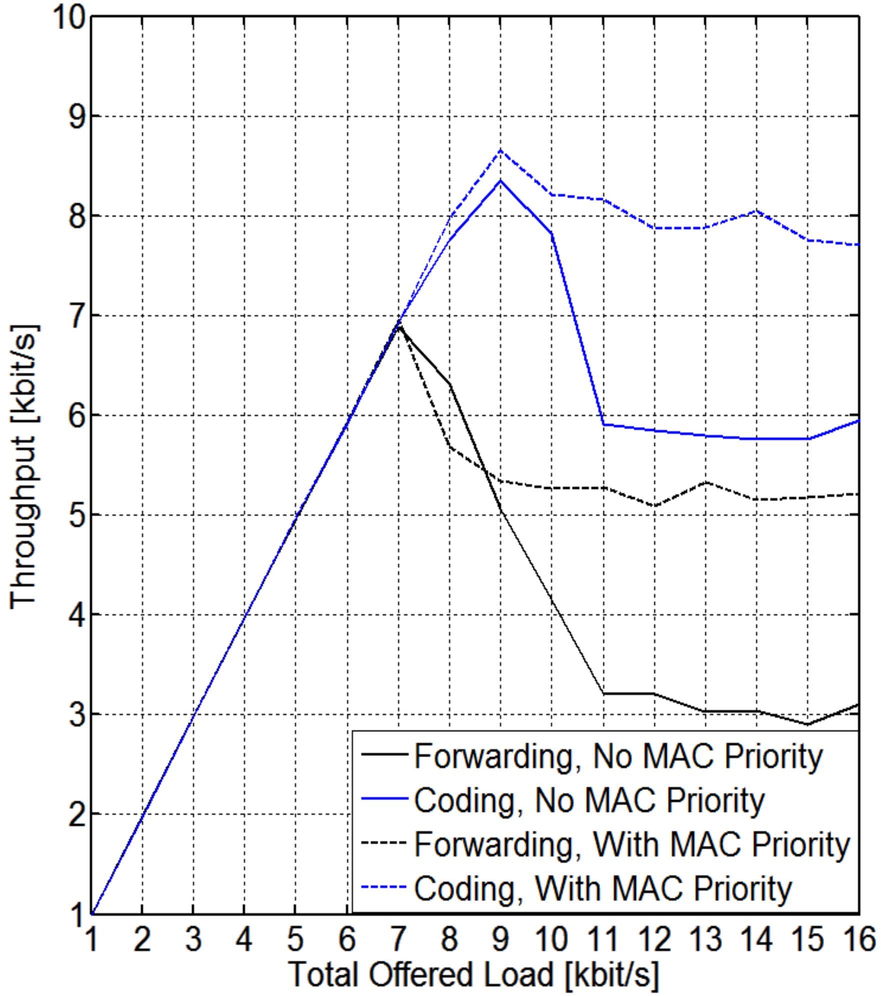


The Cross (MAC) + Priority

Expected



Measurement

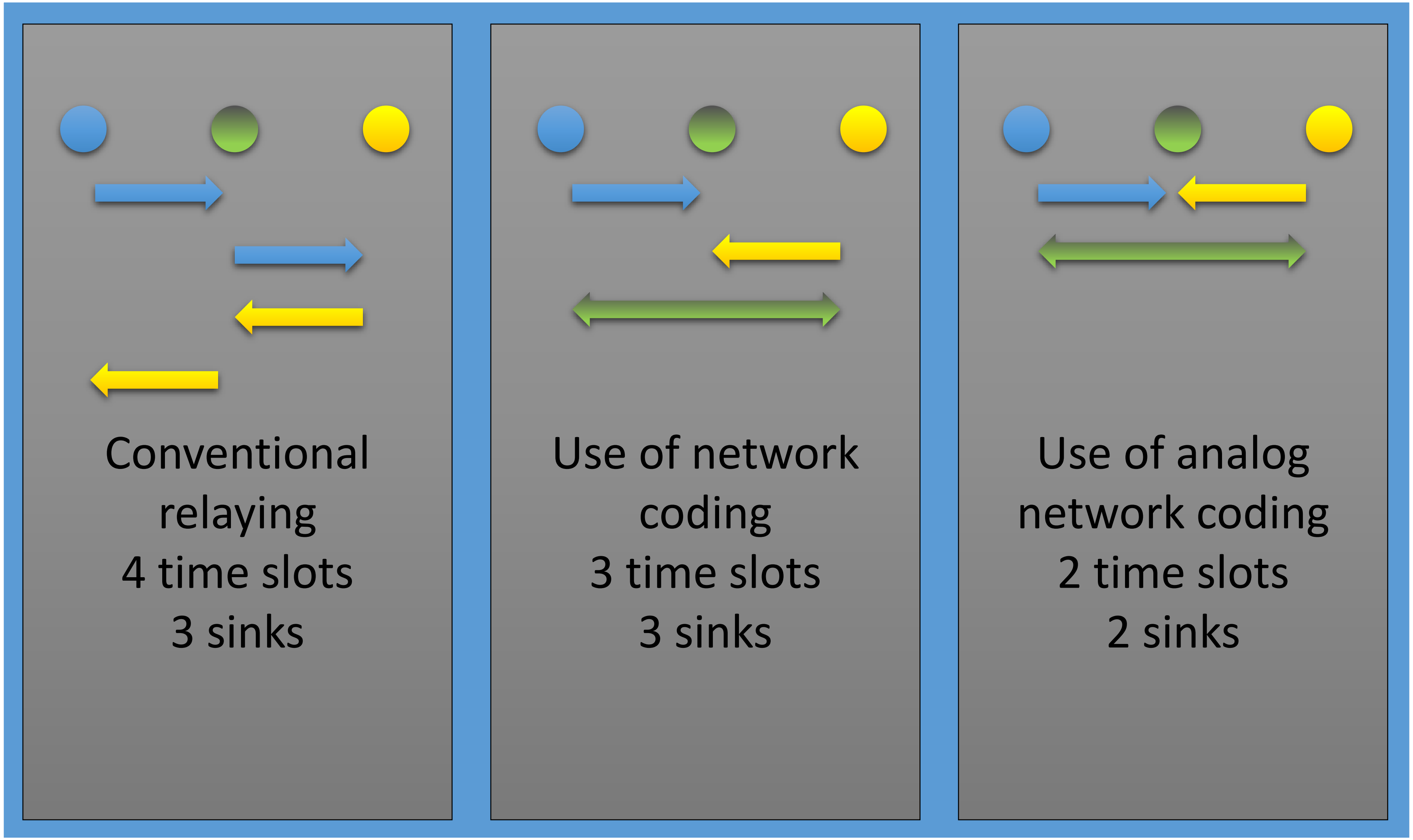


Analog Network Coding

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

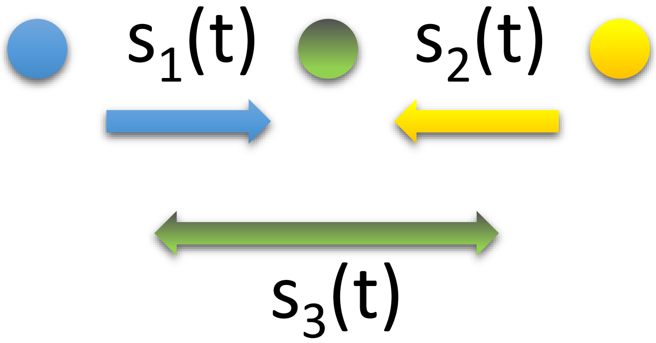


Analog Network Coding for Wireless Networks

- 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



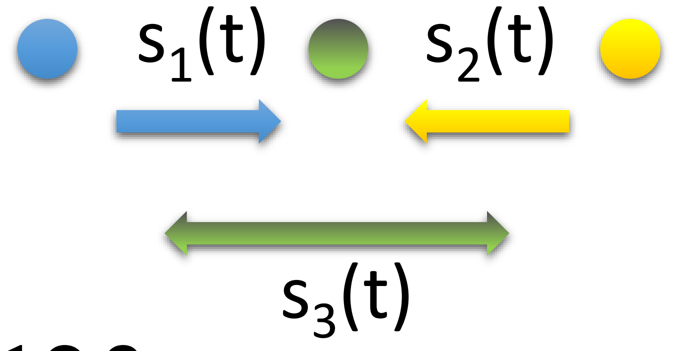
$$
\begin{aligned}
r_3(t) &= s_1(t) + s_2(t) + n(t) \\
&= [a_1 \cos(\omega t) + b_1 \sin(\omega t)] + [a_2 \cos(\omega t) + b_2 \sin(\omega t)] + n(t) \\
&= (a_1 + a_2)\cos(\omega t) + (b_1 + b_2)\sin(\omega t) + n(t)
\end{aligned}
$$

- 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 $a_1 + a_2$:

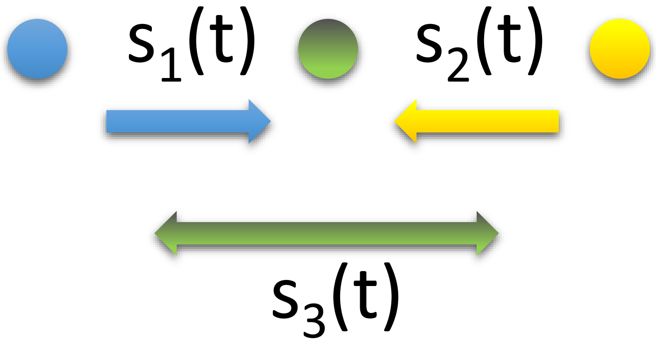
- ”-2” and ”2” correspond to $a_1 = a_2$
- ”0” corresponds to $a_1 = -a_2$

Physical Layer Network Coding

Example with BPSK:

Let us generate $s_3(t)$

(hint: XOR-like operation)



If $a_1 = a_2$, then $a_3 = 1 \quad (\text{logical "0"})$

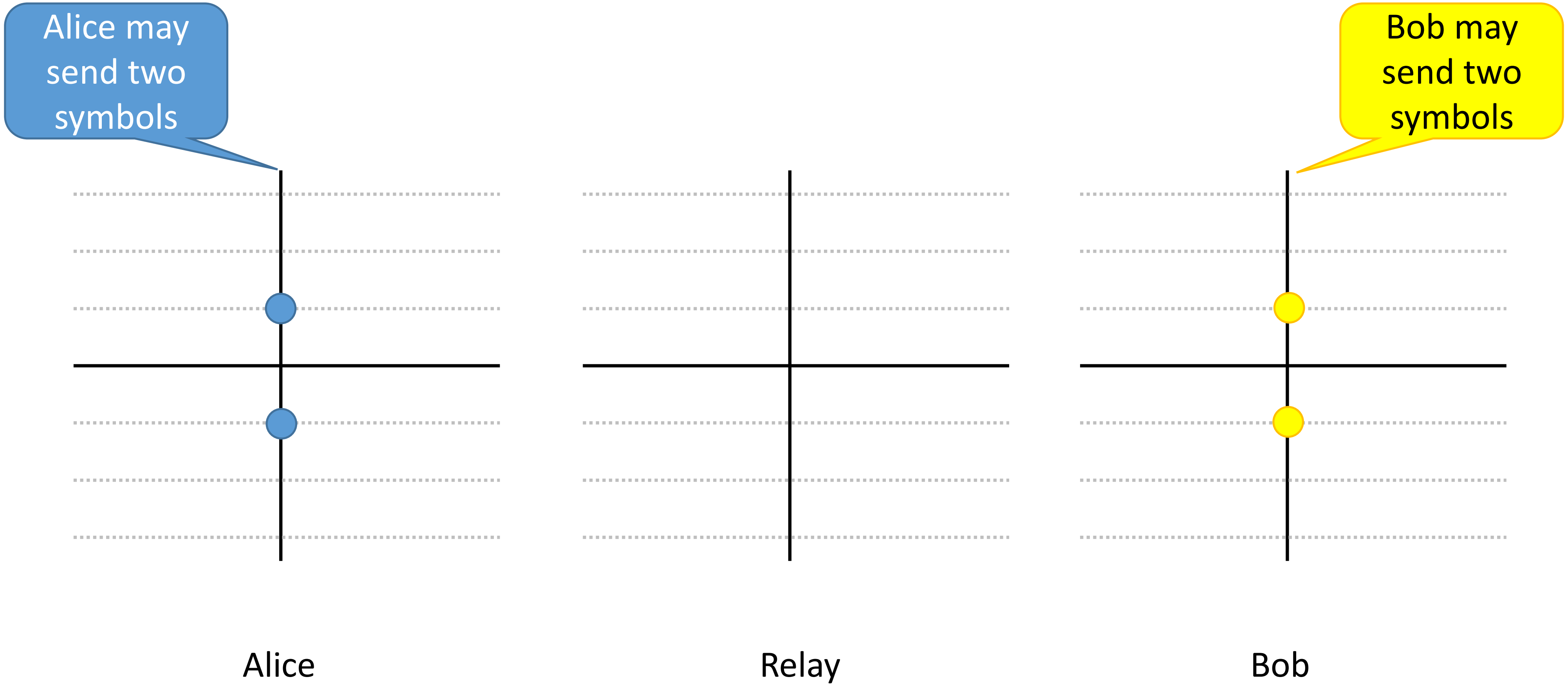
If $a_1 = -a_2$, then $a_3 = -1 \quad (\text{logical "1"})$

Alice and Bob receive as standard BPSK modulation

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

Analog Network Coding

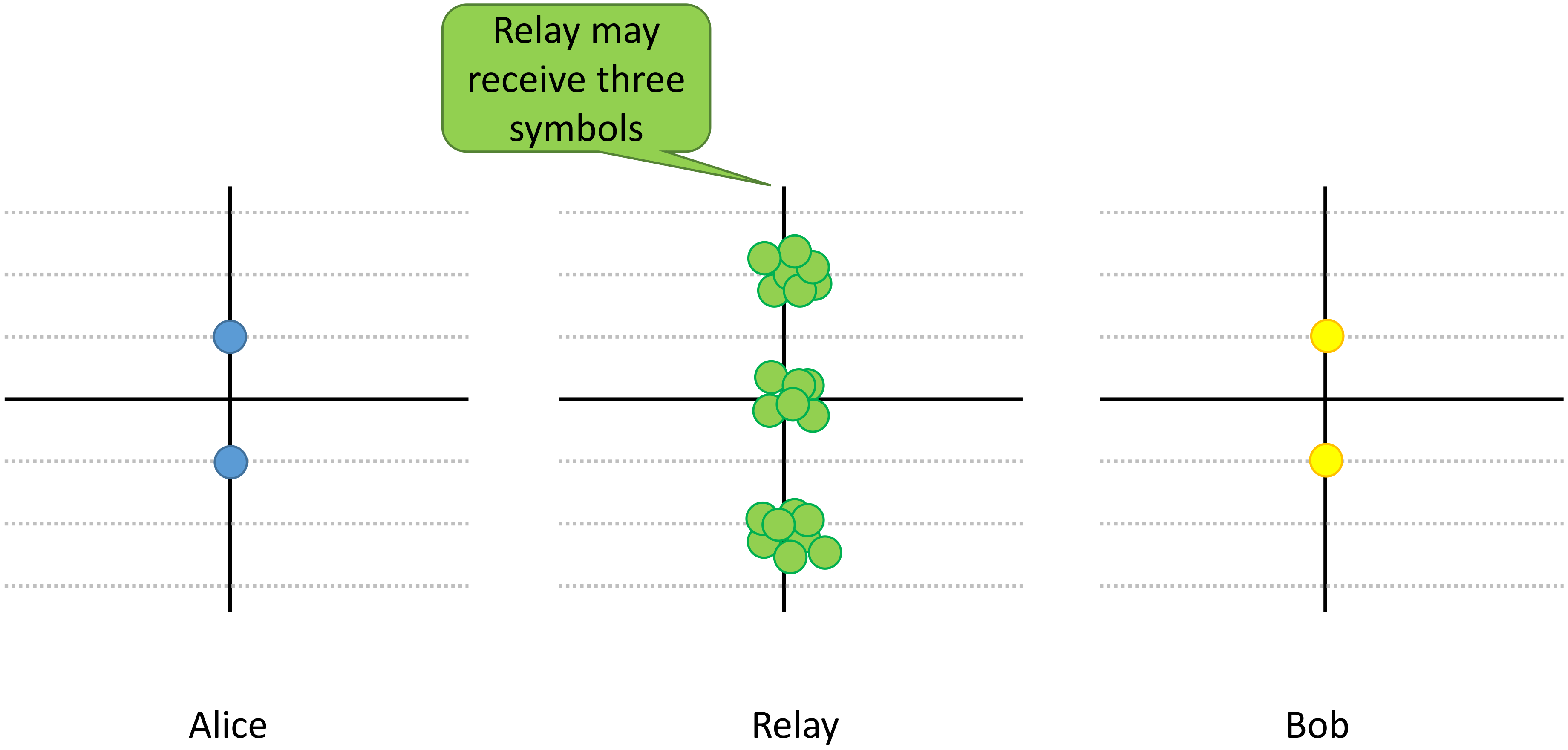
What if we A&F? 1st step – coding in the air



BPSK Example

Analog Network Coding

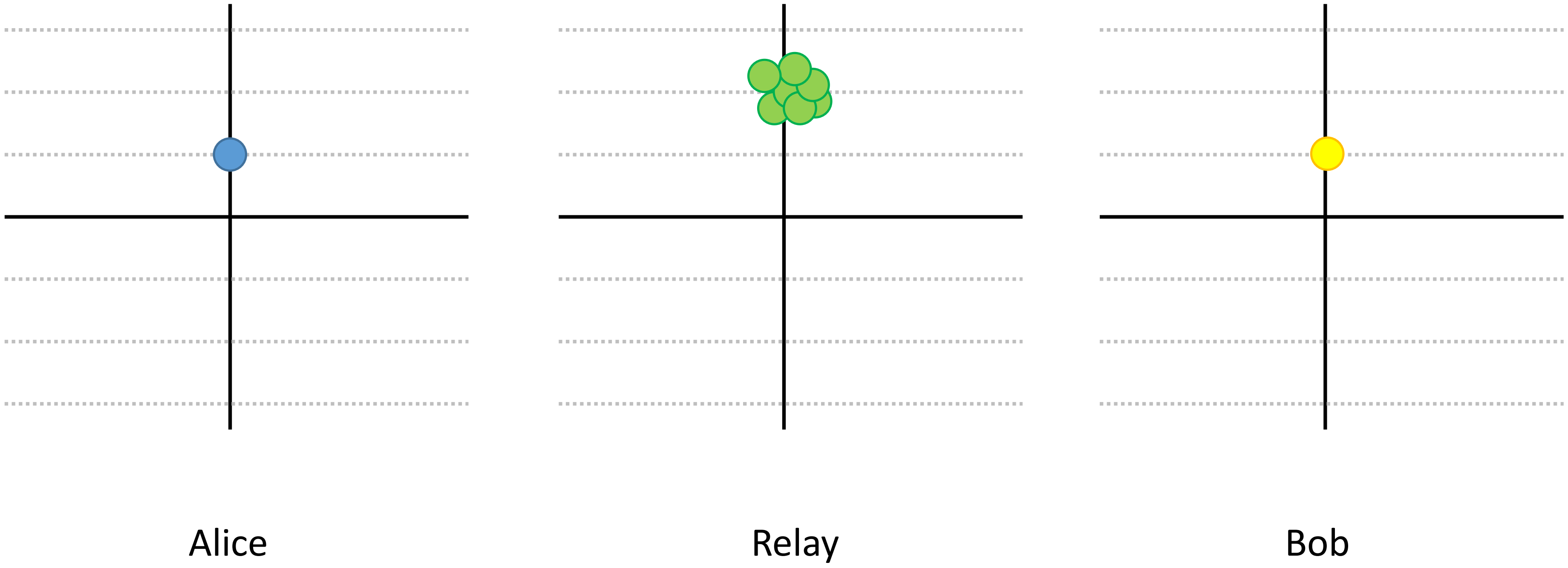
What if we A&F? 1st step – coding in the air



BPSK Example

Analog Network Coding

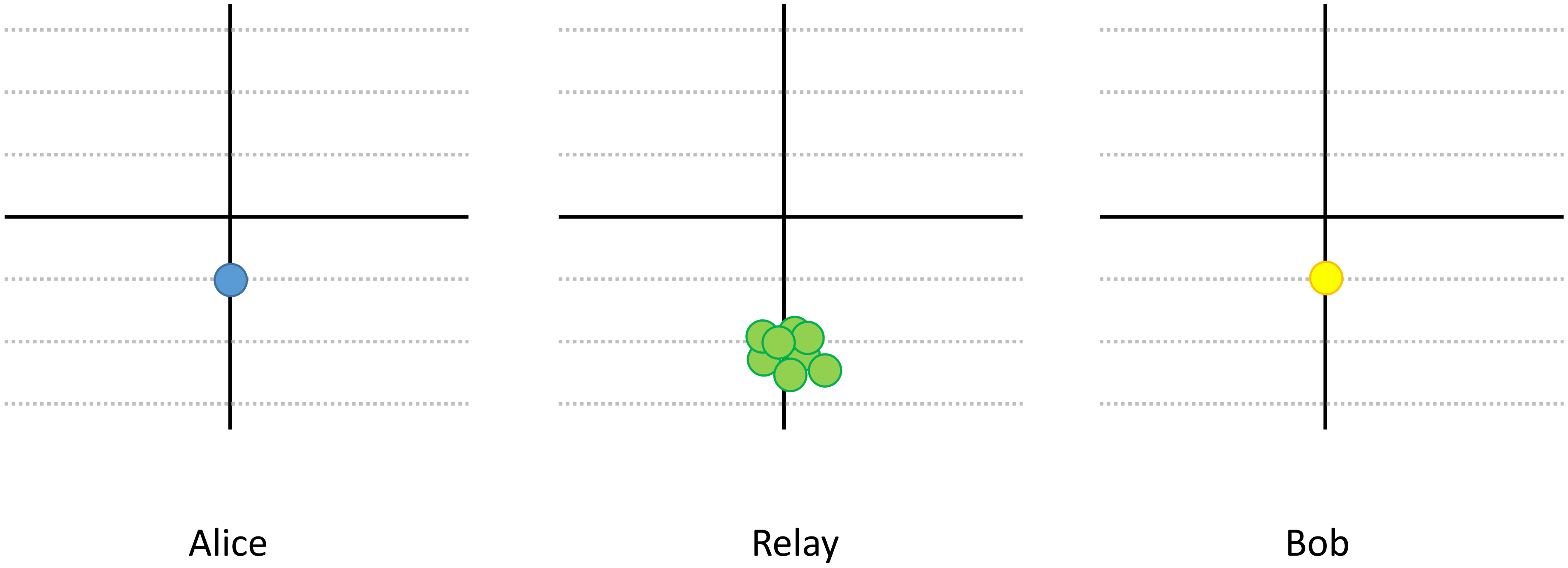
1st step – coding in the air – e.g. 1/1



BPSK Example

Analog Network Coding

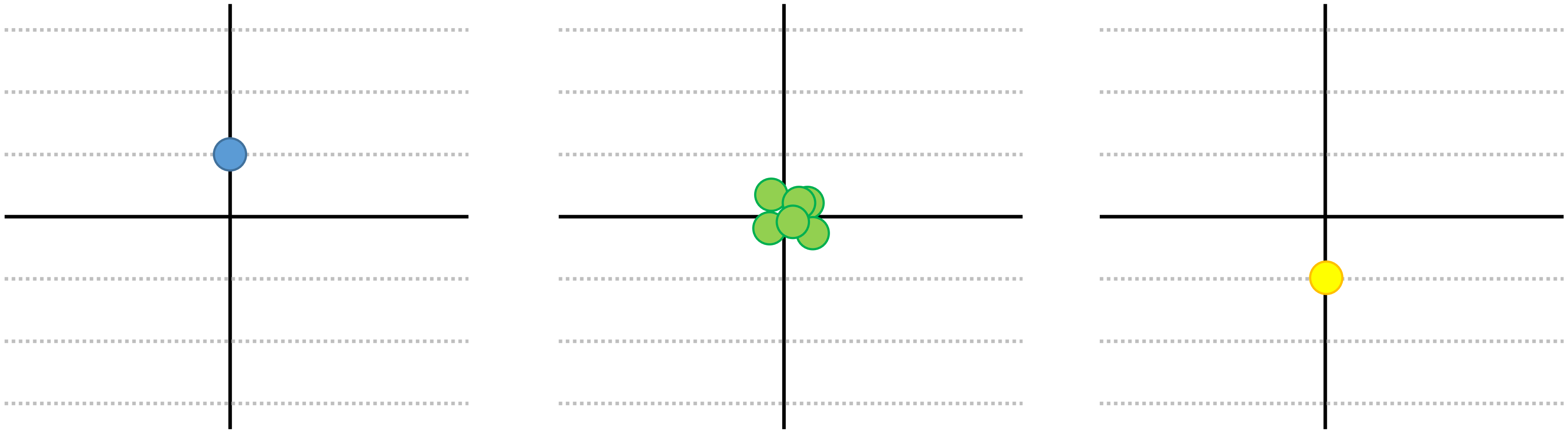
1st step – coding in the air – e.g. 0/0



BPSK Example

Analog Network Coding

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

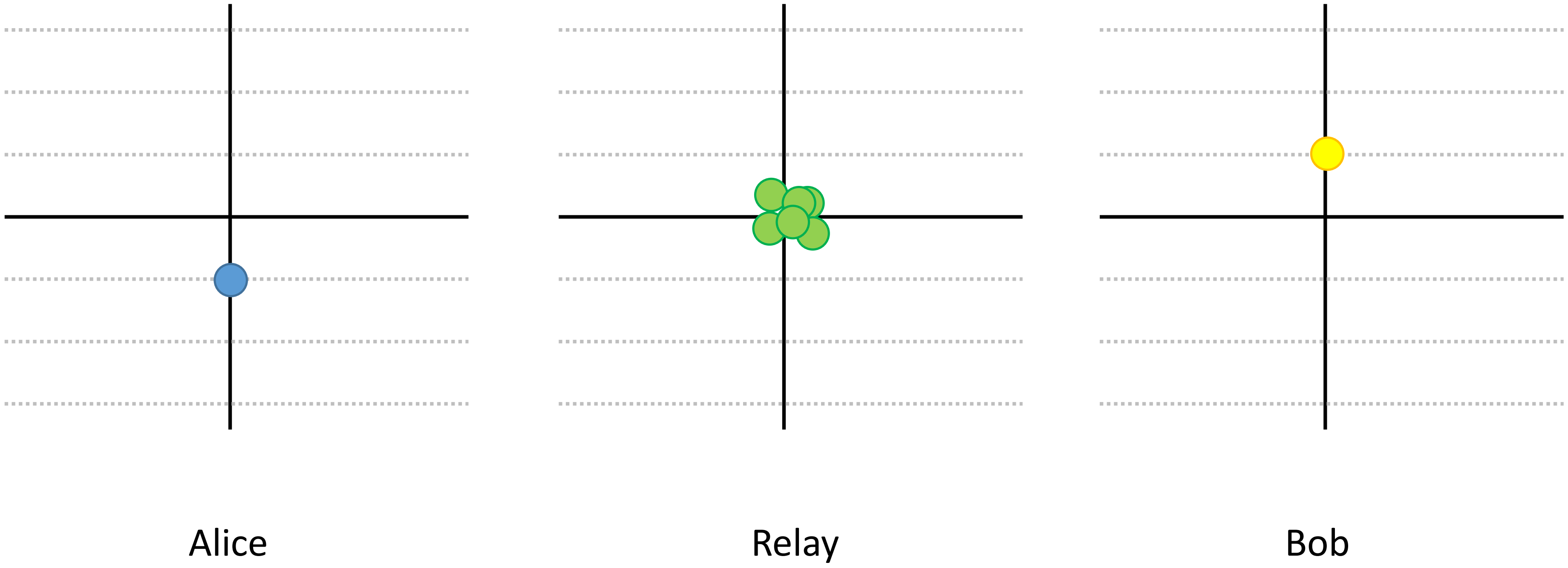


Alice | Relay | Bob

BPSK Example

Analog Network Coding

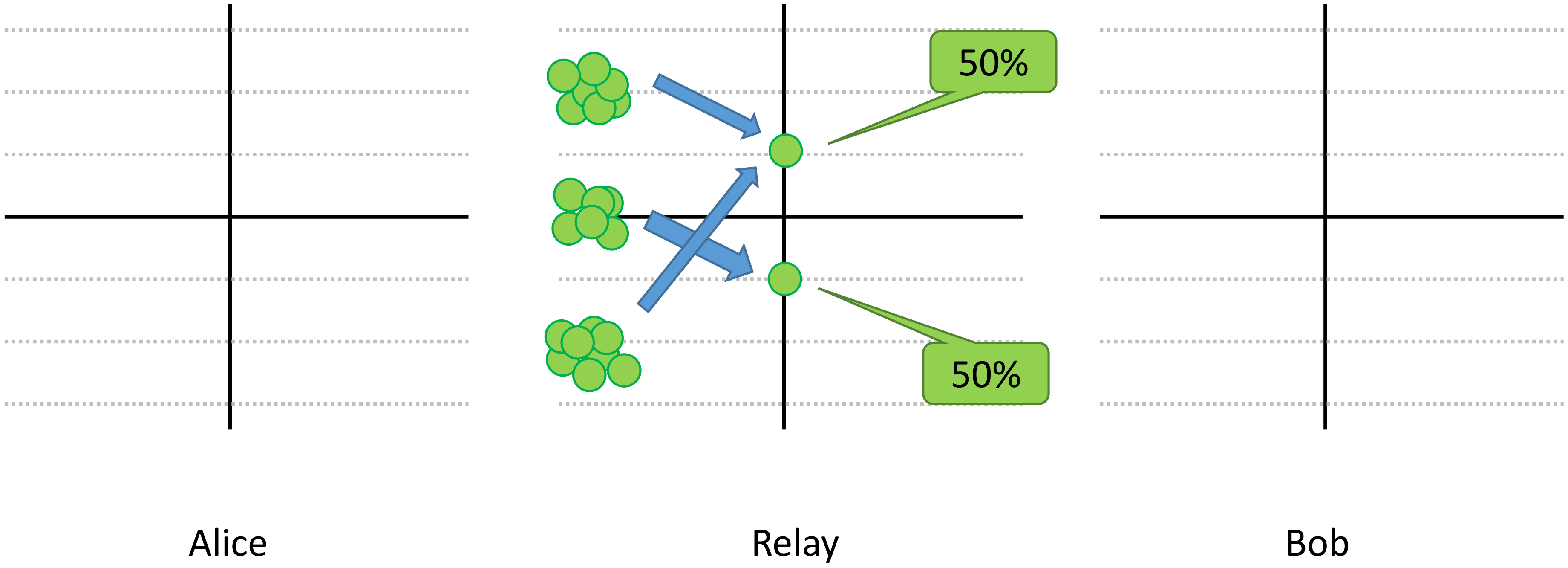
1st step – coding in the air – e.g. 0/1



BPSK Example

Analog Network Coding

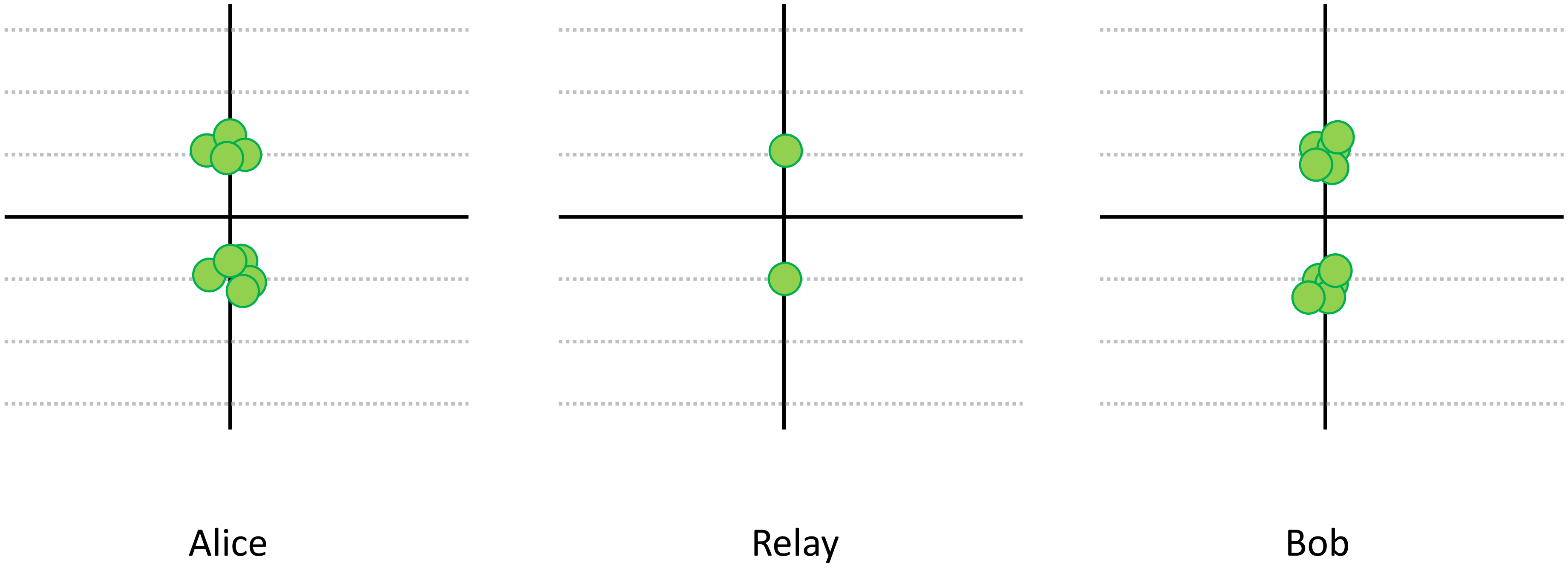
2nd step - relay



BPSK Example

Analog Network Coding

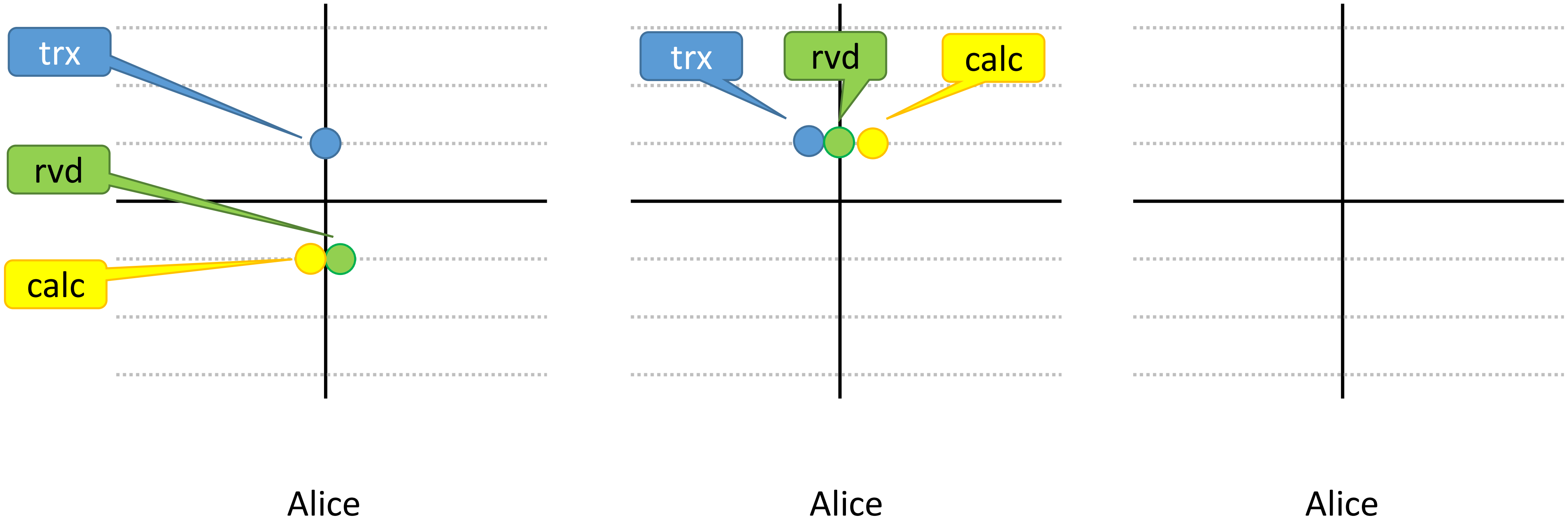
2nd step - relay



BPSK Example

Analog Network Coding

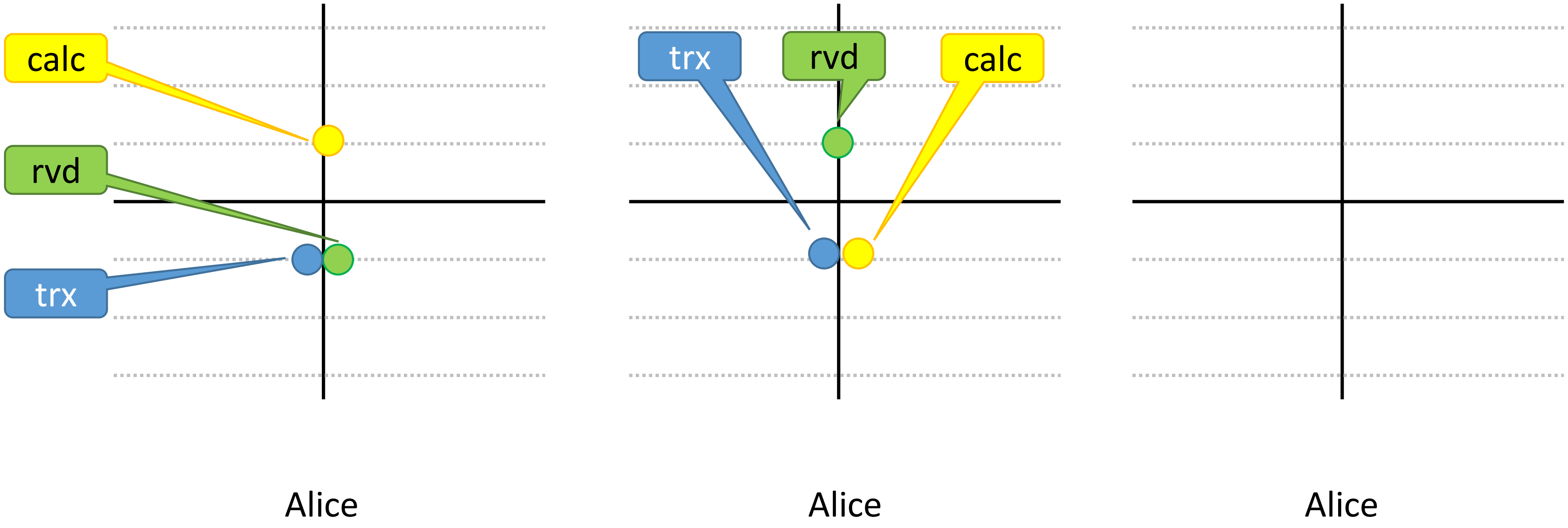
3rd step decoding



BPSK Example

Analog Network Coding

3rd step decoding



BPSK Example

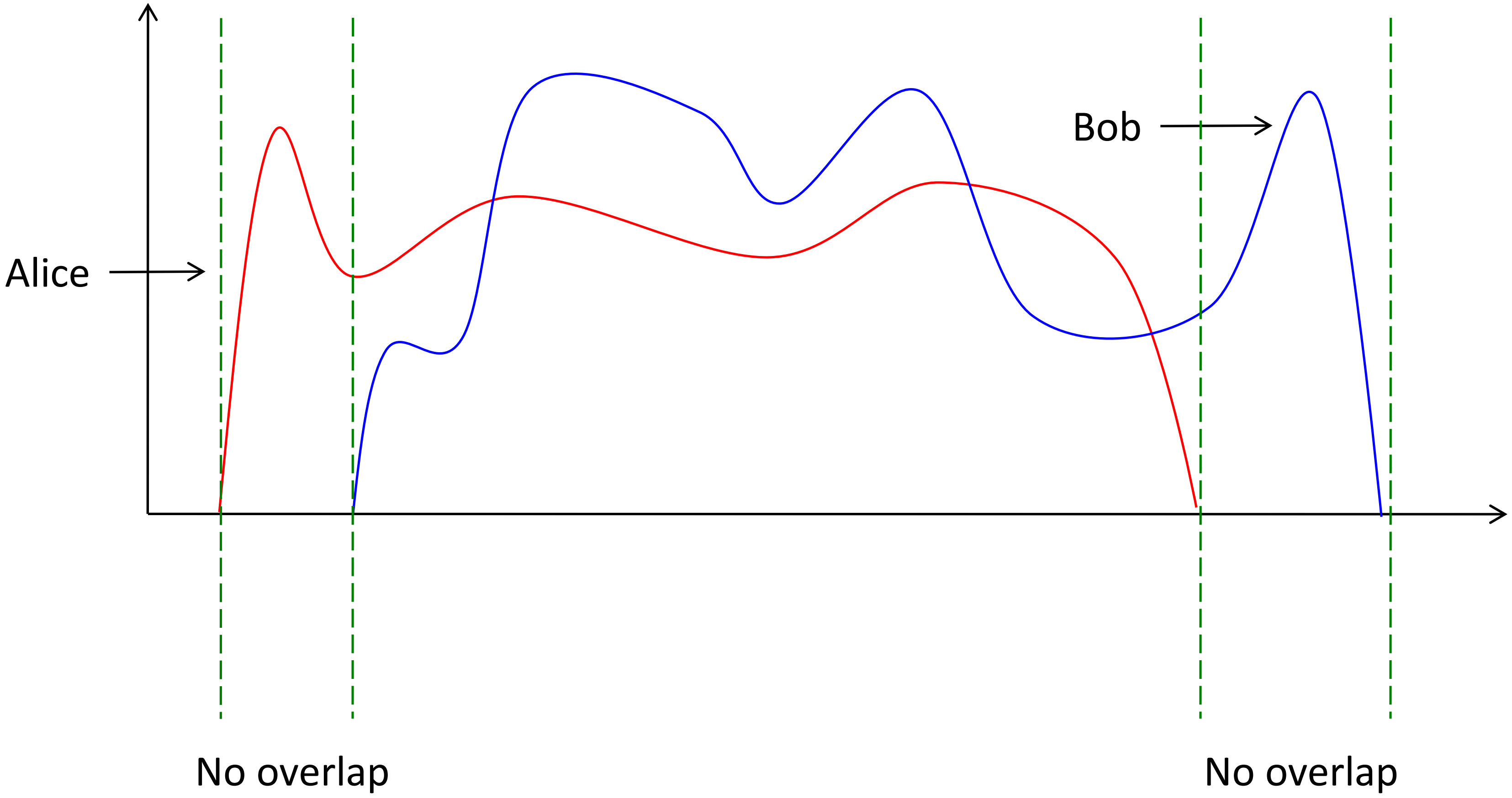
Analog Network Coding

- 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)

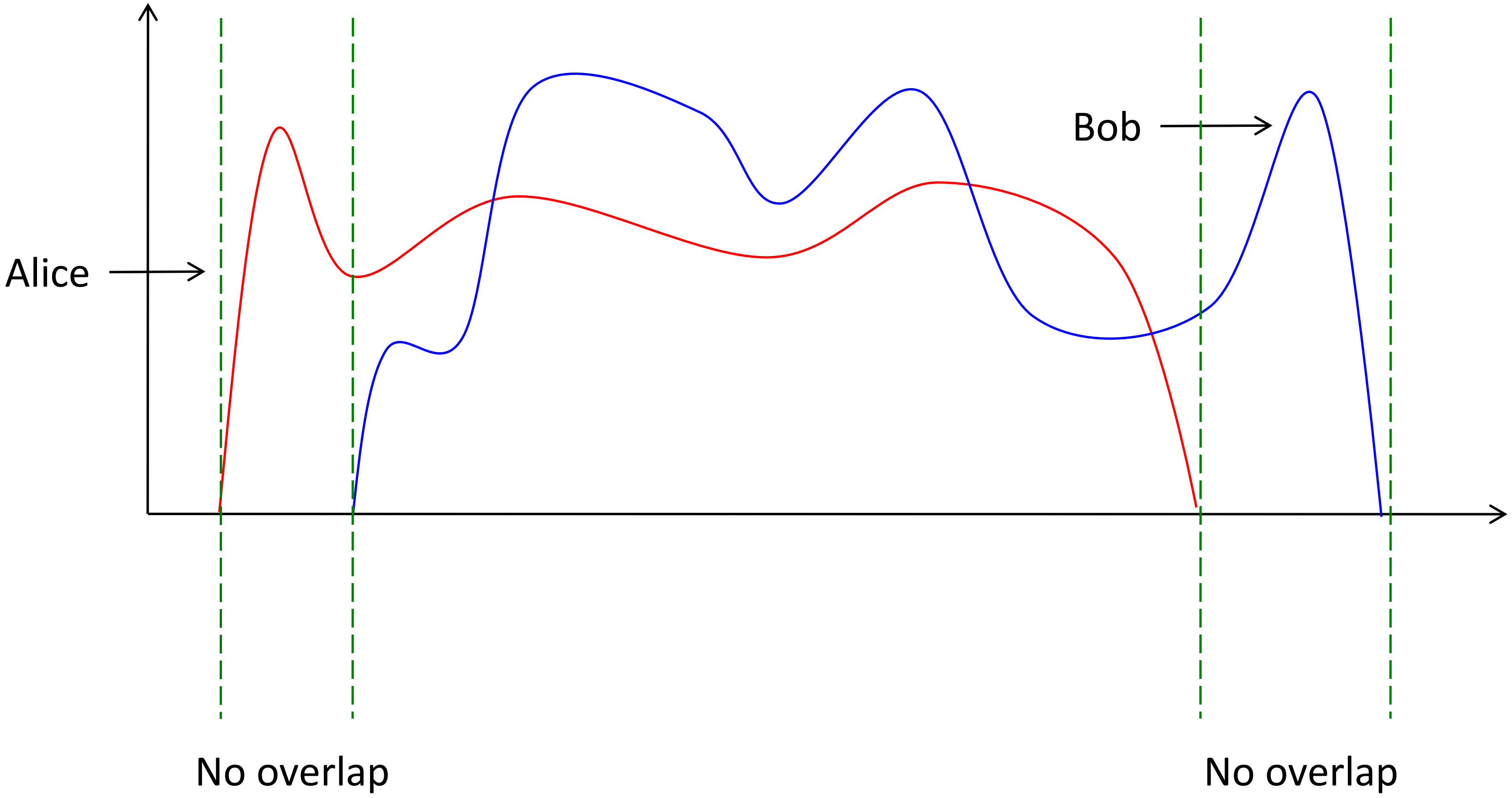
Analog Network Coding

- Key intuition: exploit asynchrony [Katti et al 2007]



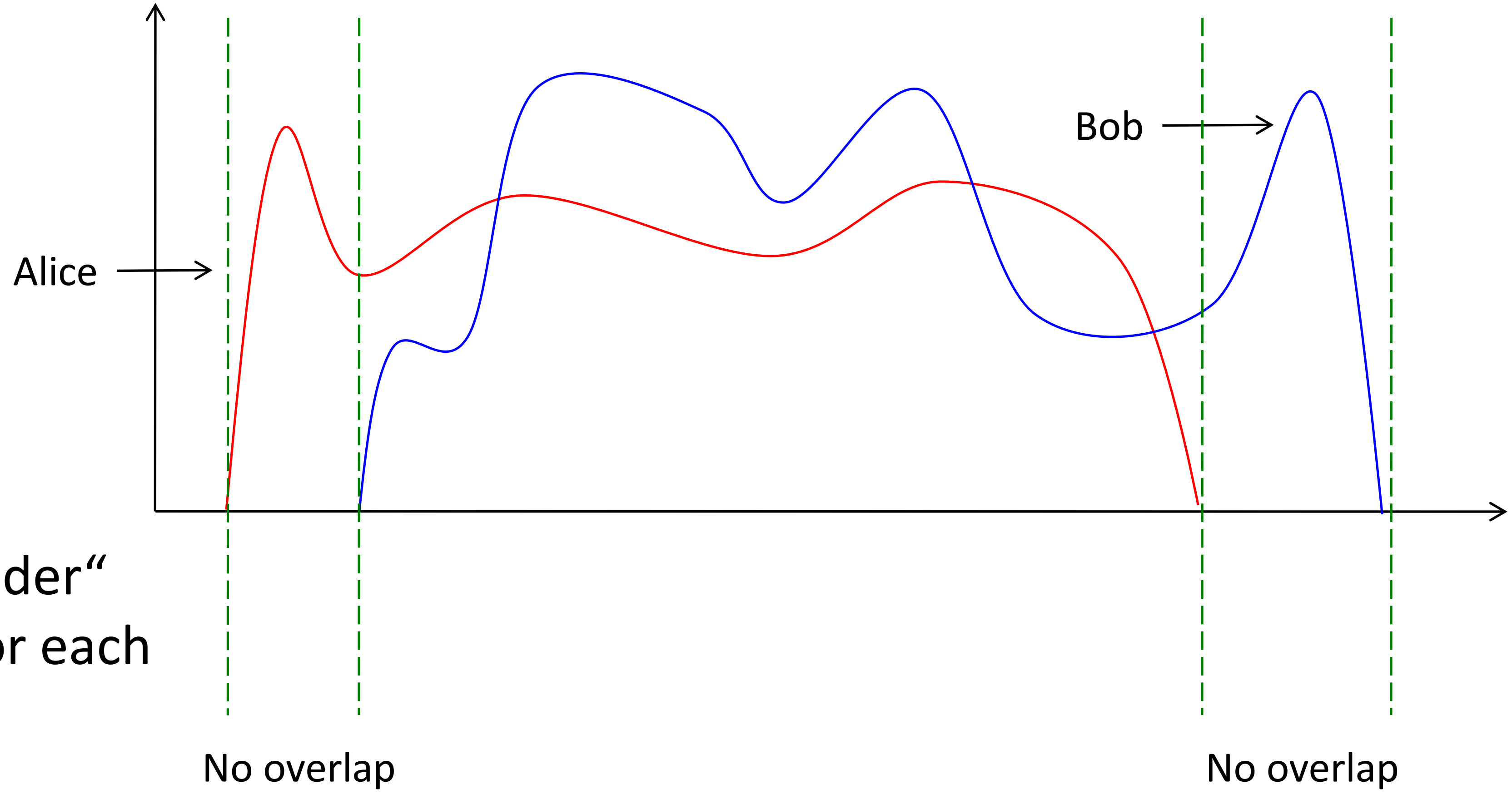
Analog Network Coding

- Areas with no overlap allow us to address some of the key challenges



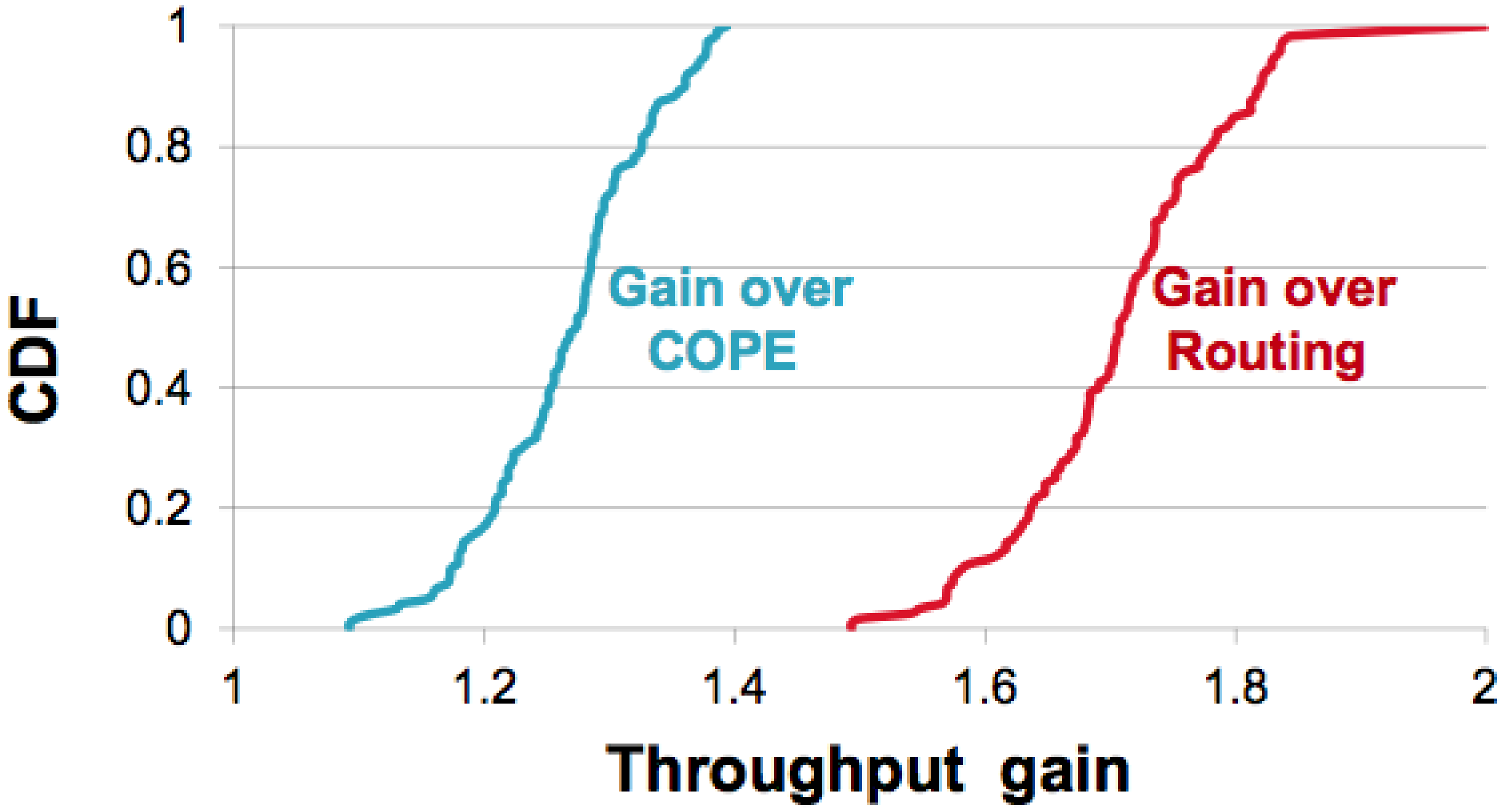
Analog Network Coding

- 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

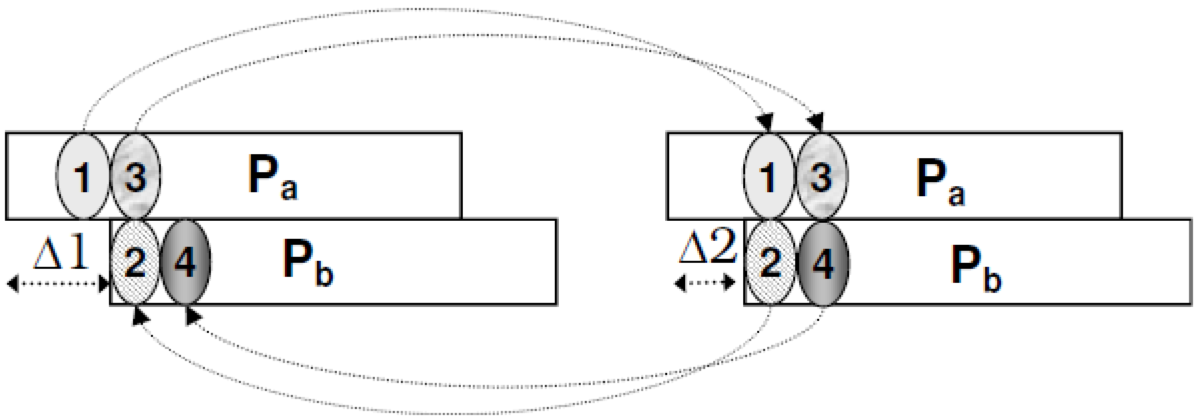


ZigZag Decoding

- 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]

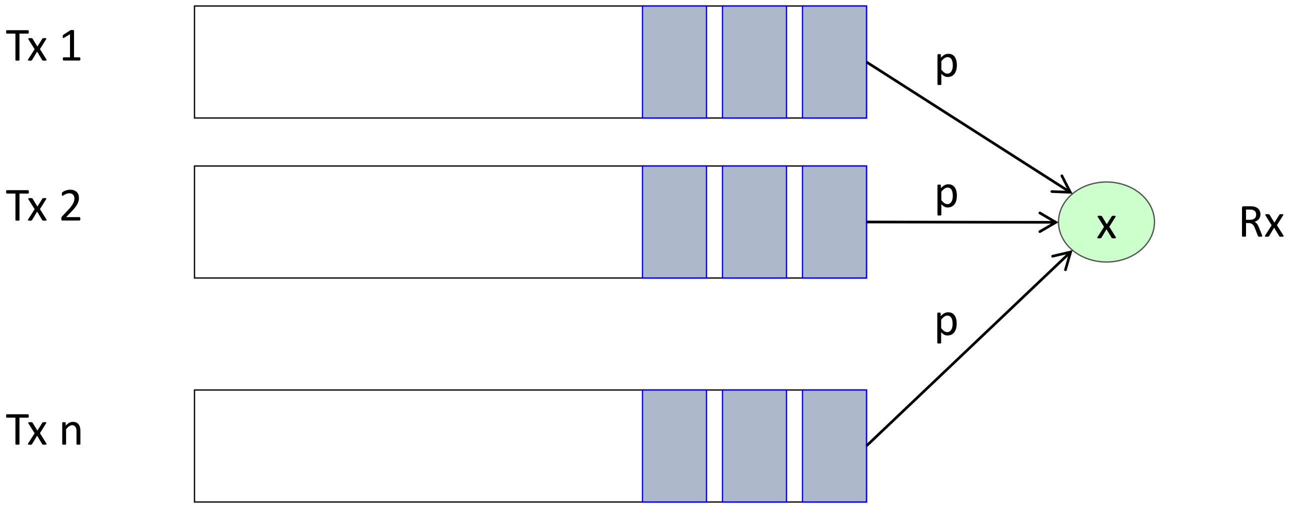
ZigZag Decoding: Basic Idea

- 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



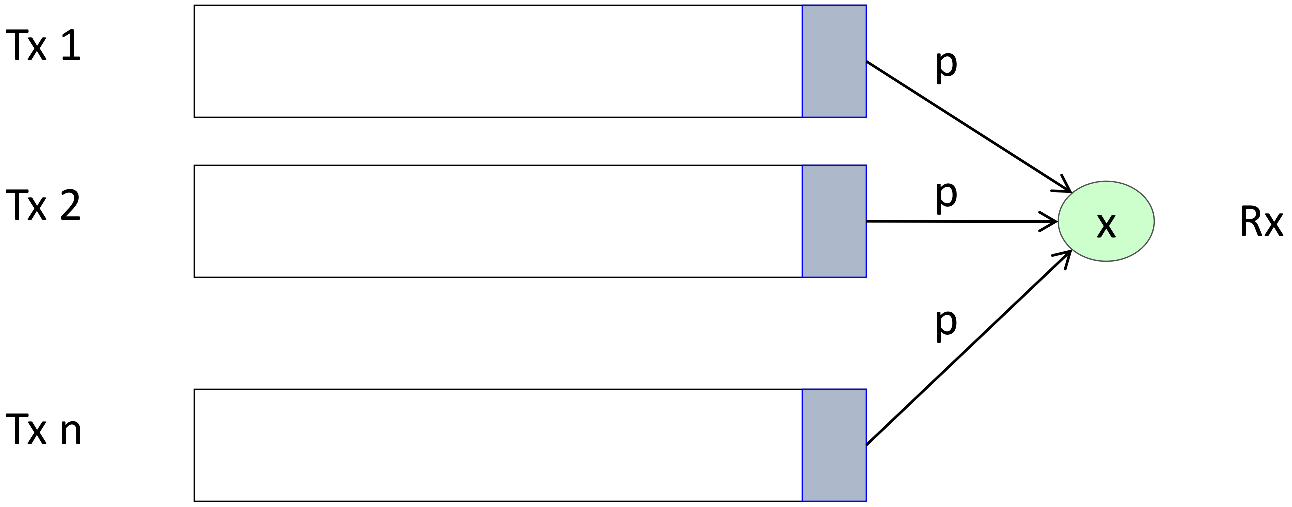
ZigZag Decoding: Single Hop Analysis

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

p = ½, n = 3

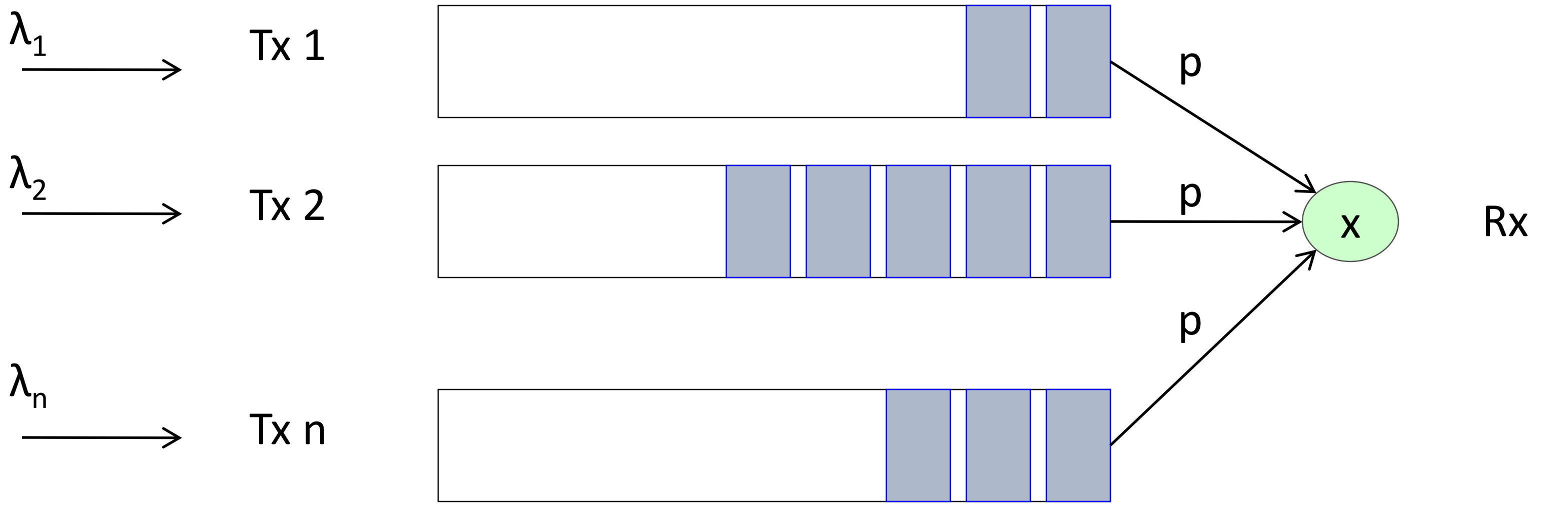
ZZ: 4+ 10/21

PS: 6

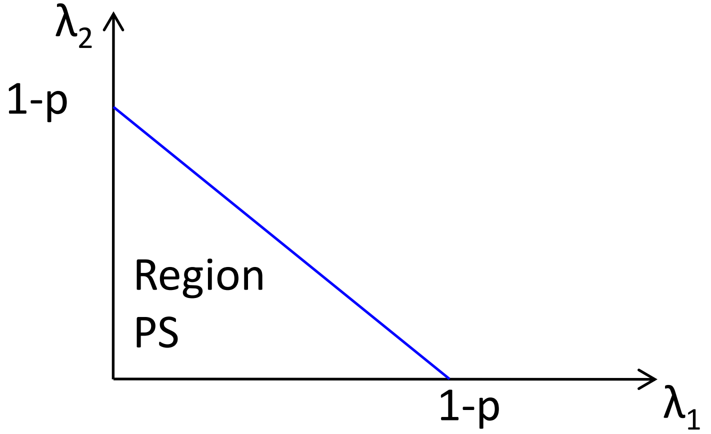
Perfect scheduler (no collisions): $$E[T_D] = \frac{n}{1-p}$$

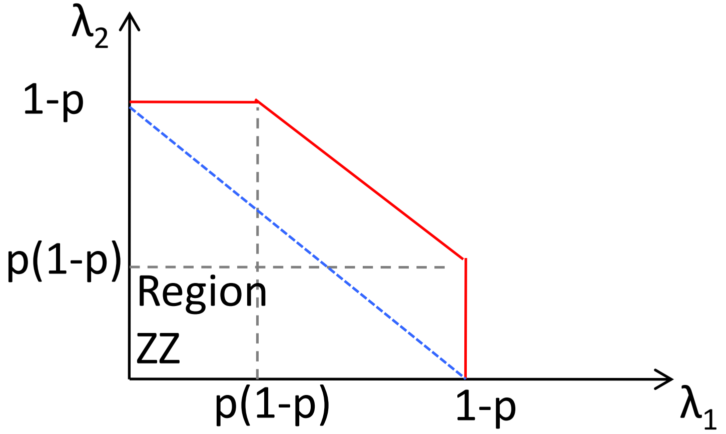
ZigZag Decoding: Single Hop Analysis

Work in [ParandehGheibi et al 2010] http://arxiv.org/pdf/1001.1948v1.pdf



Second result: Stable throughput increases



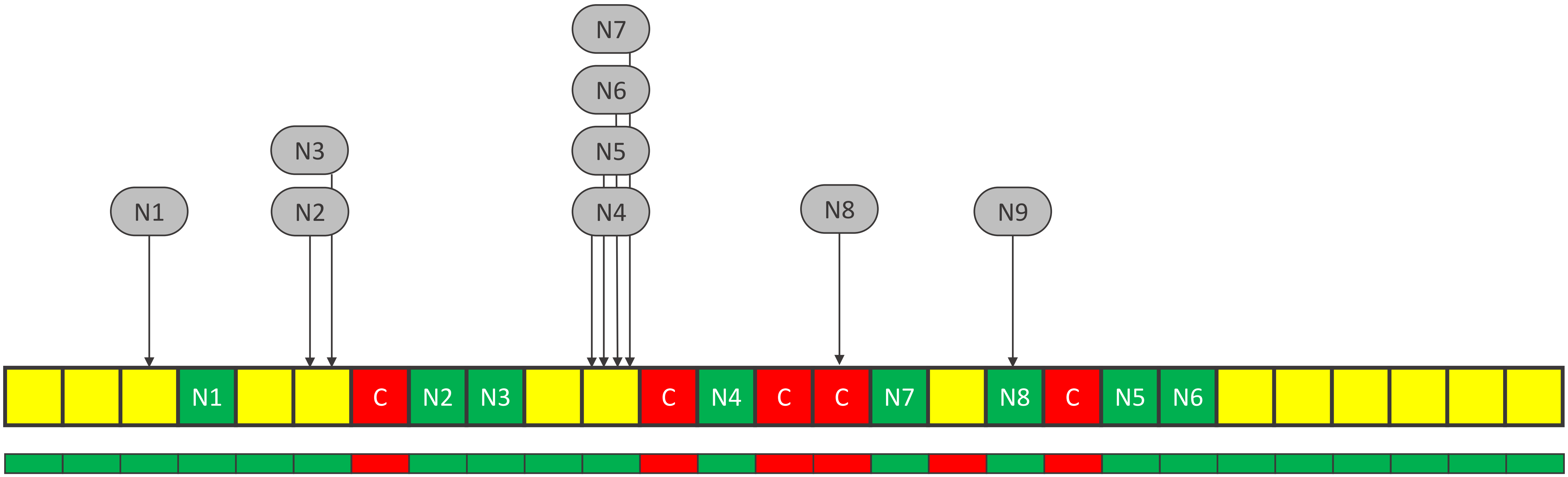


Coded Access

Multiple Access SoA

- Random access was the key to get access to the scheduler
- In time slotted systems
  - Idle slots: nobody was transmitting
  - One transmission: successful access to the resources
  - More than one transmission: Collision

SoA Access



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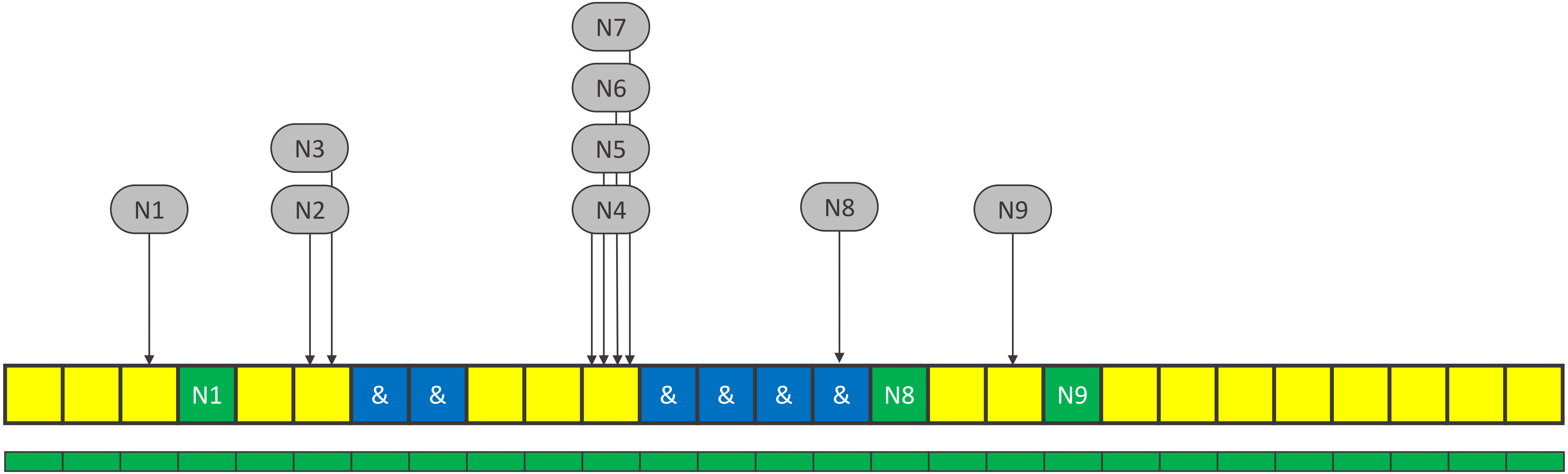
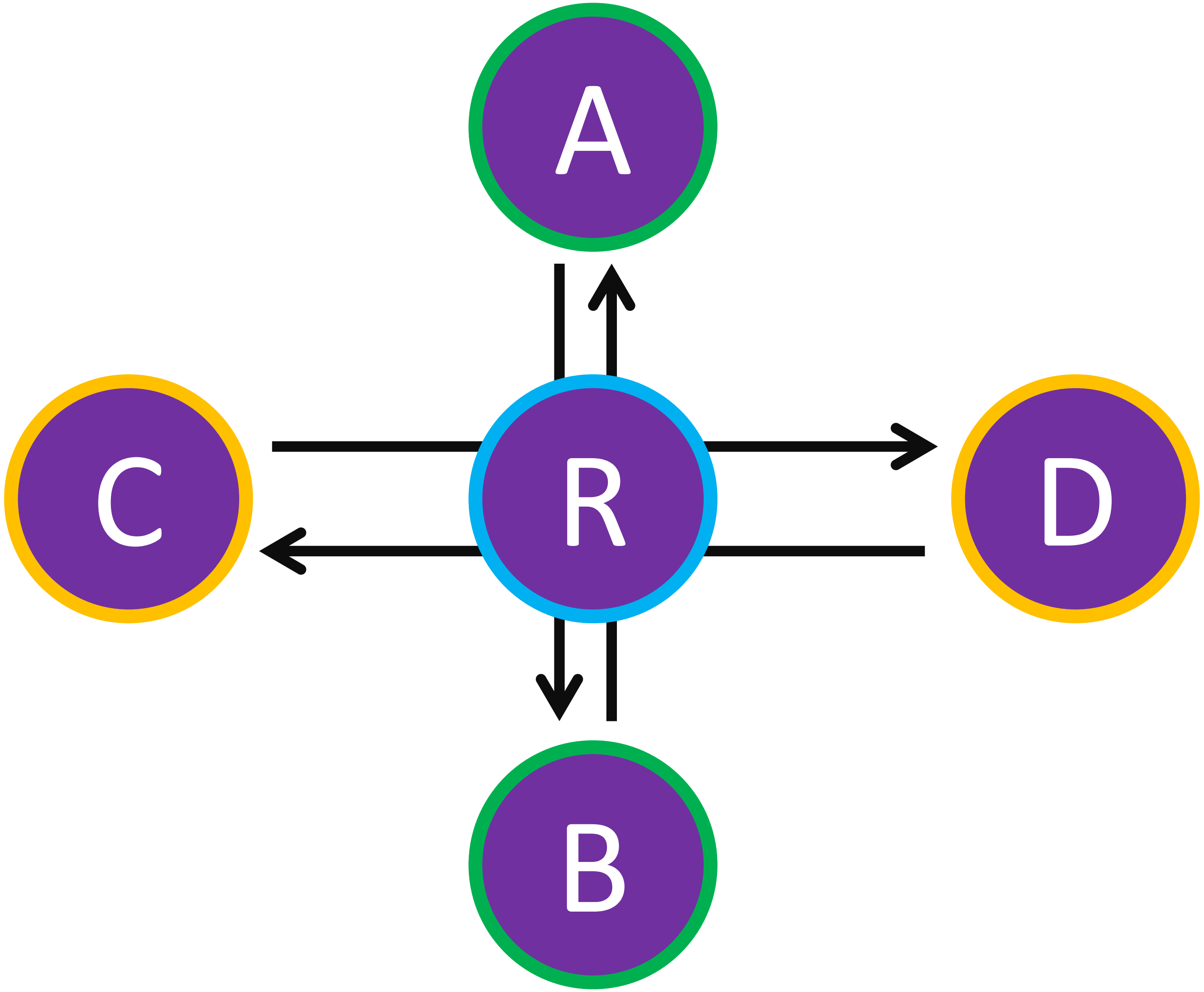
Coded Access

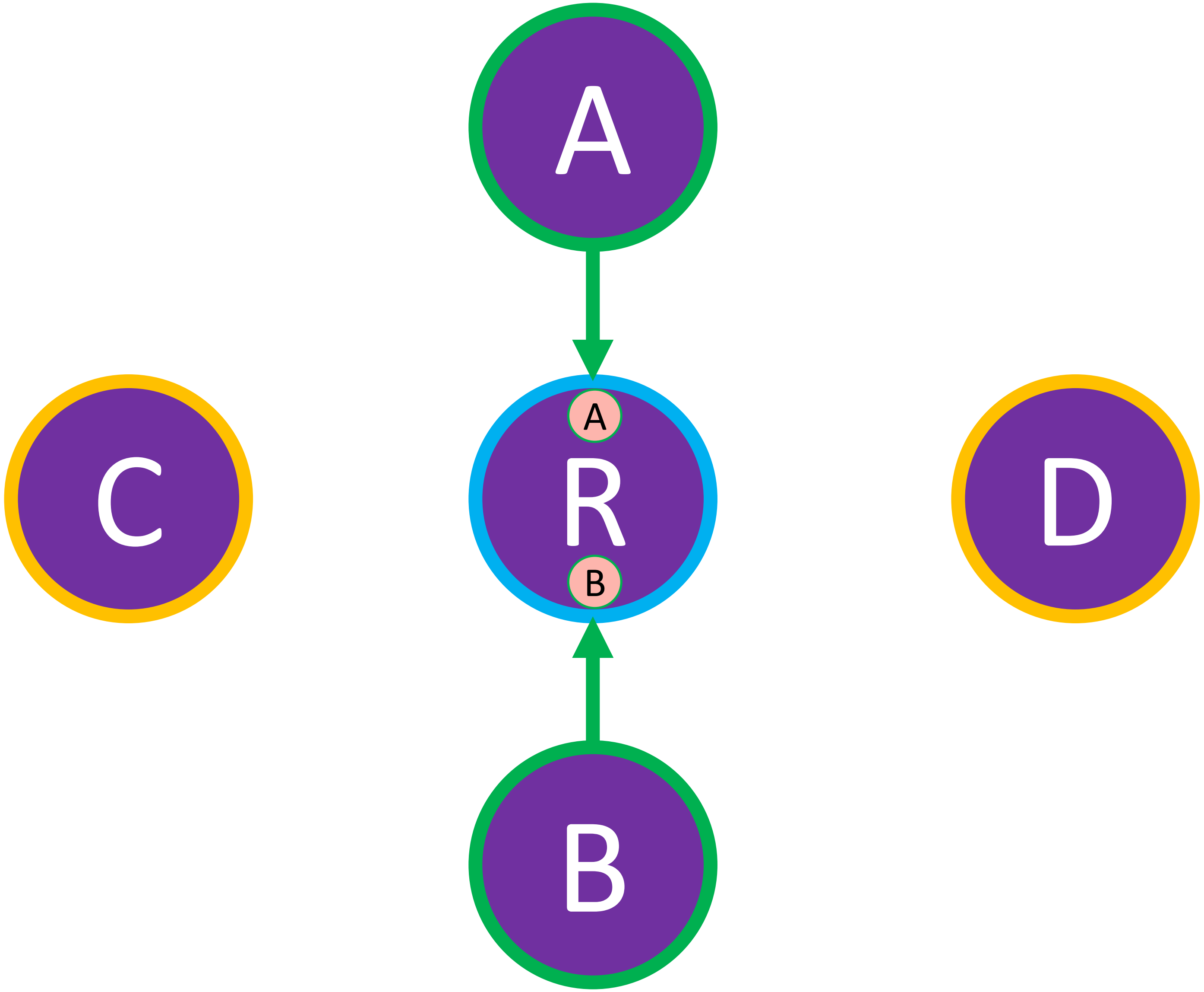


ANC for topologies

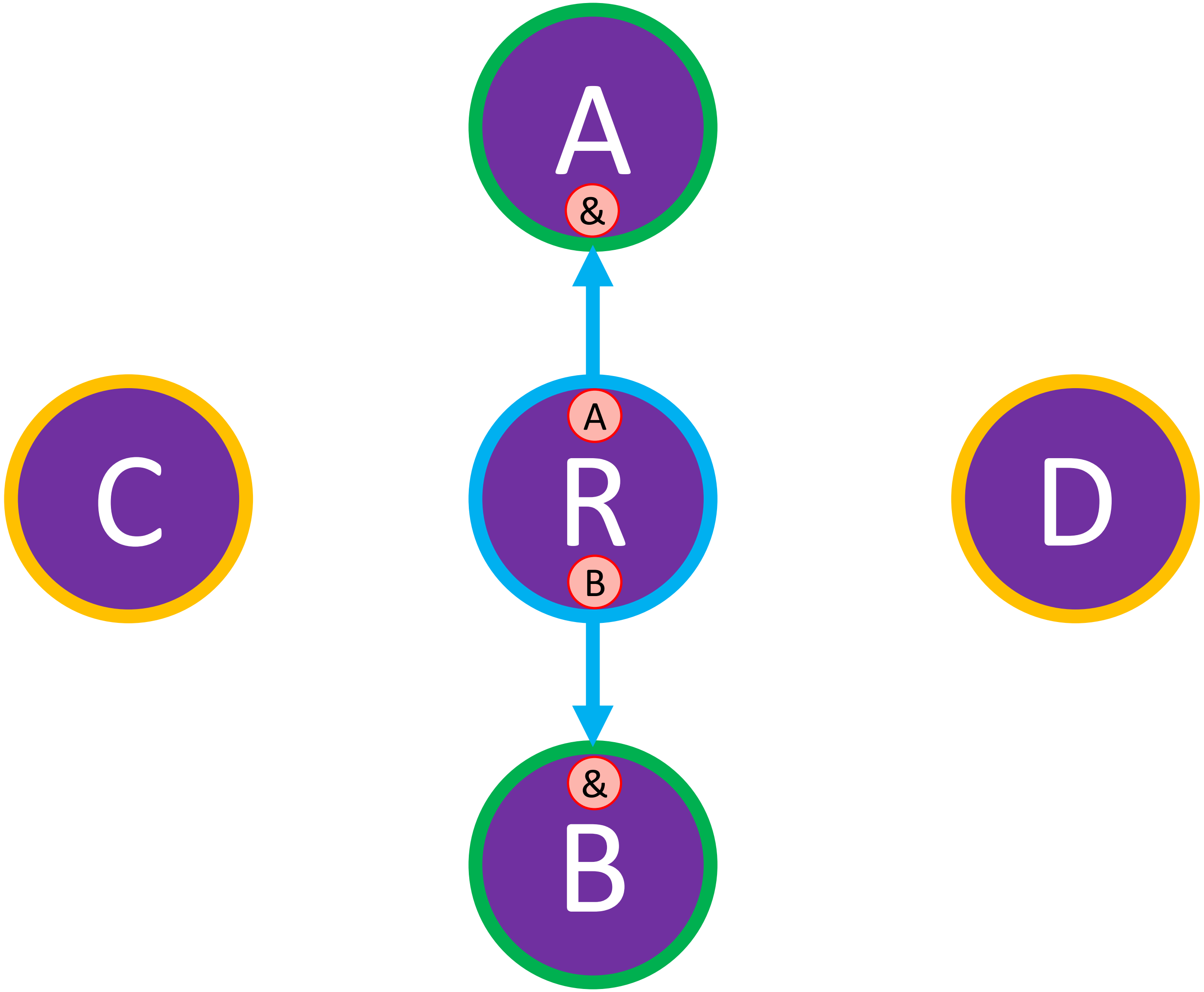
Cross Topology without Overhearing



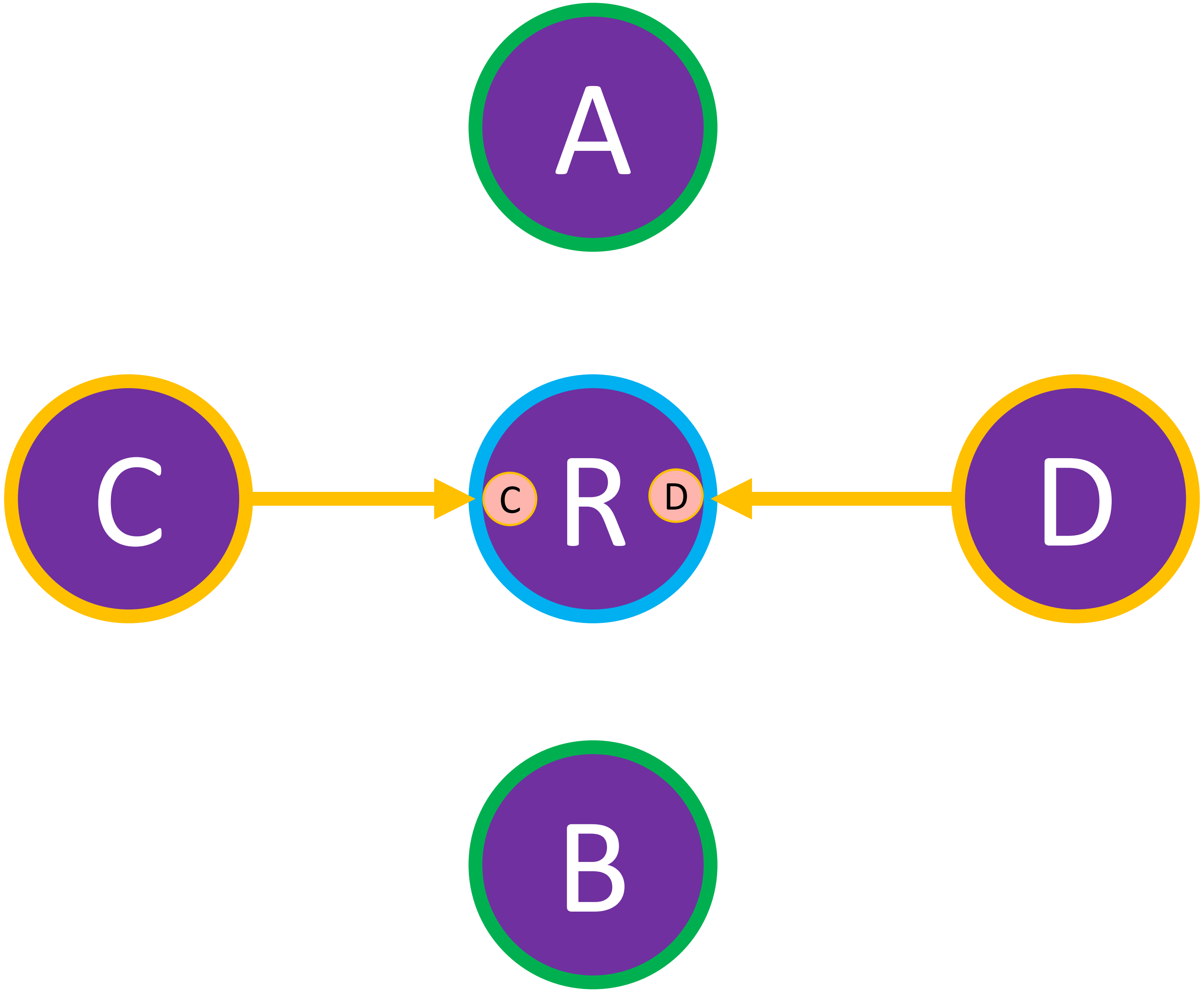
Cross Topology with Overhearing – Slot 1



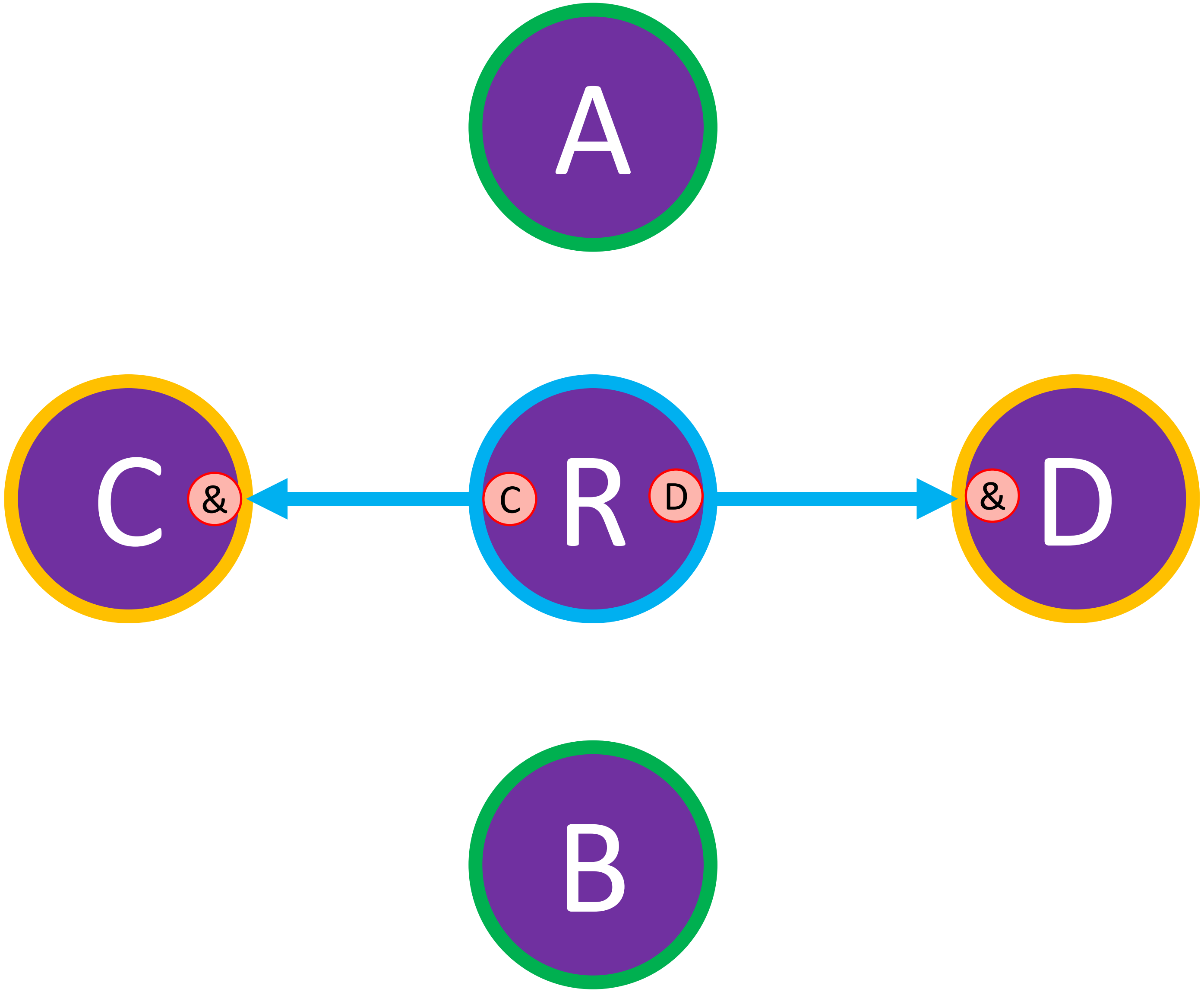
Cross Topology with Overhearing – Slot 2



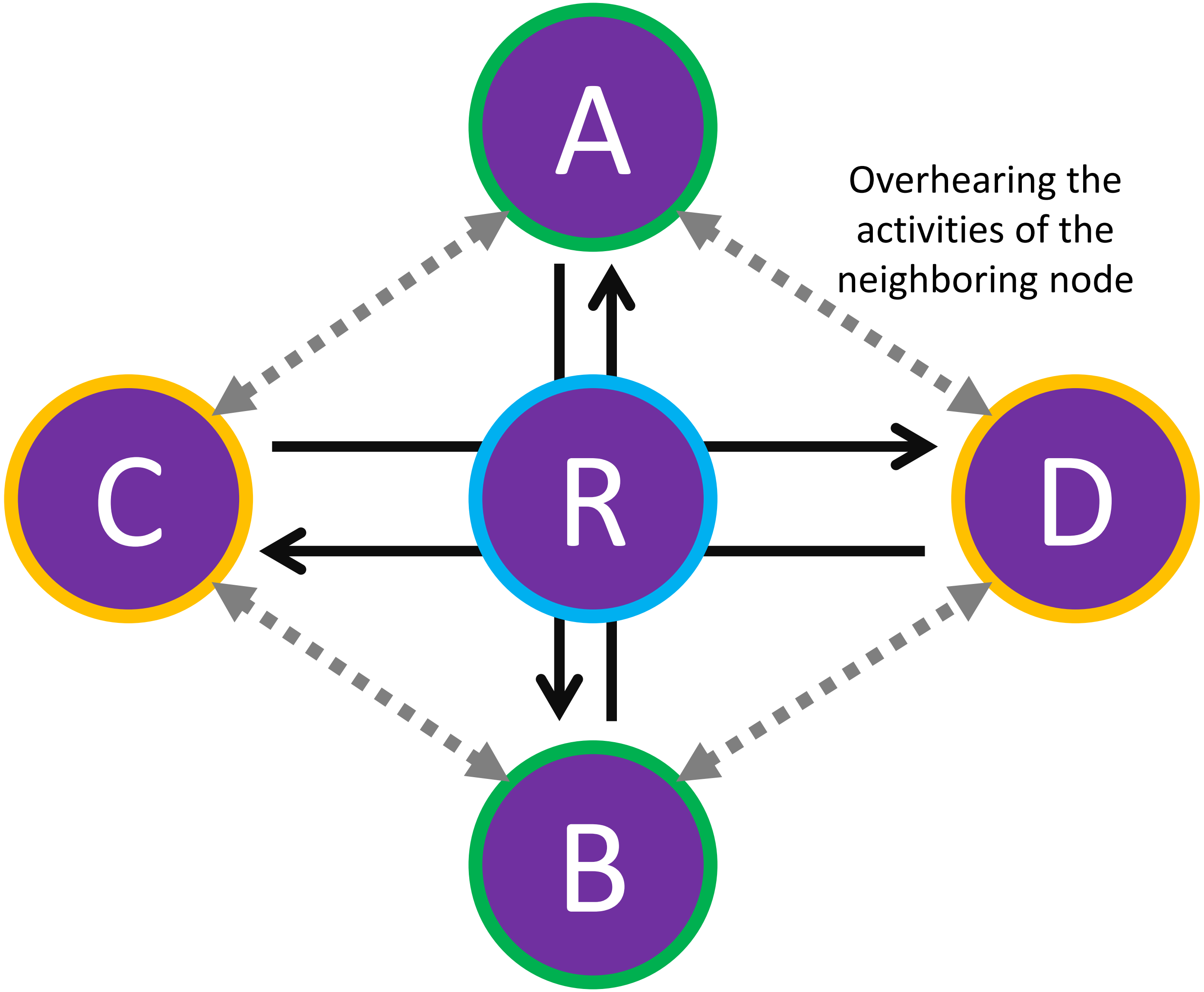
Cross Topology with Overhearing – Slot 3



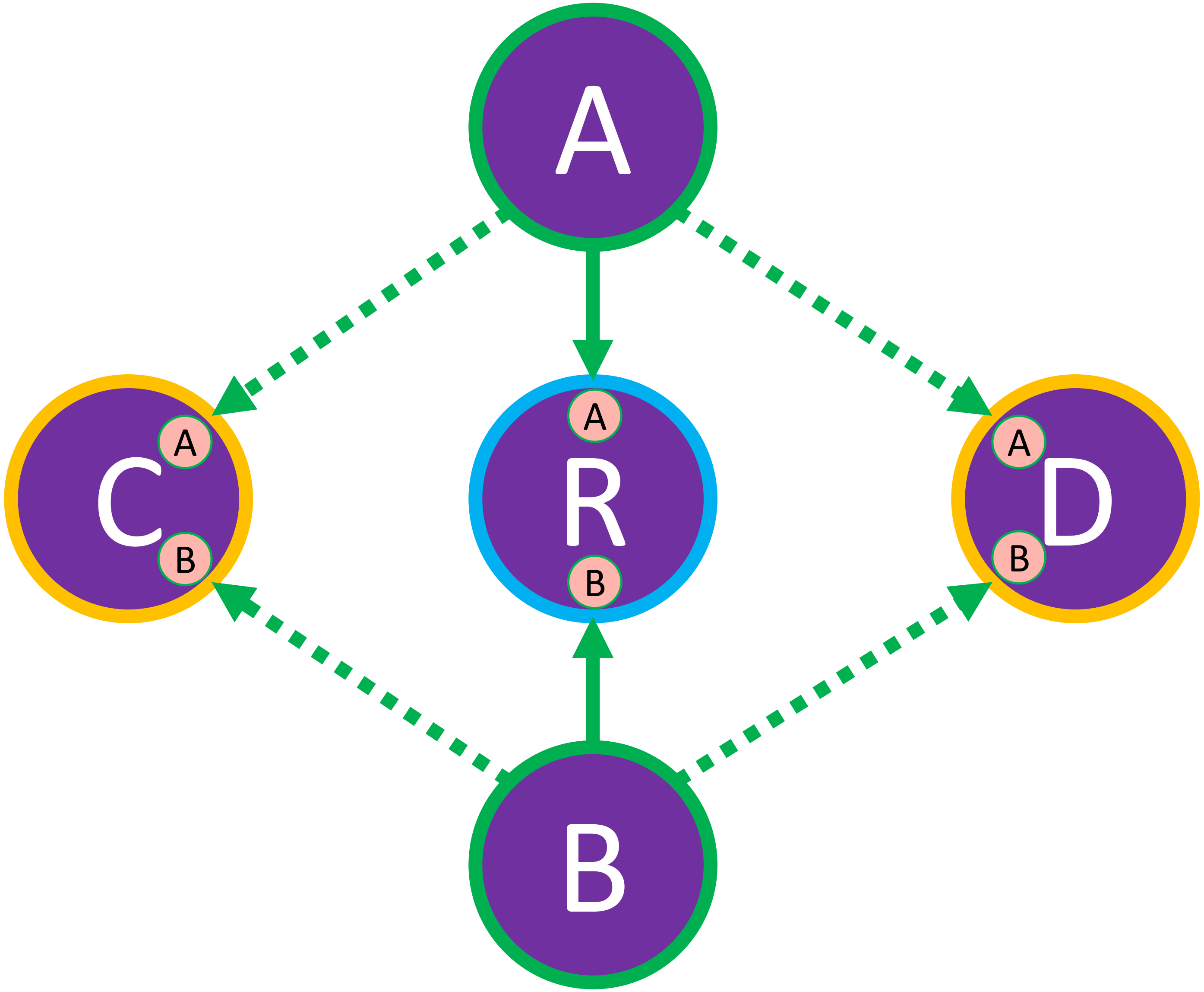
Cross Topology with Overhearing – Slot 4



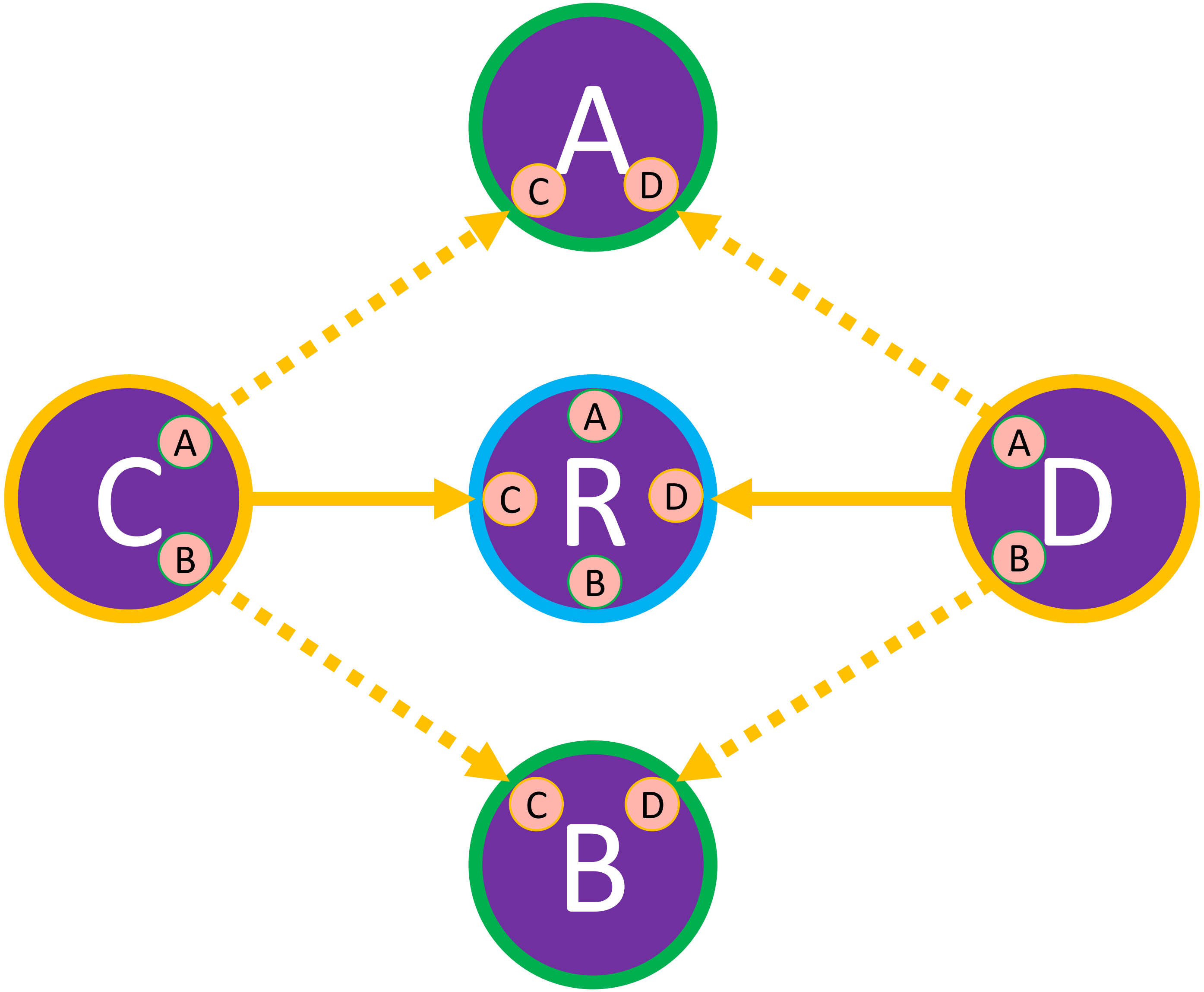
Cross Topology with Overhearing



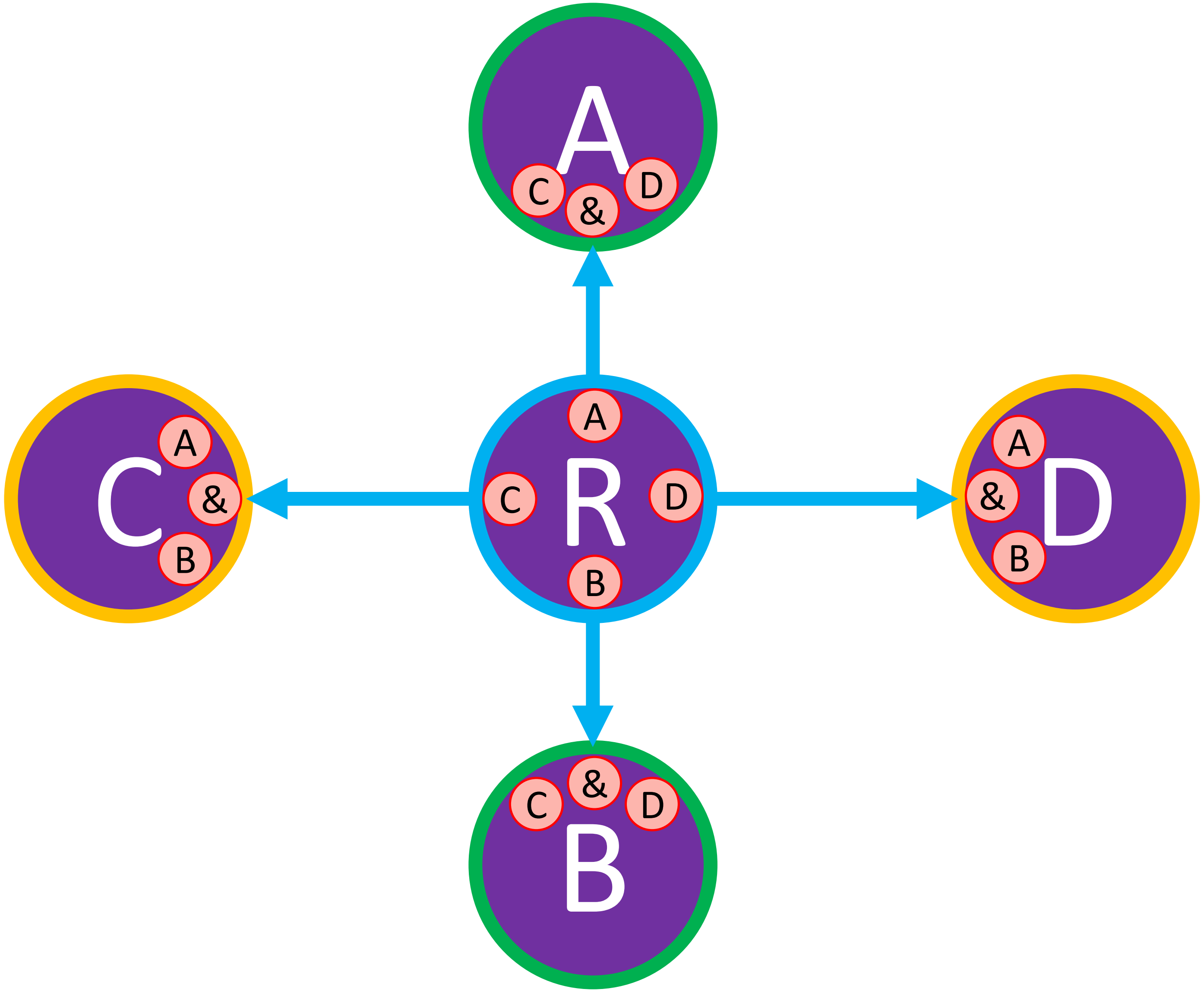
Cross Topology with Overhearing – Slot 1



Cross Topology with Overhearing – Slot 2



Cross Topology with Overhearing – Slot 3



Throughput for the Cross Topology