Network-Coded Multiple Access

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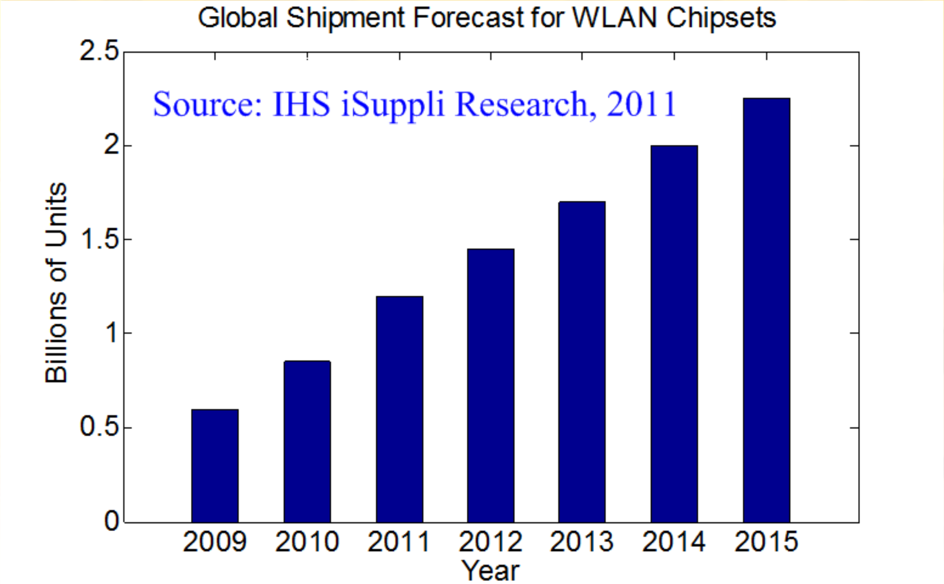
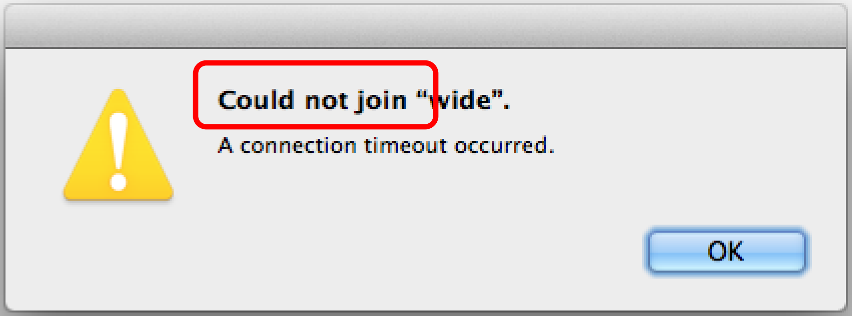
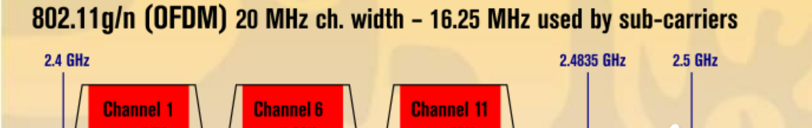
Joint work with Mr. Lizhao You and Prof. Soung-Chang Liew

Number of Wi Fi Devices Hits 2 Billions

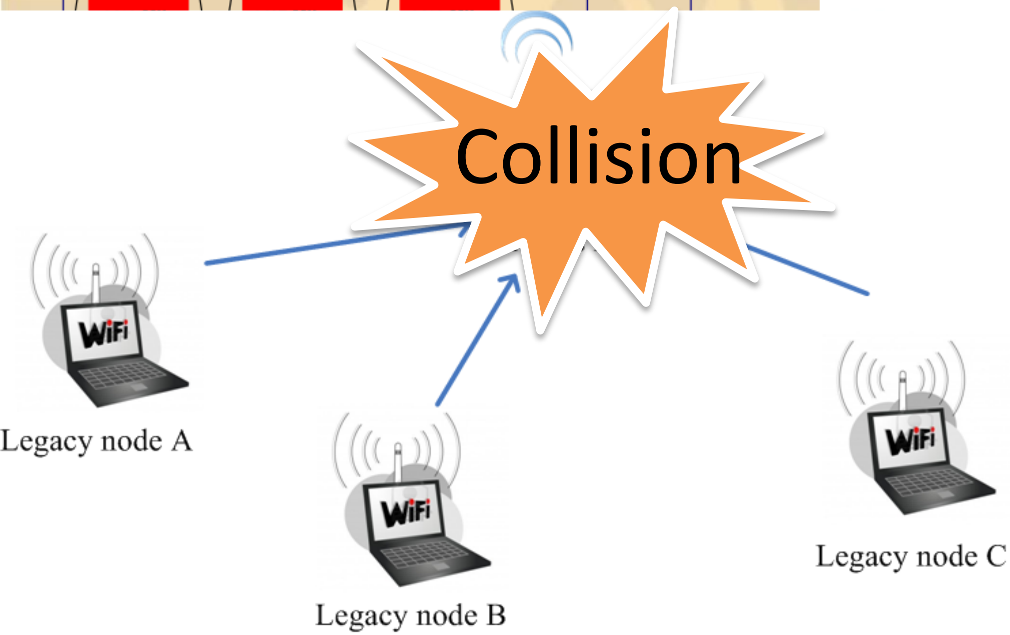


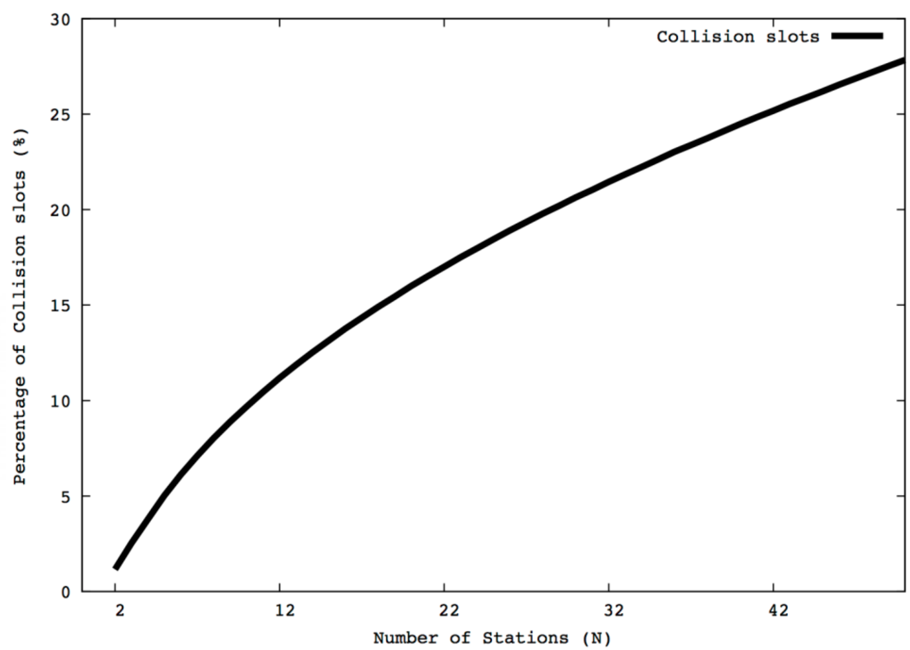


Number of WiFi Channels is Limited



"Future Evolution of CSMA Protocols for the IEEE 802.11 Standard," arXiv:1303.3734 (2013)





- *Collisions increase with the number of stations*
- *Each collision takes as much channel time as successful transmissions –> Throughput Drop*

Make Use of Collisions!

Physical-Layer Network Coding

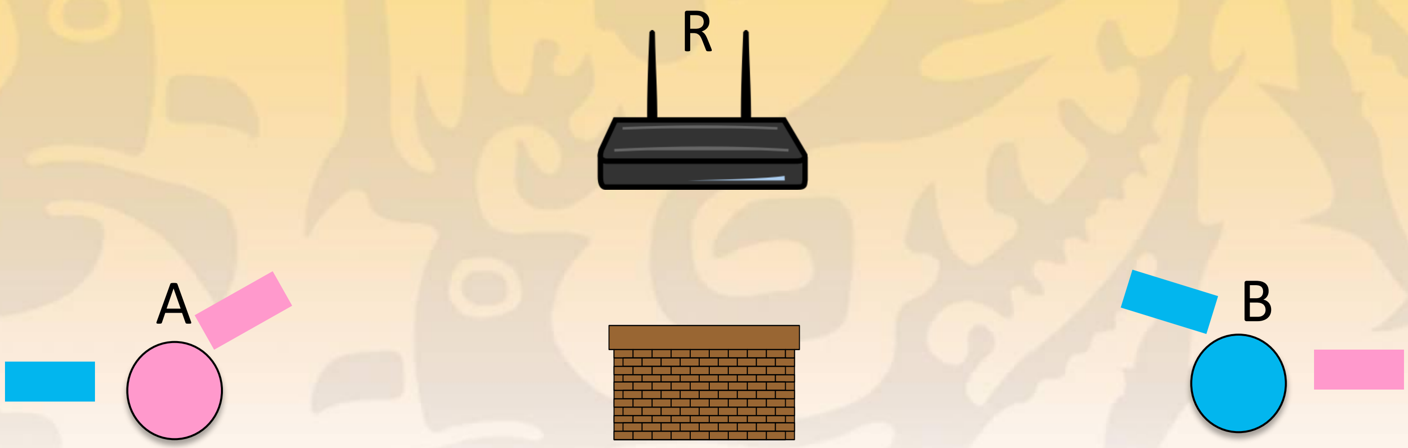
Outlines

- 1. Physical-layer Network Coding (PNC)
  - Review of PNC
  - PNC Prototype
- 2. Network-Coded Multiple Access (NCMA)
  - PHY-layer Bridging
  - MAC-layer Bridging
- 3. NCMA Performance Evaluation
  - Experimental Setup
  - Results
- 4. Conclusions and Remarks

What is PNC?

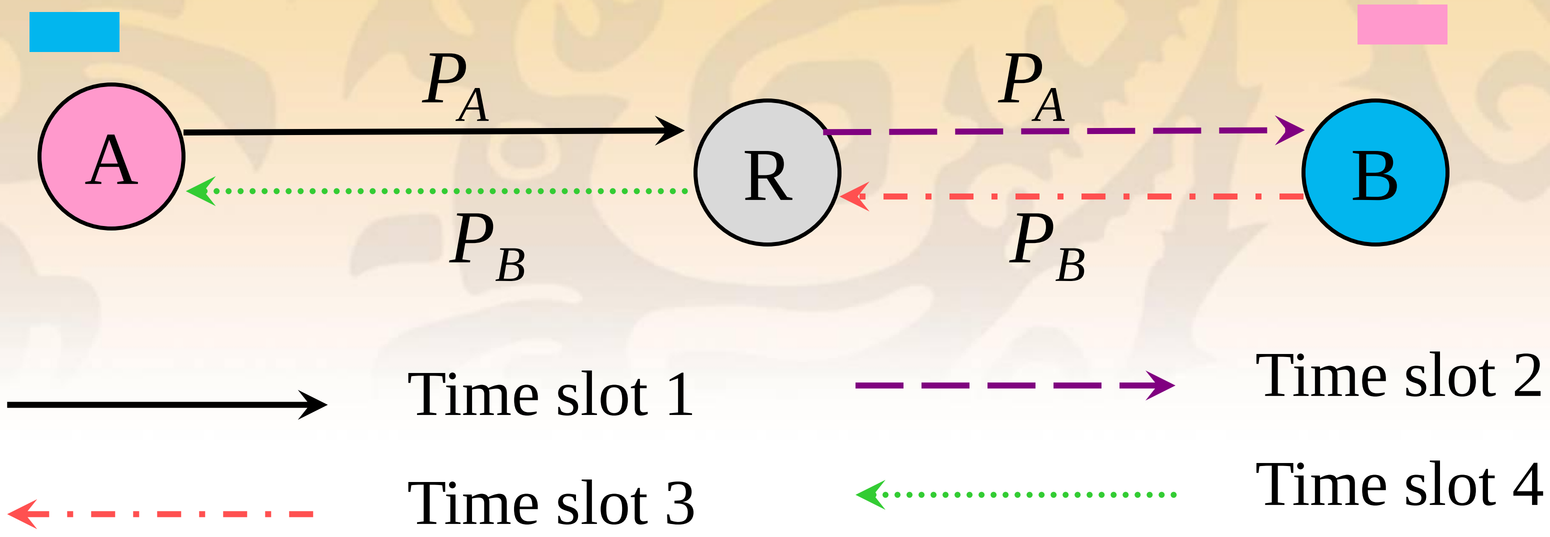
- Traditional view in wireless networking: interference is bad.
- PNC turns things around by exploiting *network coding (NC) performed by nature*.
- When electromagnetic waves superimpose, they add, a form of NC.
- Benefits of PNC:
  - boost throughput

Simplest Set-up: Two-Hop Relay Network



- System Model: Two-way Relay Network (TWRN)
  - No direct channel between nodes A and B.
  - Half duplex: nodes cannot transmit and receive at the same time.
  - What is the minimum number of time slots needed for nodes A and B to exchange one packet via relay node R?

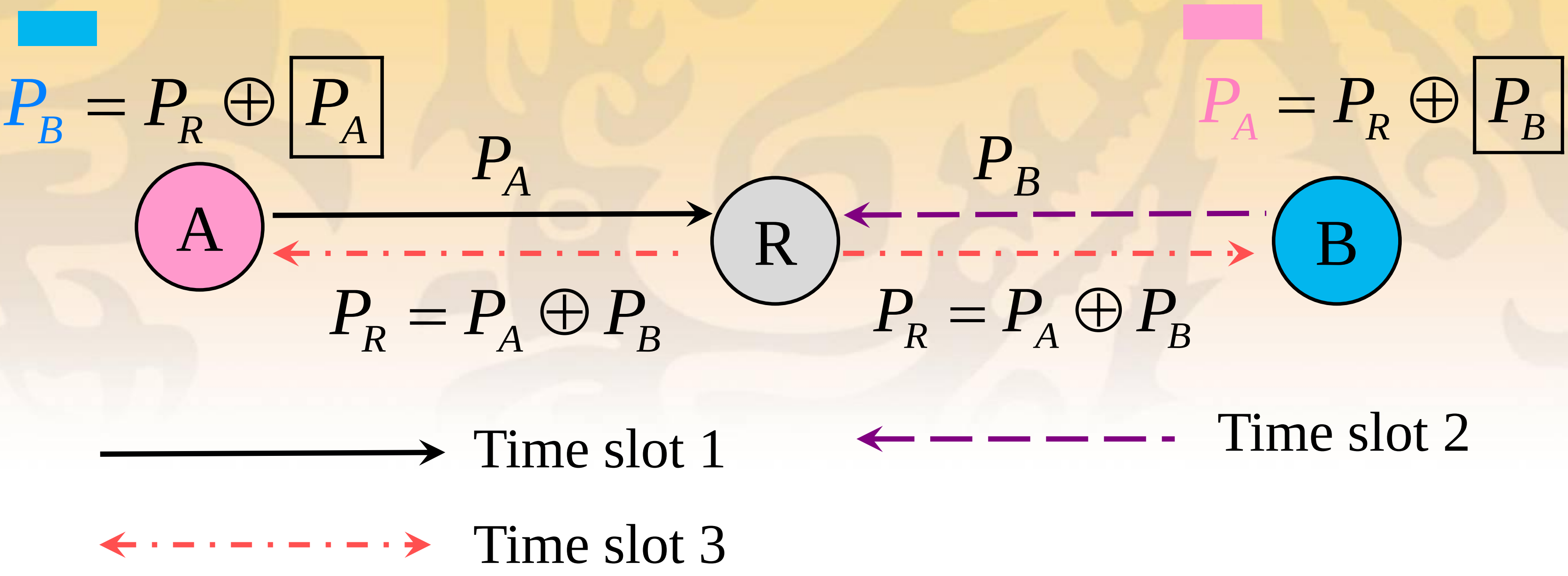
Traditional Scheduling (TS)



- *Transmissions non-overlapping in time*

4 Time Slots Needed

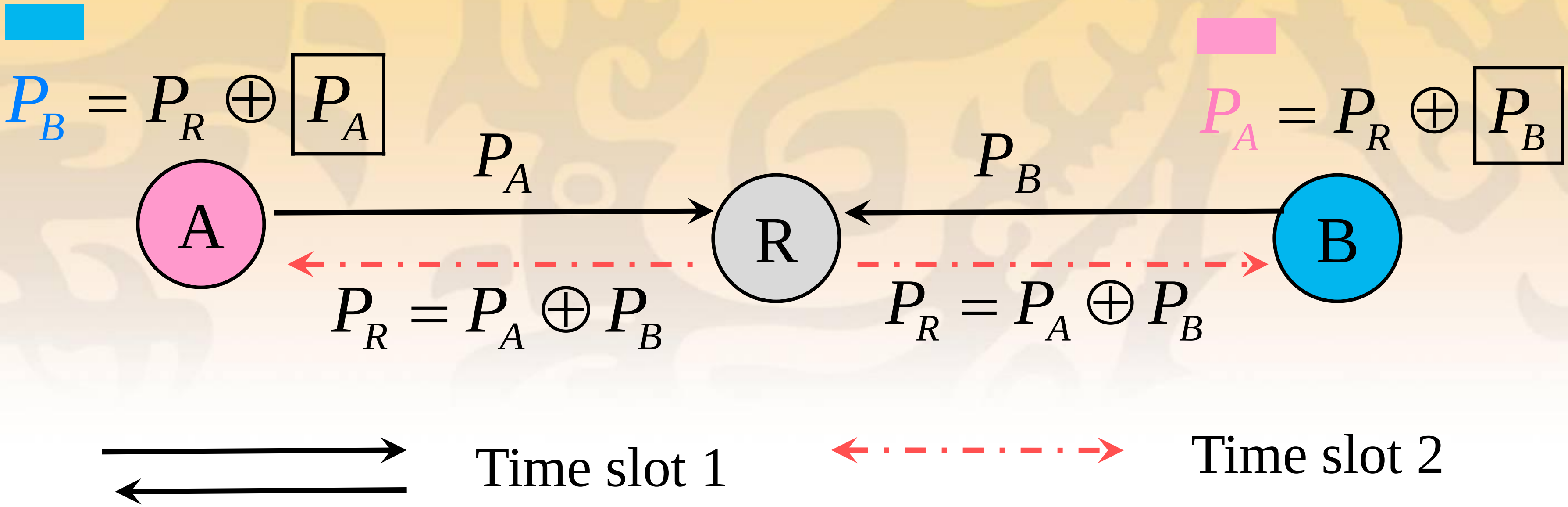
Straightforward Network Coding (SNC)



- *Transmissions by nodes A and B still non-overlapping*
- *Relay R uses **one** time slot to broadcast*

3 Time Slots Needed

Physical-layer Network Coding (PNC)



- *Transmissions by nodes A and B are* ***simultaneous!***

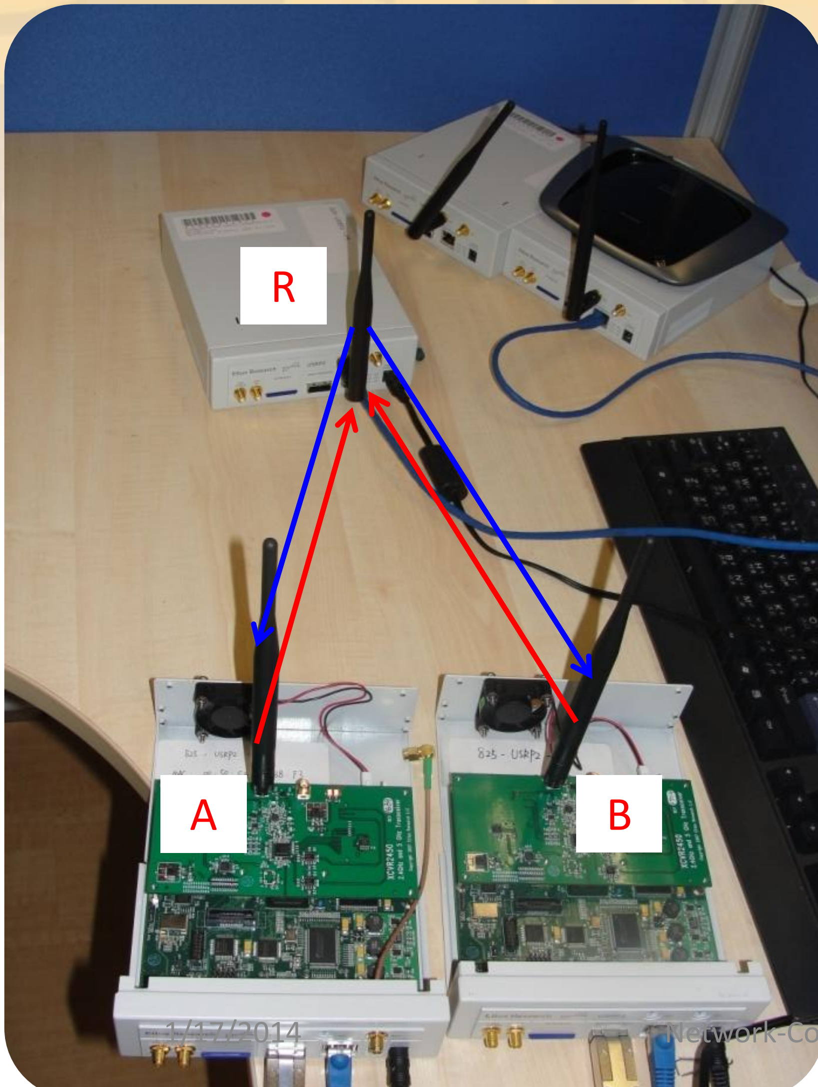
2 Time Slots !

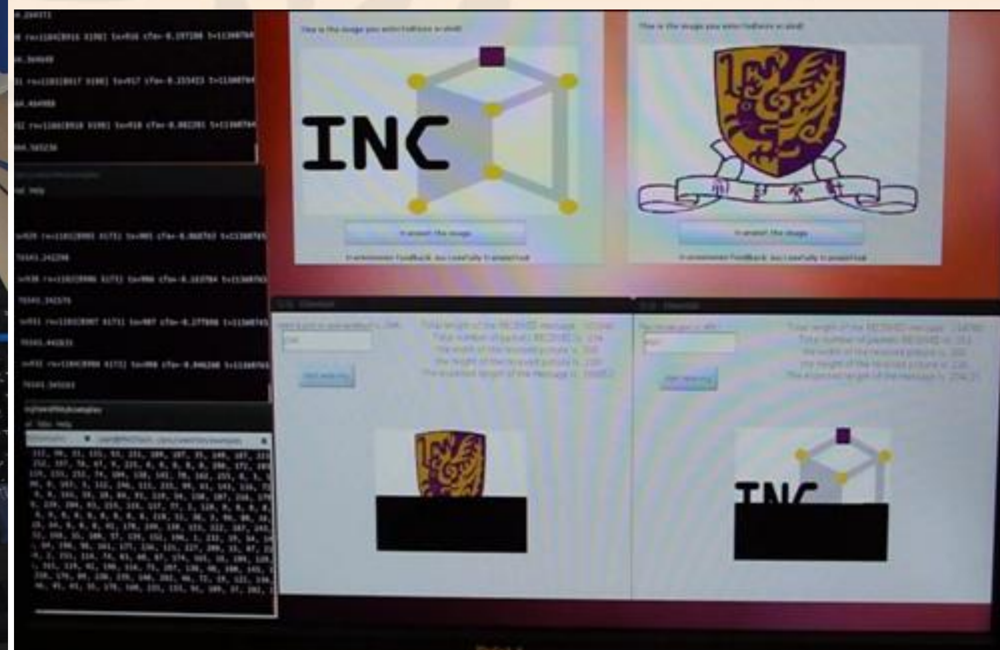
Real-time PNC Prototype: Specifics

- Frequency-domain PNC (FPNC) for TWRC
  - Build on OFDM technology as used in Wi-Fi
  - First PNC implementation in 2012
  - First real-time PNC implementation in 2013
    - Support "real" application in real-time through API

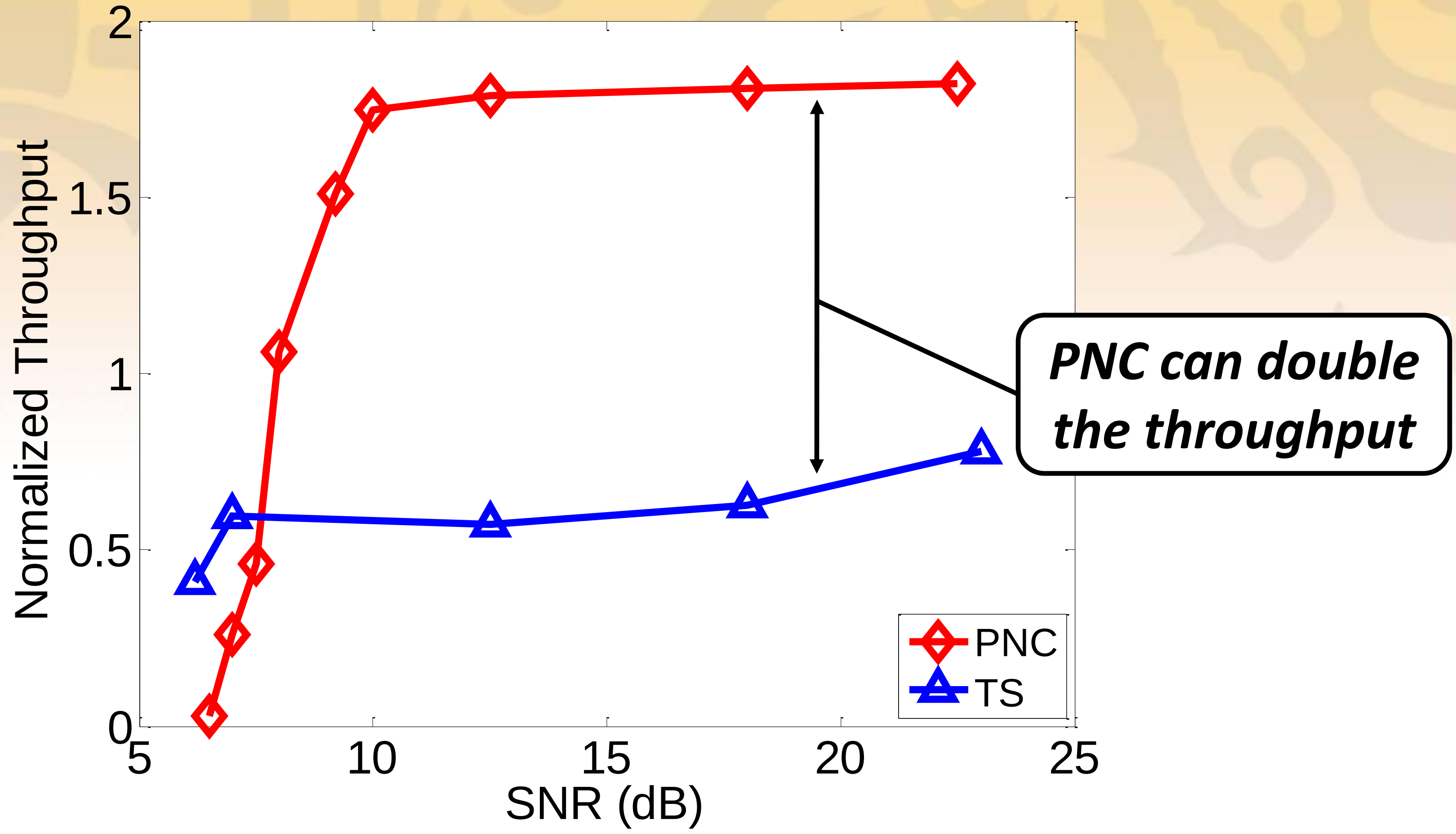
Real-time PNC Prototype: Platform

- Frequency-Domain PNC (FPNC) in GNU Radio testbed





Normalized throughput of PNC and TS



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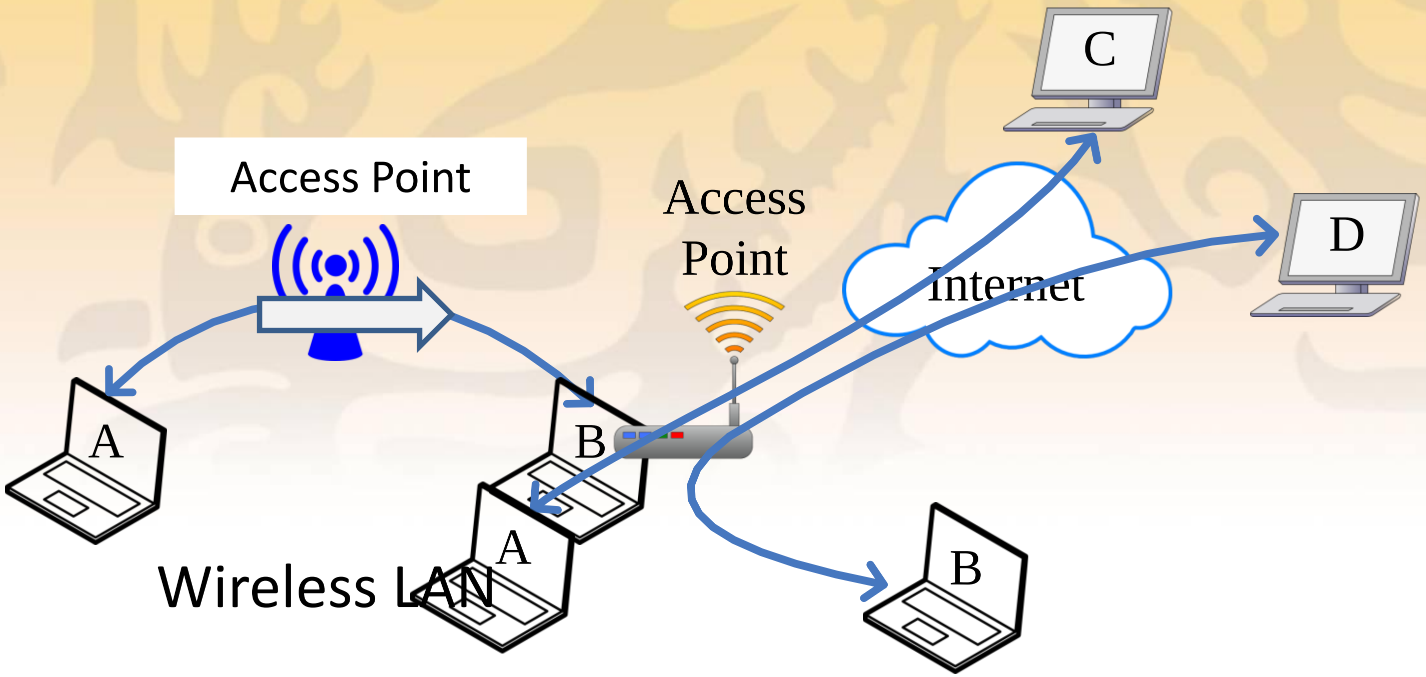
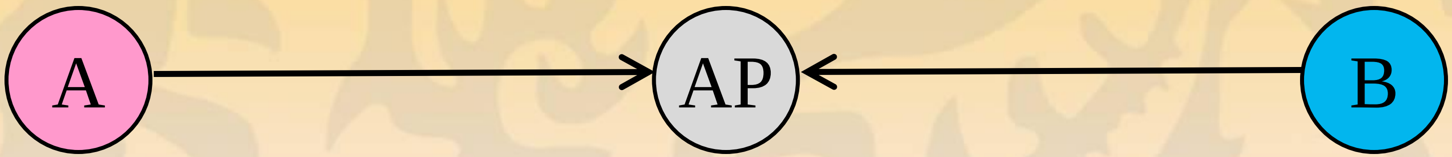
PNC in Non-Relay Setting?



- Access point wants to get both Message A and Message B, not just their XOR.
- Does PNC have a role to play?

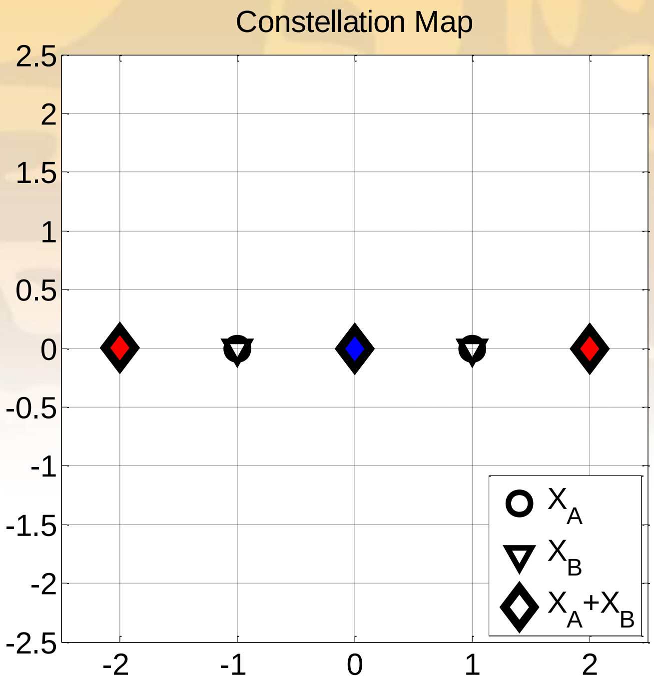
Network-Coded Multiple Access (NCMA)

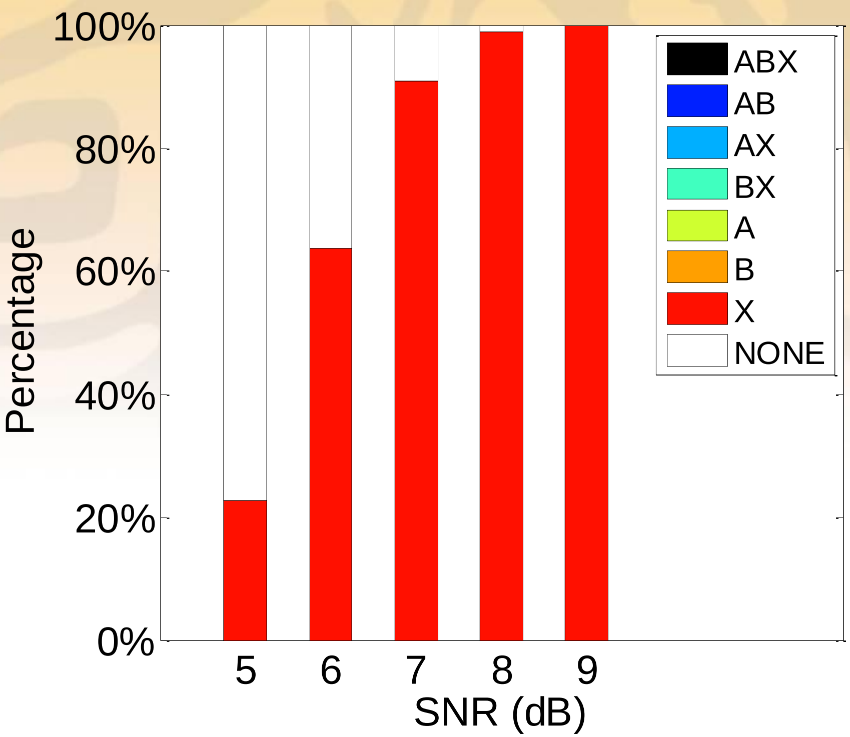


- Nodes A and B send to AP simultaneously
- AP uses three decoders to separately decode packet A, packet B, and packet A$\oplus$
- Eight possible events:
  - Packets A, B, and A$\oplus$ B de
  - Packets A and B decoded
  - …
  - Packet A $\oplus$B decoded
  - None decoded

Packet Index	Eq^A	$Eq^{A\oplus B}$	Eq^B
1	C_1^A	$C_1^{A\oplus B}$	C_1^B
2	C_2^A	$\emptyset$	C_2^B
3	C_3^A	$C_3^{A\oplus B}$	$\emptyset$
4	$\emptyset$	$C_4^{A\oplus B}$	C_4^B
5	C_5^A	$\emptyset$	$\emptyset$
6	$\emptyset$	$\emptyset$	C_6^B
7	$\emptyset$	$C_7^{A\oplus B}$	$\emptyset$
8	$\emptyset$	$\emptyset$	$\emptyset$

Simple Example: Phase Aligned



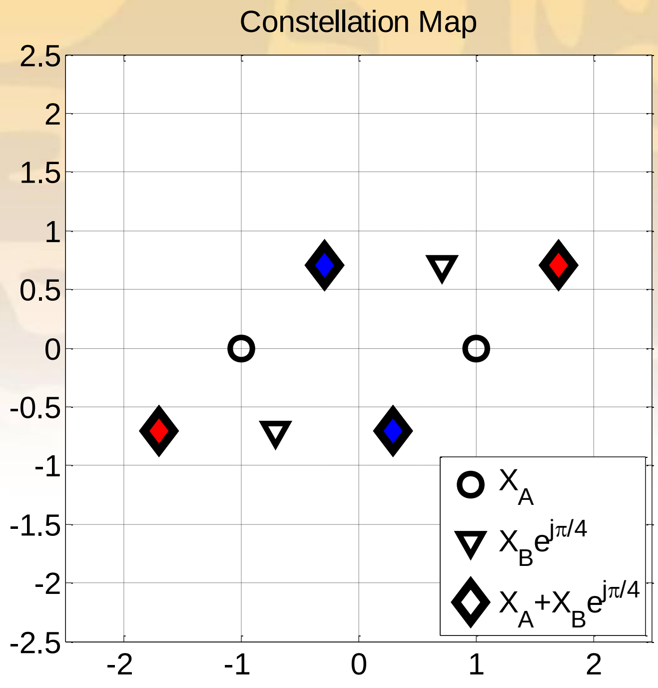


Received signal

$$Y = X_A + X_B$$

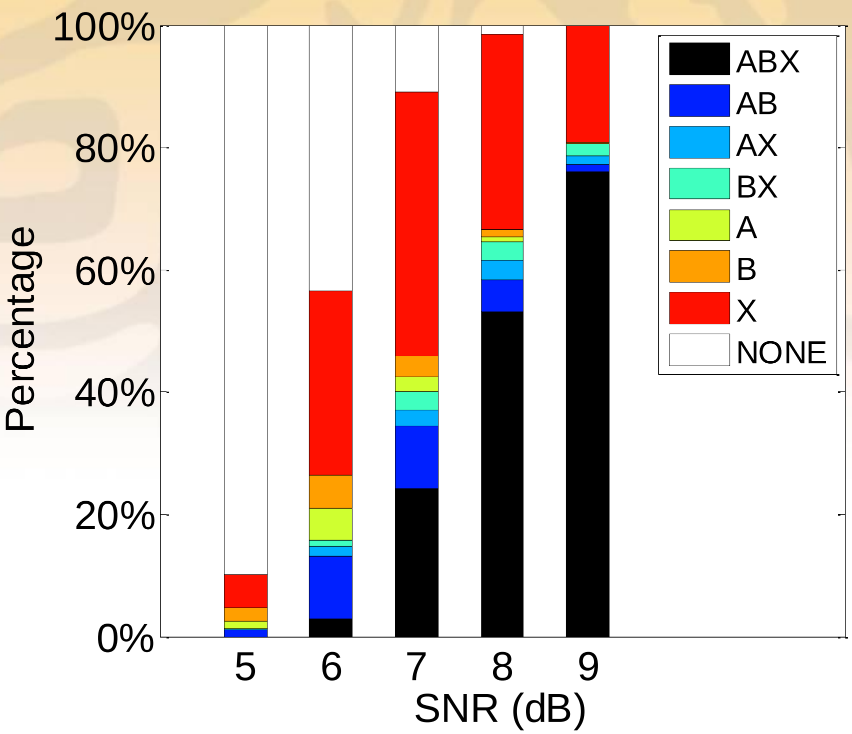
Output Distribution

Simple Example: Phase difference $\frac{\pi}{4}$



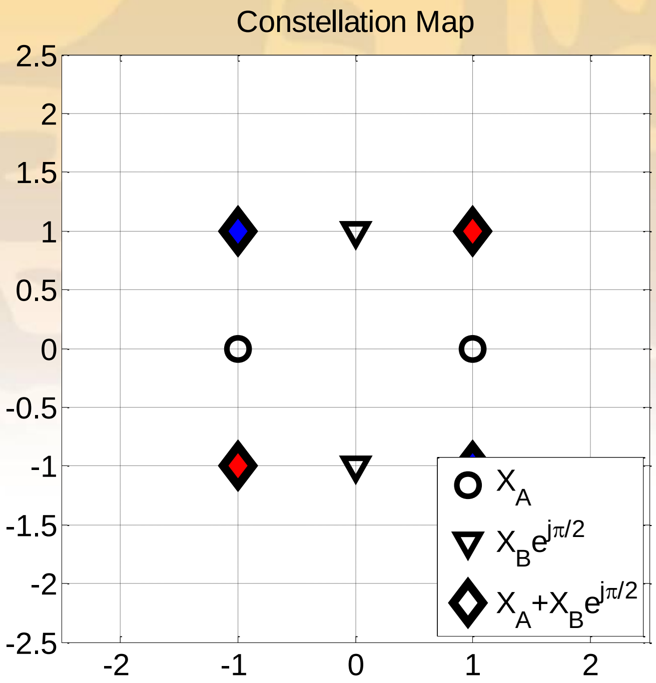
Received signal

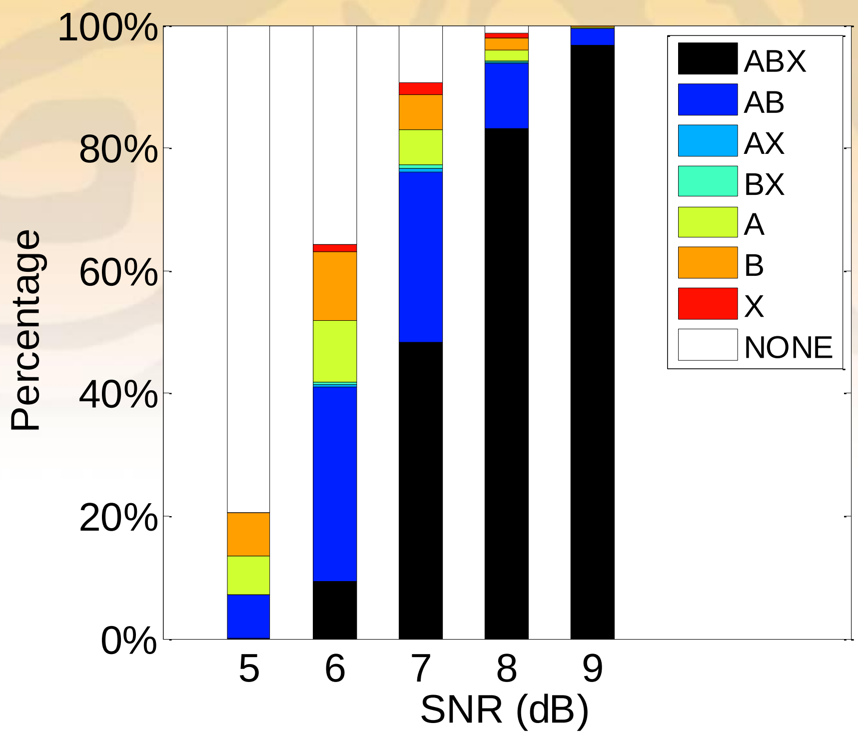
$$Y = X_A + X_B e^{-j\frac{\pi}{4}}$$



Output Distribution

Simple Example: Phase difference $\frac{\pi}{2}$





Received signal

Output Distribution

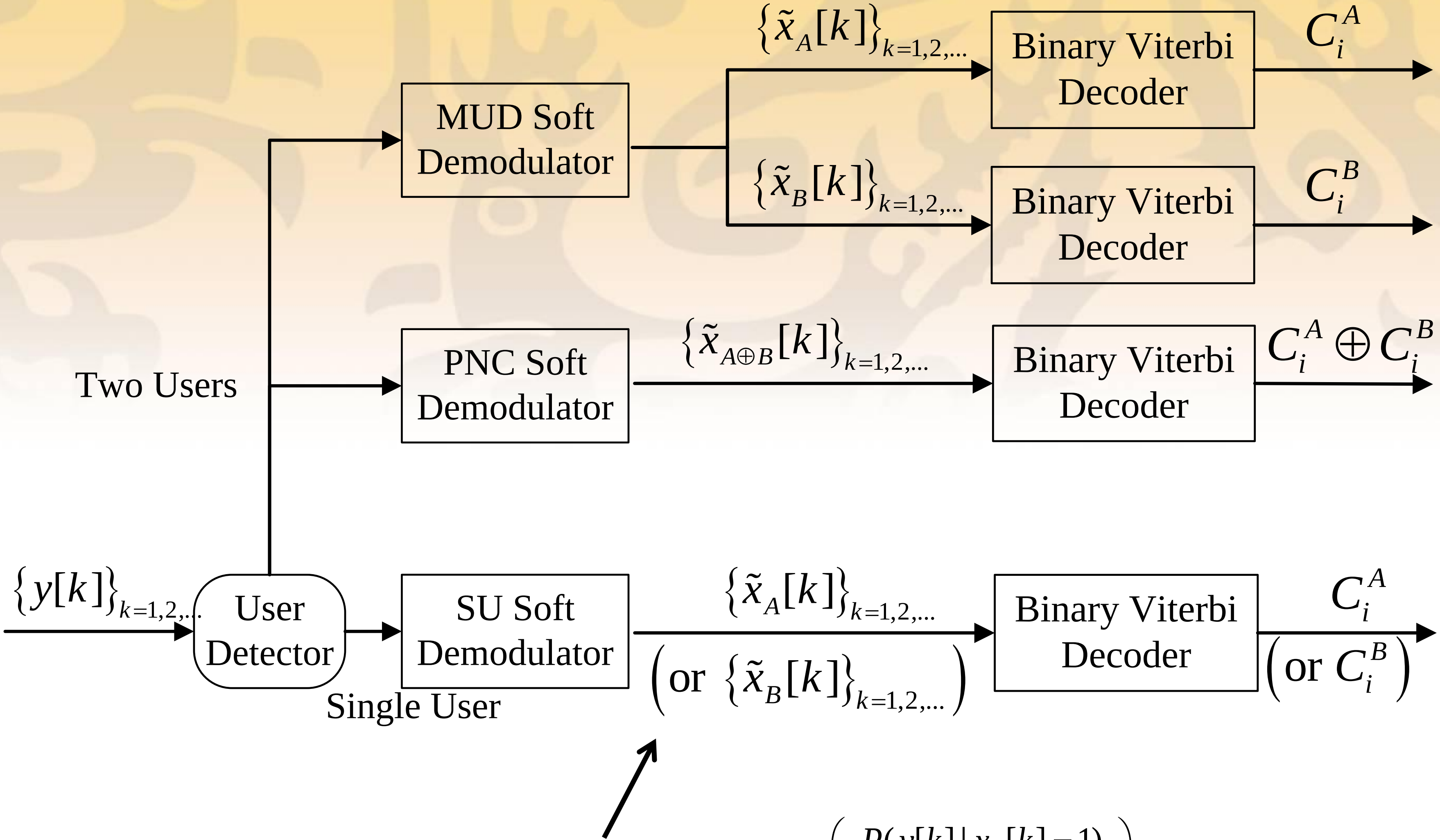
$$Y = X_A + X_B e^{-j\frac{\pi}{2}}$$

Implications

- In practice, different relative phases are possible. It is desirable to use a combination of the PNC decoder (good for phase aligned case) and MUD decoder (good for phase orthogonal case).

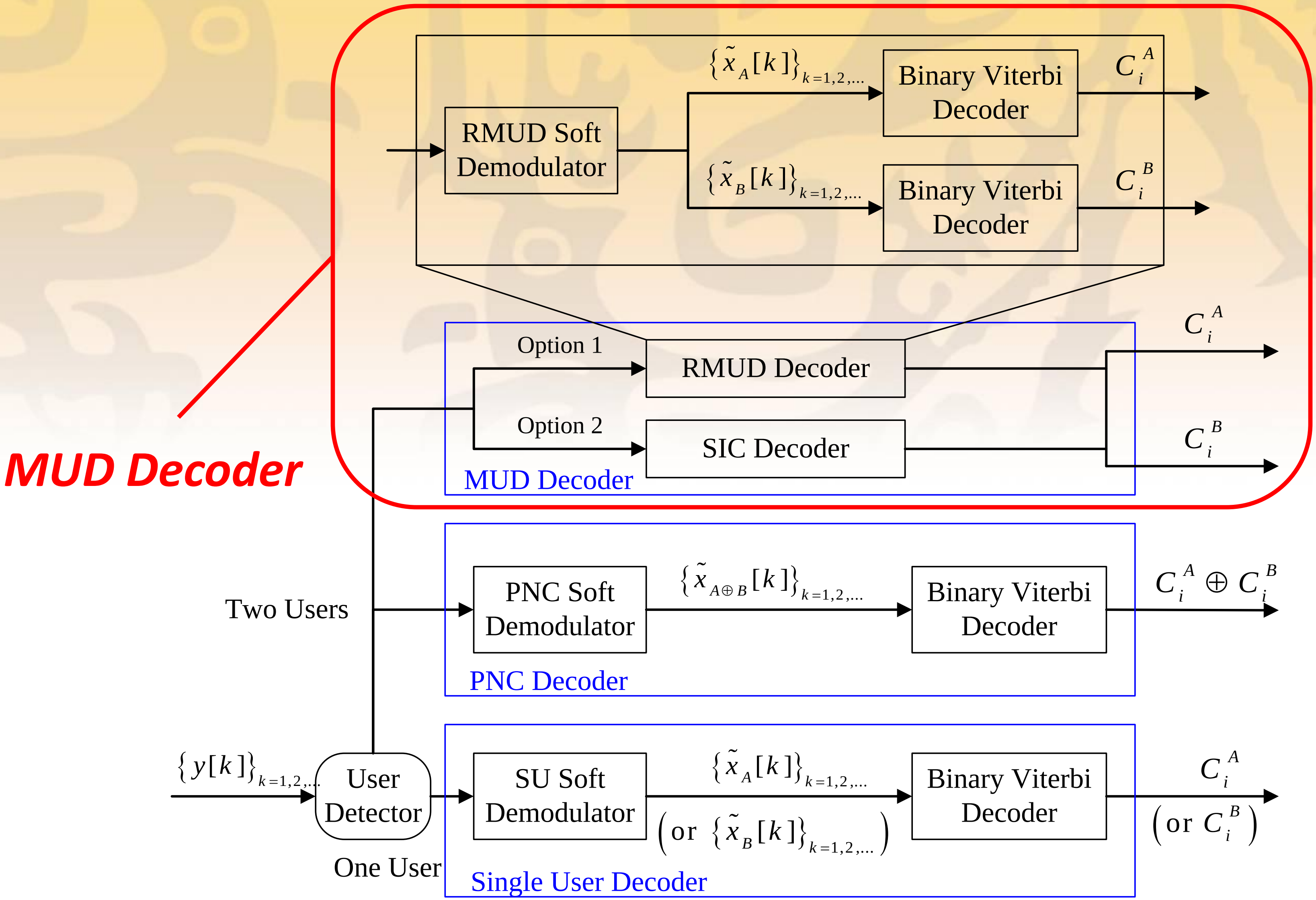
- For our OFDM system, things are more complicated. The combined use of the PNC and MUD decoders allows the system to adapt to the channel phases dynamically.

PHY-Layer Decoders of NCMA



Soft Information (Log Likelihood Ratio: $\log\left(\frac{P(y[k]\,|\,x_B[k]=1)}{P(y[k]\,|\,x_B[k]=-1)}\right)$, $k = 1, 2, \ldots$)

Alternatives for MUD Decoding



NCMA: PHY-layer Bridging

Packet Index	Eq^A	$Eq^{A\oplus B}$	Eq^B
1	C_1^A	$C_1^{A\oplus B}$	C_1^B
2	C_2^A	$\emptyset$	C_2^B
3	C_3^A	$C_3^{A\oplus B}$	C_3^B
4	$\emptyset$	$C_4^{A\oplus B}$	C_4^B
5	C_5^A	$\emptyset$	$\emptyset$
6	$\emptyset$	$\emptyset$	C_6^B
7	$\emptyset$	$C_7^{A\oplus B}$	$\emptyset$
8	$\emptyset$	$\emptyset$	$\emptyset$

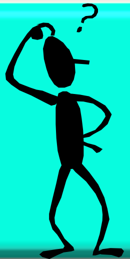
Problem:

➢ **There is no mutual information between <u>lone XOR packet</u> and <u>individual user packets</u>.**

Packet Index	Eq^A	$Eq^{A\oplus B}$	Eq^B
1	C_1^A	$C_1^{A\oplus B}$	C_1^B
2	C_2^A	$\emptyset$	C_2^B
3	C_3^A	$C_3^{A\oplus B}$	$\emptyset$
4	$\emptyset$	$C_4^{A\oplus B}$	C_4^B
5	C_5^A	$\emptyset$	$\emptyset$
6	$\emptyset$	$\emptyset$	C_6^B
7	$\emptyset$	$C_7^{A\oplus B}$	$\emptyset$
8	$\emptyset$	$\emptyset$	$\emptyset$

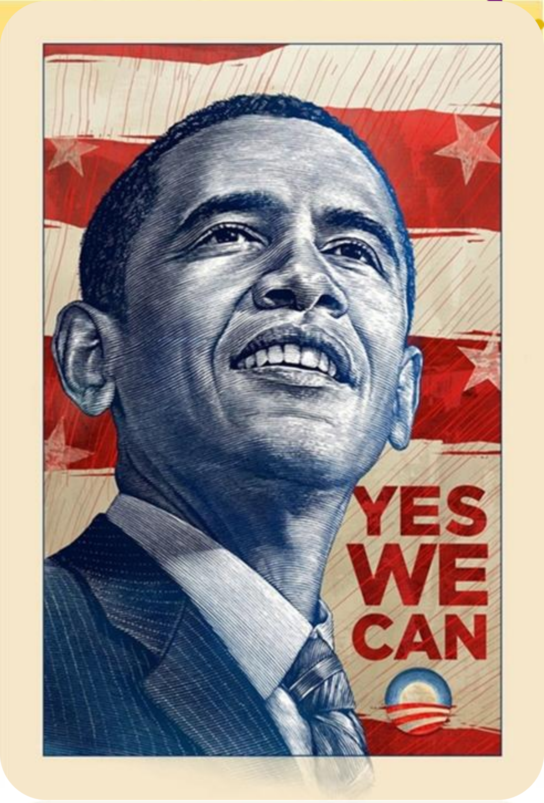
Complementary XOR

Lone XOR



Do lone XOR packets have a role to play?

Critical Idea: MAC-Layer Era



Message $M^A \rightarrow$ Packets $\{C_1^A, C_2^A, \ldots$

Message $M^B \rightarrow$ Packets $\{C_1^B, C_2^B, \ldots$

If RS code is used, as soon as AP decodes any L

packets $\{C_1^A, C_2^A, \ldots, C_N^A\}$, it can obtain M^A.

Similarly for M^B.

Can we make use of XOR packets, $\{C_1^A \oplus C_1^B,\ C_2^A \oplus C_2^B,\ \ldots, C_N^A \oplus C_N^B\}$?

Solution:

- **Mutual information can be established if we have another layer of channel coding.**

NCMA: MAC-Layer Bridging

Example: Decoding M^B, based on M^A and $M^A \oplus M^B$, with $L = 3$

Packet Index	Eq^A	$Eq^{A\oplus B}$	Eq^B
1	C_1^A		
2		$C_2^{A\oplus B}$	
3			C_3^B
4	C_4^A	$C_4^{A\oplus B}$	C_4^B
5	C_5^A		

RS Decoding

Packet Index	Eq^A	$Eq^{A\oplus B}$	Eq^B
1	C_1^A		
2	C_2^A	$C_2^{A\oplus B}$	
3	C_3^A		C_3^B
4	C_4^A	$C_4^{A\oplus B}$	C_4^B
5	C_5^A		

PNC Decoding

Packet Index	Eq^A	$Eq^{A\oplus B}$	Eq^B
1	C_1^A		
2	C_2^A	$C_2^{A\oplus B}$	C_2^B
3	C_3^A		C_3^B
4	C_4^A	$C_4^{A\oplus B}$	C_4^B
5	C_5^A		

RS Decoding

Packet Index	Eq^A	$Eq^{A\oplus B}$	Eq^B
1	C_1^A		C_1^B
2	C_2^A	$C_2^{A\oplus B}$	C_2^B
3	C_3^A		C_3^B
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5	C_5^A		C_5^B

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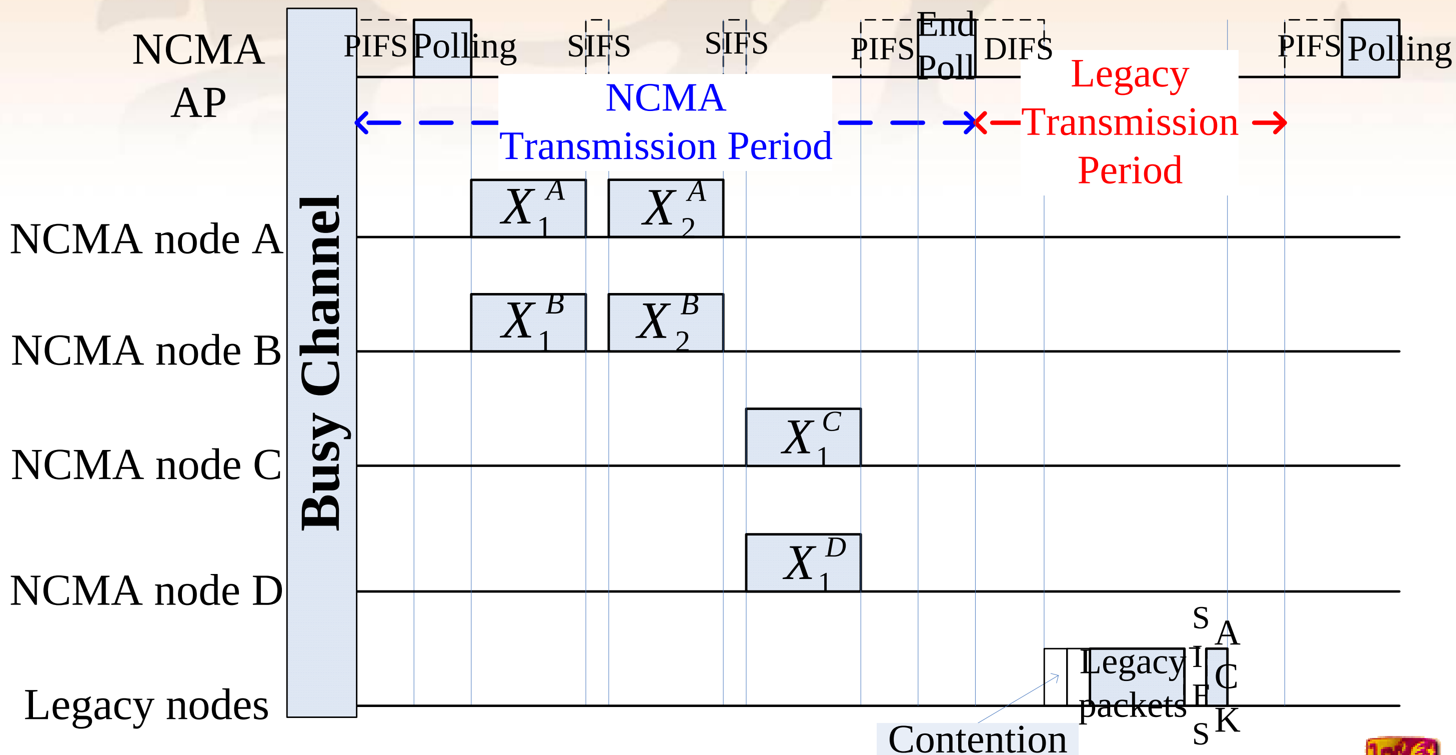
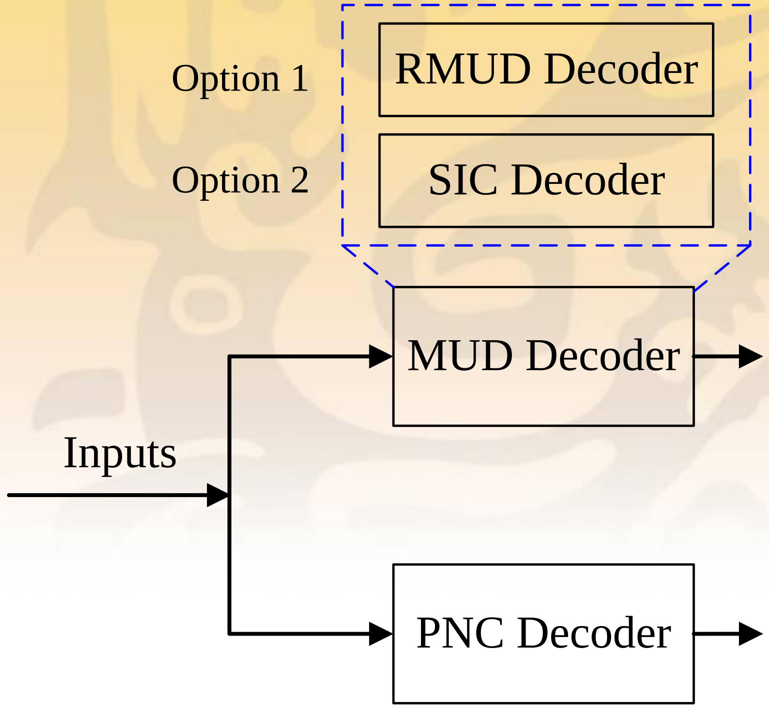
NCMA Performance Evaluation

- 9 USRP N210 Nodes
- Build on OFDM technology as used in Wi-Fi
- Beacon triggered MAC protocol

Polling Table	
Timeslot 1	A, B
Timeslot 2	A, B
Timeslot 3	C, D



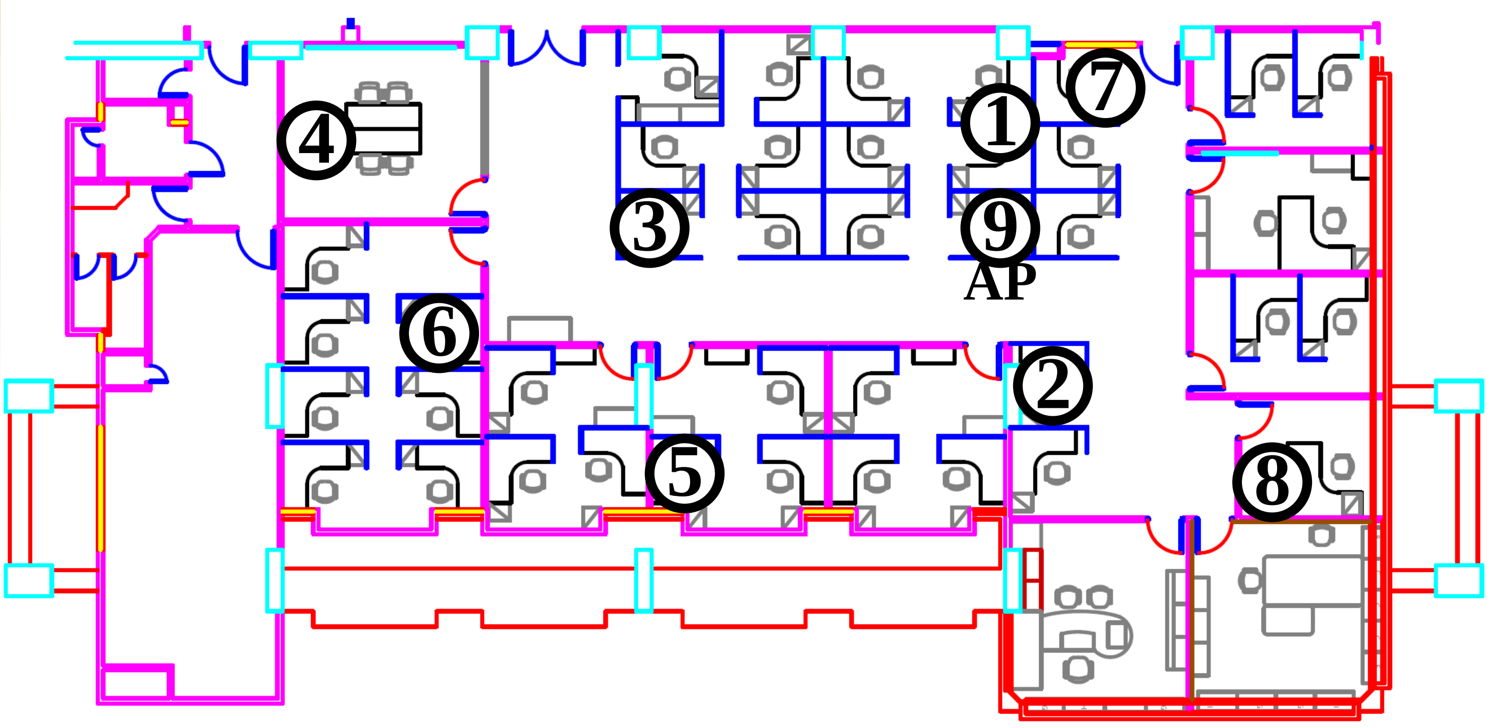
Decoder Latency Measurements



Packet interval \ Decoder Type	RMUD	PNC	RMUD+PNC
6ms	0.949ms	0.809ms	1.217ms
7ms	0.774ms	0.690ms	1.018ms
8ms	0.756ms	0.677ms	0.926ms

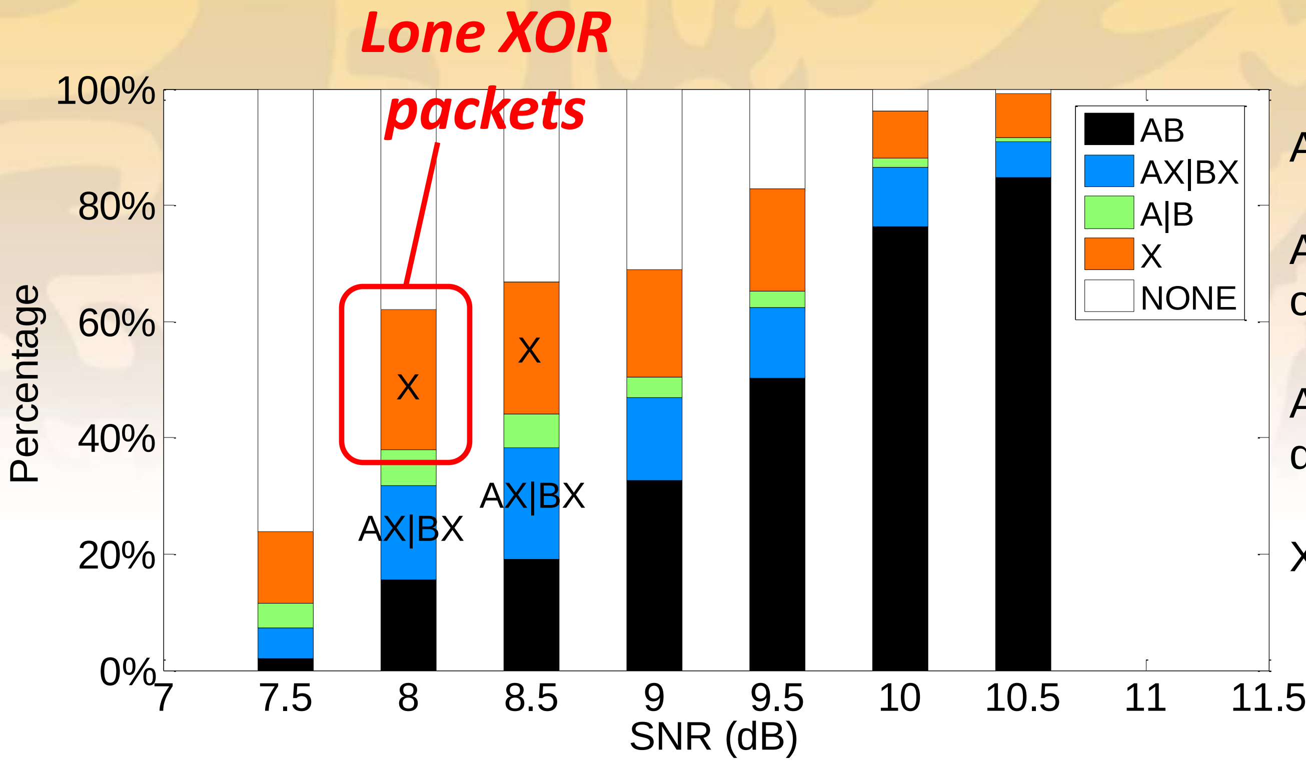
Processing time of different PHY-layer decoders

Layout of Indoor Experiments



Institute of Network Coding (INC)

PHY-Layer Packet Decoding Statistics (Balanced Power Case)

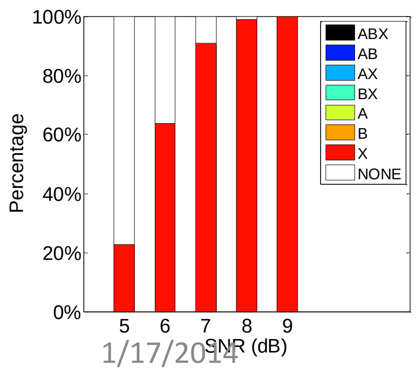


AB: Both A and B decoded

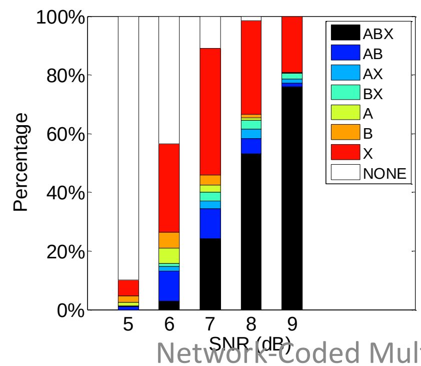
AX|BX: A and XOR decoded or B and XOR decoded

A|B: Either only A or only B decoded

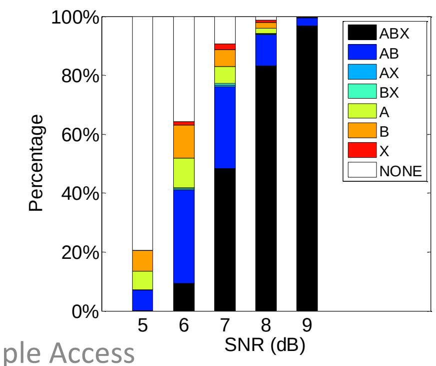
X: Only XOR decoded



(a) phase aligned



(b) phase difference $\frac{\pi}{4}$

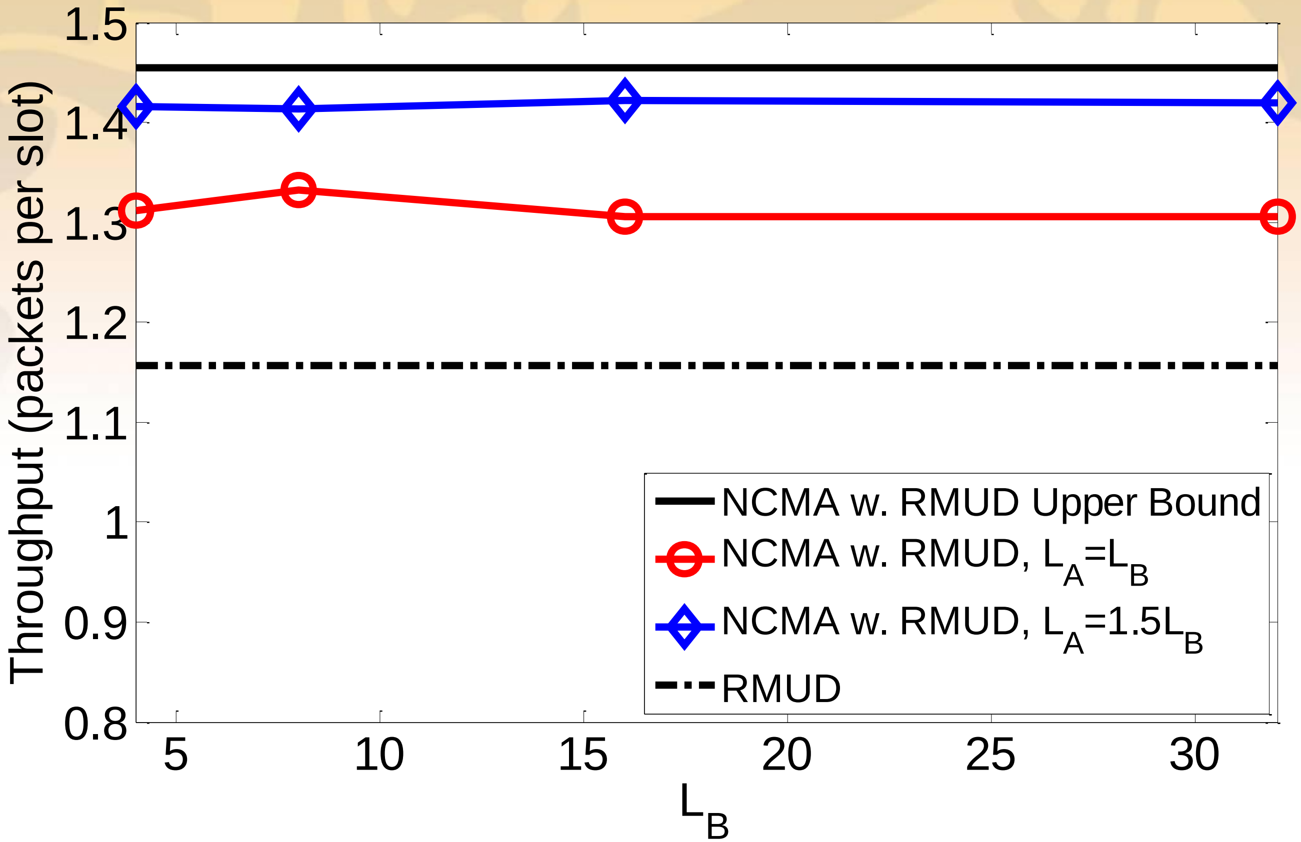


(c) phase difference $\frac{\pi}{2}$

AWGN Channel Simulations

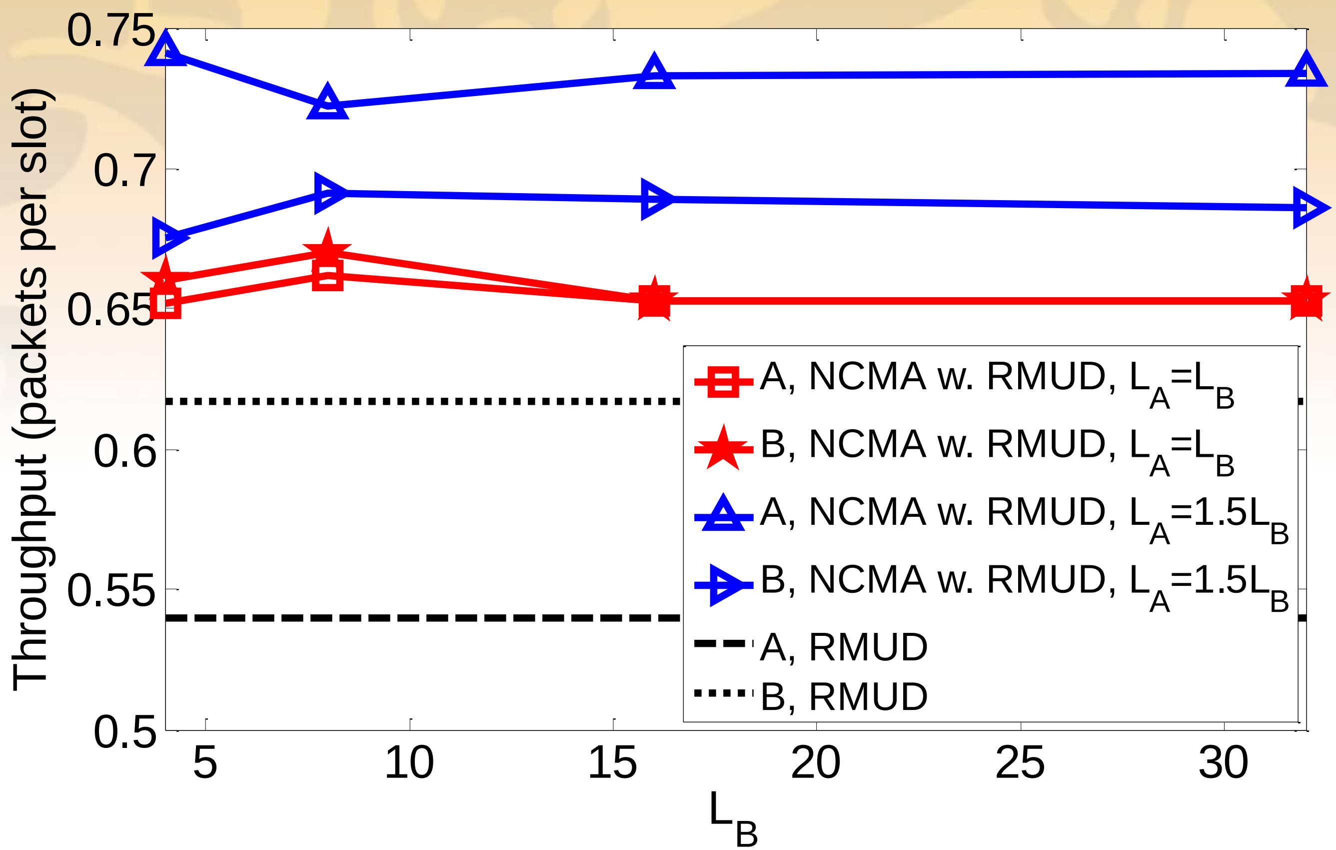
Overall Throughputs (Balanced Power): Aggregated Throughput

INC



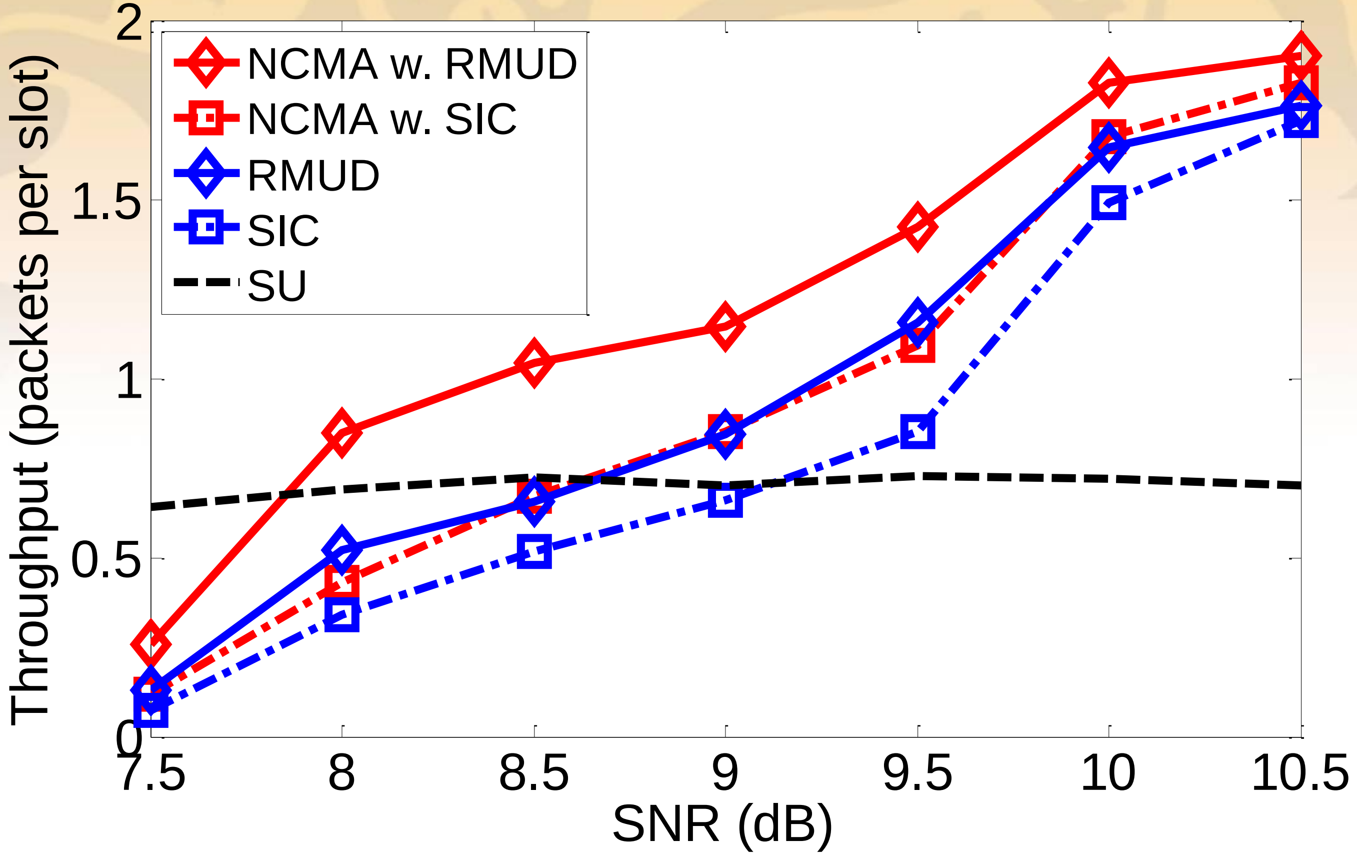
- RS code parameter L_A = 4, 8, 16, 32, and fixed SNR = 9.5 dB
- The Upper Bound and RMUD curves are benchmarks with constant values that do not vary with L_B

Overall Throughputs (Balanced Power): Individual Throughputs of A and B



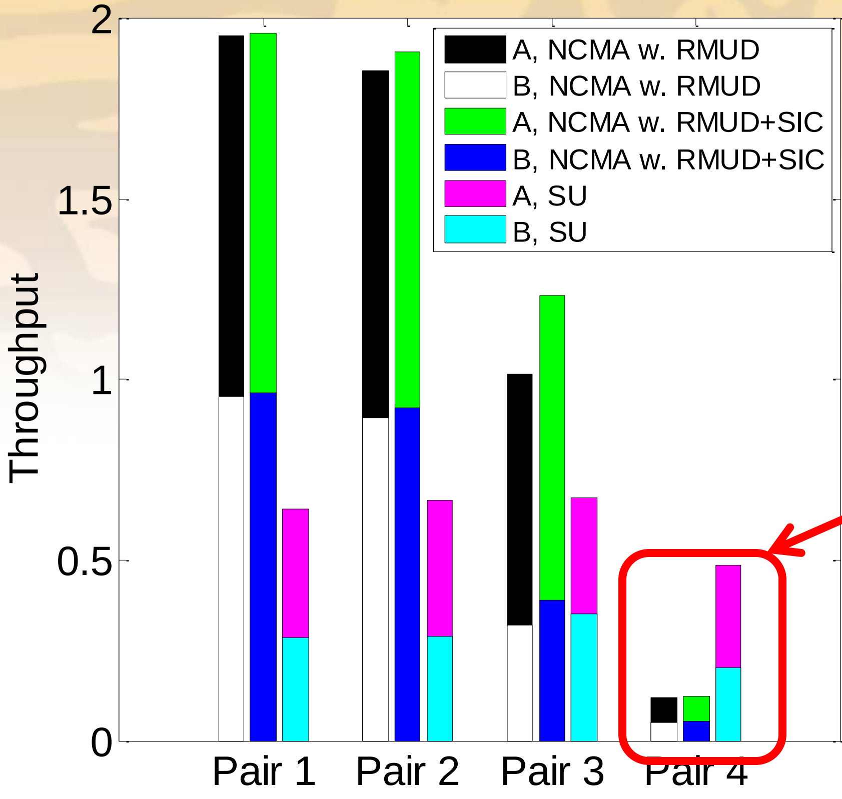
- RS code parameter L_A = 4, 8, 16, 32, and fixed SNR = 9.5 dB

Overall Throughputs (Balanced Power Case): Different SNRs



$$L_A = 1.5 \times L_B = 24$$

Throughputs of Four User Pairs



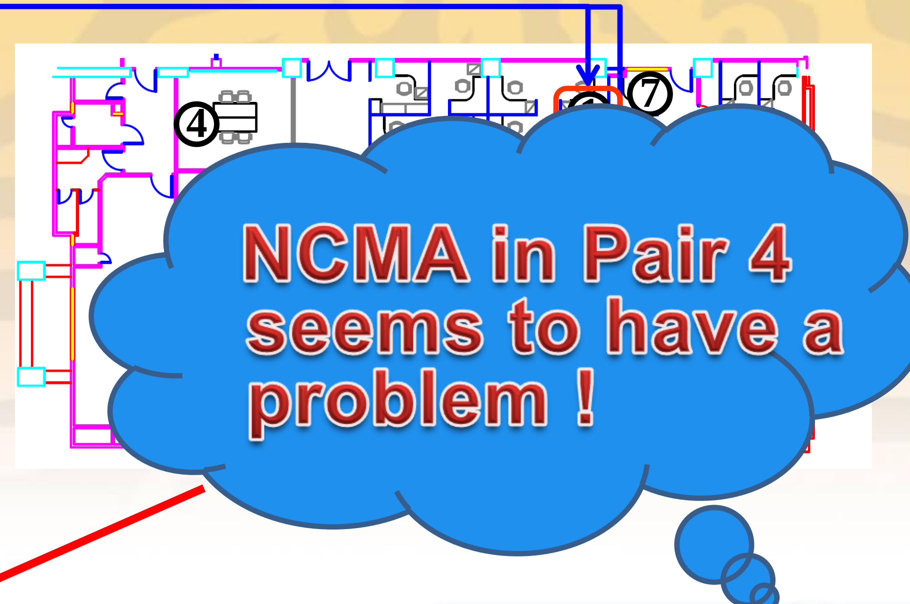
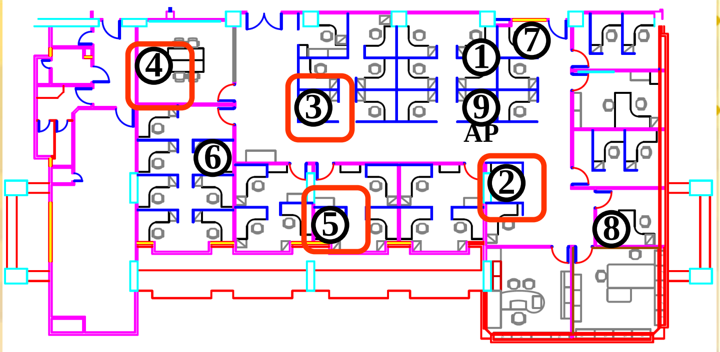
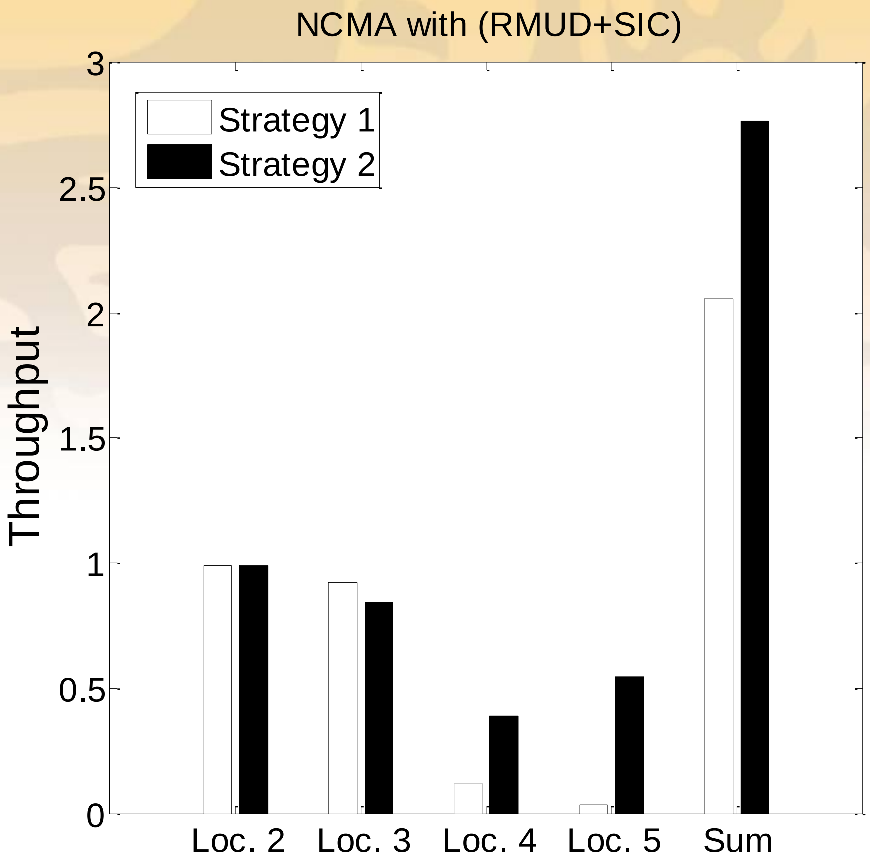


Table 1: User pairing

User Pair	User A
P1	Location 1 (20
P2	Location 2 (12
P3	Location 3 (9d
P4	Location 4 (7d
P5	Location 2 (12

Pairing Strategies





Scenario: Four users at locations 2, 3, 4, 5. How to form pairs?

Strategy 1: P2 and P4
Strategy 2: P3 and P5

Table 1: User pairing in random topology

User Pair	User A	User B
P1	Location 1 (20dB)	Location 2 (12.3dB)
P2	Location 2 (12.3dB)	Location 3 (9dB)
P3	Location 3 (9dB)	Location 4 (7dB)
P4	Location 4 (7dB)	Location 5 (7.4dB)
P5	Location 2 (12.3dB)	Location 5 (7.4dB)

Pair "strong with weak" rather than "strong with strong and weak with weak"

NCMA: Overall Summary

- First venture into non-relay setting for PNC
- PNC may have a role to play in the multiple access scenario
  - for simplification of decoder design
  - for jumbo messages

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To Probe Further

INC

- **Network-Coded Multiple Access:**

1. L. Lu, L. You, and S. C. Liew, "Network-Coded Multiple Access," IEEE Transactions on Mobile Computing (under second-round review), 2014. available at http://arxiv.org/abs/1307.1514.
2. US Patent Application 61/865,391 "Network-Coded Multiple Access," S. C. Liew, L. Lu, and L. You, filed August 2013.

- **Implementation of Physical-Layer Network Coding:**

3. L. Lu, L. You, Q. Yang, T. Wang, M. Zhang, S. Zhang, and S. C. Liew, "Real-time Implementation of Physical-Layer Network Coding," in ACM SIGCOMM SRIF Workshop, August 2013.
4. L. Lu, T. Wang, S. C. Liew, and S. Zhang, "Implementation of Physical-Layer Network Coding," Elsevier Physical Communication, vol. 6, no. 1, pp. 74-87, March 2013.
5. L. Lu, T. Wang, S. C. Liew, and S. Zhang, ``Implementation of Physical-Layer Network Coding,'' in *Proc. IEEE ICC*, June 2012.

Conclusions

- There has been a lot of theoretical work on PNC
- Relatively few experimental investigations
- PNC: The first real-time PNC prototype
- NCMA: PNC can be applied in a non-relay setting to boost system throughput
- Future:
  - Apply PNC and NCMA to commercial wireless networks: cellular (e.g., LTE-A) and WLAN
  - Use advanced rateless channel codes (e.g., Raptor Codes) to replace the RS codes for NCMA


Thank You!


Q&A