Network-Coded Multiple Access

Lu Lu

17th January 2014

Joint work with Mr. Lizhao You and Prof. Soung-Chang Liew
Number of Devices Hits 2 Billions

Global Shipment Forecast for WLAN Chipsets

Source: IHS iSuppli Research, 2011

Known networks will be joined automatically. If no known networks are available, you will have to manually select a network.

Could not join "vide".
A connection timeout occurred.
Number of WiFi Channels is Limited

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: inter\textit{ference is bad}.
• PNC turns things around by exploiting \textit{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

\[ P_A \quad P_B \quad P_A \quad P_B \]

Time slot 1

Time slot 3

Time slot 2

Time slot 4

- **Transmissions non-overlapping in time**

4 Time Slots Needed
Straightforward Network Coding (SNC)

\[ P_B = P_R \oplus P_A \]

\[ P_A = P_R \oplus P_B \]

\[ P_R = P_A \oplus P_B \]

- **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)

- $P_B = P_R \oplus P_A$
- $P_A = P_R \oplus P_B$
- $P_R = P_A \oplus P_B$
- 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

PNC can double the throughput
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
• Access point wants to get both **Message A and Message B**, not just their XOR.
• Does PNC have a role to play?
• Nodes A and B send to AP simultaneously
• AP uses three decoders to separately decode packet A, packet B, and packet $A \oplus B$
• Eight possible events:
  – Packets A, B, and $A \oplus B$ decoded
  – Packets A and B decoded
  – …
  – Packet A $\oplus B$ decoded
  – None decoded

<table>
<thead>
<tr>
<th>Packet Index</th>
<th>$Eq^A$</th>
<th>$Eq^{A\oplus B}$</th>
<th>$Eq^B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$C_1^A$</td>
<td>$C_1^{A\oplus B}$</td>
<td>$C_1^B$</td>
</tr>
<tr>
<td>2</td>
<td>$C_2^A$</td>
<td>$\emptyset$</td>
<td>$C_2^B$</td>
</tr>
<tr>
<td>3</td>
<td>$C_3^A$</td>
<td>$C_3^{A\oplus B}$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>4</td>
<td>$\emptyset$</td>
<td>$C_4^{A\oplus B}$</td>
<td>$C_4^B$</td>
</tr>
<tr>
<td>5</td>
<td>$C_5^A$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>6</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>$C_6^B$</td>
</tr>
<tr>
<td>7</td>
<td>$\emptyset$</td>
<td>$C_7^{A\oplus B}$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>8</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
</tr>
</tbody>
</table>
Simple Example: Phase Aligned

Received signal

\[ Y = X_A + X_B \]
Simple Example: Phase difference $\frac{\pi}{4}$

Received signal

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

Output Distribution

Constellation Map

SNR (dB) Percentage

ABX
AB
AX
BX
A
B
X
NONE

0% 20% 40% 60% 80% 100%
Simple Example: Phase difference \( \frac{\pi}{2} \)

Received signal

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

Output Distribution
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

Two Users

\{ y[k] \}_{k=1,2,...}

User Detector

\{ x_A[k] \}_{k=1,2,...}

MUD Soft Demodulator

\{ x_B[k] \}_{k=1,2,...}

PNC Soft Demodulator

\{ x_{A\oplus B}[k] \}_{k=1,2,...}

Binary Viterbi Decoder

\{ x_A[k] \}_{k=1,2,...}

SU Soft Demodulator

\{ x_B[k] \}_{k=1,2,...}

Binary Viterbi Decoder

\{ x_{A\oplus B}[k] \}_{k=1,2,...}

Binary Viterbi Decoder

\{ C_i^{A} \}

\{ C_i^{B} \}

\{ C_i \}

\{ C_i^{A} \oplus C_i^{B} \}

Soft Information (Log Likelihood Ratio: \( \log \left( \frac{P(y[k] | x_B[k] = 1)}{P(y[k] | x_B[k] = -1)} \right) \), \( k = 1, 2,... \))
Alternatives for MUD Decoding

MUD Decoder

Two Users

{y[k]}_{k=1,2,...}

User Detector

RMUD Soft Demodulator

{\tilde{x}_A[k]}_{k=1,2,...}

Binary Viterbi Decoder

C^A_i

RMUD Decoder

Option 1

Option 2

SIC Decoder

C^A_i

C^B_i

PNC Soft Demodulator

{\tilde{x}_{A\oplus B}[k]}_{k=1,2,...}

Binary Viterbi Decoder

C^A_i \oplus C^B_i

PNC Decoder

One User

{y[k]}_{k=1,2,...}

Single User Decoder

{\tilde{x}_A[k]}_{k=1,2,...}

(or \{\tilde{x}_B[k]\}_{k=1,2,...})

Binary Viterbi Decoder

C^A_i

(or C^B_i)

Figure 1: Diagram of Alternatives for MUD Decoding. The diagram illustrates the flow of signals through various demodulators and decoders for both one and two users.
NCMA: PHY-layer Bridging

<table>
<thead>
<tr>
<th>Packet Index</th>
<th>$Eq^A$</th>
<th>$Eq^{A\oplus B}$</th>
<th>$Eq^B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$C_1^A$</td>
<td>$C_1^{A\oplus B}$</td>
<td>$C_1^B$</td>
</tr>
<tr>
<td>2</td>
<td>$C_2^A$</td>
<td>$\emptyset$</td>
<td>$C_2^B$</td>
</tr>
<tr>
<td>3</td>
<td>$C_3^A$</td>
<td>$C_3^{A\oplus B}$</td>
<td>$C_3^B$</td>
</tr>
<tr>
<td>4</td>
<td>$\emptyset$</td>
<td>$C_4^{A\oplus B}$</td>
<td>$C_4^B$</td>
</tr>
<tr>
<td>5</td>
<td>$C_5^A$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>6</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>$C_6^B$</td>
</tr>
<tr>
<td>7</td>
<td>$\emptyset$</td>
<td>$C_7^{A\oplus B}$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>8</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
</tr>
</tbody>
</table>
Are Lone XOR Packets Useful?

Problem:

- There is no mutual information between lone XOR packet and individual user packets.

<table>
<thead>
<tr>
<th>Packet Index</th>
<th>$E_{q}^A$</th>
<th>$E_{q}^{A \oplus B}$</th>
<th>$E_{q}^B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$C_1^A$</td>
<td>$C_1^{A \oplus B}$</td>
<td>$C_1^B$</td>
</tr>
<tr>
<td>2</td>
<td>$C_2^A$</td>
<td>$\emptyset$</td>
<td>$C_2^B$</td>
</tr>
<tr>
<td>3</td>
<td>$C_3^A$</td>
<td>$C_3^{A \oplus B}$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>4</td>
<td>$\emptyset$</td>
<td>$C_4^{A \oplus B}$</td>
<td>$C_4^B$</td>
</tr>
<tr>
<td>5</td>
<td>$C_5^A$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>6</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>$C_6^B$</td>
</tr>
<tr>
<td>7</td>
<td>$\emptyset$</td>
<td>$C_7^{A \oplus B}$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>8</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
</tr>
</tbody>
</table>

Complementary XOR

Lone XOR

Do lone XOR packets have a role to play?
Critical Idea: MAC-Layer Erasure Coding

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 $L = 3$

<table>
<thead>
<tr>
<th>Packet Index</th>
<th>$Eq^A$</th>
<th>$Eq^{A\oplus B}$</th>
<th>$Eq^B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$C_1^A$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$C_2^{A\oplus B}$</td>
<td>$C_2^B$</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>$C_3^B$</td>
</tr>
<tr>
<td>4</td>
<td>$C_4^A$</td>
<td>$C_4^{A\oplus B}$</td>
<td>$C_4^B$</td>
</tr>
<tr>
<td>5</td>
<td>$C_5^A$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Packet Index</th>
<th>$Eq^A$</th>
<th>$Eq^{A\oplus B}$</th>
<th>$Eq^B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$C_1^A$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$C_2^{A\oplus B}$</td>
<td>$C_2^B$</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>$C_3^B$</td>
</tr>
<tr>
<td>4</td>
<td>$C_4^A$</td>
<td>$C_4^{A\oplus B}$</td>
<td>$C_4^B$</td>
</tr>
<tr>
<td>5</td>
<td>$C_5^A$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
NCMA Performance Evaluation

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

### Polling Table

| Timeslot 1 | NCMA node A, B |
| Timeslot 2 | NCMA node A, B |
| Timeslot 3 | NCMA node C, D |

### NCMA AP

- **Busy Channel**
  - PIFS Polling
  - SIFS
  - SIFS
  - PIFS End Poll
  - DIFS

### NCMA Transmission Period

- **X^A_1**
- **X^A_2**
- **X^B_1**
- **X^B_2**
- **X^C_1**
- **X^D_1**

### Legacy Packets

- Contention
  - Legacy packets
  - S
  - A
  - C
  - K

1/17/2014

Network-Coded Multiple Access
Decoder Latency Measurements

Processing time of different PHY-layer decoders
Layout of Indoor Experiments

Institute of Network Coding (INC)
PHY-Layer Packet Decoding Statistics (Balanced Power Case)

**Lone XOR packets**

- **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

![Graph showing decoding statistics for different SNR values](image)

**AWGN Channel Simulations**

- **(a) phase aligned**
- **(b) phase difference $\frac{\pi}{4}$**
- **(c) phase difference $\frac{\pi}{2}$**
Overall Throughputs (Balanced Power): Aggregated Throughput

- 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 Throughput (Balanced Power): Individual Throughputs of A and B

- RS code parameter $L_A = 4, 8, 16, 32$, and fixed $\text{SNR} = 9.5$ dB
Overall Throughputs (Balanced Power Case): Different SNRs

\[ L_A = 1.5 \times L_B = 24 \]
Throughputs of Four User Pairs

<table>
<thead>
<tr>
<th>Pair</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>A, NCMA w. RMUD</td>
</tr>
<tr>
<td>Pair 2</td>
<td>B, NCMA w. RMUD</td>
</tr>
<tr>
<td>Pair 3</td>
<td>A, NCMA w. RMUD+SIC</td>
</tr>
<tr>
<td>Pair 4</td>
<td>B, NCMA w. RMUD+SIC</td>
</tr>
</tbody>
</table>

Table 1: User pairing

<table>
<thead>
<tr>
<th>User Pair</th>
<th>User A</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Location 1 (20)</td>
</tr>
<tr>
<td>P2</td>
<td>Location 2 (12)</td>
</tr>
<tr>
<td>P3</td>
<td>Location 3 (9)</td>
</tr>
<tr>
<td>P4</td>
<td>Location 4 (7)</td>
</tr>
<tr>
<td>P5</td>
<td>Location 2 (12)</td>
</tr>
</tbody>
</table>

NCMA in Pair 4 seems to have a problem!
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

Pair “strong with weak” rather than “strong with strong and weak with weak”

Table 1: User pairing in random topology

<table>
<thead>
<tr>
<th>User Pair</th>
<th>User A</th>
<th>User B</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Location 1 (20dB)</td>
<td>Location 2 (12.3dB)</td>
</tr>
<tr>
<td>P2</td>
<td>Location 2 (12.3dB)</td>
<td>Location 3 (9dB)</td>
</tr>
<tr>
<td>P3</td>
<td>Location 3 (9dB)</td>
<td>Location 4 (7dB)</td>
</tr>
<tr>
<td>P4</td>
<td>Location 4 (7dB)</td>
<td>Location 5 (7.4dB)</td>
</tr>
<tr>
<td>P5</td>
<td>Location 2 (12.3dB)</td>
<td>Location 5 (7.4dB)</td>
</tr>
</tbody>
</table>
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
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
To Probe Further

Network-Coded Multiple Access:


Implementation of Physical-Layer Network Coding:


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!