EE7330: Network Information Theory **2021**

PAPER REVIEW - NETWORK CODED MULTIPLE ACCESS - II

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Disclaimer: *This paper review has been submitted as a part of final course presentation.. This review may not contain whole information as per the reference papers.*

0.1 Introduction

This paper presents a first real-time network-coded multiple access (NCMA) system that jointly exploits physical layer network coding (PNC) and multi-user decoding (MUD) to boost the throughput of a wireless local area network (WLAN). NCMA is a new design paradigm for multi-packet reception wireless networks, in which the access point (AP) can receive and decode several packets simultaneously transmitted by multiple users. Conventionally, multi-packet reception is realized using MUD only, while the key idea of NCMA is to use PNC together with MUD to realize multi-packet reception.

The current investigation makes the following state-of-the-art contributions towards NCMA:

1. NCMA system with integrated real-time PHY-layer and MAC layer.
2. A new unified framework for MAC-layer decoding that yields higher throughput with faster decoding – the faster decoding is one of the key enablers of our real-time implementation decoding.
3. Design new PHY-layer decoding techniques that overcome the poor performance of the first generation NCMA prototype at low SNR.

Experimental results show that, compared with the previous NCMA prototype, the new NCMA prototype improves real-time throughput by more than 100% at medium-high SNR ($\geqslant$ 8 dB).

0.2 Traditional System - IEEE 802.11 (WLAN)

In generally, WLAN transmits a packet to the intended user using access point(AP) directly as and when the channel is available for transmission. It is decoded and processed at the receiver by the protocol implemented. Here the message packets are simply relayed to the destination by Access Point. Depending on the protocol, acknowledgements are sent as and when the packet is received (for TCP/IP).

In traditional routing networks, packets are cached and forwarded downstream. Therefore, if a routing node receives two packets from two sources it forwards them one after another, and queues the others in the meantime, even if both are headed for the same destination. This requires separate transmissions for each and every message delivered, which decreases network efficiency.

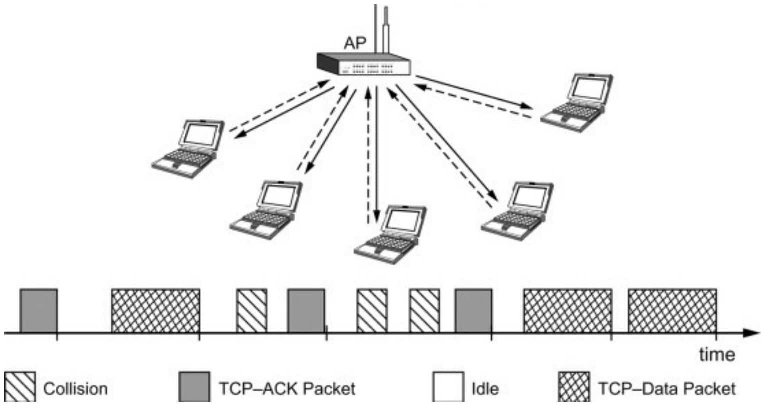

Figure 0.1: IEEE 802.11 WLAN Communication System

0.3 Definitions

0.3.1 Network Coding

Network coding is a networking technique in which transmitted data is encoded and decoded to increase network throughput, reduce delays and make the network more robust. In network coding, algebraic algorithms are applied to the data to accumulate the various transmissions. The received transmissions are decoded at their destinations. This means that fewer transmissions are required to transmit all the data, but this requires more processing at intermediary and terminal nodes.

In network coding, algorithms are used to merge those two messages and the accumulated result is forwarded to the destination. After receiving the accumulated message, it is decoded at the destination using the same algorithm. In order for this technique to work, the destination node needs to be completely synchronized with the transmitting nodes.

Network coding is perceived to be useful in wireless mesh networks, messaging networks, storage networks, multicast streaming networks, file-sharing peer-to-peer networks and other networks where the same data needs to be transmitted to a number of destination nodes. The regular topology change that occurs in peer-to-peer networks poses a challenge to the network coding technique because it complicates network synchronization. In addition, the peers may need a large amount of processing time while trying to decode data. Overall, large networks can increase their efficiency through the use of network coding.

0.3.2 NCMA - Network Coded Multiple Access

NCMA is about applying the principle of Network Coding by allowing EM waves to add up physically in a wireless broadcast situation. NCMA can support IPv6 jumbograms or other large messages from the network layer. Instead of chopping a large message M from the network layer into independent packets, it makes use of an erasure channel code to encode the message into multiple packets, $C_1, C_2, ...$(codewords). The erasure channel code adopted could be the Reed Solomon (RS) code or a rateless channel code. Provided a sufficient number of these packets are received correctly, then the original source message can be decoded at the receiver. At the PHY layer, each packet C_i is further channel-coded into a packet X_i. The RS code at the MAC layer and the convolutional code at the PHY layer are adopted by NCMA in this experimental

setup.
In the NCMA mode, the node transmits packets $X_1, X_2, ...$ in different time slots and a packet will not be retransmitted even if it cannot be received successfully. Also, the receiver will not return acknowledgements for individual packets; it will return an acknowledgement only when the overall message M is decoded. The architecture of NCMA is given below and is similar to IEEE 802.11. In NCMA, once the packets are received

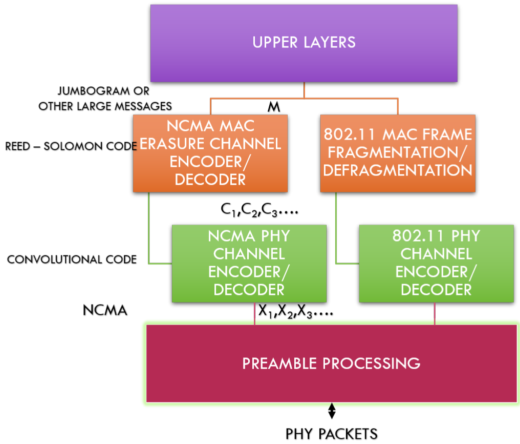

Figure 0.2: NCMA Architecture in comparison to IEEE 802.11

at the AP, then the packets are added or $\oplus$-ed. The super-imposed or added signals are sent to user at the same time so that the message may be decoded at the destination using the super-imposed signal or **XOR**-ed packets since the destination contains packet information those were sent by self. This procedure is PNC decoding. Multi-packet reception is realized using MUD in generally.

0.3.3 PNC - Physical Layer Network Coding

It is a technique to exploit wireless interference by turning the superimposed electromagnetic waves into useful network-coded information.The process of decoding for the network-coded information based on the superimposed signals is referred to as PNC decoding. Instead of forwarding the original information of the source nodes, the relay nodes (AP) forward the network-coded information to destination nodes, where self-information or side information obtained by overhearing, is used to extract the original source information.

0.3.4 MUD - Multi - User Decoding

When two nodes A and B transmit to the AP simultaneously, the MUD decoder in NCMA attempts to decode both C_i^A and C_i^B based on the overlapped signals of X_i^A and X_i^B ; the PNC decoder, on the other hand, attempts to decode $C_i^A \oplus C_i^B$ based on the same overlapped signals.

0.4 NCMA-I - First Prototype - Mathematical Statement

In WLAN, AP can receive and decode several packets simultaneously transmitted by multiple users as shown in traditional scheme discussed in below figure. In the figure, it can be observed that User A and B simultaneously transmits the data packets, but they are sent at various time slots as shown in figure.

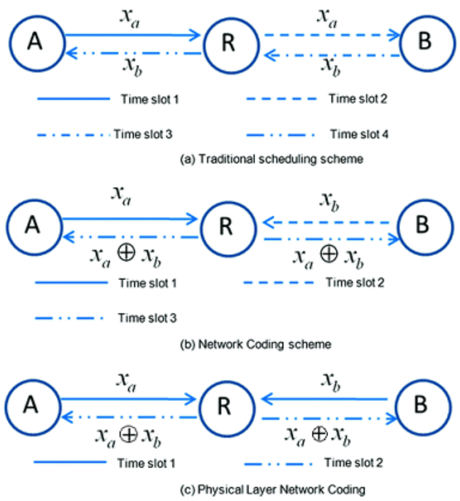

Figure 0.3: Comparison of NCMA and Traditional Transmission scheme

The Key idea of NCMA is to use PNC decoding together with MUD decoding as shown in the block diagram below at the PHY - Layer.

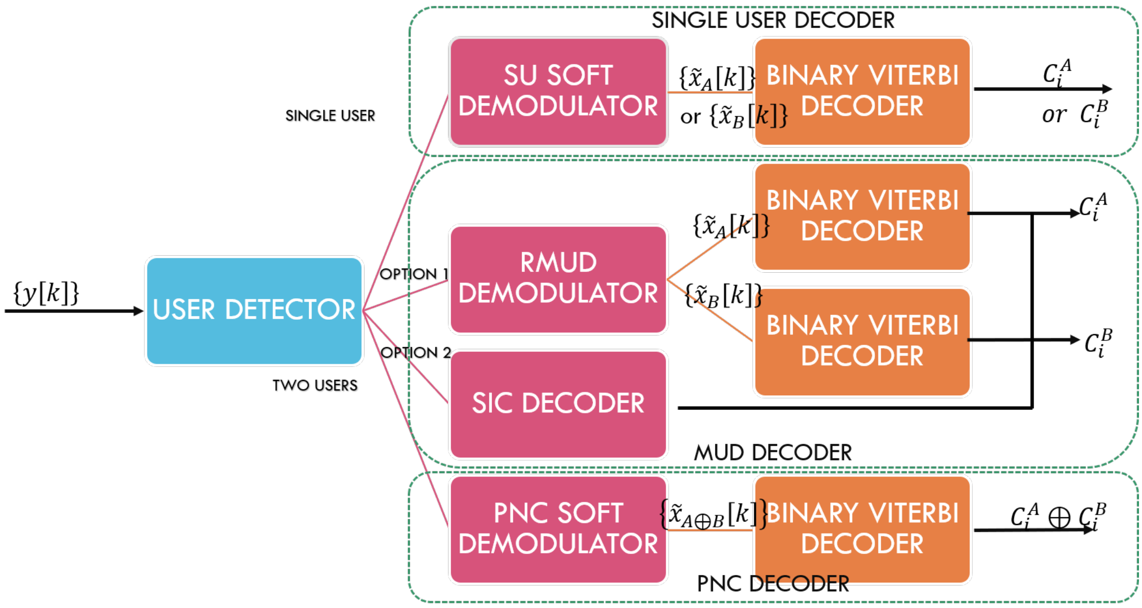

Figure 0.4: NCMA Implementation in Non- Relay Setting at PHY - Layer

At first, a MUD channel decoder is used to decode packets from both A and B(henceforth they are called packet A and packet B). If the MUD decoder successfully decodes both packets at the receivers, then the AP has successfully completed its job. However, sometimes only packet A or packet B can be obtained, and sometimes none of them. In the event that the MUD decoder can only decode either packet A or packet B, or none of them, then a PNC channel decoder is used to decode $A \oplus B$. The likelihood of the PNC decoder successfully decoding $A \oplus B$ when the MUD decoder does not have complete success in decoding packets A and B can be substantial. This procedure is referred as PHY - layer bridging mechanism where a native packet can be used with a complementary network-coded packet to recover a missing native packet at PHY-layer. The standard VA decoder is a very simple decoder that allows efficient real-time decoding and is used in all decoders.

If the MUD decoder fails to decode packets A and B. When neither A nor B can be decoded, the PNC decoder can still decode $A \oplus B$. At the MAC layer of NCMA, block messages M^A and M^B from A and B are coded using an erasure channel code (here it is Reed Solomon code) and partitioned into smaller constituent packets. With erasure channel coding, provided enough of the constituent packets of A (or B) can be decoded at the PHY layer, then M^A or M^B can be obtained at the MAC layer by the following procedure.

Suppose that at some point in time, the PHY layer has decoded enough packets of A for it to obtain M^A. Having the source message M^A then allows the AP to derive all the missing packets A in the previous PHY transmissions. This includes the time slots in which the PHY decoders could not decode both packets A and B but could decode packet $A \oplus B$. With the newly derived packets A, their corresponding missing packets B can now be recovered through the previously lone $A \oplus B$.

Once one of M^A or M^B is decoded, the lone $A \oplus B$ packets become complementary and useful. This procedure is referred to as the MAC-layer bridging mechanism of network-coded packets. At the PHY layer, each packet C_i is further channel-coded into a packet X_i. For implementation, the use of a convolutional code at the PHY layer and Reed Solomon Code at MAC layer are used. A nice property of the RS code is that as long as the number of PHY-layer packets successfully received and decoded at the AP is above a threshold L, then regardless of which L of the N packets $C_1, C_2, C_3, ...C_N$ are received correctly, the MAC-layer source message M can be decoded based on the L packets.

In NCMA, each user node transmits packets $X_1, X_2, X_3, ...X_N$ to the AP in successive time slots. Since the transmission has to be synchronous, beacons based triggers are used to transmit packets. As illustrated in Fig. 0.3, two user nodes may transmit in the same time slot. As an example the below table is considered for packet transmission.

Time Slot	A	$A \oplus B$	B
1	C_1^A	$C_1^{A\oplus B}$	C_1^B
2	C_2^A	ø	C_2^B
3	C_3^A	$C_3^{A\oplus B}$	ø
4	ø	$C_4^{A\oplus B}$	C_4^B
5	C_5^A	ø	ø
6	ø	ø	C_6^B
7	ø	$C_7^{A\oplus B}$	ø
8	ø	ø	ø

Figure 0.5: Data packets transmission at various timeslots

In timeslot 3, $C_3^A, C_3^{A\oplus B}$ are transmitted. Here by performing a bit-wise XOR of $C_3^{A\oplus B}$ and C_3^A, C_3^B is obtained. In the same, since ¿3 packets of A are available at receiver, M^A can be decoded by using erasure channel decoding as shown in fig 0.6.

0.4.1 PHY Layer Bridging and Decoding

In PHY Layer, PNC decoder and MUD decoder are employed with convolutional coding on BPSK modulated superimposed signals. This PNC decoder uses reduced constellation demodulation that facilitates soft decision decoding using Viterbi decoding algorithm. In PNC decoder, the soft information is determined by log likelihood ratio as per the equation below.

$$\begin{aligned}\log\frac{P_0}{P_1} &= \log\frac{Pr\{x_A=1,x_B=1|y\}+Pr\{x_A=-1,x_B=-1|y\}}{Pr\{x_A=1,x_B=-1|y\}+Pr\{x_A=-1,x_B=1|y\}}\\ &= \log(\exp(-\frac{|y-h_A-h_B|^2}{2\sigma^2})+\exp(-\frac{|y+h_A+h_B|^2}{2\sigma^2}))-\\ &\log(\exp(-\frac{|y+h_A-h_B|^2}{2\sigma^2})+\exp(-\frac{|y-h_A+h_B|^2}{2\sigma^2}))\end{aligned} \tag{0.1}$$

As per the constellation scheme, the MUD decoder also demodulates and decodes the message at PHY Layer. Since the data decided on these log likelihood values, a max function is used to decide the output. With BPSK modulation, (x_A, x_B) takes on four possible values, $(^+_-1,^+_-1)$. The corresponding soft bit is given by

$$\begin{aligned}&\text{for } (+1,+1) \text{ and } (-1,+1),\\ &\tilde{x}_{A\oplus B} \approx h_A.(y-h_B).\\ &\text{for } (-1,-1) \text{ and } (-1,+1),\\ &\tilde{x}_{A\oplus B} \approx -h_B.(y+h_A).\\ &\text{for } (+1,+1) \text{ and } (+1,-1),\\ &\tilde{x}_{A\oplus B} \approx h_B.(y-h_A).\\ &\text{for } (-1,-1) \text{ and } (+1,-1),\\ &\tilde{x}_{A\oplus B} \approx -h_A.(y+h_B).\end{aligned} \tag{0.2}$$

Feeding $\{\tilde{x}_{A\oplus B}[k]\}_{k=1,2,...}$ to the standard VA will yield $C^A \oplus C^B$. This MUD also uses reduced constellation demodulation and is called as RMUD. It provides information about $\tilde{x}_A, \tilde{x}_B$ for C_i^A, C_i^B.

$$\begin{aligned}\log\frac{P_0}{P_1} &= \log(\exp\{-\frac{|y-h_A-h_B|^2}{2\sigma^2}\}+\exp\{-\frac{|y+h_A+h_B|^2}{2\sigma^2}\})-\\ &\log(\exp\{-\frac{|y+h_A-h_B|^2}{2\sigma^2}\}+\exp\{-\frac{|y-h_A+h_B|^2}{2\sigma^2}\})\end{aligned} \tag{0.3}$$

0.4.2 MAC Layer Decoding and Bridging

NCMA-I proposes a three equation system for the above message decoding. Since they are non cyclic binary codes, they will have a generator polynomial in matrix form for generating codewords. Their codewords are generated using the following equations.

$$\begin{aligned}C^A &= G^A M^A\\ C^B &= G^B M^B\end{aligned} \tag{0.4}$$

These codewords are transmitted and received at the receiver end and are indicated by $\tilde{C}^A, \tilde{C}^B$. Whenever the decoding is being performed, then message

$$\begin{aligned}\hat{M}^A &= (\tilde{G}^A)^{-1}\tilde{C}^A\\ \hat{M}^B &= (\tilde{G}^B)^{-1}\tilde{C}^B\end{aligned} \tag{0.5}$$

Here the AP will perform a XOR on the packets received and broadcast them to both the users. Depending on minimum number of packets received i.e.L(here) and depending on from which user the packets received by using above equations missing packets in case of user A and B. If number of packets received are of XORed ones then the MAC bridging equations are used. They are given as below case wise.

Case - I and II: When L packets of user A or user B are received first than B or A and A ⊕ B, then following equations are used to decode

$$\begin{aligned} \tilde{G}^A M^A &= \tilde{C}^A \\ \tilde{G}^B M^B &= \tilde{C}^B \\ \bar{G}^{A\oplus B} M^B &= \bar{G}^{A\oplus B}(G^A)^{-1}C^A \oplus \bar{C}^{A\oplus B} \end{aligned} \tag{0.6}$$

Case - III: When L packets of AP i.e. A⊕B are received first than B or A, then following equations are used to decode

$$\begin{aligned} &\text{For decoding packets of A} \\ \tilde{G}^A M^A &= \tilde{C}^A \\ \bar{G}^B M^A &= \bar{C}^B \oplus (\bar{G}^B((\tilde{G}^{A\oplus B})^{-1}\tilde{C}^{A\oplus B})) \\ &\text{For decoding packets of B} \\ \tilde{G}^B M^B &= \tilde{C}^B \\ \bar{G}^A M^B &= \bar{C}^A \oplus (\bar{G}^A((\tilde{G}^{A\oplus B})^{-1}\tilde{C}^{A\oplus B})) \end{aligned} \tag{0.7}$$

The entire decoding of messages is shown in below figure.

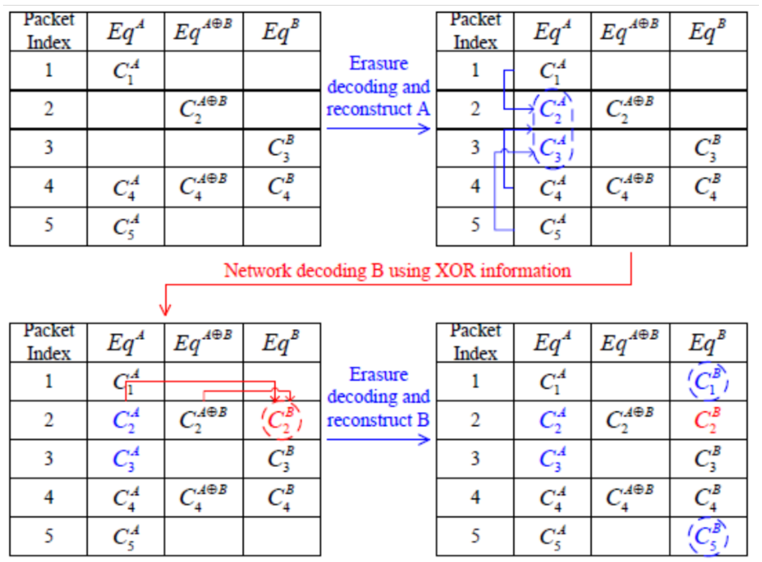

Figure 0.6: NCMA message decoding process

From the experimental results, all 100 % packets are decoded when NCMA is used. The performance of NCMA-I measured against SNR values is as below.

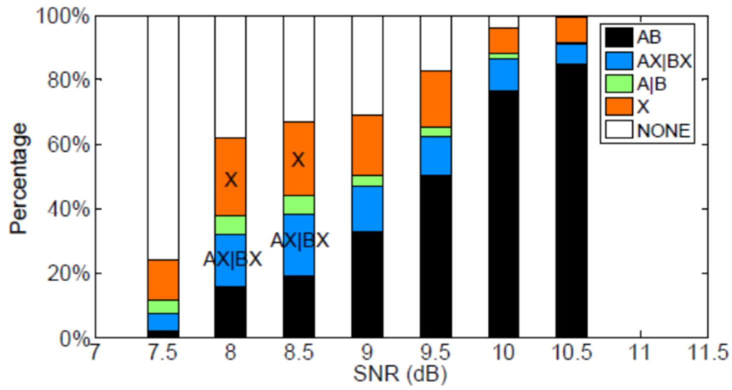

Figure 0.7: NCMA decoding process performance

Because of RMUD and PNC decoders, the latency or message processing time is of the order 1ms. The overall performance of NCMA-I as per measured throughput when measured against various SNR values can be shown as below.

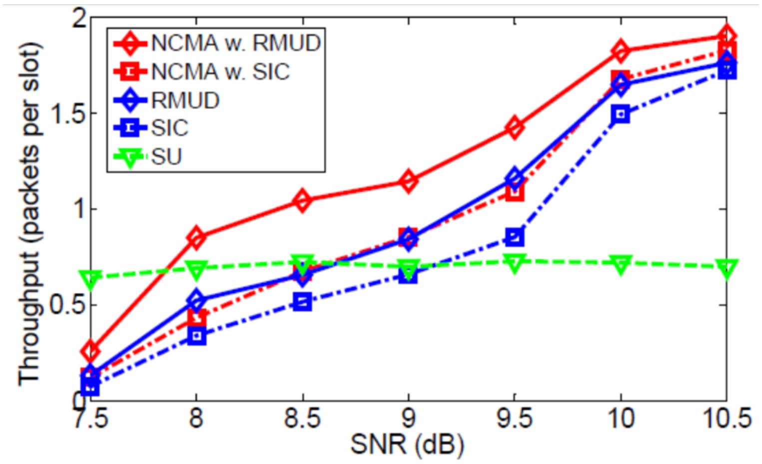

Figure 0.8: NCMA Throughput vs SNR

Initially, at SNR ranging from 7.5 to 8.5 db, though the Single user out performs NCMA-I with RMUD. However, when SNR $\geqslant$ 9.5 db, NCMA- I with RMUD performance is better than SU or other configurations. From the experimental results discussed above, NCMA-I proposes the following problems which are answered by NCMA-II:

1. PHY - layer decoding was not integrated with MAC Layer decoding.
2. PHY - layer decoding was performed online while MAC Layer decoding was performed offline. This affects the performance of system while decoding.

3. A Three Equation System was proposed of which two equations are defined for decoding native messages of two users independently and one equation for decoding a network-coded message of two users combined.

4. Performance of System was evaluated at mid-range SNR.

0.5 NCMA - II

In NCMA-II, MAC burst protocol(used for packet transmission) is modified beacon triggered transmission are added with a gap called "Inter Packet Interval" which can control the wastage of resource/ control the traffic of packets when burst transmission is performed. It is required because of unpredictable latencies introduced by experimental setup. In NCMA - II, the proposed modified Unified Equation System is proposed as below.

$$\tilde{G}\begin{pmatrix} M^A \\ M^B \end{pmatrix} = \begin{pmatrix} \tilde{G}_A^A & 0 \\ \tilde{G}_A^X & \tilde{G}_B^X \\ 0 & \tilde{G}_B^B \end{pmatrix}\begin{pmatrix} M^A \\ M^B \end{pmatrix} = \begin{pmatrix} \tilde{C}^A \\ \tilde{C}^{A\oplus B} \\ \tilde{C}^B \end{pmatrix} \tag{0.8}$$

where $\tilde{G}_A^A, \tilde{G}_B^B, \tilde{G}_A^X, \tilde{G}_B^X$ can be found out using equations as given above with slight modifications as explained in NCMA-II reference paper.And further, message B i.e. M^B also can be decoded at MAC layer by using the XOR packets. There are two conditions under which $\tilde{G}$ yields successful message decoding: Condition 1: $\tilde{G}_A^A$ has fewer than L rows, $\tilde{G}_B^B$ has fewer than L rows, but $\tilde{G}$ is full rank. Condition 2: $\tilde{G}_A^A$ has L rows or($\tilde{G}_B^B$ has L rows), but $\tilde{G}$ is not a full rank. Compared with TES, condition 1 is new. It is possible that condition 1 is fulfilled in UES (allowing both M^A and M^B to be decoded), and yet TES cannot decode any message yet . The next question is whether there are situations in which TES can decode messages, but UES cannot. The answer is no and UES is no worse than and may be better than TES.

To prove that UES performance is better than TES performance, a theorem is proposed in which the probability of $\tilde{G}$ being a full rank = 1 in condition 2 was proved by taking number of packets generated by users A and B, and minimum number of packets received at AP. If $\tilde{G}$ is a full rank, then by using XOR-ed packets, MAC layer can decode all messages successfully. Hence UES performance will be better than TES.

The performance of NCMA-II is also measure in message processing time. The comparison is given below.

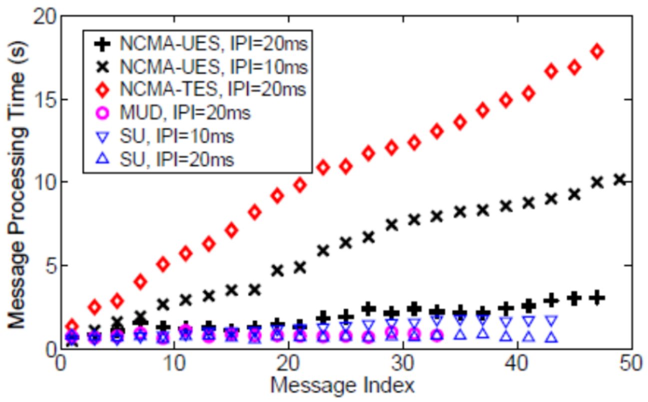

Figure 0.9: Message Decoding Procedure Time

It clearly indicates that NCMA with UES is performing better than any other configuration. The NCMA-

II when compared against various SNR values, it can be plotted as below.

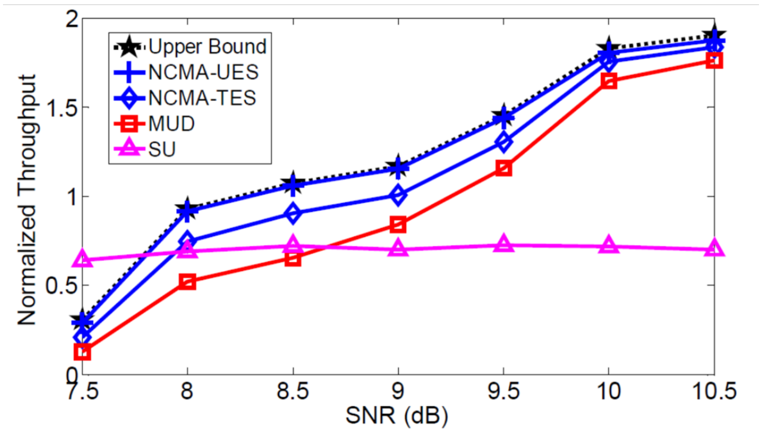

Figure 0.10: Normalized Throughput vs SNR

Here a new parameter called Normalized Throughput is used to measure performance since the processing or decoding of packets is done by using the raw samples taken by trace driven approach followed. The performance of single user decoding is better at low SNR since the PNC decoder and MUD designs are such at low SNR packets being decoded are error prone.

0.5.1 NCMA-II with SIC

This configuration with successive interference cancellation yields much better results when compared with NCMA-II with UES. Here if number of packets received at the MAC layer from MUD are less than 2 then the PHY- layer is requested for decoded packets from that particular user. Then as per the number of packets, the message is decoded fully. It can be seen as below.

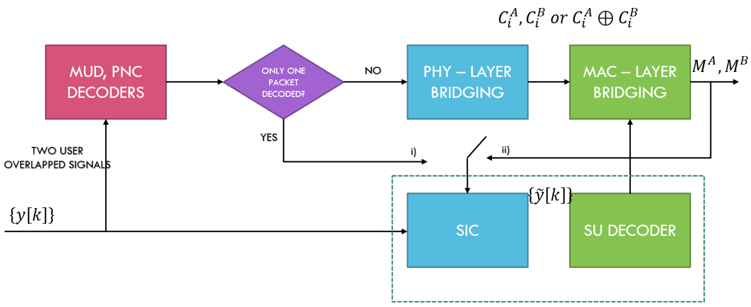

Figure 0.11: NCMA-II with SIC

The performance measured from the experimental setup is given as below.

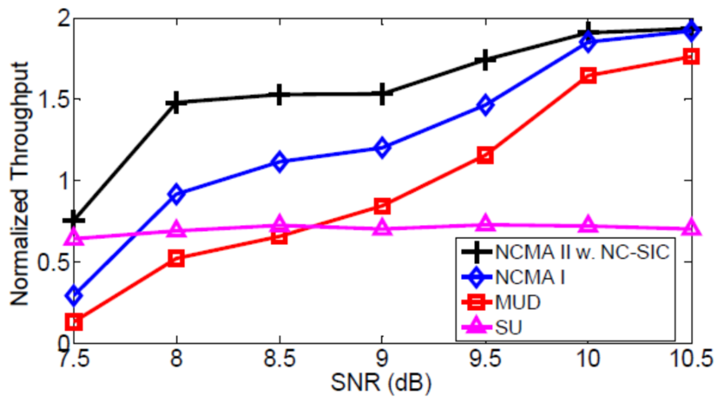

Figure 0.12: NCMA-II with SIC

0.6 Conclusion

This paper provided an insight about NCMA concept and how to implement it in a simplified way with few limitations. This paper has provided valued input with respect to parallel faster data transmission being used in latest communication technologies such as 5G etc, in which OFDM is utilized. It has also provided various data measuring techniques such as normalized throughput, message processing time which are important in any network capability measurements.

0.6.1 Notations

1. $\tilde{()}$ indicate received codewords
2. $\bar{()}$ indicates decoded codewords
3. C indicates codeword at sender side.

0.7 REFERENCES

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