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A NOVEL NETWORK CODING APPROACH: PACKETS CONFLICT BASED FOR MATRIX OPTIMIZATION

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ABSTRACT

Network coding (NC) is a technique used to improve wireless networks throughput, efficiency, and scalability. When employing this technique, wireless nodes collect several packets and combine them together in one single transmission. This technique is used to attain the maximum possible network flow with minimum number of transmissions. COPE, OpNC and FENC are widely known approaches in network coding that vary in complexity and optimality. COPE is the first proposed approach for network coding that is considered as a complex approach and may lead to a packet deadline termination; thus, transmitter should resend packets, and therefore, the overall throughput decreases. OpNC employs the COPE approach in order to find all possible codes for a set of packets, brute force searching, hence it is an exhaustive approach where the optimal solution is not always reachable. On the other hand, FENC utilizes division and conquers technique, in order to find an optimal network coding of a set of native packets, in which a repetitive algorithm is applied on the output queue more than once, in order to increase the possibility of finding an optimal coding solution.

In this paper, we propose a novel technique which utilizes two basic concepts of network coding: matrix optimization and the notion of conflict between packets. This technique is called "Conflict based Matrix Optimization for Network Coding Enhancement" (CMO-NCE), in which the opportunity of recovering more packets within the transmitted encoded packets combination is increased. Our proposed technique chooses better packets combination when transmitting the encoded stream; consequently, more packets are recovered at destination nodes. Simulation results show that the proposed technique is better in terms of complexity and optimality than other existing techniques such as COPE and OpNC. Also, it shows that the proposed CMO-NCE mechanism results are close to FENC approach. However, CMO-NCE's time complexity is less than FENC and it is linear, O(n), where n is number of wireless nodes, while FENC's time complexity is not linear, $O(\frac{P^2}{\log_2 p})$, where p is number of packets.

Keywords: *Network Coding, Packets Conflict, CMO-NCE, COPE, OpNC, FENC, Time Complexity*

1. INTRODUCTION

Over the last years, wireless networks were proposed for possible use in many applications out of which real-time and streaming video and audio delivery, remote monitoring, and indoor positioning [1-5]. A major concern about wireless network performance is throughput, especially with large scale wireless nodes deployment; therefore, network coding is a powerful technique that allows improving network capacity and packets delivery ratio. This technique is based on the fact that wireless networks

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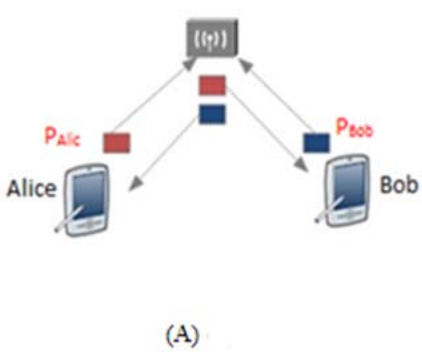
transmission's nature is broadcasting, such that when one node transmits a packet, all neighbor nodes within its transmission range can receive this packet [6-11]. Interestingly, this nature facilities network coding operation, because it allows intermediate nodes to receive and re-transmit multiple combined packets [12-18].

Network coding (NC) [19] can be defined as empowering the intermediate nodes within a network to combine the incoming packets flows, in order to reduce the number of overall transmissions between network nodes [20-24]. This process is called coding (or encoding) of packets, followed by transmitting these encoded packets to destination nodes, such that destination nodes are able to retrieve or decode packets targeted to themselves from the incoming flow (encoded packets). In wireless ad-hoc networks, this technique is a promising enhancement for packets flows [25-27], in which network throughput dramatically increases.

However, choosing the best suitable combination of received packets by intermediate node is important, in order to reduce number of transmissions and increase the probability to recover transmitted packets combinations at their destination. Hence, we are motivated in this study to propose a novel methodology, in order to select this kind of combination within a linear time complexity.

Figure 1 describes the concept of network coding in wireless networks; assume Alice and Bob want to exchange data packets, called P_{Alice} and P_{Bob}, respectively, through a wireless relay node. Figure 1.A shows packet transmission using the traditional method where network coding technique is not employed, the relay receives both packets and re-transmits each packet individually. Therefore, two transmissions are required to send each packet to its destination, and hence, an overall of four transmissions are required to exchange two packets.



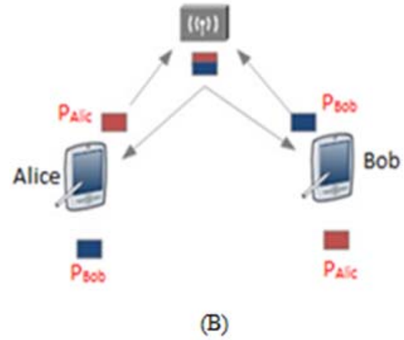


Figure 1: (A) Network Coding Technique is not Employed.
(B) Network Coding Technique is Employed.

However in Figure 1.B, a network coding approach is employed such that when (P_{Alice} and P_{Bob}) packets are received by the relay node, it combines them by applying logical XOR, then transmits only one encoded packet as ($P_{Alice} \oplus P_{Bob}$) instead of two separate packets (P_{Alice} and P_{Bob}) to their corresponding receiver nodes, Bob and Alice. Each receiver node should be able to decode the received encoded packet, because it already has buffered its recent transmitted packets. Bob can extract P_{Alice} packet by XORing the received encoded packet with its recent buffered packet, P_{Bob}, such that ($P_{Alice} \oplus P_{Bob} \oplus P_{Bob}$) = P_{Alice}. Also in same manner, Alice can extract P_{Bob} packet by XORing the received encoded packet with its buffered P_{Alice} packet. Therefore, the number of overall transmissions is reduced to three when NC technique is employed.

2. CONTRIBUTIONS AND PAPER ORGANIZATION

In this work, a new novel network coding technique is proposed that employs two basic concepts of network coding: matrix optimization and the notion of conflict between packets. This technique is called "Conflict based Matrix Optimization for Network Coding Enhancement" (CMO-NCE), where more packets are combined in one single transmission using a prediction method that is based on "Confliction of Packets" notion, in which the probability of recovering more encoded packets at their destinations is increased.

This notion is introduced to enhance packets selection strategy which results in: (a) – A near optimal encoded packets' combination, such that it rapidly reduces the search space for next new packets to be included within next transmitted encoded packets' stream. (b) - It also allows recovering more packets within the same round with lower time complexity, linear complexity, compared to other existing NC techniques, e.g.; FENC, as illustrated in results section.

Packets Conflict occurs when a packet cannot be combined with another packet, because there will be two or more missed packets in the transmitted encoded stream; therefore, it becomes impossible to extract any one of them at their corresponding destination nodes. This technique is explained in details with a case study in Section 4.

The rest of this paper is organized as follows: Section 3 presents related work. Section 4 explains our proposed technique with a comprehensive case study. Section 5 shows simulation results. Complexity analysis of our proposed CMO-NCE approach is discussed in section 6. Finally, conclusions and future work are presented in Section 7.

3. RELATED WORK

Researches introduced Network Coding (NC) technique in 2000 [28], which demonstrates that allowing routers to combine received packets improves network capacity [29-31], especially in multi-hop network where the broadcast nature of wireless transmission is utilized [42]. Also, NC is used in multimedia networks, in order to achieve better real-time streaming [32-33]. Moreover, the possible opportunities of employing NC in wireless networks are studied in [37, 39-41]. Network coding is used in wireless sensor networks to enhance coverage, increase throughput, and reduce number of transmissions [43-44], especially sensor nodes have limited resources such as energy.

The first approach of NC for wireless mesh networks is introduced in 2006 [31], called COPE, in which networks throughput is drastically enhanced. This approach attempts to increase coding opportunities in wireless medium by allowing nodes overhearing, such that each node listens to its neighbors and buffers the overheard packets, these packets are used for encoding process of any transmitted packets [35]. In order to perform this process efficiently, destination node must buffer packets to extract the node's target packet using logical XOR function. In COPE approach, a central node must find a set of packets to be encoded together, however, this process is somehow complex and may lead to packets deadlock. As a result, nodes are required to transmit all packets separately such that NC technique is not employed, and consequently network throughput is degraded.

Since the proposed system in this paper is based on COPE, we will discuss COPE in more details. Authors in [38] presented a theoretical formulation to evaluate throughput when applying COPE, they also modified COPE to be aware about network coding opportunities. In COPE technique, there are two main parts (two queues) in order to allow storing packets [31]: The first part is used to encode large packets of a size greater than 100 bytes. Second part is used to encode packets of a size less than 100 bytes. Figure 2 in the Appendix shows the pseudo-code for COPE technique [31].

In COPE method, the aim of dividing packets into small and large packets is to avoid losing throughput gain, especially when it happens that small packets are encoded with large ones. Thereby, COPE approach individually employs network coding for each packet size packets, e.g.; small packets are only encoded with the small ones.

Let's discuss another COPE-wise approach for network coding, called Optimal Network Coding (OpNC) [34-35], which is another COPE based approach and operates the same way as COPE. Initially, OpNC approach finds all possible packets combinations for the purpose of network coding, and then it selects the best possible packets combination. It is pretty much possible that OpNC method selects the encoded packets' combination which has the highest possibility of successful decoding at their corresponding destinations. However, the process of finding the best coded combination is performed in an exhaustive manner, especially for higher numbers of nodes and packets.

Authors in [36] introduced a newer COPE-wise approach and analyzed its complexity, called "Fast and Efficient Opportunistic Network Coding" (FENC) for wireless mesh networks, they claim its ability to find the encoded packets with lower complexity. The proposed approach is based on "divide and conquer" method, in order to find the optimal network coding packets. FENC approach divides N packets to n sets, such that each set includes m packets, where these sets are considered as the primary sets. Then, FENC method employs OpNC method, in order to find the best combination of packets to be encoded for each set. Then, every two primary sets are grouped as one cluster. For every cluster, combine the resultant packets for combination in pervious step with selected packets from another set within the same cluster as a new set. Repeat the previous step for new sets that are formed from clustering, until the last set is reached. That is, this last set is really the final combination of packets that can be encoded together. Authors discussed that the selected packets combination is optimal when their destination is close to the same packets set. It is worth mentioning that FENC approach time's complexity is not linear, O($\frac{P^2}{\log_2 p}$), where p is number of packets, which is lower than OpNC method time complexity.

Briefly, we can notice that the aforementioned studied approaches for network coding still have complex coding procedures. It becomes more complicated when one packet is transmitted to multiple nodes, or when one node is requesting to receive more than one packet. In addition, these approaches do not use any type of prediction when selecting the optimal encoded packets' stream.

4. THE PROPOSED APPROACH

A new network coding approach is proposed based on a notion of "Conflict based Matrix Optimization for Network Coding Enhancement" (CMO-NCE). It is a novel approach that is different from the COPE-wise approaches for network coding, because it is able to choose packets for encoding with lower complexity and higher optimality.

Selecting some packets for encoded stream and for omitting other packets are empowered by the notion of "packets confliction", therefore, packets search space domain is reduced, which in turn reduces the complexity of packets search time. On the other hand, identifying packets conflicts allows some type of prediction methods to select some packets as part of the optimal solution at earlier stages of operation, and combine more packets in one single transmission.

In the proposed technique, a binary matrix is used to indicate which packets have been buffered at any node, and which packets are required at destination nodes, this matrix can be obtained by opportunistic listening or reception reports. Once the binary matrix is obtained, these rules are applied during CMO-NCE approach operation:

- **Rule 1:** When a packet is selected as part of the encoded packets, all destination nodes of this packet will be omitted during any future search for the remaining packets, in other words, omit all matrix rows that contain zero in this column (since only one packet can be encoded for each node).
- **Rule 2:** At the same time, all missed packets at the destination nodes of the packet selected in step 1, are omitted from next searches, e.g.; omit all matrix columns that contain zeros for each zero in the selected column (since only one packet can be encoded for each node).

Table 1: An Example of Proposed CMO-NCE Technique.

	P0	P1	P2	P3	P4	P5
N0	1	0	1	0	1	1
N1	0	1	1	1	1	0
N2	1	0	0	1	0	1
N3	0	1	1	1	0	1
N4	1	1	1	1	1	0
N5	0	1	1	0	1	1

(a) Original Matrix

	P1	P2
N0	0	1
N2	0	0
N4	1	1

(b) Reduced Matrix

In order to explain aforementioned technique rules, consider a wireless network that contains 6 nodes and 6 packets, such that Table (1.a) shows their conflict binary matrix. Assume packet P0 is selected as the head of encoded packets' stream, thus this packet will be transmitted to nodes N1, N3 and N5. Therefore, based on rule 1, rows 1, 3 and 5 are omitted from the original matrix (that means no more packets can be sent to these nodes). In addition, all missed packets (columns) indicated by '0' in Table (1.a) for nodes (N1, N3 and N5) are omitted, that is no more than one packet can be decoded at these nodes at the same time, based on rule 2. In other words, packets P5, P4, and P3 at nodes N1, N3, and N5, respectively, cannot be transmitted together with packet P0 (rule 2). The highlighted rows and columns are omitted, and results in a new matrix as shown in Table (1.b).

Packet conflict occurs when packet cannot be sent with another packet, because no more than one missed packets in the encoded stream can be recovered at a given node. This concept is used in this work, in order to enhance the search process for the optimal coded packet stream selection. In the previous example, it is clear that packet P0 have a conflict of 3, which means there are three packets which cannot be encoded with packet P0 (only one packet will be encoded per node). A conflict of 3

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for packet P0 means nodes N1, N3 and N5 which miss packet P0, still have other missed packets as follows: P5 at N1, P4 at N3, and P3 at N5.

This bi-directional search for the solution rapidly decreases the size of the conflict binary matrix, hence speeding up the search process for all packets. It can be considered as having future knowledge about the current search of available packets and targeted nodes. Consequently, this approach results in a smaller search space when using the conflict binary matrix that allows extracting results faster. In addition, when transmitting encoded packets' stream, the conflict concept is used to decide which packets should be chosen first and which packets should be postponed for next transmission rounds, therefore, a near optimal coded packets is selected at each round. Simulation results show that the proposed technique increases throughput as compared to earlier network coding approaches, such as COPE.

4.1 Proposed Approach Description

This subsection presents steps of CMO-NCE approach and a detailed case study, in order to illustrate how this approach operates. The steps performed by CMO-NCE approach for network coding search process are as follows:

1. The intermediate node that is trying to transmit packets to its neighbor nodes has a binary matrix, that indicates packets existence at each node based on information obtained using opportunistic listening or reception reports exchanged with neighbors.
2. The algorithm starts by selecting the first packet in the encoding queue.
3. The destination nodes (binary matrix rows) are omitted from the search criteria for the next stages.
4. The missed packets (binary matrix columns) at nodes selected in step 3 are also omitted; due to the fact that only one packet can be encoded at each node and retrieved by its destination.
5. As a result, steps 3 and 4 reduce the size of the conflict binary matrix; because of that encoding packets' complexity is reduced.

The proposed notion of conflict for packets selection is used to accomplish near optimal encoding; where selected packet in step 2 should be the packet with the lowest conflict value. The conflict value of packet is calculated based on how many packets in node's array cannot be selected together with this packet. Choosing a packet with the lowest number of conflicts in the matrix allows receiving destination nodes to recover most possible packets. Notice that if two packets have the same conflict factor, CMO-NCE chooses the first one for encoding.

4.2 Proposed approach: A comprehensive Example scenario

To discuss the proposed approach, CMO-NCE, a wireless network case study is presented in this subsection, such that encoding rounds are presented in details until the encoding stream is formed. Table 2 shows a binary matrix that represents packets availability for the network, it consists 6 nodes (N0, N1, …, N5) and 6 packets (P0, P1, …, P5). As previously explained, '0' means the corresponding packet is missed, while '1' means the packet is buffered at its corresponding node. The conflict factor notion is employed in this example, in order to show the complexity and the optimality of the proposed approach.

Table 2: Initial Matrix (conflicts value are computed).

	P0	P1	P2	P3	P4	P5
N0	1	0	1	0	1	1
N1	0	1	1	1	1	0
N2	1	0	0	1	0	1
N3	0	1	1	1	0	1
N4	1	1	1	1	1	0
N5	0	1	1	0	1	1
Conflict	3	3	2	2	3	1

Round 1 steps for encoding process

Computing conflict factor for a packet depends on nodes that miss this packet and the missed packets at these nodes themselves. For example, P4 is missed at nodes N2 and N3. While node N2 missed packets are (P1, P2, P4), and node N3 missed packets are (P0, P4). As a result, packet P4 has a total conflict of three packets: (P1, P2) at N2 and (P0) at N3. Another example, packet P5 is missed on nodes N1 and N4. Node N1 misses packets (P0, P5), and node N4 misses only P5. Therefore, for packet P5, there is only one conflict on node N1 which between packets P0 and P5.

The CMO-NCE approach steps of round 1for the above conflict matrix, in order to choose encoded packets stream are as follows:

Step 1:

Select packet P5 as the first packet for encoding, because it has the lowest conflict value (which is equal to 1), see Table 3.

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Table 3: Select P5 (which has the lower conflict value)

	P0	P1	P2	P3	P4	P5
N0	1	0	1	0	1	1
N1	0	1	1	1	1	0
N2	1	0	0	1	0	1
N3	0	1	1	1	0	1
N4	1	1	1	1	1	0
N5	0	1	1	0	1	1
Conflict	3	3	2	2	3	1

Rows of nodes N1 and N4 are omitted from the matrix, because packet P5 will be transmitted to these nodes, rule 1. In addition, for these nodes all missed packets corresponding columns are also omitted, rule 2, since no more packets can be encoded on these nodes, e.g.; P0 is missed at node N1, consequently, P0 column is omitted. Table 4 shows the new matrix where the conflict values are re-calculated, in order to find the next best packet that should be selected in the next step.

Table 4: Resulted Matrix (recomputed conflicts)

	P1	P2	P3	P4
N0	0	1	0	1
N2	0	0	1	0
N3	1	1	1	0
N5	1	1	0	1
Conflict	3	2	1	2

Step 2:

Packet P3 has the lowest conflict value as shown in Table 4, and therefore, it is appended to coded packets stream which becomes packets (P5 and P3).

Nodes N0 and N5 rows will be omitted, because P3 will be sent to these nodes. In addition, all missed packets for these nodes can also be omitted, because no more packets can be encoded to these nodes, e.g.; packet P1 at node N0. Next, the conflict values are re-calculated, as shown in Table 5, to find the best packet to be selected in the next step.

Step 3:

In Table 5, note that packets P2 and P4 have the same conflict values, packet P2 is selected because it is the first one in the queue, thereby the encoded packets stream becomes (P5, P3, and P2).

Table 5: Selecting P2 (P2 is the prior packet in the queue with respect to P4).

	P2	P4
N2	0	0
N3	1	0
Conflict	1	1

In Table 5, node N2 row is omitted, because P2 will be transmitted to this node. Also, all missed packets for this node can also be omitted, since no more packets can be encoded to this node, such as packet P4 for node N2. Clearly, node N2 cannot recover P2 and P4 at the same time.

Therefore, at the first round, packets encoded stream is (P5⊕P3⊕P2), and it is transmitted to nodes (N0, N1, N2, N4, and N5), where these nodes can recover the corresponding packets successfully during this first round.

<u>Round 2 steps for encoding process</u>

After transmitting encoded packets (P5⊕P3⊕P2) in round 1, the corresponding packets at network nodes are recovered successfully. The conflict based matrix and its conflict factors are re-calculated as shown in Table 6, notice that packets P2, P3, and P5 are recovered at all nodes, and therefore, they are excluded from future packets encoded streams, so the new matrix is shown in Table 7.

Table 6: New Matrix for Second Round (conflicts value are recomputed).

	P0	P1	P2	P3	P4	P5
N0	1	0	1	1	1	1
N1	0	1	1	1	1	1
N2	1	0	1	1	0	1
N3	0	1	1	1	0	1
N4	1	1	1	1	1	1
N5	0	1	1	1	1	1
Conflict	1	1	0	0	2	0

Step 1:

As shown in Table 7, either packet P0 or P1 can be chosen for coding, because both have the same lowest conflict value. Let’s assume packet P0 is selected as the first packet in the encoded stream, and therefore, packet P0 corresponding column and nodes N1 and N2 corresponding rows are omitted.

Table 7: Select P0 (which has the lowest conflict value).

	P0	P1	P4
N0	1	0	1
N1	0	1	1
N2	1	0	0
N3	0	1	0
N4	1	1	1
N5	0	1	1
Conflict	1	1	2

Step 2:

After packet P0 has been chosen, the new conflict matrix is shown in Table 8. Now, actually one last column remained of packet P1, so that it is added to the encoded packets stream.

Table 8: Re-computed Matrix (after choosing packet P0 in step 1).

	P1
N0	0
N2	0
N4	1
Conflict	0

Step 3:

Transmit encoded packet (P0⊕P1) to nodes N0, N1, N2, N3, and N5. Notice that neither Packet P0 nor P1 is missed at node N4.

Round 3 steps for encoding process

Table 7 is updated after recovering packets P0 and P1 when encoding stream is decoded at nodes N0, N1, N2, N3, and N5, as shown in Table 9. Now, only packet P4 is still missing at nodes N2 and N3, as illustrated in Table 9. A neighbor node that has this packet can transmit this single packet to nodes N2 and N3, where NC technique is actually not required at this round.

Table 9: New Matrix for Third Round (conflicts value are re-computed).

	P0	P1	P4
N0	1	1	1
N1	1	1	1
N2	1	1	0
N3	1	1	0
N4	1	1	1
N5	1	1	1
Conflict	0	0	0

5. SIMULATION RESULTS

In order to compare the proposed CMO-NCE approach with other three well-known approaches in literature (COPE, OpNC, and FENC) that discussed in the related work section. We assume there is a central access point surrounded by a group of one-hop nodes. This central point has information about buffered packets in each neighbor node collected using channel's overhearing. The considered performance metrics: number of recovered packets at each round, and encoding process time complexity.

In simulation, different scenarios of packets distribution are generated with different number of nodes and packets, e.g.; Table 10 (illustrated in the Appendix) shows a binary matrix distribution for a random scenario with 25 nodes randomly distributed, number exchanged packets is 25, and a miss rate of 7%.

Results for this test scenario are shown in Table 11, in which the four approaches are compared with respect to average number of recovered packets during the first round of CMO-NCE approach, where packets miss rate is varied as 7%, 12.5%, 17.5% and 21.5%.

These results are evaluated for ten randomly generated scenarios (in other words, ten different binary matrices as matrix format shown in Table 2). Clearly, the proposed method achieves the highest average number of recovered packets for all different miss rates, while COPE approach has the worst performance.

Table 11: Average number of recovered packets for the first round of encoding with respect to different miss rates (7%, 12.5%, 17.5% and 21.5%) for four different network coding approaches.

	7%	**12.5%**	**17.5%**	**21.5%**
COPE	9.1	6.1	4.2	3.2
OpNC	10.4	8	5.7	4.5
FENC	9.4	6.4	4.7	3.4
CMO-NCE	10.9	8.6	6.1	4.8

Table 12: Comparison of all tested protocols for different parameters with respect to number of recovered packets at each round ("UR" stands for Unreachable Results within12 hours), where number of wireless nodes is fixed to 20.

Number of Packets	Miss rate (%)		Round 1	Round 2	Round 3	Round 4	Round 5
20	20	COPE	3	3	3	4	2
		FENC	3	3	3	4	2
		CMO-NCE	5	3	3	2	2
		OpNC	5	3	3	3	2
20	40	COPE	1	2	2	1	1
		FENC	2	2	2	1	1
		CMO-NCE	2	2	2	1	1
		OpNC	2	2	2	1	1
40	20	COPE	7	3	3	3	3
		FENC	6	4	3	3	3
		CMO-NCE	7	3	4	3	3
		OpNC	UR	UR	UR	UR	UR
40	40	COPE	2	1	1	1	2
		FENC	2	2	1	2	1
		CMO-NCE	2	2	2	2	2
		OpNC	UR	UR	UR	UR	UR
60	20	COPE	7	4	5	4	4
		FENC	6	4	4	5	4
		CMO-NCE	9	6	4	4	3
		OpNC	UR	UR	UR	UR	UR
60	40	COPE	3	3	1	1	1
		FENC	2	2	1	1	1
		CMO-NCE	3	2	3	2	2
		OpNC	UR	UR	UR	UR	UR
80	20	COPE	7	7	4	4	6
		FENC	6	6	5	4	4
		CMO-NCE	9	8	4	5	3
		OpNC	UR	UR	UR	UR	UR
80	40	COPE	1	2	1	1	2
		FENC	2	2	2	3	2
		CMO-NCE	3	3	3	2	2
		OpNC	UR	UR	UR	UR	UR

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Table 13: A comparison between COPE and CMO-NCE Approaches with respect to number of recovered packets at each round (with higher number of exchanged packets and nodes compared to Table 12 results).

Nodes	Packets	Miss rate (%)		Round 1	Round 2	Round 3	Round 4	Round 5	Total number of recovered packets (in five rounds)
25	100	5%	COPE	16	17	8	9	8	58
			CMO-NCE	22	17	11	8	6	64
25	200	15%	COPE	9	9	5	9	6	38
			CMO-NCE	15	12	9	8	7	51
50	100	5%	COPE	18	15	11	9	9	62
			CMO-NCE	23	14	11	8	7	63
50	200	15%	COPE	6	5	5	5	5	26
			CMO-NCE	9	7	6	6	5	33

Table 12 shows comparison results of the proposed technique, CMO-NCE, with COPE, FENC, and OpNC NC techniques for five consecutive encoding rounds during the network operation. In this simulation, number of nodes is fixed to 20, while number of exchanged packets and miss rate are varied. Interestingly, results show that the proposed CMO-NCE approach outperforms other existing approaches, because it recovers more packets during encoding rounds. Notice that CMO-NCE results are very close to OpNC approach (the optimal approach), however, OpNC coding and decoding processes require much longer time than CMO-NCE (explained later in this section) which makes CMO-NCE outperforms those three approaches in terms of recovery efficiency and time complexity.

Results show a huge amount of time is required to run OpNC algorithm that is actually used in FENC approach, as mentioned in Section 3. Consequently, in our simulation scenarios we reduce number of packets, and/or number of nodes, and/or increase miss rate in order to reduce processing time which is needed to reach a result. Unreachable results within 12 hours of processing are denoted by (UR) (actually this time is not reasonable for any type of networks) using Intel core i5 processor at 2.4 GHz, cache memory of 6 MB and RAM of 4 GB, compared to wireless nodes which have limited resources such as processing capabilities and memory size. Therefore, we assume there is a central unit, in which these calculations are conducted. OpNC approach requires a long time in order to reach results, because it enumerates all possible combination of packets, which checked against each node for validity testing. Therefore, number of possible combinations is exponential and is equal to $O(2^P)$, where P is number of packets.

Table 13 shows a comparison between CMO-NCE and COPE approaches, this time higher number of nodes and packets are simulated with five consecutive rounds with miss rates of 5% and 15 %. The valuable insights of these results are: (1) - During early encoding rounds, interestingly CMO-NCE approach produces higher number of recovered packets and in a descending order, which indicates its coding efficiency. (2) - CMO-NCE approach total number of recovered packets in five rounds is greater than COPE, e.g.; when number of nodes, packets, and miss rate are 25, 200, and 15%, respectively, the average total number of recovered packets for CMO-NCE is 51, while COPE recovered only 38 packets. That is why our proposed approach is really considered as a novel method.

Novelty Discussion:

Based on simulation results, the proposed technique is a novel method with respect to compared techniques, due to many reasons as follows:

1. The proposed CMO-NCE technique uses two concepts to enhance network coding: binary matrix optimization and conflict factor notion.
2. Matrix optimization arranges the relation between missed packets and nodes, which

allows decreasing matrix size rapidly, during encoding process operation, when a packet is selected to be in the encoding stream, corresponding rows and columns are omitted.
3. At each round in CMO-NCE approach, conflict factor is used in optimization process to select the best packets (with lowest conflict value) to be included in encoded stream.
4. Simulation results show that sometimes CMO-NCE approach performance is close to a well known approach as OpNC; however, CMO-NCE time complexity is linear while OpNC is exponential.
5. Also, CMO-NCE performance is close to FENC approach, however, CMO-NCE approach time complexity is less, because it is linear, O(N), where N is number of wireless nodes, as explained in section 6. While, FENC approach time complexity is not linear, O ($\frac{P^2}{\log_2 p}$), where p is number of packets.

6. COMPLEXITY ANALYSIS FOR THE PROPOSED APPROACH

The complexity of any network coding approach mainly depends on how many combinations are required to reach the final optimal solution for encoding. The complexity for OpNC method is O (2^P), where P is the number of packets. In FENC, the complexity is calculated by multiplying number of sets by complexity of OpNC method upon each set to obtain a complexity of O($P^2/\log_2 P$). Notice that the complexity is not linear for these two network coding techniques.

In order to evaluate the complexity of our proposed CMO-NCE approach, assume M is the miss rate, N is the number of wireless nodes, and P is the number of packets (involved in encoding process operation):

- Number of selected nodes, say X, from the binary matrix is given by equation (1).

$$X = MN \qquad (1)$$

- Number of selected packets after selecting nodes, Y, as in equation (2); where K is a constant that indicates the ratio of packets to be excluded from the coding round.

$$Y = k\,(MN)\,(MP) \qquad (2)$$

- The remaining number of packets after selecting the first packet, P_{new}, is given by equation (3).

$$P_{new} = P - K\,(MN)\,(MP) = P\,(1 - K\,M^2\,N) \qquad (3)$$

- The remaining percentage of packets is given by equation (4).

$$P_{new}/P = 1 - K\,M^2\,N \qquad (4)$$

- The percentage of total number of packets that is deleted at any round is given by equation (5).

$$\sum_{i=1}^{N} P\,(1 - K\,M^2\,i) \le P \qquad (5)$$

Finally, as in equation (5), the algorithm ends when the summation of deleted packets reached the total number of packets. Thereby, the time complexity of CMO-NCE technique is linear, which is a function of number of wireless nodes, O(N), and it is the lowest time complexity for all tested approaches, e.g.; COPE, in simulation section.

7. CONCLUSIONS AND FUTURE WORK

Employing network coding technique in wireless networks reduces the total number of required transmissions, in order to disseminate packets through the network. Therefore, throughput is maximized, bandwidth utilization is enhanced, and nodes resources such as power and memory are efficiently utilized. In this paper, we propose a new network coding approach that is based on a notion of Conflict based Matrix Optimization for Network Coding Enhancement (CMO-NCE). It is a novel approach that is different from the COPE-wise approaches for network coding, CMO-NCE approach chooses packets for encoding with lower complexity and higher optimality. This approach simply employs the conflict notion between packets, such that it rapidly reduces the search space for next new packet to be included in encoded packets stream, and also it recovers more packets within same round compared to other existing network coding techniques, as illustrated in results section. The proposed technique is applicable and scalable, where it can be implemented with large number of nodes operating packets exchange.

Simulation results illustrate that the proposed CMO-NCE technique recovers the highest number of packets in almost all tested scenarios. Recovering packets results of CMO-NCE and FENC approaches are close and their time complexities are O(N) and $O(P^2/\log_2 P)$, respectively, where N is number nodes and p is number of packets. Clearly our proposed approach time's complexity is less, because it follows a linear function.

As a future work, we plan to apply the proposed algorithm on different wireless network types, and also to develop a mechanism of choosing the best packet from packets when they have equal conflict factors during the encoding process, such that the encoding mechanism is improved.

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APPENDIX

```
Pick packet p at the head of the output queue
Natives = {p}
Nexthops = {nexthop (p)}
If size (p)>100 bytes then
   which_queue = 1
Else
   which_queue = 0
End if

For neighbor i=1 to M do
          Pick Packet pi, the head of virtual queue Q
(I, which_queue)
          If ∀ n ϵ Nexthops ∪ {i}, Pr [n can
decode p ⊕ pi] ≥ G then
                    p=p ⊕ pi
                    Natives = Natives ∪ {pi}
                    Nexthops = Nexthops ∪ {i}
                End if
End for

which_queue =! which_queue

For neighbor i=1 to M do
                Pick Packet pi, the head of virtual
      queue Q (I, which_queue)

                If ∀ n ϵ Nexthops ∪ {i}, Pr [n can
      decode p ⊕ pi] ≥ G then
                  p=p ⊕ pi
                  Natives = Natives ∪ {pi}
                  Nexthops = Nexthops ∪ {i}
              End if
End for
return p
```

Figure 2: *COPE Network Coding Procedure [31].*

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Table 10: A Random Scenario Consists 25 Nodes which Exchanging 25 Packets, where Miss Rate is 7%.

	Test #				1		# of Nodes =				25		# of Packets =				25		Miss Rate =				7%		
	Packet ID																								
Node ID	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	0
2	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	0	1	1	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1
8	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
16	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
21	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1
22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1