Efficient Reliable Opportunistic Network Coding Based on Hybrid Flow in Wireless Network

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Abstract: Although the wireless network is widely used in many fields, its characteristics such as high bit error rate and broadcast links may block its development. Network coding is an artistic way to exploit its intrinsic characteristics to increase the network reliability. Some people research network coding schemes for inter-flow or intra-flow, each type with its own advantages and disadvantages. In this paper, we propose a new mechanism, called MM-NCOPE, which integrates the idea of inter-flow and intra-flow coding. On the one hand, MM-NCOPE utilizes random liner coding to encode the NCOPE packets while NCOPE is a sub-protocol for optimizing the COPE algorithm by iteration. In NCOPE, packets are automatically matched by size to be coded. As a result, it improves the coding gain in some level. On the other hand, we adopt the partial Acknowledgement retransmission scheme to achieve high compactness and robustness. ACK is an independent packet with the highest priority rather than a part of the data packets. Compared with existing works on opportunistic network coding, our approach ensures the reliability of wireless links and improves the coding gain.

Key words: network coding; reliability; hybrid flow

I. INTRODUCTION

Wireless networks have been designed using the wired network as the blueprint [1]. However, current wireless networks suffer low throughput, unreliable and insecure link, and inadequate mobility support [2].

The characteristics of wireless networks might seem to be disadvantageous at first sight, but the broadcast nature of wireless networks provides an opportunity to deal with unreliability [3-5]. Interestingly, wireless networks exhibit significant data redundancy [6]. As a packet travels multiple hops, its content becomes known to many nodes [7]. Furthermore, wireless broadcast amplifies the redundancy because at each hop it delivers the same packet to multiple nodes within the transmitter's radio range [8]. Can an alternative design of wireless networks exploit their intrinsic characteristics to increase the network reliability? Network Coding (NC) has changed the traditional concept that node is just only responsible for receiving and forwarding. Now the node can first encode the packets before sending, and then the receiving nodes decode them according to the coding rules [9-11]. Because of the broadcasting characteristic of the physical layer, it is quite appropriate to use the network coding approach in wireless networks [12]. Currently, some literatures present researches on some network coding schemes for inter-flow or intra-flow [13]. These two types of network coding complement each other. The design to integrate them is a natural next step [14].

In this paper, we study existing wireless transmission technologies with network coding, such as opportunistic network coding, and opportunistic routing mechanism (MORE). Then, we focus on the COPE, a network coding mechanism which mainly analyzes its opportunistic listening, coding, encoding and decoding algorithms and packet format. On the basis of the intra-session network coding, we propose a new mechanism, called MM-NCOPE, which utilizes random liner coding to encode the NCOPE packets in one generation, transmits them in a multi-path method, and only needs an ACK from receiver for one generation each time. By means of random liner coding, multi-path method and ACK for one generation, MM-NCOPE improves the coding gain and ensures the reliability of wireless links.

II. NCOPE CODING ALGORITHM

COPE [9] adopts an opportunism coding mode while it divides the packets into two types by size. However, only the packets which are similar in size are coded. If this condition is not satisfied, packets will be sent without any treatment. In this section, we propose NCOPE to optimize the COPE algorithm by iteration. In NCOPE, if there is no appropriate packet for one type, the packets of the other type will be searched. As a result, it improves the coding gain in some level. The algorithm of NCOPE is as follow:

Algorithm 1: NCOPE Coding Procedure
Begin
Pick packet p at the head of the FIFO queue, **then** initialization state
Native packets Set: *Natives* = $\{p\}$
NextHops Set: *NextHops* = $\{\text{nexthop}(p)\}$
Node_State [M] = $\{0\}$
If sizeof(p) > 100 bytes **then**
Native_Queue_type = 1
Else
Native_Queue_type = 0
End if
For Neighbor $i = 1$ to M **do**
Pick packet p_i, the head of virtual queue Q (i, *Native_Queue_type*)
If every node n in $\{NextHops \cup \{i\}\}$, P_d [node n can decode $p \odot p_i$] > G($G = 0.8$)
Then
NCOPE-coded packet: $P_n = p \odot p_i$
Natives = *Natives* $\cup \{p_i\}$
NextHops = *NextHops* $\cup \{i\}$
Else Node_State [i] = 0
End if
End for
Native_Queue_type = ! *Native_Queue_type*
For Neighbor $i = 1$ to M **do**
If Node_State [i] = 0 **Then**
Pick packet p_i, the head of virtual queue Q (i, *Native_Queue_type*),
If every node n in $\{NextHops \cup \{i\}\}$, P_d [node n can decode $p \odot p_i$] > G($G = 0.8$)
Then
NCOPE-coded packet: $P_n = p \odot p_i$
Natives = *Natives* $\cup \{p_i\}$
NextHops = *NextHops* $\cup \{i\}$
End if
End if
End for
Return P_n
End

III. MM-NCOPE OVERVIEW

In this section, we propose a novel mechanism called MM-NCOPE based on NCOPE, which can adapt to the situation with high packet loss rate in wireless networks. Similar to COPE, MM-NCOPE allocates in MAC and IP levels.

The main procedure of MM-NCOPE is as follows:

(1) Before sending the native packets, nodes code them by NCOPE.

(2) Batching the NCOPE coding packets. Assuming each batch with a unique cluster ID has k NCOPE packets.

(3) Calculating the MM-NCOPE packets from the k NCOPE packets of the same batch by random linear coding.

3.1 NCOPE packet

In the MM-COPE protocol, nodes code some NCOPE packets to prepare for sending. Each node maintains a FIFO queue of packets which stores the native packets to send. According to Algorithm 1, it chooses the packets conforming to requirements in the whole queue before producing NCOPE packets. Similar to the COPE algorithm, it requires the nodes to be aware of the statement information of their neighbors. That means each node can be conscious of its neighbors´ native packets. In our scheme, nodes adapt receiving reports and intelligence guessing methods to obtain or update their neighbor statement information. Receiving reports is an appropriate method if the wireless network is stable. When the packet loss rate is high in the wireless network, receiving reports may not be listened to by nodes around and the intelligence guessing method is a good choice in this situation. As a result, we can estimate the probability of neighbors to participate in coding native packets using these two methods.

Besides, each node maintains a native packet poll which records the packets owned by its neighbors. NCOPE adopts the regulation coding packets with closing on size, so a native packet poll has two virtual queues. One stores the small packets whose size is less than T, and the other stores the rest packets. In our experiments, T is 100 bytes. Considering the convenience to realize, the two virtual queues are composed of two pointer lists. The virtual queues in native packet poll help search the opportunities to code because we only need to focus on one queue. It is worth notice that each neighbor can only choose one packet to code at most because nodes do not deal with the packets having the same destination in NCOPE.

If a node i which has m neighbors codes n native packets, NCOPE sets a probability threshold G_p ($G_p = 0.8$) to make sure that each next hop node has the decoding ability. The sender estimates the encoding probability (P_D^j) of neighbor node j ($j \neq i$, $j \in \{1, 2, ..., m\}$) as follow:

$$P_D^j = \prod_{r=1}^{n} P_r^j \tag{1}$$

where P_r^j is the probability that the neighbor node j listens to r th packets.

Definition 1: If $P_D^j \geq G_p$, $j \neq i$, $j \in \{1, 2, ..., m\}$, the probability that the coding packet can be encoded is not less than G_p.

If Definition 1 is satisfied, node i could code and send the NCOPE packet P_{nc}, where

$$PT_{nc} = PT_1 \oplus PT_2 \oplus ...... \oplus PT_n \tag{2}$$

Each NCOPE packet has a NCOPE header which includes some information about native packet such as its IP address, hash value and the next hop node. At the same time, the NCOPE header also presents the neighbor packet statement of source node in order to provide some useful information for other nodes´ updating.

3.2 MM-NCOPE packet

When node calculates some NCOPE packets by the before-mentioned method, according to different time slots, it temporarily stores them into NCOPE packets pool which is divided into Big_NCOPE and Small_NCOPE packet generations. The number of packets in Big_NCOPE packet generation is G_B and that in Small_NCOPE packet generation is G_S. If G_B is less than the threshold of generation G_T, node selects some packets from Small_NCOPE packet generation to code, vice versa. It should be noted that only the NCOPE packets belonging to the same generation can be coded. In this paper, we adopt a stochastic linear coding algorithm to calculate MM-NCOPE packet which is composed of k NCOPE packets in G_B or G_S. For example, node selects k NCOPE packets(PT_{N_1}, PT_{N_2}, ... PT_{N_k}) from Big

_NCOPE packet generation, it transforms them into MM-NCOPE packet PT_{MM_j} as follow:

$$P_{MM_j} = (C_{j1} \quad \cdots \quad C_{jk}) \begin{pmatrix} P_{N_1} \\ \vdots \\ P_{N_k} \end{pmatrix} \tag{3}$$

where $(C_{j1} \quad \cdots \quad C_{jk})$ is the stochastic code vector which is used to encode.

After MM-NCOPE packet is generated, the sending node adds a MM-NCOPE header into NCOPE packet which includes code vector, generation ID, source IP address and the receiver list. At last, the MM-NCOPE packet is sent to the destination nodes. The sending node produces various MM-NCOPE packets of the same generation until it receives the ACK packets from the destination packets. The ACK packets mark the end of this generation.

3.3 Packet decoding

MM-NCOPE code is only related to two-hop nodes, so the relay node is a single-hop node. According to MM-NCOPE coding principle, relay node also can be the destination node at the same time. When a node receives a MM-NCOPE packet, it checks whether it is in the receiver list.

The main idea of decoding packets is as follows:

1) Checking whether it is an innovative packet. That means whether the packet is linear independent with existing MM-NCOPE packets in buffer.

2) If it is an innovative packet, node stores it in buffer. Otherwise, node drops it.

$$\begin{pmatrix} PT_{N_1} \\ \vdots \\ PT_{N_2} \end{pmatrix} = \begin{pmatrix} PT_{MM_1} \\ \vdots \\ PT_{MM_k} \end{pmatrix} \cdot \begin{pmatrix} C_{11} & \cdots & C_{1k} \\ \vdots & \ddots & \vdots \\ C_{k1} & \cdots & C_{kk} \end{pmatrix}^{-1} \tag{4}$$

3) After receiving k linear independent MM-NCOPE packets, node picks up the code vectors from them. According to equation (4), it can decode the vector $(PT_{N_1}, PT_{N_2}, \ldots \ldots PT_{N_k})$. Then, it updates the neighbor statement list by k NCOPE packets.

It is worth notice that the array $\{C_{ij} \mid i, j \in \{1, 2, \ldots, k\}\}$ must be reversible.

4) Checking whether it accords with the decoding condition of NCOPE. If the condition is satisfied, node resumes n native packets.

5) Decoding packets which node needs according to equation (2).

3.4 Packet structure

Compared with native packet, MM-NCOPE packet has two extra headers which are NCOPE header and MM-NCOPE header. The header structure is shown in Figure 1.

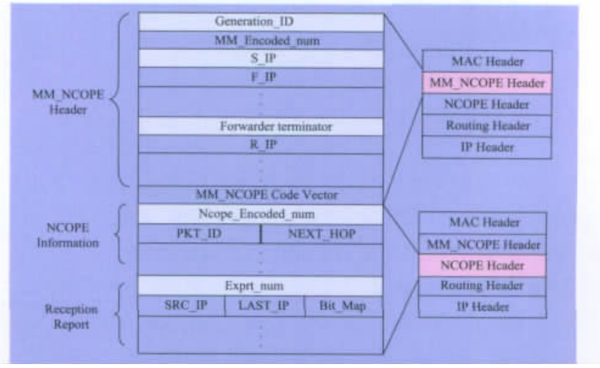

Fig. 1 **MM-NCOPE header**

In our scheme, the packet header consists of MAC header, MM-NCOPE header, NCOPE header, Routing header and IP header. As shown in Figure 1, NCOPE header only includes two parts of COPE header in data packet. The ACK information is sent as control packet which has the highest priority level. In NCOPE header, NCOPE information contains some elements used to decode: Ncope_Encoded_num refers to the number of native packets; PKT_ID denotes the hash value of source IP address and IP sequence; NEXT_HOP represents the next hop node. Reception Report is made up by the number of reception reports and a reception report list of neighbor statement.

MM-NCOPE header which allocates between MAC header and NCOPE header consists of three parts. The first part includes Generation_ID and MM_Encoded_num. Generation_ID is the identification of generation and MM_Encoded_num is the identification of MM-NCOPE packet in the same generation. The second part includes the sender IP address S_IP, relayer IP address list F_IP and receiver IP address list R_IP. The third part presents the code vectors.

3.5 Partial acknowledgement retransmission scheme

In most common existing network coding protocol, there are two types of ACK packets which are ACK (Acknowledgement) and NACK (Negative Acknowledgement). If a node can decode the coding packets, it returns an ACK packet to the source node; otherwise, it returns a NACK packet. In MM-NCOPE, the NACK packet is not necessary. The source node continues to send the coding packets for some time. That means the source node sets an overtime threshold T_d (the default value is 5s). It dispatches the linear relevant MM-NCOPE packets of the same generation until it receives the ACK packets or T_d decreases to zero. If T_d becomes zero, it means the sending process is failed; otherwise, it is successful.

In this paper, we adopt the partial acknowledgement retransmission scheme. ACK is an independent packet with the highest priority rather than a part of the data packets. After decoding MM-NCOPE and NCOPE packets of the same generation, node recovers the native packets and acknowledges this generation. The ACK packet shows which native packets can be resumed successfully and which native packets cannot be recovered. In addition, we utilize the accumulated acknowledgement scheme which has high compactness and robustness. Though it brings some redundant information, it is necessary to resist dropping packet and increase the robustness.

Figure 2 exhibits the formation of the ACK packet. Each node has a 16-bit counter which denotes the sequence of the ACK packets. When a node sends an ACK packet to the source node, it increases by 1 and copies the counter value to Local_Ack_Seq_Num, which is a part of the head of ACK packet.

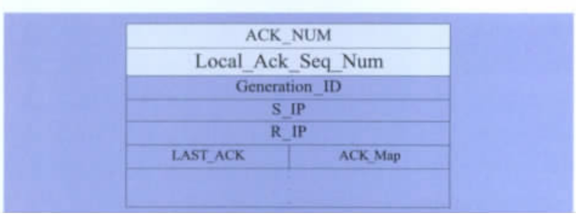

Fig. 2 The formation of ACK packet

IV. SIMULATION AND ANALYSIS

In this session, we analyze the performance of COPE, MM-NCOPE from the result of simulation experiments. The parameters we consider mainly cover three respects.

1) Throughput vs. The number of dataflows

In Figure 3, we set the scene in which nodes are fixed and the bit error rate is low. Obviously, the throughputs of COPE and MM-NCOPE are on steep rise when the number of dataflows increases from 5 to 40. With the increase of dataflow, the ascending trend is limited and the throughput becomes smooth and steady. From the picture, we can find out that the more dataflow, the bigger promotion MM-NCOPE achieves. It reveals that MM-NCOPE has higher coding gain and is more robust in collision.

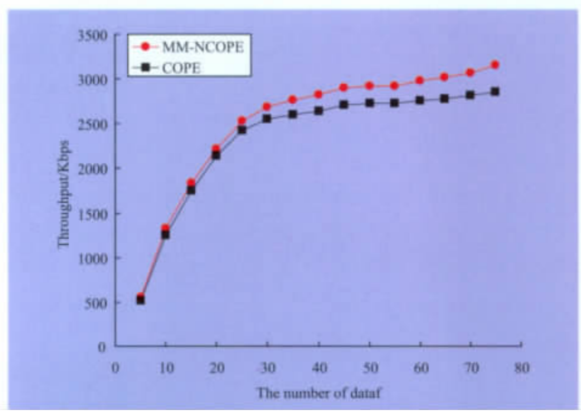

Fig. 3 200 nodes, stable network, Throughput vs. The number of dataflows

In contrast, we set the lossy wireless environment in Figure 4. When the number of dataflows changes from 5 to 30, the movement of the curve is similar to that in Figure 3. However, marked difference appears during the stage from 30 to 80, where the throughput of COPE descends, while the MM-NCOPE remains stable and gradually grows as the number of dataflows increases.

We can acquire the conclusion as follow: (a) MM-NCOPE has higher throughput threshold and average throughput than that of COPE; (b) The worse the wireless network environment is, the more reliable MM-NCOPE is.

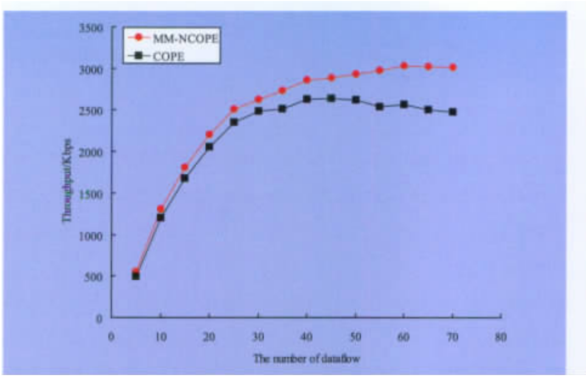

Fig. 4 200 **nodes, lossy network,**
Throughput vs. The number of dataflows

2) Throughput vs. The number of nodes

From Figure 5, we can see the change of average throughput as the number of nodes increases in the stable wireless network environment. When the number of nodes increases from 50 to 300, the throughputs of COPE, MM-NCOPE are both rising rapidly. After the number of nodes exceeds 300, the increasing trend becomes mild because of channel collusion. When there are 500 nodes in the network, MM-NCOPE can still reach 4400Kbps which is about 88% of the ideal model.

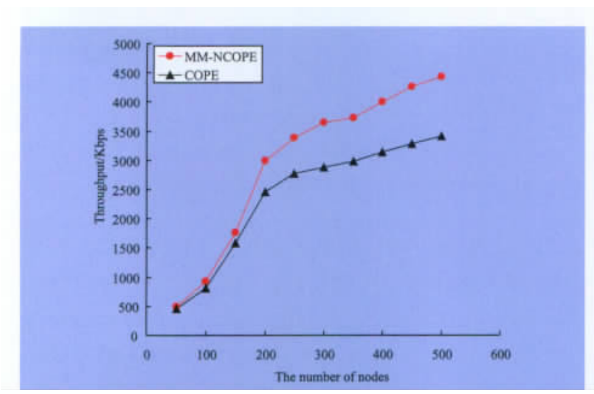

Fig. 5 50 ~ 500 **node, stable network,**
throughput vs. the number of nodes

Figure 6 describes the throughput change with different numbers of nodes in the lossy network. When the number of nodes increases from 50 to 300, though the absolute value is lower than that in Figure 5, the throughput curve ascends quickly. Interestingly, the throughput of COPE becomes stable from 350 and the same situation happens in MM_NCOPE from 450.

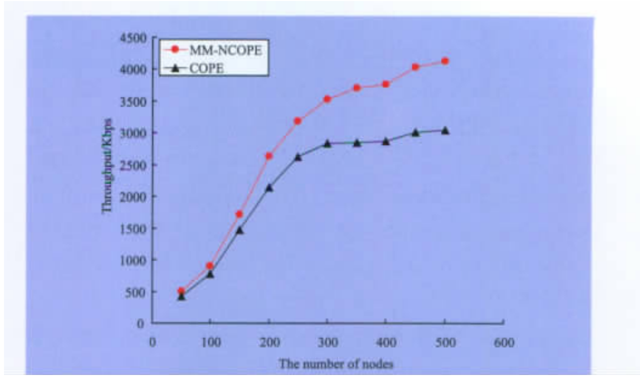

Fig. 6 50 ~ 500 **node, lossy network,**
throughput vs. the number of nodes

From the above phenomena, we draw some conclusions: (a) The more nodes in the network, the higher coding gain in MM_NCOPE than that in COPE; (b) In the lossy environment, MM-NCOPE which is more reliable has better performance than COPE; (c) Though COPE increases with the increasing number of flows, an inter-flow network coding protocol, it does not apply to unidirectional traffic and cannot deal with dead spots. As a result, the performance of MM_NCOPE is more closely related to the theoretical capability of the network while there is no collusion or loss in the network.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a transmission mechanism, called MM-NCOPE, which is based on network coding in wireless networks. It considers the characteristics of inter-flow and intra-flow at the same time. Utilizing random linear coding and partial acknowledgement retransmission scheme, the proposed mechanism increases the coding gain and enhances the network reliability. In addition, the multi-path method improves the transmission success rate remarkably which means high throughput and dependability.

Our future work mainly includes several aspects as follows:

Coding-awareness is an important direction to improve network performance and make the network more reliable. Hence, we tend to integrate the coding-aware routing and our MM-NCOPE.

In MM-NCOPE, we only consider the channel state in multi-path design. It is not enough to describe the network environment. Therefore, we will take other facts such as node state and neighbor state into account to make it more efficient and reliable.

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Biography

Chen Jing, received his Ph. D. degree from Huazhong University of Science and Technology, China. He is currently an associate professor at Wuhan University. His research interests include network security and wireless network.