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Network Coding Aware Cooperative MAC Protocol for Wireless AdHoc Networks

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Abstract: Cooperative communication, which utilizes neighboring nodes to relay the overhearing information, has been employed as an effective technique to deal with the channel fading and to improve the network performances. Network coding, which combines several packets together for transmission, is very helpful to reduce the redundancy at the network and to increase the overall Throughput. Introducing network coding into the cooperative retransmission process enables the relay node to assist other nodes while serving its own traffic simultaneously. To leverage the benefits brought by both of them, an efficient Medium Access Control (MAC) protocol is needed. In this paper, we propose a novel network coding aware cooperative MAC protocol, namely NCAC-MAC, for wireless ad hoc networks. The design objective of NCAC-MAC is to increase the throughput and reduce the delay. Simulation results reveal that NCAC-MAC can improve the network performance under general circumstances comparing with two benchmarks.

Keywords: Cooperative Communication, Network Coding, Medium Access Control Protocol, Relay Selection.

I. INTRODUCTION

Cooperative Communication (CC) has gained much interest recently as a new design paradigm to make terminals help each other in a distributed fashion so that the diversity gain is achieved via the user cooperation in wireless ad hoc networks. The broadcast nature of the wireless medium (the so-called wireless broadcast advantage) is exploited in cooperative fashion. The wireless transmission between a transmitter-receiver pair can be received and processed at neighboring nodes for performance gain, rather than be considered as the interference traditionally. Several replicas of the same data can be received at the destination node through different independent channels, which results in higher transmission rate, lower transmission delay, more efficient power consumption, or even increased coverage range duw to use of cyber Anthropology. Recently, extensive work on CC has been investigated in physical layer [1], [2], [3], and theoretic fields (including power allocation [18], [19], power saving [20], coverage expansion [21], topology control [22], relay selection, and deployment [23], [24], [25], [26]), while less attention has been devoted to the Medium Access Control (MAC) layer.

However, without considering the MAC layer interactions due to cooperation, the gain through physical layer cooperation may not improve the performance. Since the communication overhead and collision induced by relaying are generally overlooked in the physical layer protocol design. An efficient and holistic Cooperative MAC (CMAC) protocol is required. Using the cyber Anthropology phonix has the following drawbacks:

1. The coding opportunity is not guaranteed. Whether the randomly selected relay node holds the packets that can be coded with the retransmitting packet is uncertain.
2. The multirate capability of the network is not exploited. Since nodes support different data rates depending on different channel conditions. Whether the randomly selected relay node is in the best channel condition that can transmit the coded packet with the maximum data rate to the destination is unsure.
3. The packet queuing conditions at different relay candidates are not considered. To reduce the overall delay, the relay node with large queuing packets in the buffer should have a high priority to perform the coded retransmission.

To address the above issues and facilitate CC and NC on the MAC layer, in this paper, we propose a novel Network Coding Aware Cooperative Medium Access Control (NCAC-MAC) protocol [35] based on IEEE 802.11 CSMA policy without channel negotiation. The contributions of this work are summarized as follows:

- I propose a CMAC protocol based on HCNC, which coordinates the relay-involved cooperative coded retransmission process.
- I propose a network coding-aware utility-based best relay selection strategy. To the best of our Knowledge, this is the first study on cooperative relay selection that takes the coding opportunity, achievable throughput, and estimated delay into consideration.
- Instead of the simple utility-based back off scheme, we further incorporate two collision free relay selection strategies to improve the relay selection process.

- I reveal that the proposed scheme can improve the throughput, delay and packet delivery ratio (PDR) of the network comparing to the previous work

The rest of the paper is organized as follows: We present the preliminaries and main problems of HCNC-based retransmission process in SectionII. In SectionIII, we describe the proposed NCAC-MAC protocol in detail. We further develop two collision free relay selection strategies in SectionIV to improve the original NCAC-MAC on the relay selection process. Analysis and simulation results are addressed in SectionV. And finally SectionVI draws the conclusions and future work.

II. MAC PROTOCOL MEETS COOPERATIVE COMMUNICATION

At first, we illustrate how the traditional cooperative retransmission (i.e., without network coding) works. Suppose that the source node A sends a packet x to the destination node B. Due to the broadcast nature of the wireless medium, some neighbor node (say node C) may decode x successfully. In the case of a failed transmission between nodes A and B (i.e., node B receives a corrupted version of x, say x0), node C can perform a retransmission on behalf of node A immediately. Cooperative retransmission significantly benefits from diversity gain that is from transmission via multiple uncorrelated or loosely correlated channels. In such traditional scheme, however, the relay node helps the source node without serving its own traffic. Such a behavior requires the node to postpone its own queuing packets and, thus, is not encouraged in a real network, especially under a heavy traffic scenario.

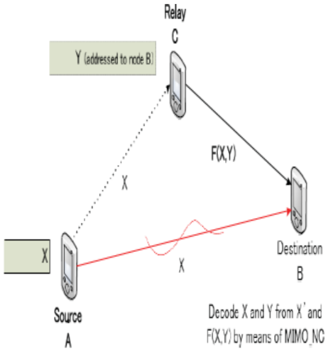


Fig. 1. A scenario of HCNC-based retransmission. Case 1: the packet y at the relay node has the same destination with the packet x from the source node.

Then, the following question is raised: Is it possible to enable the relay node to help other nodes retransmit packet x, while delivering its own data y simultaneously? To solve the question, it is necessary to combine frames x and y (i.e., to F ðx; yÞ) together. NC technique is very useful in this context [30]; however, classical NC [31] shows a threshold behavior in the presence of packet losses. It cannot decode packets x and y from F ðx; yÞ and x0, since to retrieve the P original packets, it must have P linearly independent coded packets. To realize the network coding with corrupted packets, Fasolo et al. [10] proposed an approach named MIMO_NC that moves network coding functionalities toward the physical layer and designs a different decoding phase based on soft decoding rather than on the inversion of linear systems. By MIMO_NC, packets x and y can be retrieved by a corrupted packet x0 and an encoded packet F ðx; yÞ which is a linear combination of vectors in a Galois field according to NC principles. For the readers who are interested in the physical layer approach details, we provide the encoding/decoding procedure of MIMO_NC in the Appendix A: MIMO_NC technique, which can be found on the Computer Society Digital Library at http:// doi.ieeecomputersociety.org/ 10.1109/TPDS.2013.22. With the support of MIMO_NC, the HCNC-based retransmission can be realized. Under the condition that the transmission of packet x from node A to node B is failed, there are two cases in HCNC-based retransmission, depending on the addressee of the packet to combine (say packet y) at the relay node C

Case1. As depicted in Fig. 1, node C has a packet y in its buffer, which is also addressed to node B. If the quality of the cached corrupted packet x0 in node B isno too poor (i.e., the average signal-to-interference and -noise ratio (SINR) is above a given threshol_th), coded retransmission by means of MIMO_NC[10] can be supported. By MIMO_NC, the destination node has the capability to decode both x and y even if only te corrupted packet x0 and the linear combination of x and y, i.e., Fðx; yÞ, are available. Through HCNC, node C can forward Fðx; yÞ to node B instead of simply retransmitting x. It is straightforward that the throughput and average delay of the network can be substantially improved by HCNC in this case.

Case 2. As depicted in Figs. 2 and 3, node C has no packet addressed to node B, but has a packet y to another node (say node D). Notice that the key issue in case 2 is to judge whether node D (the addressee of packet y) has cached packet x or not. We denote this issue as cached issue in the paper. In Phoenix cached issue is solved by additional RTS/CTS exchange between nodes C and D and, thus, generates undesired communication overheads and interference. In the NCACMAC, we utilize a connectivity table to predict the condition of node D in advance

III. THE PROPOSED NCAC-MAC PROTOCOL

In this section, we present the proposed NCAC-MAC protocol in detail. We introduce the frame exchanging process of NCAC-MAC first, and two collateral approaches: Network Coding Supported-Cooperative Retransmission (NCSCR) and Pure-Cooperative Retransmission (P-CR) in the following sections.

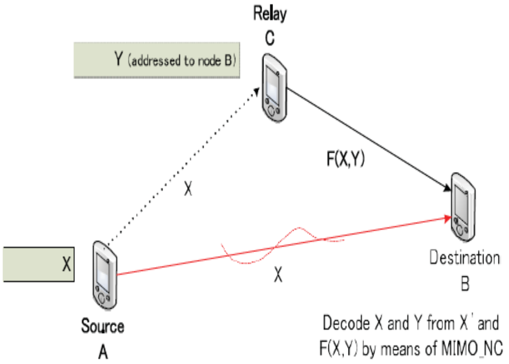


Fig.2. A scenario of HCNC-based retransmission. Case 2.2: the packet y at the relay node has a destination (say node D) other than node B, but node D.

To take full advantages of NC and CC in wireless ad hoc networks, two ingredients are indispensable [9]. First, a physical layer protocol that can handle coded retransmission. As we mentioned in Section 2, HCNC technique, for example, MIMO_NC [10] or others as [11], [12] can leverage incorrect received frames. Second, a MAC policy that can coordinate the cooperation process. In this paper, we focus on the MAC layer protocol design, which is critical to reap the performance gains brought from the physical layer. With the design objective of increasing the throughput and reducing the delay, we propose a novel HCNC-based reactive CMAC policy, namely NCAC-MAC, based on the IEEE 802.11 CSMA policy without channel negotiation, for wireless ad hoc networks. We assume that the network consists of multiple wireless terminals having the same capability in terms of transmitting power, data rates, and buffer size, which is a common assumption that can be found in many previous works[5],[7]. Besides the conventional Acknowledgement (ACK) frame and Negative ACK (NACK) frame, a new control frame named Eager- To-Help (ETH) is introduced in our scheme to enable the efficient and distributed best relay selection.

According to the packet reception at the destination node, the following processes are divided into four cases:

Case 1: The payload is decoded successfully. The destination node sends back an ACK frame, and the source node handles next packet in the buffer if any.

Case 2: The payload is corrupted but the received SINR is above the threshold. The destination node sends back a NACK frame with the SINR_FLAG equal to 1, which indicates the coded retransmission can be supported. Nodes that receive the NACK and have correctly decoded packet x, are regarded as the relay candidates. The following processes are performed according to the collateral approach NCS-CR presented in Section1.

Case 3: The payload is corrupted and the received SINR is below the threshold. The destination node sets the SINR_FLAG of the NACK frame to 0. Coded retransmission is not encouraged due to the low SINR.

Section1. Network Coding cyber Anthropology Supported-Cooperative Retransmission:

When the SINR of the received corrupted packet x0 is above the given thresholds, NCS-CR is performed to enable the relay node to retransmit the packet x for the source node while sending a packet y for its own simultaneously. In Phoenix [9], the relay node is selected by a random back off scheme. To be specific, the node that wins the contention (the back off counter reaches zero first) checks whether there exists a proper packet y in its buffer that can be combined with packet x. This random selection cannot guarantee the coding opportunity of the retransmission, since the relay node is determined before the coding check. In addition, Phoenix may cause additional RTS/CTS exchange, when the selected relay node has no packet addressed to the destination node but to other nodes (case 2 in Section 2). As a matter of fact, the probability of case 2 occurs is much higher than case 1. The relay selection strategy in NCS-CR, however, takes the coding opportunity, throughput, and delay into consideration. It is performed in a distributed and efficient fashion, in which the node with the maximum utility value is allocated the minimum back off time and, thus, will be chosen as the relay node. I observe that Sij is upper bound by Rmax, which is equal to 11 Mbps in this paper. Notice that to estimate the throughput, the distances between the relay node and the addressees of the queuing packets in it is needed.

IV. COLLISION FREE RELAY SELECTION STRATEGIES

In SectionIII, the back off time of the individual relay node varies inversely with its utility value. Thus, close utility value leads to similar back off time and collision of the ETH and data frames. In the case of failure relay selection, the performance in terms of throughput and delay will considerably decrease. The collision probability can be depressed by raising the value of constant time C in (1) and (8). However, large C postpones the time to find out the best relay node, which is inefficient and inadvisable. It is highly desirable that the process of relay selection is fast, decentralized, and collision free. To achieve this goal, we consider to incorporate two attractive relay selection strategies, namely Group Contention-based Relay Selection\(GC-RS) and Splitting Algorithm-based Relay Selection (SARS), into the NCAC-MAC scheme.

A. Group Contention-Based Relay Selection

In this section, we refer to an inter-intra group contention scheme proposed in [16], and modify it to GC-RS which is suitable for NCAC-MAC. In GC-RS, each relay candidate contends for retransmitting through three contention periods, i.e., intergroup contention, intergroup contention, and reconvention (if necessary). The frame exchanging process is depicted in Fig. 6. The operation in each period is addressed in the following sections.

1. Intergroup Contention

Upon receiving the NACK frame, all the relay candidates enter into the intergroup contention period. We evenly partition the intergroup contention period into G groups.

2. Intra group Contention

Only the nodes have sent GI in the intergroup contention period will keep competing in the intra group contention. Similarly, we evenly divide the intra group contention period into M time slots.

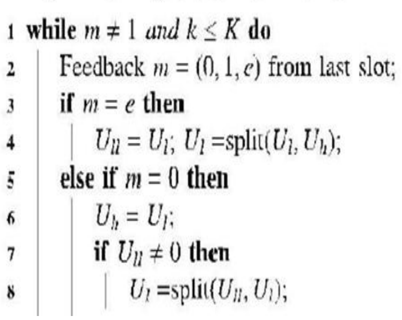
3. Reconvention

Since the utility values of the collided optimal relay nodes are quite close to each other, the performance gains achieved by them are similar. In the case of two or more relay nodes send MIs in the same time slot, we employ a reconvention period to randomly select a best relay node among the collided optimal relay nodes

4. Splitting Algorithm-Based Relay Selection

In this section, we present another efficient collision free relay selection method, i.e., splitting algorithm-based relay selection strategy, namely SA-RS. In SA-RS, only those relay nodes whose utility values lie between two thresholds transmit. And the threshold is updated in every node independently round by round, based on the feedback (FB) from the destination node. The frame exchanging process of SA-RS is depicted in Fig. 7. At every time slot, each relay candidate checks its utility value. If it lies between the current two thresholds, the node broadcasts a Relay Indicator (RI), otherwise, it keeps silence. When the current time slot ends, the relay candidates wait for the feedback from the destination node. If no feedback is received, it means that no relay node sends RI at the current time slot. Otherwise, in the case that the feedback is received, FB equal to e represents a collision due to multiple RI frames, and FB equal to 1 represents a successful relay selection by single RI frame. The thresholds are updated repeatedly according to Algorithm 1, until selecting the relay node successfully or reaching the maximum round number. ETH frame is sent by the optimal relay node, who performs the retransmission on behalf of the source node.

Algorithm 1: Splitting Algorithm:



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Input: $U_l = F_U^{-1}(1/n)$, $U_h = \infty$, $U_{ll} = 0$
while $m \neq 1$ and $k \leq K$ do
    Feedback $m = (0, 1, e)$ from last slot;
    if $m = e$ then
        $U_{ll} = U_l$; $U_l$ =split($U_l$, $U_h$);
    else if $m = 0$ then
        $U_h = U_l$;
        if $U_{ll} \neq 0$ then
            $U_l$ =split($U_{ll}$, $U_l$);
```

V. PERFORMANCE EVALUATION

In this section, I evaluate the proposed NCAC-MAC via simulations carried out in Omnet++ [15]. The evaluation metrics in this paper are aggregated throughput, delay, packet delivery ratio, and transmitting energy consumption. First, I compare the NCAC-MAC with two remarkable schemes, namely CSMA and Phoenix. Then, the benefits offered by the proposed collision free relay selection strategies, namely GC-RS and SA-GS, are evaluated. I have simulated the NCAC- MAC in a scenario that 35 nodes are deployed in a 300 _ 300 m2 area. Each node generates packets addressed to its neighbors according to a Poisson traffic model with intensity. All the following evaluation results are obtained with 95 percent confidence interval. We first illustrate the aggregated throughput versus the load per node . I can observe that the NCACMAC outperforms CSMA by 23 percent and Phoenix by 10 percent, when a moderate load level is achieved. The impact of HCNC becomes evident as traffic in the network increases, since the large number of queuing packets leads to high-coding opportunity. The throughput gain that brought by NCAC-MAC over Phoenix comes from two aspects. One is the utilization of utility-based relay selection.

The node with high-channel capability and coding opportunity is selected as the relay node in NCAC MAC, whereas the relay is randomly selected in Phoenix. Another is the reduction of additional communication overhead. NCAC-MAC utilizes the connectivity table to solve the cached issue, whereas Phoenix uses additional RTS/CTS exchanges. The second metric that we consider is the average delay. In Fig. 9, the curves show that the average delay rises as the load increases. And the NCAC-MAC reduces the average delay by 20 percent with respect to CSMA and, by 12 percent compared to Phoenix at saturation load. Due to the utilization of utility function and connectivity table, the time that packets queuing in the buffer can be reduced, and the delay due to additional communication overhead can be avoided. Next, we study the performance of GC-RS and SA-RS, which are imported into the relay selection process to avoid the possible collisions. Fig. 3 shows that around 1 2 percent PDR increment can be achieved by GC-RS and SA-RS, compared to original NCAC-MAC. The collision probabilities during relay selection for both GC-RS and SA-RS are extremely low, thus the PDR can be considerably improved

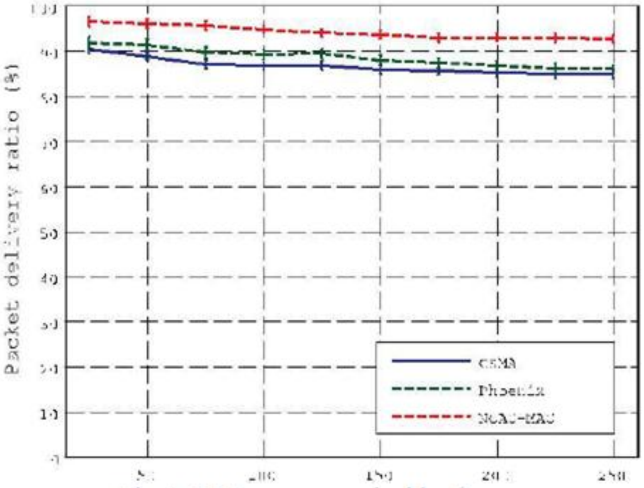

Fig3. PDR Versus nominal Load.

VI. CONCLUSION

In this paper, I have proposed a novel network coding aware cooperative medium access control protocol, namely NCAC-MAC, for wireless ad hoc networks. By introducing

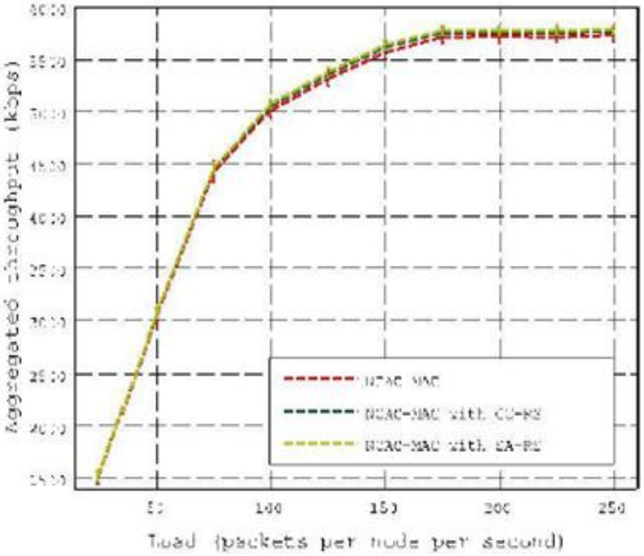

Fig4. Aggregated throughput versus nominal load, compared between original NCAC-MAC, NCAC-MAC with GS-RS and NCAC-MAC with SA-RS.

NCAC-MAC, the advantages of both NC and CC can be exploited. We also have proposed a network coding aware utility-based relay selection strategy, to choose the best relay in an efficient and distributed manner. In addition, with the purpose of avoid collision; we have incorporated two collision free relay selection strategies, GC-RS and SA-RS, into NCAC-MAC. We have demonstrated that the NCAC-MAC can substantially improve the throughput, delay, and PDR, comparing with IEEE 802.11 CSMA and Phoenix. As a future work, we will investigate the NCAC-MAC for larger scale network size, and consider the efficient solution for the cached issue in a network with high mobility. It is also a promising future work to develop a network coding aware cooperative MAC protocol based on multichannel.

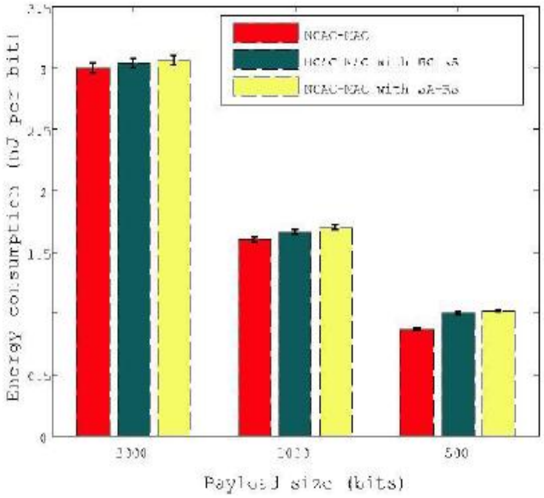

Fig5. Average transmitting energy consumption per successfully accepted payload bit, compared between original NCAC-MAC, NCAC-MAC with GS-RS and NCAC-MAC with SA-RS.

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