Coding-aware MAC: Providing Channel Access Priority for Network Coding with Reverse Direction DCF in IEEE 802.11-based Wireless Networks*

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Abstract—An important challenge for the implementation of network coding in IEEE 802.11-based wireless networks is to give additional priority for channel access to the relay stations responsible for coding. These relay stations are able to provide more information in a single transmission than those that forward single packets, hence improving throughput and energy efficiency. The Distributed Coordination Function (DCF) of the IEEE 802.11 standard is a contention-based Medium Access Control (MAC) protocol that provides an equal distribution of channel access opportunities for all competing stations. However, the relay station represents a congestion point and additional transmission slots should be assigned to it to increase the overall network performance. To address this issue we investigate a coding-aware MAC protocol, called Reverse Direction DCF (RD-DCF), which enables bidirectional communications between the relay station and another station with a single channel access invocation. This simple and backwards compatible mechanism allows the relay station to transmit a coded packet together with the acknowledgement immediately after receiving a data packet. The simulation results show a gain of up to 130\% in terms of both throughput and energy efficiency for RD-DCF with network coding when compared to DCF.

I. INTRODUCTION

Network coding is a promising technique that can be used to improve throughput and energy efficiency in wireless networks by allowing the relay stations of a network to combine several received packets for transmission. Since the introduction of network coding in [1], extensive research has been undertaken to analyse the performance of network coding in several network scenarios. However, most of the existing works are mainly theoretical and little attention has been paid to the practical issues involved in the implementation of network coding.

As an important step forward to bridge the gap between theory and practice, the work in [2] introduced a network coding-enabled architecture for wireless networks, referred to as COPE. COPE is the first implementation of a practical network coding protocol in a real IEEE 802.11-based wireless network. In COPE a coding element is introduced between the data link layer and the network layer. It is responsible for identifying opportunities for coding by which the received packets from different sources are combined and forwarded in a single transmission. One of the main contributions of COPE was to show the impact of the Medium Access Control (MAC) protocol on the performance of network coding. COPE follows the specifications of the MAC layer of the IEEE 802.11 standard [3]. The fundamental access method defined in this standard is the Distributed Coordination Function (DCF). This MAC protocol is based on Carrier Sense Multiple Access (CSMA) with Collision Avoidance (CA) and a binary exponential backoff mechanism.

An important characteristic of DCF is that it provides the same channel access priority for all competing stations. Hence, all participating stations obtain a similar share of the available bandwidth in situations of heavy traffic and similar channel conditions. However, if we consider the Alice-and-Bob network shown in Fig. 1a, the relay station needs to access the channel more frequently to forward the packets from Alice and Bob to their respective destinations. As a result, the relay station becomes a bottleneck for the network since it is unable to send out packets with the same rate

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as they arrive. Network coding proved in [2] to allow the relay station to achieve a higher capacity in the Alice-and-Bob scenario, as shown in Fig. 1b. However, with the increase in the number of stations under the relay’s coverage network coding may not be sufficient to compensate for the lower amount of channel access opportunities given to the relay station. Therefore, providing additional channel access priority for the relay station is essential to fully exploit the advantages of network coding.

In the literature prior work [4]–[7] has focused on adjusting the size of the contention window based on the level of congestion, the state of channel contention, and network coding information to assign different channel access priorities. These approaches assume a contention-based operation of stations as defined in the legacy 802.11 DCF. Hence, a relay station ready to transmit a coded packet will compete for the channel against all other stations in its coverage area.

In this paper we propose a novel coding-aware MAC protocol, called Reverse Direction DCF (RD-DCF), to increase the amount of transmission opportunities given to relay stations. RD-DCF is backwards compatible with DCF. It introduces a simple modification into the rules of DCF by which a relay station is able to initiate a contention-free channel access as soon as it receives a data packet from another station. In particular, if a relay station recognises a coding opportunity, it will immediately reply with the coded packet, instead of transmitting an explicit acknowledgement (ACK). Thus, the relay station does not need to contend for access to the channel and can achieve a higher share of the available bandwidth in comparison with the stations around it. We evaluate the performance of the RD-DCF protocol in the Alice-and-Bob network by means of computer-based simulation. The results presented in this paper show that RD-DCF can outperform DCF, with and without network coding, in terms of throughput and energy efficiency.

The paper is organised as follows. The COPE system and the DCF of the IEEE 802.11 standard are summarised in Section II. We also provide an overview of the related work in this section. The RD-DCF protocol is then described in Section III. In Section IV, we present a comprehensive performance evaluation of the protocol via computer-based simulations. Finally, Section V concludes the paper and outlines possible future work.

II. BACKGROUND AND RELATED WORK

The basic idea of network coding can be explained using the Alice-and-Bob network illustrated in Fig. 1. In this example, Alice and Bob exchange a pair of packets through a relay station. Without network coding (Fig. 1a), the relay station forwards the packets from Alice and Bob to their respective destinations. In total, 4 transmissions are required for the exchange of packets between Alice and Bob through the relay station. However, when network coding is used (Fig. 1b), the relay station is able to combine the two packets using the XOR operation and broadcast the new coded packet. Then, Alice and Bob can subtract the packet of each other by performing the XOR operation with the received coded packet and their own packet. In this case, 3 transmissions, instead of 4, are required. By exploiting the broadcast nature of the wireless channel, network coding can improve the network throughput, since 1 transmission out of 4 can be used to send new data. In addition, it reduces the amount of redundant transmissions and can reduce the number of collisions in contention-based MAC protocols.

A. COPE and IEEE 802.11 DCF

The evaluation of COPE [2] was carried out in a testbed consisting of 20 IEEE 802.11 compliant stations employing DCF [3] for channel access in ad hoc communication mode. The DCF method defines a basic mode and an optional CA mode. In the basic mode, a source station performs the transmission of data without any previous communication with the intended destination. Each successful reception of a data packet is immediately acknowledged by the destination station with the transmission of an ACK packet. When the CA mode is enabled, a handshake of control packets called Request-To-Send (RTS) and Clear-To-Send (CTS) is performed between source and destination before the transmission of data. The aim of this handshake is to reduce collisions of data packets and to overcome the problem of hidden terminals.

Fig. 2a illustrates an example of the joint operation of DCF and network coding as defined in COPE for the Alice-and-Bob scenario when the CA mode is enabled. The MAC layer of Alice receives at $t_0$ a new data packet (a) to be transmitted to Bob while it is performing virtual sensing because of a previous data transmission from the Relay. A new data packet (b) destined to Alice arrives at the MAC layer of Bob at $t_1$. After a DCF Inter Frame Space (DIFS), both Alice and Bob randomly choose a backoff counter uniformly distributed within a Contention Window (CW) to reduce the probability of collisions. Due to a lower backoff counter, Alice obtains the channel access earlier and initiates an RTS/CTS handshake by transmitting an RTS packet. After a Short IFS (SIFS), the Relay sends a CTS packet back to Alice. At this time, Bob overhears the CTS packet and stops decrementing its backoff counter freezing it to 2, and updates its Network Allocation Vector (NAV) with the time that the wireless channel will remain busy. This information is retrieved from the duration field of the overheard CTS packet. When Alice receives the CTS packet, it sends a and the Relay immediately replies with an ACK packet.

After a DIFS, Bob resumes decrementing its backoff counter while the Relay randomly selects a backoff counter equal to 4 and also starts decrementing it before transmitting a to Bob. The backoff counter of Bob reaches 0 earlier than that of the Relay. Bob then sends an RTS packet to the Relay and after a SIFS the Relay stops decrementing the backoff counter freezing it to 2 and sends a CTS packet to Bob. When Alice overhears the CTS packet, it reads the duration field of the CTS packet and updates its NAV. Upon reception of the CTS packet from the Relay, Bob sends b and the Relay acknowledges it by transmitting an ACK packet.
The Relay identifies a coding opportunity and combines $a$ and $b$ into $a \oplus b$. It chooses at random Alice as the destination and includes its address in the MAC header of the coded packet. The MAC address of Bob is also provided in the coding packet header as a potential decoding destination. After a DIFS, the Relay resumes decrementing its backoff counter down to 0. Then it establishes a new RTS/CTS handshake with Alice to send $a \oplus b$. After successful reception of the coded packet, Alice replies with an ACK packet and obtains $b$ as it has stored $a$ for a given time. Since all stations are equipped with omni-directional antennas and enable the promiscuous mode to monitor all transmissions, Bob can receive $a \oplus b$. It has also stored $b$ and can decode the coded packet to retrieve $a$. Bob then schedules an ACK to be included in the next transmitted data packet or in periodic control packets to notify the Relay of successful decoding.

B. Existing coding-aware MAC-layer priority schemes

The example of Fig. 2a shows that the data exchange between a pair of stations through a relay station is inefficient when using legacy 802.11 DCF. The main efficiency issues of DCF are the overhead generated by the exchange of control packets, the channel sensing and backoff periods, and the collision of packets. In particular, an important problem of DCF is the share of transmission opportunities given to the relay station and the rest of stations. All the stations follow the same backoff rules to gain the channel access but the relay station needs to transmit more frequently. Network coding helps the relay station reduce the amount of traffic to be conveyed but may not be the only optimal solution when the traffic load and the number of competing stations increase. In such a case, it would be desirable to give higher channel access priority to the relay station when it has a coded packet ready to transmit because coded packets contain more information in a single transmission than non-coded packets.

For content distribution, the work in [4] proposes to adjust the CW size based on the amount of encoded data in the coded packets in order to control the channel access priority of each station. To give higher transmission priority to the relay station, an autonomous mechanism that optimises the minimum CW size based on the number of competing stations is defined and evaluated in [5]. Similarly, the work in [7] analyses and implements a new MAC protocol that dynamically adapts the CW size of the relay station based on the amount of traffic to be conveyed and considering the influence of network coding. In contrast, the key idea in [6] is that the relay station assigns different CW sizes to the stations in its coverage area to increase coding opportunities. The assignment is based on the link quality with each station and the number of packets available in the queues from each station.

III. CODING-AWARE CHANNEL ACCESS

Most of the existing approaches specify that a relay station ready to transmit a coded packet should use a smaller CW size to achieve higher channel access priority. However, the relay station still needs to execute a backoff process of random duration before attempting to transmit, hence increasing access delay. In order to overcome this problem, our proposal elaborates on the idea of introducing bidirectional communications in the rules of DCF. This approach has been studied in several works [8]–[11] to increase capacity and throughput in ad hoc networks and to achieve fairness between uplink and downlink flows in infrastructure-based networks. These works are based on the observation that the basic operation of DCF only allows initiating unidirectional transmissions of data between pairs of stations. When bidirectional data transmissions are enabled, upon successful reception of a data packet the destination station can respond with a data packet instead of an ACK packet. Therefore, it does not need to contend for the channel.

Inspired by these works, we propose a new coding-aware MAC protocol, called Reverse Direction DCF (RD-DCF), which based on both congestion and network coding information enables bidirectional communications between the relay station and any other station. To our knowledge this is the first
work that investigates the interaction between network coding and a MAC protocol implementing bidirectional communications in ad hoc networks. An important benefit of RD-DCF is that it can be implemented and tested on commercial off-the-shelf Wi-Fi products together with network coding, e.g., CATWOMAN [12]. RD-DCF can be adapted to the operation of the RD protocol defined in IEEE 802.11n [3]. With RD, once the source station has obtained a Transmission Opportunity (TXOP), it may grant permission to the destination station to send information back during its TXOP.

The new RD-DCF MAC protocol has been designed to fully exploit network coding at the relay stations. The access rules of RD-DCF are essentially the same as those defined in DCF. However, in RD-DCF, when the relay station receives a data packet from another station, it can initiate a data transmission in the reverse direction. Specifically, the relay station can transmit a coded packet whose destination is the source station of the received packet. The transmitted coded packet could have already been encoded and stored in the output queue or can be the result of coding the newly received packet with another packet in the queue. By enabling this mechanism in the relay stations, it is possible to reduce channel contention and improve throughput, access delay, and energy efficiency.

We describe the joint operation of the proposed RD-DCF protocol and network coding with the example shown in Fig. 2b. This example follows the same description as in Fig. 2a to explain the operation of the DCF protocol in combination with network coding. However, when the Relay receives the RTS packet from Bob, it identifies a coding opportunity with the previously received data packet from Alice (a). Then it freezes its backoff counter to 2 and replies with a CTS packet whose duration field includes the additional time required for the transmission of the possible coded packet, based on the information available in the RTS packet. The value of the duration field accounts for the transmission time of the data packet in the forward direction (b), the coded packet in the reverse direction (a⊕b), the trailing ACK packet, and all the SIFS periods. Other stations that overheard the CTS packet (e.g., Alice) read the duration field and update their NAVs, thus making this mechanism fully compatible with the existing standard.

Upon successful reception of the CTS packet, Bob initiates the transmission of b. If the data packet is received without errors, the Relay combines a and b into a⊕b. In the header of the new coded packet, the Relay specifies the address of Bob as the destination station and the address of Alice as an additional decoding station. It then sets its backoff counter to 0 and immediately transmits a⊕b to Bob. This newly received coded packet can be interpreted by Bob as an ACK packet to its own data packet. In addition, the exchange of RTS and CTS packets for the transmission of the coded packet can be avoided, hence reducing the amount of control packets.

After a SIFS, Bob acknowledges the received coded packet with the transmission of an ACK packet and then retrieves a by performing the XOR of a⊕b and b. When Alice overhears the coded packet destined to Bob, it determines whether it is a decoding station by reading the header of the packet and then decodes to retrieve b. Alice will notify the Relay of successful decoding in the next data transmission by including an ACK event in the header of the transmitted packet. Otherwise, the ACK information will be included in periodic control packets.

To increase coding opportunities, we specify a nonzero time that a relay station can store the received packets before forwarding them without coding. We refer to this period of time as the holding time. In this particular case, the relay station is allowed to send a non-coded packet upon successful reception of a data packet only if the holding time of such packet has expired. Otherwise, it can only reply with the ACK packet and must follow the basic access rules of DCF to transmit non-coded packets.

The joint operation of RD-DCF and network coding in the basic mode (without RTS/CTS) is similar to that described in Fig. 2b, where the RTS/CTS handshake is enabled.

IV. Performance Evaluation

An open-source computer-based simulator, which is available under request by email, has been implemented in Python to simulate the rules of the four protocols under evaluation, i.e., RD-DCF, RD-DCF with Network Coding (RD+NC), DCF, and DCF with Network Coding (DCF+NC).

A. Simulation Setup

The simulation scenario consists of two source stations and a relay station, as shown in Fig. 1. Alice and Bob are out of the transmission range of each other and can only communicate through the Relay. They generate data packets of constant length with arrival according to a Poisson distribution. The data packets generated at Alice are addressed to Bob whereas those generated at Bob are addressed to Alice. The Relay does not generate traffic but only forwards the traffic from Alice and Bob. We assume that all packets are received with no errors.

Four different networks have been studied: (i) a DCF-enabled network wherein all the stations execute the CA mode of DCF but the relay station does not employ network coding; (ii) a DCF+NC-enabled network wherein all the stations execute the CA mode of DCF and the relay station employs network coding; (iii) an RD-DCF-enabled network wherein all the stations execute the proposed RD-DCF protocol but the relay station does not employ network coding; and (iv) an RD-DCF+NC-enabled network wherein the source stations execute the CA mode of DCF and the relay station employs the proposed RD-DCF protocol with network coding.

Table I summarises the simulation parameters. The system parameters correspond to one of the possible configurations of the IEEE 802.11g amendment [3]. The Extended IFS (EIFS) is the time interval that follows after a collision of RTS packets. It is calculated as a DIFS, a SIFS, and the transmission time of an ACK. The transmission times of control packets are obtained for the lowest basic rate (control rate) of 6 Mbps. Both the control rate for the MAC header and/or the coding header and the data rate for the payload are used to calculate the transmission time of a data packet. The MAC Protocol
TABLE I
SIMULATION PARAMETERS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFS</td>
<td>10 $\mu$s</td>
<td>Service</td>
<td>6 b</td>
</tr>
<tr>
<td>DIFS</td>
<td>28 $\mu$s</td>
<td>Tail</td>
<td>16 b</td>
</tr>
<tr>
<td>EIFS</td>
<td>86.3 $\mu$s</td>
<td>RTS</td>
<td>20 B</td>
</tr>
<tr>
<td>Slot Time</td>
<td>9 $\mu$s</td>
<td>RTS, ACK</td>
<td>14 B</td>
</tr>
<tr>
<td>Preamble</td>
<td>16 $\mu$s</td>
<td>MAC Header</td>
<td>34 B</td>
</tr>
<tr>
<td>Signal</td>
<td>4 $\mu$s</td>
<td>Coding Header</td>
<td>40 B</td>
</tr>
<tr>
<td>Signal Extension</td>
<td>6 $\mu$s</td>
<td>MPDU</td>
<td>1500 B</td>
</tr>
<tr>
<td>Time of RTS</td>
<td>56.33 $\mu$s</td>
<td>Payload</td>
<td>1466 B</td>
</tr>
<tr>
<td>Time of CTS, ACK</td>
<td>48.33 $\mu$s</td>
<td>Data Rate</td>
<td>54 Mbps</td>
</tr>
<tr>
<td>Time of DATA</td>
<td>292.19 $\mu$s</td>
<td>Control Rate</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>Time of CODED DATA</td>
<td>345.52 $\mu$s</td>
<td>Transmit Mode</td>
<td>1.65 W</td>
</tr>
<tr>
<td>Holding Time</td>
<td>10 ms</td>
<td>Receive Mode</td>
<td>1.4 W</td>
</tr>
<tr>
<td>$CW_{\text{min}}, CW_{\text{max}}$</td>
<td>16, 1024</td>
<td>Idle Mode</td>
<td>1.15 W</td>
</tr>
</tbody>
</table>

Data Unit (MPDU) is fixed to 1500 bytes, which makes the payload 1466 bytes. We choose a holding time of 10 ms. Coding and decoding using the XOR operation consumes 3.5 $\mu$J for 1466 bytes based on [13]. The values of power consumption for transmission, reception, and idle modes are taken from [14]. All simulation runs were repeated 10 times for the duration of 20 s.

B. Simulation Results

The end-to-end throughput as a function of the offered network load is shown in Fig. 3a. It is calculated as the amount of successfully delivered bits of information by the Relay to Alice and Bob over the simulation time. All the curves grow linearly until the saturation point is reached, where the performance is stabilised. When the traffic load is low, the Relay is able to forward all the traffic from Alice and Bob to the final destination. However, as the traffic load and the channel contention increase, the Relay has fewer chances to access the wireless channel in the DCF-enabled network, since it has to compete with Alice and Bob for the channel access. As a result, the end-to-end throughput is significantly reduced for offered loads above 10 Mbps.

In the DCF+NC-enabled network, the Relay can achieve a higher capacity up to an offered load of 14 Mbps as it can combine the packets from Alice and Bob for transmission, hence substantially improving the end-to-end throughput. In the saturation point, the throughput gain, also known as Coding+MAC gain [2], reaches 92% in comparison with DCF. A similar gain of 96% is observed in the RD-DCF-enabled network. With RD-DCF the Relay can transmit a data packet whenever it has received a data packet from either Alice or Bob. Therefore, it can transmit as many packets as Alice and Bob. The difference in the throughput gain between DCF+NC and RD-DCF is due to the additional overhead introduced by network coding and the lower overhead of control packets in RD-DCF. In the RD-DCF+NC-enabled network, the Relay is able to transmit a coded packet when either Alice or Bob gains channel access, without additional channel contention. As a result, the end-to-end throughput is further improved up to 16 Mbps by a gain of 127%, 18%, and 16%, having as reference DCF, DCF+NC, and RD-DCF, respectively.

Fig. 3b shows the end-to-end energy efficiency expressed in useful bits per consumed Joule. The values for energy efficiency are obtained using the amount of successfully delivered bits of information by the Relay to Alice and Bob over the energy consumed by all the stations during the simulation. The curves of energy efficiency follow a similar shape to those for throughput. When the channel activity is low, the stations transmit normally and consume little energy since they are idle most of time. As the traffic load increases, the wireless channel becomes more congested and collisions occur more frequently. In the DCF-enabled network, the Relay requires more time to obtain a transmission opportunity and consume significant energy to overhear the transmissions of Alice and Bob. As a result, energy efficiency is reduced significantly.

In the DCF+NC-enabled network, the Relay benefits from network coding to increase the information content of each transmission, hence reducing the number of transmissions and saving energy. For this reason, energy efficiency is increased by 80%. Similarly, RD-DCF can provide a gain of 82% in energy efficiency since the Relay consumes less time and energy for channel contention by exploiting opportunities for bidirectional communications. In the RD-DCF+NC-enabled network, the Relay receives a distribution of transmission opportunities proportional to the amount of coding opportunities. Due to more efficient data transmission, a gain of up to 120%, 22%, 21% can be achieved in terms of energy efficiency in comparison with DCF, DCF+NC, and RD-DCF, respectively.

We also provide the end-to-end energy per bit expressed in consumed Joules per useful bit of information in Fig. 3c. For low traffic loads, the energy per bit is high since the stations transmit few packets and mainly consume energy to be idle. As the traffic load increases, the energy-per-bit ratio decreases until it remains constant. Similar conclusions to those detailed for Fig. 3b can be inferred from this figure. However, it is important to mention that RD-DCF+NC can achieve a reduction of up to 55%, 17%, and 15% in the energy per bit when compared to DCF, DCF+NC, and RD-DCF, respectively.

In Figs. 3d-3f we show the distribution of energy consumption in transmission, reception, and idle periods for DCF, DCF+NC, and RD-DCF+NC. The energy consumption is calculated as the sum of the products of the power consumed in each of these periods and the time spent in each of them for all the stations. In all these figures, the impact of the idle energy consumption is high for low traffic loads and quickly decreases as the traffic load increases. When the traffic load is low, the stations are inactive for most of the time. As the traffic load increases, the stations transmit more frequently and consume more energy to monitor ongoing transmissions. As a result, the share of energy consumption for packet reception grows rapidly and becomes clearly predominant in saturation conditions. In addition, the share of the transmission energy has a significant overall contribution since many packets are transmitted when the traffic load is high.

In the DCF+NC-enabled network, the overall energy contributions of transmission and reception periods are reduced
for traffic loads below 14 Mbps by exploiting the advantages of network coding (see Fig. 3e). This directly translates into a higher impact of the idle energy on the overall energy consumption of the network. When the saturation point is reached, the distributions of energy consumption for transmission and reception are higher than those presented in the DCF-enabled network (Fig. 3d) above 14 Mbps due to the additional overhead for network coding. In general, a similar behaviour is observed for the RD-DCF+NC-enabled network (Fig. 3f). However, the percentage of energy consumed in transmission and reception is further reduced below 16 Mbps in comparison with both DCF- and DCF+NC-enabled networks.

V. CONCLUSIONS

In this paper a new coding-aware MAC protocol based on DCF of the IEEE 802.11 standard, coined RD-DCF, has been proposed to improve throughput and energy efficiency in wireless networks using network coding. Unlike existing proposals that rely on the basic operation of DCF, our proposal exploits bidirectional communications to provide more contention-free transmission opportunities for the relay station when coded packets are ready for transmission. The simulation results show that RD-DCF outperforms DCF, with and without network coding. The increase in throughput and energy efficiency is up to 127% and 120%, respectively, whereas a 55% of saving in energy consumption per bit can be achieved.

Motivated by the promising results presented in this paper, ongoing work is aimed at testing the new RD-DCF protocol in combination with network coding in a wireless testbed consisting of MAC-reconfigurable platforms. In future work, we will also evaluate the performance of the proposed protocol as the number of stations increases and considering the control and data packet losses.

REFERENCES