Analysis of a Network Coding-Aware MAC Protocol for IEEE 802.11 Wireless Networks with Reverse Direction Transmissions*

Raul Palacios[a], Habtegebreil Haile[a], Jesus Alonso-Zarate[b] and Fabrizio Granelli[a]

[a]*{palaciostrujillo@disi, habtegebreil.haile@studenti, granelli@disi}.unitn.it*, University of Trento, Italy

[b]*jesus.alonso@cttc.es*, Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Barcelona, Spain

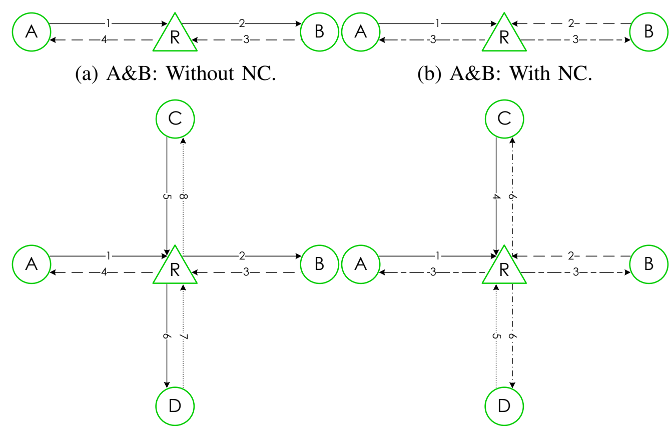
***Abstract*—The implementation of Network Coding (NC) in IEEE 802.11-based wireless networks presents the important challenge of providing additional transmission priority for the relay nodes responsible for coding. These nodes are able to convey more information in each transmission than those that forward single packets, by combining several received packets in a single coded packet. To transmit data, the nodes execute the IEEE 802.11 Medium Access Control (MAC) protocol, called the Distributed Coordination Function (DCF). Thus, they compete for the access to the wireless channel and get equal transmission opportunities under high congestion. As a result, congested relay nodes will severely limit the performance of the network. In this paper, we investigate a backwards-compatible mechanism, called Reverse Direction DCF (RD-DCF), that allows relay nodes to transmit data upon successful reception of data. We analyze the performance limits of the proposed protocol with and without NC in terms of throughput and energy efficiency. The performance evaluation considers different traffic loads, packet lengths, and data rates. The results of this work show that the proposed RD-DCF+NC protocol can improve throughput and energy efficiency up to 335% when compared to legacy DCF.**

I. Introduction

Network Coding (NC) is a promising technique that can be used to improve throughput and energy efficiency in wireless networks [1]. The basic principle of NC is to transmit combined information from different sources, by means of intermediate relay nodes, leading to a reduction in the number of channel accesses. Fig. 1 shows the advantages of NC over traditional store-and-forward schemes in two canonical scenarios, namely, the Alice-and-Bob and cross topologies.

The implementation of NC in wireless networks requires an efficient Medium Access Control (MAC) protocol that manages the access to the wireless channel being aware of the NC approach [2]. Unfortunately, the widely used Distributed Coordination Function (DCF) of the IEEE 802.11 [3] is not suitable for the implementation of NC, mainly due to its long-term fairness, which provides the same amount of channel access opportunities per device in average.

The motivation examples are shown in Figs. 1c, 1d, where two bidirectional flows intersect at the relay node. Without coding, 8 transmissions are necessary for each flow to send one packet to its destination. Using simple XOR coding, the relay node can combine pairs of packets from the source nodes and



(a) A&B: Without NC. (b) A&B: With NC. (c) Cross: Without NC. (d) Cross: With NC.

Fig. 1. Reference scenarios: Alice-and-Bob and cross topologies. (a)-(c): Without NC, R forwards the packets from A, B, C, and D to their respective destinations. (b)-(d) With NC, R encodes pairs of packets from A and B and C and D, respectively, and broadcasts single coded packets.

forward them to their respective destinations. However, due to the DCF fairness, the relay node will only get a transmission opportunity to send one coded packet. Therefore, providing additional transmission priority for the relay node is essential to fully exploit the advantages of NC.

Previous works [4]–[7] propose to adjust the size of the contention window based on the level of congestion, the state of channel contention, and NC information, so that several priorities can be assigned to different nodes. These approaches assume that relay nodes ready to transmit a coded packet will compete for the channel access as if they were regular nodes. Hence, probabilistic access priority can only be provided for the relay nodes, which does not guarantee the channel access when they actually need it.

In our previous works [8], [9], we presented and evaluated the performance of a new mechanism based on DCF, coined Reverse Direction DCF (RD-DCF). RD-DCF guarantees a balanced share of the channel for a relay node with respect to the rest of nodes in its coverage area by allowing it to transmit data when it receives data. In [10], we extended the operation of RD-DCF to fully exploit NC by allowing a relay node to transmit a coded packet immediately after receiving a data packet. We evaluated the performance of RD-DCF with NC in

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the Alice-and-Bob scenario and showed around 20% and 130% gains when compared to DCF with NC and standard DCF, respectively. However, the results were obtained by means of computer-based simulations and we did not consider the cross topology to evaluate the performance of the proposed protocol. Therefore, the main contributions of this paper are:

1) We theoretically derive the maximum throughput and energy efficiency of the DCF and DCF+NC and the proposed RD-DCF and RD-DCF+NC protocols.
2) We analyze and discuss the performance limits of the protocols in the Alice-and-Bob and cross topologies considering different traffic loads, data packet lengths, and data rates.

The structure of the paper is as follows. In Section II, we briefly introduce a well-known DCF+NC protocol referred to as COPE [2] and summarize the proposed RD+NC protocol. Section III decribes the analysis of throughput and energy efficiency for the protocols under evaluation. The performance analysis and discussion of the protocols is then provided in Section IV. Finally, Section V concludes the paper.

II. NC-Aware MAC Protocols

In this section we provide a brief description of the COPE, or DCF+NC, protocol and the proposed RD-DCF+NC protocol, and show examples of operation in the Alice-and-Bob and cross topologies in Figs. 2 and 3, respectively.

A. COPE (DCF+NC)

COPE [2] exploits NC by setting the nodes in promiscuous mode to allow them to store and process overheard packets for a limited time. COPE allows intermediate nodes to opportunistically combine two received packets from different flows for transmission by using the XOR operation. COPE introduces an additional header in the coded packet to allow the receiving nodes to identify decoding opportunities. To provide reliability for coded packets, COPE specifies that coded packets should be addressed to one of the intended receivers in order to generate synchronous ACK packets. Upon successful decoding, the other receivers should schedule ACK events that will be sent together with data packets or periodic control packets.

COPE uses the DCF of the IEEE 802.11 at the MAC layer. This MAC protocol is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism and a Binary Exponential Backoff (BEB) algorithm. As shown in Figs. 2a, 3a, in each data transmission the transmitting node waits for a DCF Inter Frame Space (DIFS) and a random backoff time (BO). Then, it initiates a Request-To-Send/Clear-To-Send (RTS/CTS) exchange with the receiving node before sending data. Upon successful reception of data, the receiving node responds with a positive acknowledgment (ACK) after a Short Inter Framce Space (SIFS).

When the COPE protocol is running on a wireless network, the node operation is as follows. In Fig. 2b, the relay node R combines a and b into $a \oplus b$ and then chooses B at random as the intended receiver. When B receives $a \oplus b$, it can retrieve a by using b and $a \oplus b$. A overhears $a \oplus b$, because it is in promiscuous mode, and can also decode it to get b by using a. As a result, R only needs one transmission slot to forward two packets to their respective destinations. Similarly shown in Fig. 3b, R sends a coded packet from A and B to B. The RTS and coded packets are overheard by A, C, and D whereas the CTS and ACK packets are only overheard by C and D. A similar operation will follow when R encodes the packets from C and D and transmits the coded packet to one of them. By exploiting NC, R only needs two transmission slots to forward four packets from A, B, C, and D to their respective destinations.

B. RD-DCF+NC

RD-DCF+NC [10] exploits NC based on COPE with an enhanced access mechanism using RD-DCF. As shown in Figs. 2c, 3c, in RD-DCF a realy node can transmit a data packet upon successful reception of a data packet without additional channel contention. However, in RD-DCF+NC the relay node is able to transmit a coded 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.

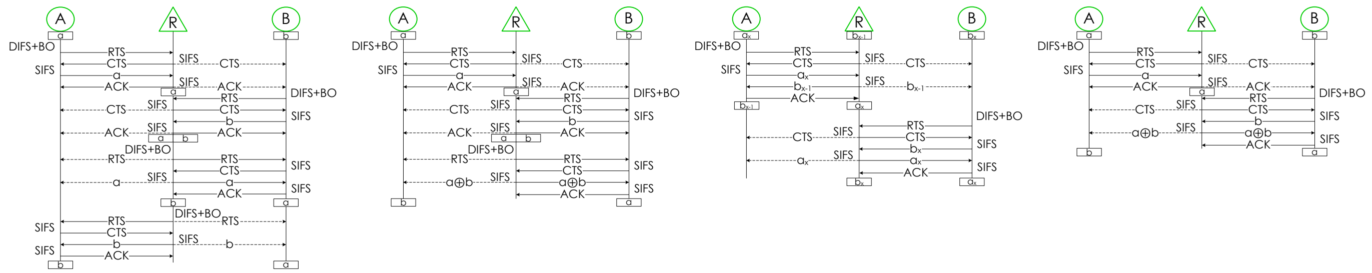
The operation of the RD-DCF+NC protocol in a wireless network is as follows. In Fig. 2d, A sends a using standard DCF rules. After a DIFS, R invokes the backoff procedure to send a to B. However, B gets a transmission opportunity earlier. When R receives the RTS packet from B, it identifies a coding opportunity with a. Then, it freezes the backoff procedure and sends a CTS packet to B with the duration field including the additional time to transmit the possible coded packet. This information is computed based on the value of the duration field contained in the RTS packet. When B receives the CTS packet, it sends b to R after a SIFS. R combines a and b into $a \oplus b$ and transmits $a \oplus b$ to B. A and B can retrieve the packet of each other as explained above for DCF+NC. Similarly shown in Fig. 3d, R can send a coded packet when it receives a data packet from D. This must precede the transmission of a data packet from C to R using DCF, in a a way similar to A in Fig. 3a. In this example, A and B overhear the entire communication while C can only overhear the CTS and coded packets.

III. Analysis

In this section we derive the expressions of maximum theoretical throughput and energy efficiency for the protocols under consideration, i.e., DCF, DCF+NC, RD-DCF, and RD-DCF+NC.

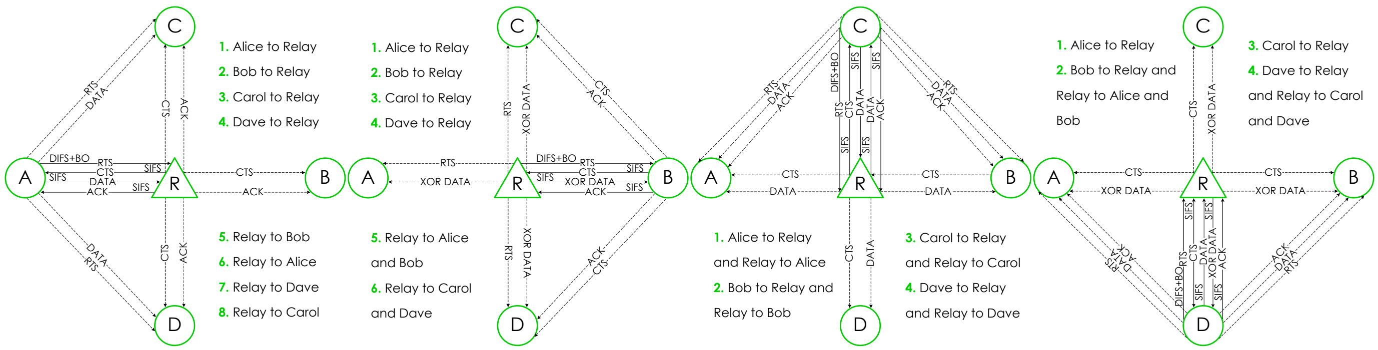
A. Network Model and Assumptions

We consider two network scenarios namely the Alice-and-Bob topology and the cross topology shown in Fig. 1. Each scenario is composed of a relay node and N source nodes all equipped with IEEE 802.11g wireless interfaces. Thus, full capabilities of IEEE 802.11g can be exploited. We assume that the relay node does not generate own traffic but only forwards



(a) DCF. (b) DCF+NC. (c) RD-DCF. (d) RD-DCF+NC.

Fig. 2. Examples of operation of the DCF, DCF+NC, RD-DCF, and RD-DCF+NC in the Alice-and-Bob topology.



(a) DCF. (b) DCF+NC. (c) RD-DCF. (d) RD-DCF+NC.

Fig. 3. Examples of operation of the DCF, DCF+NC, RD-DCF, and RD-DCF+NC in the cross topology.

the data packets from the source nodes to their respective destinations. All data packets have a constant length.

Since the aim is to compute the upper bound of the throughput and energy efficiency in idealistic conditions, we assume that: 1) the probability of collision is negligible, 2) there are no packet losses due to channel errors. In addition, no packet losses exist due to buffer overflow. Fragmentation is not used and the propagation delay is neglected. For the NC-enabled protocols, we also assume that coding and decoding using the XOR operation consume negligible time and energy.

While in on state, the IEEE 802.11g wireless interface of a node can be in one of the following operational states: transmitting, receiving or overhearing (i.e., receiving packets not destined to itself), and idle (i.e., the wireless interface is ready to receive but not signal is received by the radio transceiver). Each of these operational states has an associated power consumption that will vary depending on the product hardware. Let P_t, P_r, and P_i, denote the power consumed while transmitting, receiving, and being idle, respectively.

B. IEEE 802.11g ERP-OFDM Physical Layer

The IEEE 80211g amendment introduces an Extended Rate PHY (ERP) specification that uses the OFDM modulation and provides 8 transmission modes with different modulation schemes and coding rates. Table I summarizes the characteristics of each mode, where the supported data rates and the Number of Data Bits per OFDM Symbol (N_{DBPS}) are shown.

The structure of an ERP-OFDM packet is described as follows. Each MAC data packet or MAC Protocol Data Unit (MPDU) consists of a MAC header, frame body or MAC Service Data Unit (MSDU), and Frame Check Sequence (FCS). The MAC header and FCS together are up to 34 octets, the RTS packet is 20 octets, and the CTS and ACK packets are 14 octets long. Note that an XOR header of 40 octets will be added after the MAC header to create a coded packet [2].

When a MPDU is to be transmitted, it is passed to the PHY Layer Convergence Procedure (PLCP) sublayer where it is called PLCP Service Data Unit (PSDU). In order to form a PLCP Protocol Data Unit (PPDU), a PLCP preamble and a PLCP header are added to a PSDU. The duration of the PLCP preamble field (T_{pre}) is 16 μs. The PLCP header except the SERVICE field constitutes the SIGNAL field whose duration (T_{sig}) equals the duration of a single OFDM symbol (T_{sym}) with 4 μs. The 16-bit SERVICE field (L_{serv}) and the MPDU along with 6 tail bits (L_{tail}) and pad bits, represented by DATA, are transmitted at the data rate specified in the RATE field. Finally, a period of no transmission with a length of 6 μs called the signal extension (T_{sigEx}) follows after the end of ERP-OFDM transmission. All the above parameters and their values are provided in Table II.

The basic rate set is {6, 12, and 24} Mbps and each node should support these rates and control response packets should be transmitted at these rates. The use of each basic rate will depend on whether the RTS and data packets were received at 6 or 9, 12 or 18, and 24, 36, 48 or 54 Mbps, respectively.

We can thus obtain the time to transmit each packet at the IEEE 802.11g PHY layer. The transmission times of a data packet and a coded packet with L_{MSDU} octets of data payload, a RTS packet, and CTS and ACK packets are given in (1), (2), (3), and (4), respectively. The ceiling function $\lceil x \rceil$ returns the

TABLE I
ERP-OFDM PHY MODES AND TRANSMISSION TIMES IN μS FOR CONTROL AND DATA PACKETS IN IEEE 802.11G.

Mode	Modulation	Code rate	Data rate	N_{DBPS}	T_{RTS}	T_{CTS}	T_{ACK}	T_{DATA} (1500 bytes)	$T_{XORDATA}$ (1500 bytes)
1	BPSK	1/2	6 Mbps	24	58	50	50	2078	2130
2	BPSK	3/4	9 Mbps	36	50	50	50	1394	1430
3	QPSK	1/2	12 Mbps	48	42	38	38	1054	1078
4	QPSK	3/4	18 Mbps	72	38	38	38	710	730
5	16-QAM	1/2	24 Mbps	96	34	34	34	542	554
6	16-QAM	3/4	36 Mbps	144	34	34	34	370	378
7	64-QAM	2/3	48 Mbps	192	30	34	34	286	290
8	64-QAM	3/4	54 Mbps	216	30	34	34	254	262

TABLE II
PARAMETERS OF PHY AND MAC LAYERS FOR 802.11G.

Parameter	Value	Parameter	Value
T_{slot}	9 μs	L_{serv}	16 b
T_{SIFS}	10 μs	L_{tail}	6 b
T_{DIFS}	28 μs	L_{RTS}	20 B
CW_{min}	15	L_{CTS}=L_{ACK}	14 B
CW_{max}	1023	L_{MAChdr}	30 B
T_{BO}	67.5 μs	L_{XORhdr}	40 B
T_{pre}	16 μs	L_{FCS}	4 B
T_{sig}	4 μs	P_t	1.65 W
T_{sym}	4 μs	P_r	1.4 W
T_{sigEx}	6 μs	P_i	1.15 W

smallest integer value greater than or equal to x. Table I shows the transmission time of each packet for each transmission rate.

$$T_{DATA}{=}T_{pre}{+}T_{sig}{+}T_{sigEx}$$
$$T_{sym}\left\lceil\frac{L_{serv}{+}(L_{MAChdr}{+}L_{MSDU}{+}L_{FCS})8{+}L_{tail}}{N_{DBPS}}\right\rceil \quad (1)$$

$$T_{XORDATA}{=}T_{pre}{+}T_{sig}{+}T_{sym}\times$$
$$\left\lceil\frac{L_{serv}{+}(L_{MAChdr}{+}L_{XORhdr}{+}L_{MSDU}{+}L_{FCS})8{+}L_{tail}}{N_{DBPS}}\right\rceil$$
$$+T_{sigEx} \quad (2)$$

$$T_{RTS}{=}T_{pre}{+}T_{sig}{+}T_{sym}\left\lceil\frac{L_{serv}{+}L_{RTS}8{+}L_{tail}}{N_{DBPS}}\right\rceil$$
$$+T_{sigEx} \quad (3)$$

$$T_{CTS}{=}T_{ACK}{=}T_{pre}{+}T_{sig}{+}T_{sym}\left\lceil\frac{L_{serv}{+}L_{ACK}8{+}L_{tail}}{N_{DBPS}}\right\rceil$$
$$+T_{sigEx} \quad (4)$$

C. Throughput Analysis

The throughput is defined as the amount of bits contained in a MSDU divided by the time in microseconds required to transmit the data packet that includes the MSDU. Depending on the MAC protocol under consideration the throughput can be derived as follows:

1) DCF: The transmission cycle of DCF consists of a DIFS interval, a backoff period, a RTS transmission, a SIFS interval, a CTS transmission, a SIFS interval, a data transmission, a SIFS interval and an ACK transmission. The duration of a DIFS interval (T_{DIFS}) is $T_{SIFS}{+}2T_{slot}$, where T_{SIFS} is the duration of a SIFS interval and T_{slot} is the duration of a slot time. Since there are no collisions, the average backoff time (T_{BO}) is equal to $(CW_{min}/2)T_{slot}$, where CW_{min} is the minimum Contention Window (CW) size. The values associated with these periods are shown in Table II.

To compute the maximum throughput of DCF, the source nodes should send N data packets to the relay node, which should forward them to their respective destinations. In total, $2N$ transmission slots are required to forward N data packets from end to end. We can thus express the maximum throughput of DCF by (5) contained in Table III.

However, the saturation throughput of DCF will be lower than the maximum throughput. Due to the long-term fairness of DCF, the relay node will only get a transmission opportunity once every N transmissions from the source nodes. The saturation throughput of DCF is then given by (6).

2) DCF+NC: The transmission cycle of DCF+NC is similar to that of DCF but it includes the transmission of a coded packet from the relay node. To compute the maximum throughput of DCF+NC, the relay node should forward $N/2$ coded packets for every N received data packets from the source nodes. As a result, N data transmissions and $N/2$ coded data transmissions are required to forward N data packets from end to end. However, under saturation, the relay node will only be able to send a single coded packet every N transmissions from the source nodes, due to the DCF fairness. Thus, two data packets will be delivered from end to end. The maximum throughput and the saturation throughput of DCF+NC are obtained by (7), (8), respectively.

3) RD-DCF: The transmission cycle of RD-DCF contains the same as that of DCF but it includes an additional data transmission and a SIFS interval. To compute the maximum throughput of RD-DCF, we assume that the relay node has a data packet ready to transmit when it receives a data packet from a source node. Therefore, the relay node can forward N data packets from end to end every N transmissions from the source nodes. The maximum throughput of RD-DCF is then given by (9).

4) RD-DCF+NC: The transmission cycle of RD-DCF+NC includes the same as that of RD-DCF except that there is a coded data transmission from the relay node. To compute the maximum throughput of RD-DCF+NC, the source nodes should perform N data transmissions and the relay node should perform $N/2$ coded data transmissions using reverse direction communication. Hence, N transmission slots are required to exchange N data packets from end to end. The maximum throughput of RD-DCF+NC is expressed by (10).

TABLE III
THROUGHPUT FORMULAS.

DCF maximum throughput	
$\frac{L_{MSDU}8}{\frac{2N}{N}(T_{DIFS}+T_{BO}+T_{RTS}+T_{CTS}+T_{DATA}+T_{ACK}+3T_{SIFS})}$	(5)
DCF saturation throughput	
$\frac{L_{MSDU}8}{(N+1)(T_{DIFS}+T_{BO}+T_{RTS}+T_{CTS}+T_{DATA}+T_{ACK}+3T_{SIFS})}$	(6)
DCF+NC maximum throughput	
$\frac{L_{MSDU}8}{\frac{1}{N}\left[(N+\frac{N}{2})(T_{DIFS}+T_{BO}+T_{RTS}+T_{CTS}+T_{ACK}+3T_{SIFS})+NT_{DATA}+\frac{N}{2}T_{XORDATA}\right]}$	(7)
DCF+NC saturation throughput	
$\frac{L_{MSDU}8}{\frac{1}{2}\left[(N+1)(T_{DIFS}+T_{BO}+T_{RTS}+T_{CTS}+T_{ACK}+3T_{SIFS})+NT_{DATA}+T_{XORDATA}\right]}$	(8)
RD-DCF maximum and saturation throughput	
$\frac{L_{MSDU}8}{\frac{N}{N}\left[(T_{DIFS}+T_{BO}+T_{RTS}+T_{CTS}+2T_{DATA}+T_{ACK}+4T_{SIFS})\right]}$	(9)
RD-DCF+NC maximum and saturation throughput	
$\frac{L_{MSDU}8}{\frac{1}{N}\left[N\left(T_{DIFS}+T_{BO}+T_{RTS}+T_{CTS}+T_{DATA}+T_{ACK}\right)+\frac{N}{2}(7T_{SIFS}+T_{XORDATA})\right]}$	(10)

D. *Energy Efficiency Analysis*

The energy efficiency is defined as the amount of bits contained in a MSDU divided by the energy consumed in microjoules to transmit the data packet that includes the MSDU. The energy efficiency of each protocol is as follows:

1) DCF: During the transmission cycle of DCF, the transmitting node, either a source node or the relay node, consumes energy to transmit the RTS and data packets and to receive the CTS and ACK packets from the receiving node. On the other hand, the receiving node consumes energy to receive the RTS and data packets from the transmitting node and to respond with the CTS and ACK packets. The $N-1$ source nodes not involved in transmission consume energy to overhear the exchange of packets except one that can only overhear the packets sent from the relay node. The N source nodes and the relay node also consume energy to listen to the wireless channel for a DIFS interval, a backoff period, and all SIFS intervals. In addition, one source node is idle when one of the source nodes is transmitting to the relay node.

The maximum energy efficiency and the saturation energy efficiency of DCF are expressed by (11), (12). For easy comprehension, we split the energy consumed by the nodes into the different operational states, namely, transmitting (E_t), receiving (E_r) and idle (E_i).

2) DCF+NC: In the transmission cycle of DCF+NC, nodes consume similar amounts of energy to those shown for a transmission cycle of DCF. However, the relay node will consume energy to transmit a coded packet and the N source nodes will consume energy to receive it. As a result, the maximum energy efficiency and the saturation energy efficiency of DCF+NC are given by (13), (14).

3) RD-DCF: The energy consumed in the transmission cycle of RD-DCF equals that of DCF with the following additional contributions. The relay node and a source node consume energy to transmit a data packet and an ACK packet, respectively. The N source nodes consume energy to receive the packets, except one that only receives the data packet. In addition, the relay node and the source nodes are idle for a SIFS and one source node is idle during the ACK transmission. The energy effficiency of RD-DCF is expressed as (15).

4) RD-DCF+NC: The transmission cycle of RD-DCF+NC consumes the same amounts of energy as that of RD-DCF. However, additional energy consumption is required for the relay node to transmit a coded packet in the reverse direction and to receive it by the N source nodes. We obtain the maximum energy efficiency of RD-DCF+NC by (16).

IV. NUMERICAL RESULTS

In this section, we use the expressions derived in the previous section to discuss the upper bounds of the throughput and energy efficiency of the different protocols in the Alice-and-Bob and cross topologies.

A. *System Layout*

In the Alice-and-Bob topology, there are 2 source nodes and a relay node. On the contrary, in the cross topology, there are 4 source nodes and a relay node. All the nodes are operating

TABLE IV
ENERGY EFFICIENCY FORMULAS.

DCF maximum energy efficiency	
$\frac{L_{MSDU}8}{\frac{N}{N}\left[(T_{RTS}+T_{CTS}+T_{DATA}+T_{ACK})(2P_t+(2N-1)P_r+P_i)+2(T_{DIFS}+T_{BO}+3T_{SIFS})(N+1)P_i\right]}$	(11)
DCF saturation energy efficiency	
$\frac{L_{MSDU}8}{E_t+E_r+E_i}\begin{cases}E_t=(T_{RTS}+T_{CTS}+T_{DATA}+T_{ACK})(N+1)P_t\\E_r=((T_{RTS}+T_{DATA})(N(N-1)+N)+(T_{CTS}+T_{ACK})(N^2+N-1))P_r\\E_i=((T_{DIFS}+T_{BO}+3T_{SIFS})(N+1)^2+(T_{RTS}+T_{DATA})N+T_{CTS}+T_{ACK})P_i\end{cases}$	(12)
DCF+NC maximum energy efficiency	
$\frac{L_{MSDU}8}{\frac{1}{N}\left(E_t+E_r+E_i\right)}\begin{cases}E_t=((T_{RTS}+T_{CTS}+T_{ACK})(N+\frac{N}{2})+T_{DATA}N+T_{XORDATA}\frac{N}{2})P_t\\E_r=(T_{RTS}(N(N-1)+\frac{N^2}{2})+T_{DATA}N(N-1)+T_{XORDATA}\frac{N^2}{2}+(T_{CTS}+T_{ACK})(N^2+\frac{N}{2}(N-1)))P_r\\E_i=((T_{DIFS}+T_{BO}+3T_{SIFS})(N+1)(N+\frac{N}{2})+(T_{RTS}+T_{DATA})N+T_{CTS}+T_{ACK})P_i\end{cases}$	(13)
DCF+NC saturation energy efficiency	
$\frac{L_{MSDU}8}{\frac{1}{2}\left(E_t+E_r+E_i\right)}\begin{cases}E_t=((T_{RTS}+T_{CTS}+T_{ACK})(N+1)+T_{DATA}N+T_{XORDATA})P_t\\E_r=(T_{RTS}(N(N-1)+N)+T_{DATA}N(N-1)+T_{XORDATA}N+(T_{CTS}+T_{ACK})(N^2+N-1))P_r\\E_i=((T_{DIFS}+T_{BO}+3T_{SIFS})(N+1)^2+(T_{RTS}+T_{DATA})N+T_{CTS}+T_{ACK})P_i\end{cases}$	(14)
RD-DCF maximum and saturation energy efficiency	
$\frac{L_{MSDU}8}{\frac{1}{N}\left(E_t+E_r+E_i\right)}\begin{cases}E_t=((T_{RTS}+T_{CTS}+T_{ACK}+2T_{DATA})NP_t\\E_r=((T_{RTS}+T_{ACK})(N-1)+T_{CTS}N+T_{DATA}(N+N-1))NP_r\\E_i=((T_{DIFS}+T_{BO}+4T_{SIFS})(N+1)+T_{RTS}+T_{DATA}+T_{ACK})NP_i\end{cases}$	(15)
RD-DCF+NC maximum and saturation energy efficiency	
$\frac{L_{MSDU}8}{\frac{1}{N}\left(E_t+E_r+E_i\right)}\begin{cases}E_t=((T_{RTS}+T_{CTS}+T_{ACK}+T_{DATA})N+T_{XORDATA}\frac{N}{2})P_t\\E_r=((T_{RTS}+T_{DATA})N(N-1)+(T_{CTS}N+T_{XORDATA}\frac{N}{2})N+T_{ACK}(\frac{N^2}{2}+\frac{N}{2}(N-1)))P_r\\E_i=(((T_{DIFS}+T_{BO})N+7T_{SIFS}\frac{N}{2})(N+1)+(T_{RTS}+T_{DATA})N+T_{ACK}\frac{N}{2})P_i\end{cases}$	(16)

in the ERP-OFDM-only mode. Thus, we can take advantage of the additional features provided by pure IEEE 802.11g. The system parameters and their values are provided in Table II. The values of the power consumed for transmit, receive, and idle states are taken from [11].

B. Discussion

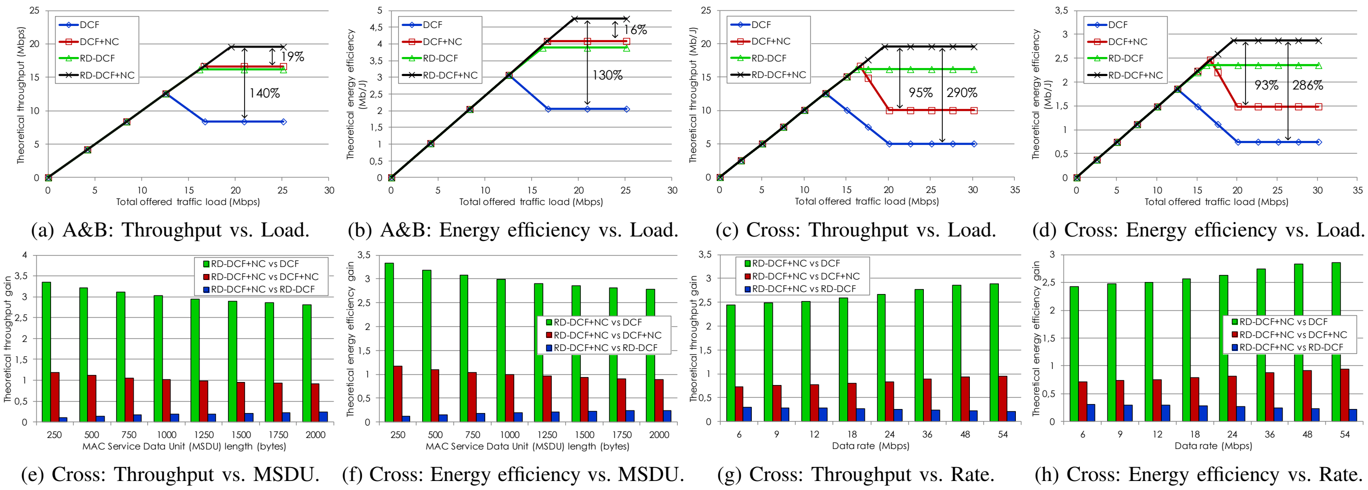
The throughput versus the traffic load in the Alice-and-Bob topology is plotted in Fig. 4a. Likewise, the energy efficiency is shown in Fig. 4b. We consider a MSDU of 1500 bytes and a data rate of 54 Mbps.

In general, the performance of the protocols under evaluation increases linearly as the traffic load from Alice and Bob increases since the relay node needs to forward more packets. The performance of DCF reaches a maximum value and then decreases until a stable value under saturation. The maximum value corresponds to $1/2$ of the traffic load from Alice ($1/4$) and Bob ($1/4$). Since the relay node needs to forward twice as many packets as Alice and Bob, it will use half of the channel accesses. Otherwise, the saturation value corresponds to $2/3$ of the traffic load from Alice ($1/3$) and Bob ($1/3$). Due to the DCF fairness, when Alice and Bob attempt to transmit at a higher rate, the relay node is unable to increase its capacity and can only get $1/3$ of the channel.

When NC is enabled, DCF+NC allows the relay node to send twice as fast as Alice and Bob, although it will still get $1/3$ of the channel. The relay node is able to send two packets in a single transmission and will be able to increase its capacity as Alice and Bob do. The maximum throughput of DCF+NC will be around $2/3$ of the channel throughput due to the additional overhead required for coding.

The proposed RD-DCF protocol can achieve a similar performance to DCF+NC because the relay node is able to send a packet when it receives a packet from either Alice or Bob. However, the relay node will have to transmit twice as many packets as Alice and Bob and so the nodes will consume higher amounts of energy. In contrast, the proposed RD-DCF+NC protocol achieves the highest performance as it allows the relay node to send a coded packet as soon as it receives a data packet from either Alice or Bob.

In Figs. 4c, 4d, we show the throughput and energy efficiency of the protocols versus the traffic load in the cross topology. The proposed protocols can achieve significantly higher gains when compared to the DCF and DCF+NC protocols. The saturation throughput of DCF is significantly lower than that shown in the Alice-and-Bob topology. The relay node needs to compete for the channel access with 4



(a) A&B: Throughput vs. Load. (b) A&B: Energy efficiency vs. Load. (c) Cross: Throughput vs. Load. (d) Cross: Energy efficiency vs. Load.

(e) Cross: Throughput vs. MSDU. (f) Cross: Energy efficiency vs. MSDU. (g) Cross: Throughput vs. Rate. (h) Cross: Energy efficiency vs. Rate.

Fig. 4. Theoretical throughput and energy efficiency of the DCF, DCF+NC, RD-DCF, and RD-DCF+NC as a function of the traffic load, MSDU length (1500 bytes), and data rate (54 Mbps) in the Alice-and-Bob and cross topologies.

source nodes. Thus, it can only get $1/5$ of the channel whereas the source nodes get $4/5$ of the channel. When NC is used, the maximum performance is shown at $2/3$ of the load where each source node gets $1/6$ of the channel and the relay node gets $1/3$. However, the performance will be reduced to $2/5$ of the channel capacity at $4/5$ of the load since the relay node will only get $1/5$ of the channel to transmit coded packets.

Figs. 4e-4h summarize the maximum throughput and energy efficiency gains as a function of the MSDU length and the data rate in the cross topology. The gain of RD-DF+NC versus DCF decreases as the packet length increases whereas it decreases as the data rate increases. The gain compared with DCF+NC shows a similar behaviour whereas when compared with RD-DCF the gain shows an opposite behaviour. The main reason for this is that the time of data transmission has a certain influence on the overall performance of the protocols. In the RD-based protocols, two data packets are transmitted within the same RTS/CTS exchange. When the packet length is short or the data rate is high, the impact of data transmission on the overall transmission time is small. As the packet length increases or the data rate decreases, its contribution to the overall transmission time becomes more significant.

V. Conclusions

In this paper, we have analyzed the upper bounds of the throughput and energy efficiency of two RD-based MAC protocols with and without NC, namely, RD-DCF and RD-DCF+NC. Unlike DCF, RD-DCF allows an intermediate relay node receiving a data packet to respond with a data packet together with the ACK packet. Unlike DCF+NC, RD-DCF+NC allows an intermediate relay node to transmit a coded packet upon successful reception of a data packet. We have studied two network topologies, namely, the Alice-and-Bob topology and the cross topology. We have derived closed expressions for the maximum and saturation throughput and energy efficiency for the proposed protocols and have shown numerical results as a function of the traffic load, data payload length, and data rate. A comparison with the performance of DCF and DCF+NC has also been provided. The maximum gains vary from 335% to 91% as the packet length increases and from 73% to 289% as the data rate increases. Furthermore, we have shown that the proposed protocols can achieve higher gains as the number of source nodes under the relay's coverage increases.

Ongoing work is aimed at modeling the throughput and energy efficiency of the proposed protocols considering the backoff periods and contention, as well as non-saturated traffic conditions and realistic wireless channel conditions.

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