Adaptive Cooperative Network Coding Based MAC Protocol for Device-to-Device Communication

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***Abstract*—Device-to-Device (D2D) communication allows the direct connection of mobile devices in a cellular network. In D2D networking, cooperative communication is inherent due to the proximity of the devices that are able to overhear and forward information. Particularly, adjacent devices can act as relays and assist the communication of other devices. Network Coding (NC) can further increase the cooperation gains, since a number of packets can be encoded and transmitted together. However, the contention among multiple relays causes channel access issues that must be regulated by effective Medium Access Control (MAC) protocols. In this context, we propose an Adaptive Cooperative Network Coding-based MAC (ACNC-MAC) protocol that utilizes cooperative relaying and exploits NC opportunities in a D2D topology. Both analytical and simulation results show that the proposed protocol is advantageous in terms of energy efficiency without sacrificing the Quality of Service (QoS).**

Keywords—Cooperation, Network coding, D2D communication, Medium Access Control (MAC), LTE-Advanced networks.

I. Introduction

Currently, Long Term Evolution Advanced (LTE-A) cellular networks provide the end-users with a large variety of multimedia applications, like content sharing and social networking related services. The unprecedented increase of data exchanged between network components, such as LTE-A evolved NodeB base stations (eNBs), relays and user terminals (UEs), has raised complex technical challenges for the mobile network operators. On one hand, the required Quality of Service (QoS) must be achieved without inflating the servicing cost; on the other hand, serving each UE through the eNB tends to provoke cell congestion, especially when high data rate services (e.g., online gaming, video sharing, location–aware applications, etc.) are supported [1]. Recently, the Third Generation Partnership Project (3GPP) has brought to the spotlight the concept of Device-to-Device (D2D) communication that enables the direct connection among UEs, with the purpose to offload users from the cellular network and improve the network performance in terms of energy efficiency and throughput. D2D connections can either operate in the licensed frequency band along with cellular communication links (*inband D2D*) or in the unlicensed spectrum, by utilizing wireless technology standards, like Wi–Fi Direct or Bluetooth (*outband D2D*) [2].

Outband D2D connections can be either under cellular control, i.e., managed by eNBs, or autonomous and coordinated by the users. In autonomous outband D2D communications, the UEs can be connected to other UEs through Wi–Fi, creating a *D2D mobile cloud* [3], where neighboring devices can be interconnected, share resources and relay received information. Indeed, the capability of modern smart UEs for content sharing is leveraged by the D2D connectivity. Data dissemination among devices has empowered numerous social services and commercial applications that take advantage of UEs' proximity. Even cooperative downloading can be performed among nearby devices that are interested in the same digital content. The devices may receive data via direct LTE-A connections and exchange the desired content fractions by establishing bidirectional flows [4].

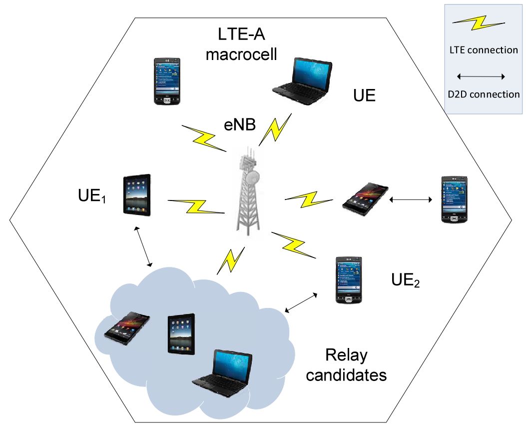
Nevertheless, the dynamic multi–user nature of D2D wireless links induces two main issues that affect the potential of D2D networking. First, the links among devices willing to communicate may suffer from low Signal-to-Noise Ratio (SNR) that might cause a large number of packet retransmissions, leading to unacceptable delay values. In such cases, cooperation can be useful so that UEs in the same area can benefit from idle UEs that can act as relays. The second major issue that arises concerns the synchronization of multiple relays that contend for the wireless channel aiming to help the direct transmissions. Following the IEEE 802.11 Standard specification, the Distributed Coordination Function (DCF) can be used as MAC mechanism [5] during the relay–assisted cooperative retransmission process. Random access inevitably causes collisions, especially at heavy traffic load, thus, making imperative the need for MAC protocols that coordinate the relay transmissions [6].

Further network performance gain from D2D cooperation can be achieved with the aid of Network Coding (NC) technique, which combines packets from the same or different information flows at intermediate nodes or relays [7]. In the last few years, various cooperative MAC protocols have appeared that exploit NC and the existence of multiple overheard packets in the nodes. NC packets can be encoded together, resulting in more efficient bandwidth utilization [8], [9]. The COPE protocol [8] was the first work that applied NC in MAC layer, utilizing the capability of neighboring nodes to overhear transmitted packets (opportunistic listening). Building upon COPE, the BEND protocol [10] suggests proactive packet mixing at potential relays where multiple unidirectional flows intersect, although the opportunistic forwarding relies on the information conveyed in large size ACK frames. In the context of bidirectional flows, the authors of [9] have introduced NCCARQ–MAC, an NC–based MAC protocol that coordinates the transmissions among a set of relay nodes. It helps the communication between nodes in saturated conditions but allows cooperation only when NC conditions are met. In [11] and [12], cooperative retransmission processes that extend coding opportunities, by using corrupted packets, are proposed. However, these schemes either require additional packet exchange [11] or strict synchronization [12], in order to fully exploit the NC potential in case of bidirectional communications.

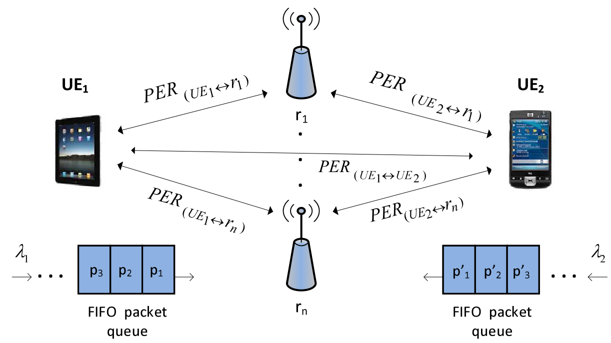
Particularly in the case of D2D connections, where battery–powered devices are involved, it is reasonable that a MAC scheme should harness coding opportunities as much as possible. To that end, we propose an Adaptive Cooperative Network Coding-based MAC (ACNC–MAC) protocol that takes advantage of NC in order to effectively manage packet retransmissions in relay–aided bidirectional communication over D2D links. Furthermore, even if NC conditions are not satisfied, ACNC–MAC behaves as a simple cooperative protocol. The main contribution of this work consists in the following:

(i) We present an energy–efficient NC–based protocol, which allows neighboring idle UEs that overhear cooperation requests to participate in cooperative transmissions and support communication flows among other UEs.
(ii) We provide an analytical model for the achieved network throughput in saturated conditions. Also, extensive simulation study in both saturated conditions and non-saturated conditions with varied traffic rates is performed.

The rest of the paper is organized as follows. The considered system model is described in Section II. In Section III, the ACNC–MAC protocol is presented, while the throughput analysis for saturated conditions is given in Section IV. Simulation results are provided in Section V and conclusions are drawn in Section VI.



(a) A D2D–enabled cellular network



(b) Relay–aided bidirectional communication between two UEs

Fig. 1: Considered communication scenario

II. System Model

In the D2D-enabled cellular network of Fig. 1a, multiple UEs reside in the same cellular cell. Apart from the LTE links to the local eNB, each UE can connect to other UEs via Wi–Fi. We consider the example of D2D connection depicted in Fig. 1b, where the sources UE_1 and UE_2 intend to initiate communication. The source UE_1 sends its queued packets to source UE_2, and conversely UE_2 intends to send packets to UE_1, establishing a bidirectional flow. The packets of each source are generated according to a Poisson arrival process with intensity λ_1 and λ_2 for UE_1 and UE_2, respectively.

Since the SNR of the D2D link between UE_1 and UE_2 may vary in time, the instantaneous channel conditions might deteriorate, causing erroneous packet receptions. After the source (UE_1 or UE_2) fails to receive a packet correctly, it will ask for cooperation from other UEs in the area. Arbitrarily distributed adjacent UEs are potential relays that can be used to help the $UE_1 \leftrightarrow UE_2$ connection through opportunistic listening, and are able to retransmit the overheard packets. In the considered D2D topology, the UEs that can support the $UE_1 \leftrightarrow UE_2$ communication decide whether they will join the relay set $\mathbf{R} = \{r_1, r_2, \ldots, r_n\}$, according to their status (in transmission or idle mode). Given that the traffic between UE_1 and UE_2 is bidirectional, NC can be applied by the relays so that packets of both flows are served simultaneously.

The channels between the sources UE_1 and UE_2 and the relays are assumed to be independent of each other. The packet error rates (PERs) $PER_{(UE_1 \leftrightarrow UE_2)}$, $PER_{(UE_1 \leftrightarrow r)}$ and $PER_{(UE_2 \leftrightarrow r)}$, $r \in \mathbf{R}$ are different for each D2D link. For each transmission, the UEs can use different data rates, noted as $R_{s,r}$ for the sources and $R_{r,s}$ for the idle relay candidates, where $s \in \mathbf{S} = \{UE_1, UE_2\}$ and $r \in \mathbf{R}$.

Moreover, each UE that wishes to transmit utilizes the DCF method of IEEE 802.11 Standard, based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique. DCF resolves collisions through multiple levels of contention windows and backoff stages. In the initial backoff stage, the value of contention window has the minimum value cw_{min}. After each collision, the value will be doubled until the maximum cw_{max} is reached. The contention window will be reset to cw_{min} after each successful transmission.

III. The ACNC-MAC Protocol

In this section, the operation of ACNC–MAC protocol is described.

A. *Design details*

We consider the topology of Fig. 1b, where two sources UE_1 and UE_2 start a new communication round. Each source that has a packet to transmit in its queue will contend for channel access. It senses the channel idle for DCF Inter Frame Space (DIFS) time and waits for a random backoff time RB before attempting to transmit.

Letting UE_1 be the UE that wins channel access and sends its packet p_1, UE_2 overhears the transmission but cannot decode the packet correctly. UE_2 will ask for cooperation by sending a special control frame, the *Request-for-Cooperation*

(RFC) frame after a Short Inter Frame Space (SIFS) period of silence. If UE_2 has another packet p_1' in its queue ready for transmission, it can be sent along with RFC.

The neighboring idle UEs are triggered by the reception of RFC. Each UE–relay candidate that can help the $UE_1 \leftrightarrow UE_2$ transmission will contend for channel access by selecting the appropriate backoff value according to the number of received packets. Then, it will send its own control frame, the *Eager-To-Cooperate* (ETC) frame, after sensing the channel for SIFS. ETC will be transmitted piggy–backed with the overheard data packets which have been received successfully by the relay. Either one or two packets encoded together are transmitted and ETC indicates the number of ACK frames expected. As the number of packets received by the relays at each transmission round varies, the cooperation phase must be adapted so that the maximum number of packets is served. This can be achieved by the backoff arrangement discussed in Section III-B.

Due to the variable duration of the cooperation phase, the sources cannot be aware of the number of packets correctly received by the relays, thus they do not know when the cooperation round ends and might attempt to initiate a new transmission. To handle this issue, it is sufficient for the sources to know how many ACK frames are expected so as to schedule their subsequent transmissions. This information is available at the relay that wins the contention phase and can be included in the transmitted ETC frame. According to the number of packets existing in the relays, ACNC–MAC handles three different cases at the relay selection phase:

Case 1: At least one relay has received packets from both UEs. This means that the relays that have both packets p_1 and p_1' gain priority and ETC+($p_1 \oplus p_1'$) is transmitted. Thus, two ACK frames have to be sent in order to terminate the cooperation.

Case 2: Some of the relays have correctly decoded one packet only, either p_1 or p_1', while others may not have received any packet. None of the relays have both packets. In this case, p_1' was not sent or was not correctly received by some relays. Also, p_1 was not decoded correctly by all the relays. The relay that wins channel access will transmit either ETC+p_1 or ETC+p_1'. Only one ACK is expected and it will be sent by the receiver UE.

Case 3: None of the relays have received any packet, thus only an ETC frame will be transmitted. No ACK frame will be sent and the two UEs will contend again for access.

B. Relays' backoff selection

In order to prioritize retransmissions that will serve the maximum possible number of packets, relays that have overheard the maximum number of packets should gain channel access. For the arrangement of the relay prioritization, different non-overlapping ranges can be used for the backoff counter. The backoff range is divided into several small ranges according to the number of packets i existing in each relay. Depending on i and given $cw(k)$ as the contention window of the current backoff stage k, each relay will select the contention window $cw_i \in [cw_{\min}, cw_{\max}]$ from the following ranges, as shown in Fig. 2:

$$cw_i \in \begin{cases} [2cw(k), 3cw(k)-1], & \text{if } i = 0 \\ [cw(k), 2cw(k)-1], & \text{if } i = 1 \\ [0, cw(k)-1], & \text{if } i = 2 \end{cases} \quad (1)$$

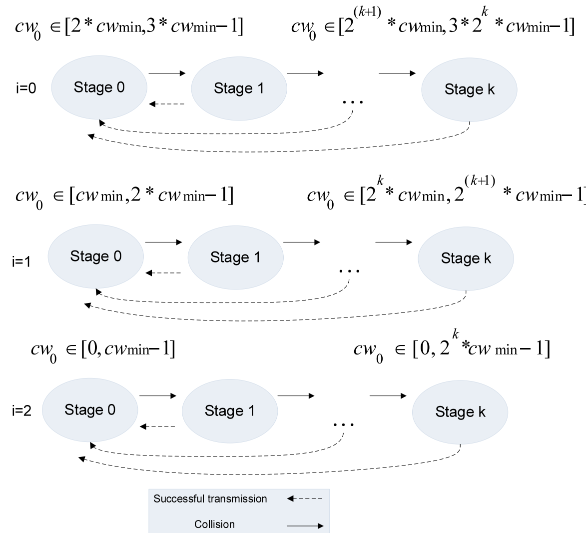


Fig. 2: DCF backoff stages for ACNC–MAC

For example, starting with cw_{min} equal to 32, the backoff values cw_2 of the relays that have received two packets will be chosen randomly in [0, 31]. If a collision occurs among relays, cw_{min} is doubled and the values are selected from the range [0, 63].

C. Operational examples

Having described the basic components of ACNC–MAC, let us now provide two examples that better illustrate its operation for the cases mentioned in Section III–A, considering the network topology of Fig. 1b.

In case 1 (Fig. 3a), relays with zero, one or two packets may exist simultaneously. Their contention windows are cw_0, cw_1 and cw_2, respectively. As the relay(s) with both packets have the shortest backoff value, one of them will gain channel access and transmit the encoded packet, along with ETC. After decoding the XOR-ed packet, the two sources acknowledge the received packets.

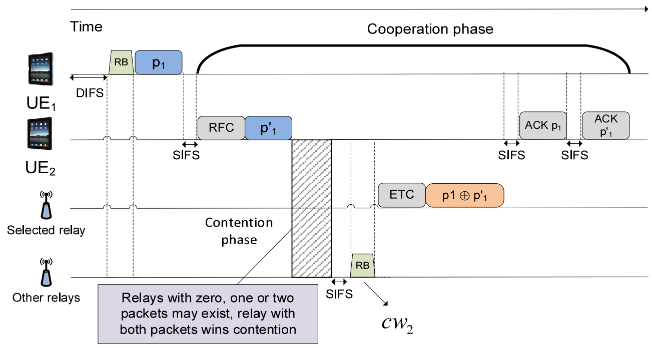
Fig. 3b refers to cases 2 and 3. Each relay has at most one packet (p_1). If both sources transmitted a packet, the packet would be either p_1 or p_1'. If all relays have failed to receive any packet, they enter contention phase with contention window equal to cw_0. The winner sends an ETC frame only. The relays that have decoded the packet use a cw_1 contention window, while the rest of them that have not decoded any packet use a cw_0 contention window. The winner relay transmits ETC along with the packet it has received. The cooperation phase ends upon the reception of one ACK frame.

IV. SATURATION THROUGHPUT ANALYSIS

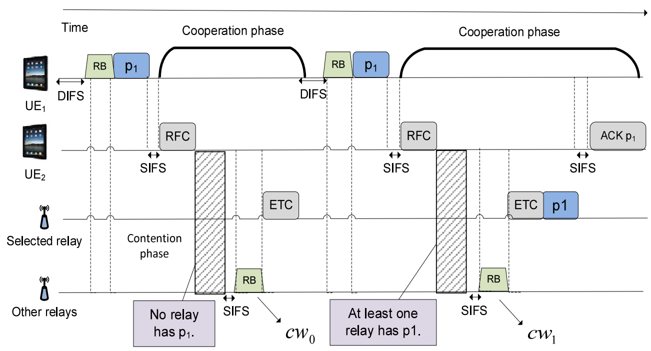
In this section, we present the analysis for the saturation throughput of ACNC–MAC. In saturated conditions, both sources transmit a packet at each round. The network throughput can be defined as the ratio of the expected successfully delivered payload bits $\mathbf{E}[P]$ and the average time for a packet to be delivered to the destination $\overline{T}_{total}$:

$$\overline{S} = \frac{\mathbf{E}[P]}{\overline{T}_{total}}. \quad (2)$$

The average packet payload $\mathbf{E}[P]$ is a function of the probability P_1 that one packet is successfully delivered at the end of



(a) Case 1: At least one relays has received two packets



(b) Case 2: Relays have received maximum one packet

Fig. 3: ACNC–MAC operation examples

cooperation and the probability P_2 that packets of both sources are successfully received:

$$\mathbf{E}[P] = P_1 s + 2P_2 s, \tag{3}$$

where s is the payload size. The total time required for the successful reception of two source packets is defined as:

$$\overline{T}_{total} = \overline{T}_2 P_2 + \overline{T}_1 P_1 + \overline{T}_0 P_0. \tag{4}$$

The term $\overline{T}_{total}$ is the weighted sum of three delay values that are related to cooperation phases with different outcomes.

The weights P_2, P_1 and P_0 are the probabilities of the different numbers of packets acknowledged at the end of cooperation and refer to the three cases mentioned in Section III-A. P_2 is the probability that two packets are successfully received. This case occurs when at least one relay receives two packets and can encode them together. Letting $P_{e,(UE_1 \leftrightarrow r)}$ and $P_{e,(UE_2 \leftrightarrow r)}$ be the packet error probabilities in the D2D links $\forall r \in \mathbf{R}$, the probability that a relay r correctly receives both packets is given by $P_{r,2} = (1 - P_{e,(UE_1 \leftrightarrow r)})(1 - P_{e,(UE_2 \leftrightarrow r)})$. If at least one relay decodes both source packets and can perform NC, the cooperation phase ends with the reception of two ACK frames. Therefore, the probability P_2 can be calculated as:

$$P_2 = 1 - \prod_{r=1}^{R} (1 - (1 - P_{r,2})). \tag{5}$$

The case that one packet is received by one of the two sources occurs with probability P_1. At least one of the relays receives one of the two source packets and the cooperation terminates with the reception of one ACK frame. The probability that a relay r correctly receives exactly one packet is given by $P_{r,1} = (1 - P_{e,(UE_1 \leftrightarrow r)}) + (1 - P_{e,(UE_2 \leftrightarrow r)}) - 2(1 - P_{e,(UE_1 \leftrightarrow r)})(1 - P_{e,(UE_2 \leftrightarrow r)})$. Thus, P_1 can be derived by:

$$P_1 = \left[1 - \prod_{r=1}^{R} (1 - P_{r,1})\right] \prod_{r=1}^{R} (1 - P_{r,2}). \tag{6}$$

P_0 is the probability that no packet is received by any source finally. This event occurs when none of the relays receives any packets. As the probability that a relay r fails to receive both packets is equal to $P_{e,(UE_1 \leftrightarrow r)} P_{e,(UE_2 \leftrightarrow r)}$, the probability that all the relays do not receive any packet is the probability that no packet is acknowledged at the end of cooperation and can be expressed as:

$$P_0 = \prod_{r=1}^{R} P_{e,(UE_1 \leftrightarrow r)} \prod_{r=1}^{R} P_{e,(UE_2 \leftrightarrow r)}. \tag{7}$$

The aforementioned probabilities are associated with the delay values $\overline{T}_2$, $\overline{T}_1$ and $\overline{T}_0$. $\overline{T}_2$ is the average time required for the successful reception of two packets and $\overline{T}_1$ is the average time required for the successful reception of only one packet. The term $\overline{T}_0$ is the average delay of a cooperation phase that does not deliver any packet, since the relays have failed to receive any of the transmitted packets. Each of these terms comprises of two components: the minimum average delay in case of perfect synchronization of relays (contention–free cooperation phase) and the additional delay induced by the contention of the relays during the cooperation phase. These values differentiate according to the number of packets the relay transmits. Under these considerations, the average delay induced in a cooperation phase that ends with i ACK frames, $i \in \{0, 1, 2\}$, is:

$$\overline{T}_i = \overline{T}_{i,min} + \overline{T}_{i,cont}. \tag{8}$$

When no packet is acknowledged, namely $i = 0$, the minimum average delay is:

$$\begin{aligned} \overline{T}_{0,min} = {} & DIFS + T_{p_1} + T_{RFC} + T_{p'_1} + SIFS \\ & + T_{ETC} + 2SIFS + \mathbf{E}[r](SIFS + T_{ETC}). \end{aligned} \tag{9}$$

Similarly, for the case that one packet only is acknowledged, $i = 1$, the minimum average delay of contention–free cooperation phase is:

$$\begin{aligned} \overline{T}_{1,min} = {} & DIFS + T_{p_1} + T_{RFC} + T_{p'_1} + SIFS \\ & + T_{ETC} + 2SIFS + T_{ACK} + \mathbf{E}[r](SIFS + T_{ETC} + T_{p_1}). \end{aligned} \tag{10}$$

When both sources receive their desired packets the minimum average delay of the cooperation phase is equal to:

$$\begin{aligned} \overline{T}_{2,min} = {} & DIFS + T_{p_1} + T_{RFC} + T_{p'_1} + SIFS + T_{ETC} \\ & + 2SIFS + 2T_{ACK} + \mathbf{E}[r](SIFS + T_{ETC} + T_{p_1 \oplus p'_1}). \end{aligned} \tag{11}$$

The average delay of a cooperation phase includes also the term $\overline{T}_{i,cont}$, which refers to the delay due to relays contention and is expressed as:

$$\overline{T}_{i,cont} = \mathbf{E}[r] \overline{T}_{c,i}, \; i \in \{0, 1, 2\}, \tag{12}$$

Parameter	Value	Parameter	Value
Payload size	1500 bytes	MAC header	34 bytes
PHY header	96 μs	$cw_{\min}$	32
RFC	14 bytes	ETC	16 bytes
ACK	14 bytes	time slot	10 μs
SIFS	10 μs	DIFS	50 μs
Queue length	100	Simulation time	10 s
λ	[100-2500]	$PER_{(UE_1 \leftrightarrow UE_2)}$	1
$PER_{(UE_1 \leftrightarrow r)}$	[0-0.9]	$PER_{(UE_2 \leftrightarrow r)}$	[0-0.9]

TABLE I: Simulation parameters

where $\mathbf{E}[r]$ is the expected number of retransmissions, directly related with $PER_{(UE_1 \leftrightarrow r)}$ and $PER_{(UE_2 \leftrightarrow r)}$ [13]. The term $\overline{T}_{c,i}$ corresponds to the average time required to transmit packets during the contention phase among the relays and obtains a different value for each i, given that the number of packets a relay receives varies. Furthermore, the average backoff times selected by the relays from different ranges, according to the number of packets i they wish to transmit, changes as well. They can be estimated using the backoff counter model described in [9].

V. Performance Evaluation

In this section, we validate the analytical model in saturated conditions and we assess the performance of the proposed protocol in different scenarios. An event–driven C++ simulator has been developed that applies the rules of ACNC–MAC using the settings described in Section V-A. The simulation results are discussed in Section V-B.

A. Simulation Setup

We consider the topology of Fig. 1b with $n = 5$ and simulate the bidirectional communication of the two active UEs, UE_1 and UE_2, aided by 5 adjacent and initially idle UEs that can be used as relays. It is assumed that $PER_{(UE_1 \leftrightarrow r)} = PER_{(UE_2 \leftrightarrow r)}$ and the UEs generate packets according to a Poisson traffic model with the same intensity λ. It is assumed that $PER_{(UE_1 \leftrightarrow UE_2)} = 1$, thus a cooperation phase is always initiated. The power level of transmission state P_T is set to 1900 mW, while for reception and idle states it is $P_R = P_I$ =1340 mW. The control frames RFC, ETC and ACK are transmitted at the rate of 6 Mb/s. Two data rate scenarios are tested, using the simulation parameters and settings of Table I. The transmission rates for the active UEs are $R_{s,r} = \{6, 54\}$ Mb/s for low and high data rate scenario, respectively, while the relays transmit in both scenarios at a constant rate $R_{r,s} = 54$ Mb/s.

For the evaluation of our MAC scheme, we compare it with a version of NCCARQ–MAC [9], modified to operate under non–saturated conditions. Upon the erroneous reception of a packet, the destination UE will send an RFC frame along with its own packet, if its queue is not empty. The relays begin contention only when they have received packets from both UEs and can perform NC.

ACNC–MAC and NCCARQ–MAC were tested in two cases: (a) in saturated conditions with variable PERs for both links and (b) using different Poisson traffic values $\lambda \in [100, 2500]$. The performance of both schemes is evaluated in terms of the aggregated network throughput and the energy efficiency metric η [14].

B. Simulation Results

Figure 4(a) shows the throughput performance for the first test case with regard to different PERs considering two different data rate scenarios. As observed, the simulation and theoretical results for throughput performance match, thus verifying the proposed throughput analysis for saturated conditions. ACNC–MAC achieves better performance than NCCARQ–MAC, as it better exploits cooperation opportunities by serving at least one packet per communication round. For PERs in [0, 0.5], ACNC–MAC achieves an improvement up to 71% and 73% in low and high data rate scenario, respectively.

In Fig. 4(b), the energy performance in the first test case is depicted. It is obvious that the energy efficiency curves are similar to throughput curves, as expected. As PER increases, more retransmissions are required in order to correctly deliver each packet, thus the energy efficiency for each successful packet transmission reduces. ACNC–MAC performs better than NCCARQ–MAC in both data rate scenarios for all PER values. More useful bits are delivered under the same energy consumption, as ACNC–MAC allows for relays retransmissions, even when NC is not possible. In each cooperation round of NCCARQ–MAC, either two packets are delivered or none. The gain of ACNC–MAC is higher when high data rates are used, reaching a 71% increase for PER=0.3.

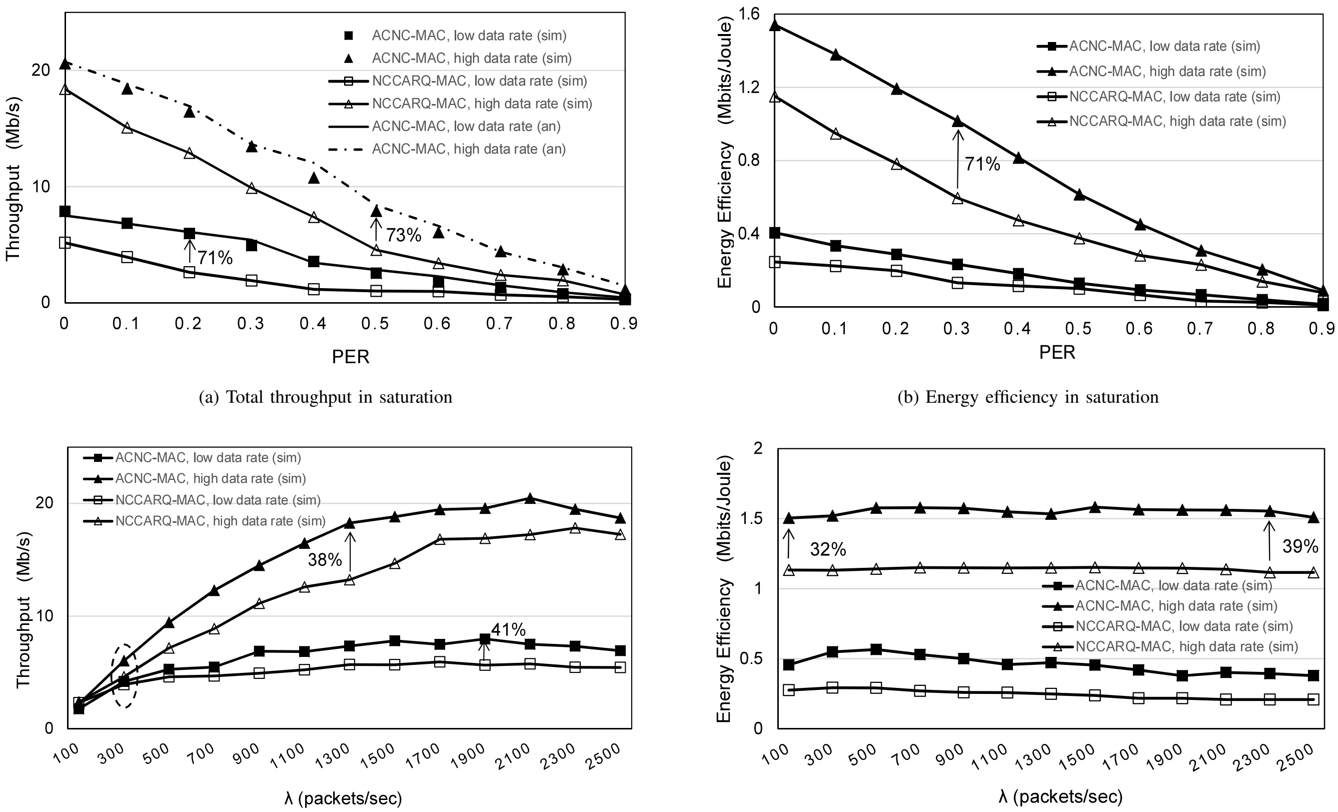
In Fig. 4(c), the throughput performance for the second test case is presented. For lower traffic intensity, namely $\lambda < 300$, the gains of NC are not fully exploited, due to scarce packet arrivals. Instead, as traffic in source increases, NC possibility becomes higher leading to a throughput increase. ACNC–MAC achieves throughput gains up to 41% in low rate scenario and up to 38% in high rate scenario, for λ in [900, 2300].

Figure 4(d) shows the performance in terms of energy efficiency for the second test case. Notably, for ACNC–MAC the energy efficiency is higher than NCCARQ–MAC in both data rate scenarios. For high data rate the energy energy efficiency is $32 - 39\%$ higher, when ACNC–MAC is used. As for the low rate scenario, both schemes' energy efficiency deteriorates. Still, with ACNC–MAC the energy efficiency is almost doubled comparing to NCCARQ–MAC.

It is also worth pointing out that throughput and energy efficiency plots exhibit a similar behavior in case of saturated conditions, whereas they differentiate when varied traffic values are used. Moreover, as traffic intensity increases, the energy efficiency remains at the same levels. These observations can be explained by the fact that, for small λ, fewer packets are delivered and more idle slots exist, while for higher λ more packets are delivered but the energy efficiency is similar, since less idle slots exist but more packet receptions occur, given that $P_R = P_I$.

VI. Conclusions

In this paper, a new NC–based cooperative MAC protocol (ACNC–MAC) for outband D2D communication has been presented. ACNC–MAC allows the exploitation of idle UEs with the aim of helping the bidirectional communication of neighboring UEs. The conducted simulations have illustrated that ACNC–MAC is beneficial in terms of both throughput and energy efficiency, mainly in saturation and high traffic cases and particularly when high data rates are used. In our future work, we plan to design analytical models for the non-saturation case and study the impact of the cellular links on the D2D communication.



(a) Total throughput in saturation

(b) Energy efficiency in saturation

(c) Total throughput for various λ and PER=0

(d) Energy efficiency for various λ and PER=0

Fig. 4: ACNC–MAC performance results

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