Energy Efficient Network Coding-based Cooperative ARQ Scheme for Wireless Networks

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Abstract. In this paper we present an energy consumption model for a network coding-based cooperative ARQ (Automatic Repeat reQuest) scheme for wireless networks. Applying network coding techniques, we achieve a significant enhancement in the energy efficiency of the network without compromising the Quality of Service in terms of throughput and packet delay. In order to evaluate the proposed solution, we compare our protocol with simple cooperative ARQ protocols, where the retransmissions take place via relays without any network coding capabilities. Finally, both analytical and simulation results are used in order to verify our conclusions.

Keywords: Network Coding, Cooperative Networks, Automatic Repeat reQuest (ARQ), Energy Efficiency.

1 Introduction

Last years there is a trend towards designing energy efficient protocols, since power consumption is one of the most critical issues in mobile communications. The purpose of these new protocols is twofold: i) to extend the battery's life in the portable devices and ii) to efficiently use the environment's natural resources. Therefore, "green"[1] communications have become one of the hottest topics in the research community.

Network Coding [1],[2] is a technique that has been introduced in order to benefit the wireless communication in terms of throughput. However, minimizing the total number of transmissions, inherently implies savings in the energy consumption. The impact of network coding in "green" communications has been already studied in the literature, especially in broadcast and multi-cast scenarios [3]-[6].

The recent research work that investigates the energy aspect of network coding applications, focuses mostly on the network layer. In [7], an algorithm that generates a multipath route is presented. The simulation results confirm that

[1] "Green" refers to all environment-aware methods.

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the energy consumption is lower compared to traditional simple path routes. Cui et al. [8] introduce CORP by using a suboptimal scheduling algorithm that exploits network coding opportunities, thus achieving a significant power saving over pure routing.

Towards this direction, and since network coding affects the MAC layer of the network as well, this paper presents an energy consumption model for a network coding-based scheme designed for cooperative wireless networks. Our main objective is to investigate the energy efficiency of network coding-based protocols and determine key ideas in order to optimize the design of such schemes, without degrading the provided Quality of Service (QoS).

The rest of the paper is organized as follows. Section 2 briefly describes the network coding-based cooperative ARQ (NCC-ARQ) scheme. In Section 3 we present our proposed energy consumption model for NCC-ARQ. The simulation set up and the results (both numerical and simulation) are provided in Section 4. Finally, Section 5 concludes the paper.

2 Network Coding-based Cooperative ARQ Scheme

2.1 Introduction

NCC-ARQ [9] is one of the fundamental works that implement network coding in cooperative ARQ schemes. In our previous work, it has been shown that NCC-ARQ improves the total throughput of the system, while at the same time the average packet delay is reduced. In this section we will briefly review the basic aspects of the protocol in order to make the paper self-standing and facilitate the comprehension of our proposed energy consumption model.

2.2 Protocol Description

When NCC-ARQ is applied in the network, all the nodes should operate in promiscuous mode in order to be able to capture all ongoing transmissions and cooperate if required. In addition, they should keep a copy of any received data packet (regardless of its destination address) until it is acknowledged by the destination station.

Whenever a data packet is received with errors at the destination node, a cooperation phase can be initiated. The error control could be performed by checking a cyclic redundancy code (CRC) attached to the header of the packet or any other equivalent mechanism. The cooperation phase is initiated by the destination station by transmitting a Call for Cooperation (CFC) message to the best relay in terms of channel conditions (i.e. SINR) after sensing the channel idle for a Short Interframe Space (SIFS) period. This message has the form of a control packet and higher priority over regular data traffic, since data transmissions in IEEE 802.11 take place after a longer period of silence (DIFS). Furthermore, in the special but not rare case of bidirectional traffic, when the destination station has a data packet for the source station, it transmits this packet piggybacked with the CFC message.

Upon the reception of the CFC, the helper node gets ready to forward its information. Since the relay has already stored the packets that destined both to the destination (the cooperative packet) and to the source (the piggybacked packet), it creates a new coded packet by combining the two existing data packets, using the XOR method. In this point we have to state that NCC-ARQ is backwards compatible with IEEE 802.11 Standard, as it uses the same frame structure and follows the same principles with the standard. However, there have been some modifications that are necessary in order for the protocol to exploit efficiently the advantages of using both cooperative and network coding techniques:

1. There is no expected ACK packet associated to each transmitted packet that is sent piggybacked with the CFC message.
2. In case of bidirectional traffic, the packet that is destined back to the source is sent along with the Call for Cooperation packet, without taking part in the contention phase.
3. There are ACK packets for the multicast transmission of the coded packet in order to provide a reliable communication scheme.

Once the source and the destination receive the network coded packet from the relay, they are able to decode it and extract the respective original data packets. Subsequently, they acknowledge the received data packet by transmitting the respective ACK, thus terminating the cooperation phase. In case that the received coded packets can not be decoded after a certain maximum cooperation timeout due to transmission errors, the relay is obliged to forward again the network coded packet. Figure 1 graphically demonstrates the general idea of our proposed NCC-ARQ scheme.

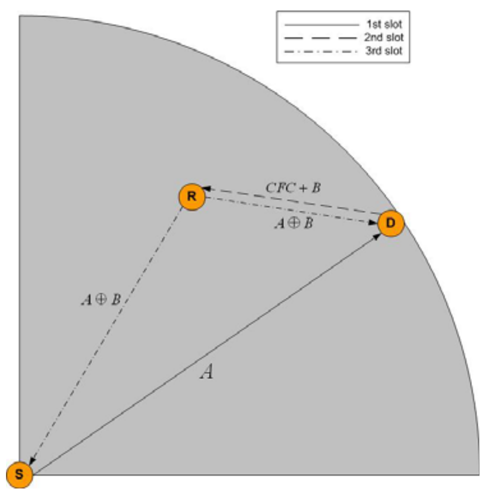

Fig. 1. General idea of NCC-ARQ scheme

2.3 Operational Example

In this subsection we provide a simple example in order to clarify the operation of the protocol. A basic network topology with 3 stations is considered, all of them in the transmission range of each other. A source station (S) transmits a data packet (A) to a destination station (D) that has also a packet (B) destined to the source station. There is also one relay (R) that has been chosen as the most appropriate helper node in terms of Signal to Interference-Noise Ratio (SINR) and supports this particular bidirectional communication. The whole procedure is depicted in Figure 2 and explained as follows:

1. At instant t_1, station S wins the contention phase and sends the data packet A to station D.
2. Upon reception, at instant t_2, station D fails to demodulate the packet A, thus transmitting a CFC packet to R along with the data packet B, destined to the station S.
3. At instant t_3, the relay R transmits the coded packet $A \oplus B$ to the nodes S and D simultaneously.
4. At instant t_4 the station D sends back an ACK packet since it is able to decode properly the XOR-ed packet and retrieve the original packet A.
5. At instant t_5 the node S acknowledges the packet B since it is able to decode properly the coded packet $A \oplus B$.

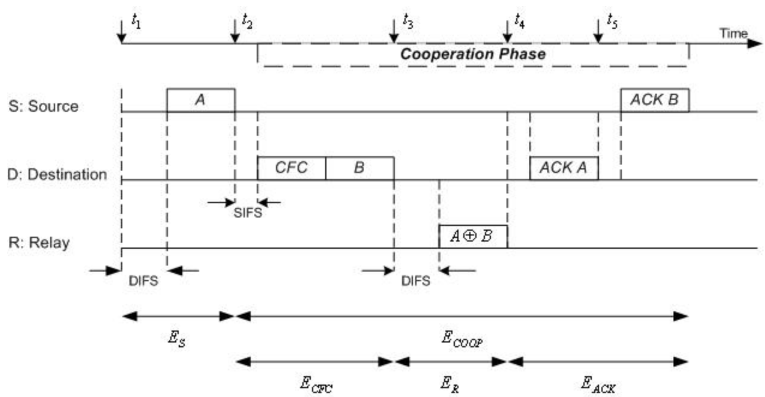

Fig. 2. NCC-ARQ example of operation

3 Energy Consumption Model

As we have already mentioned, the formed network consists of three nodes: the source, the destination and the relay. Considering the operation of NCC-ARQ protocol, we derive a closed-form expression that describes the power consumption in the network:

$$E_{TOTAL} = E_S + E_{COOP} \tag{1}$$

where E_S and E_{COOP} are the energy consumptions during the initial transmission from the source and the cooperative phase, respectively. The term E_{COOP} could be further expressed as:

$$E_{COOP} = E_{CFC} + E[r] \cdot E_R + E_{ACK} \tag{2}$$

where E_{CFC} represents the energy consumption during the beginning of the cooperation, E_R is the energy waste during the relay's transmission, while E_{ACK} is the energy that is consumed during the transmission of the acknowledgement (ACK) packets. The energy consumption during the particular time intervals is graphically demonstrated in Figure 2. $E[r]$ is the average number of the retransmissions that are required in order to properly decode the X-OR packets at the destination nodes. It depends on the channel conditions and specifically on the packet error rate (PER) between the relay and the destination nodes. Lower values of PER imply higher probability for successful decoding of the packets at the destination nodes. This relationship could be mathematically expressed as:

$$E[r] = 1/(1 - PER_{R \to D}) \tag{3}$$

In order to clarify the equation (1), we try to compute each term analytically. We consider three different modes:

1. **Transmission mode**, when the node is transmitting data/control packets
2. **Reception mode**, when the node is receiving data/control packets
3. **Idle mode**, when the node is sensing the medium, without performing any action.

The power levels associated to each mode are P_T, P_R and P_I respectively. Furthermore, the relationship between energy and power is given by $E = P \cdot T$, where the terms E, P and T represent the energy, the power and the time, respectively. Therefore, considering the network's topology, we have:

$$E_S = 3 \cdot P_I \cdot T_{DIFS} + P_T \cdot T_A + 2 \cdot P_R \cdot T_A \tag{4}$$

$$E_{CFC} = 3 \cdot P_I \cdot T_{SIFS} + P_T \cdot T_{CFC} + 2 \cdot P_R \cdot T_{CFC} + P_T \cdot T_B + 2 \cdot P_R \cdot T_B \tag{5}$$

$$E_R = 3 \cdot P_I \cdot T_{DIFS} + P_T \cdot T_{A \oplus B} + 2 \cdot P_R \cdot T_{A \oplus B} \tag{6}$$

$$E_{ACK} = 2 \cdot 3 \cdot P_I \cdot T_{SIFS} + 2 \cdot P_T \cdot T_{ACK} + 2 \cdot 2 \cdot P_R \cdot T_{ACK} \tag{7}$$

The above equations (4)-(7) are based on the following ideas:

- All stations remain idle during the SIFS and DIFS times.
- When a station transmits a packet (control or data), the rest stations are in promiscuous mode, thus capturing the packets.

4 Performance Results

In order to evaluate the performance of the NCC-ARQ we have developed an event-driven C++ simulator that executes the rules of the protocol. In this section we present the simulation set up and results of our experiments.

4.1 Simulation Scenario

We simulate an 802.11g network formed by a pair of transmitter-receiver (the two nodes are both transmitting and receiving data) and a relay node that facilitates the communication, all of them in the transmission range of each other. Furthermore, the relay node is able to perform network coding to its buffered packets before relaying them. In order to focus the analysis of the impact of both network coding and cooperative communication on energy consumption, the following assumptions have been made:

1. The traffic is bidirectional, i.e. the destination node has always a packet destined back to the source node.
2. Original transmissions from source to destination are always received with errors, thus initiating a cooperative phase.
3. The packet error rate (PER) - and consequently the required number of retransmissions that have to be made by the relay until the packets received correctly - is known in advance.

The configuration parameters of the stations in the network are summarized in Table 1 considering the IEEE 802.11g PHY layer [10]. Ebert et al. [11] have measured the power consumption of a wireless interface during the transmission and reception phase. Based on their work, we have chosen the following power levels for our scenarios: $P_T = 1900mW$, $P_R = P_I = 1340mW$. The value of P_T has been selected as an average value of transmission consumed power, since it varies according to the Radio Frequency (RF) power level.

Table 1. System Parameters

Parameter	**Value**	**Parameter**	**Value**
MAC Header	34 bytes	*PHY Header*	96 μsec
DIFS	50 μsec	*SIFS*	10 μsec
CFC, ACK	14 bytes	P_T	1900 mW
P_R	1340 mW	P_I	1340 mW

In order to evaluate the energy performance of our proposed solution, we consider various scenarios with different SNR values between the original source and the destination. The control packets are transmitted always at the rate of 6 Mb/s, while the transmission rate for the data packets is 6, 24 and 54 Mb/s for low, medium and high SNR values, respectively. On the other hand, given that the relays are usually placed close to the destination, we assume that the transmission rates for all scenarios are 6 and 54 Mb/s for control and data packets, respectively. The three different scenarios are summarized in Table 2. Furthermore, the network operates under saturated conditions, which means that the nodes have always packets to send in their buffers.

Table 2. Simulation Scenarios

SNR (S-D)	**Source Control Rate**	**Source Data Rate**	**Relay Control Rate**	**Relay Data Rate**
Low	6Mb/s	6Mb/s	6Mb/s	54Mb/s
Medium	6Mb/s	24Mb/s	6Mb/s	54Mb/s
High	6Mb/s	54Mb/s	6Mb/s	54Mb/s

In this point, we have to describe the transmission procedure in simple cooperative schemes (C-ARQ), where the bidirectional communication takes place in two steps. In the first step, node S sends the packet to D and, upon the erroneous reception, D transmits the CFC packet, thus triggering the relay to retransmit the packet. In the second step, node D transmits its own packet to S and the same procedure as in the first step is repeated, thus consuming valuable network resources.

In order to evaluate the performance of NCC-ARQ compared to simple cooperative schemes in terms of energy, we use as metric the energy efficiency of a protocol, which was introduced in [12]. The energy efficiency (denoted by η) is defined as:

$$\eta = \frac{total\ amount\ of\ useful\ data\ delivered\ (bits)}{total\ enery\ consumed\ (Joule)} \tag{8}$$

Before proceeding to the simulation results, it is worth mentioning that the definition in equation (8) inherently implies that network coding benefits the energy efficiency of a protocol, as the number of the delivered bits increases by combining different data packets.

4.2 Simulation Results

As it has been already mentioned, it is of paramount importance to save energy without decreasing the performance of the network. The simulation results that are plotted in Figures 3 and 4 show that using our proposed scheme, we are able to enhance the QoS of the network, compared to simple cooperative schemes. Figure 3 depicts the system's aggregated throughput for the three described scenarios in both NCC-ARQ and C-ARQ protocols. We can see that in all cases our proposed solution outperforms the simple cooperative ARQ scheme, since the throughput is greatly increased. On the other hand, regarding the packet delay, we notice that using the NCC-ARQ scheme, the total packet delay is decreased, as it is shown in Figure 4.

Figures 5 and 6 show that our analysis verifies the simulation results with regard to the energy performance. Comparing our proposed network coding-based scheme with simple cooperative protocols for different number of retransmissions (and consequently different PER between the relay and the destinations), we observe that our scheme is more energy efficient than non-network-coding-based schemes, since more bits are delivered over the same amount of consumed energy. Keeping constant the data packet length (1500 bytes), the energy efficiency of NCC-ARQ is decreased as the number of relay retransmissions grows. However, the difference with simple cooperative schemes remains steadily over 80% (Figure 5).

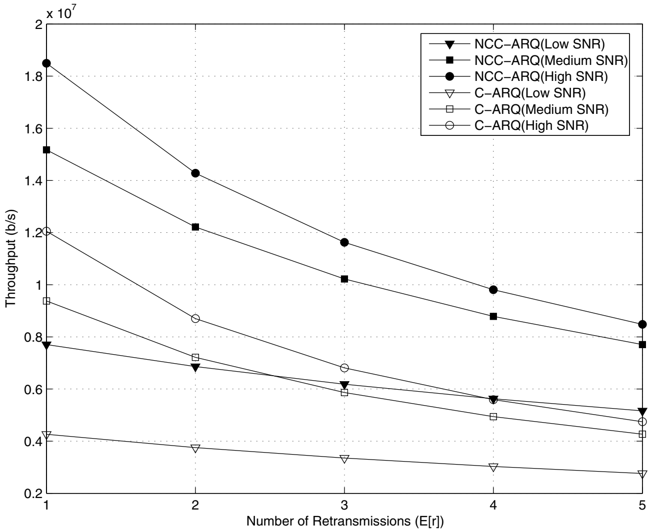

Fig. 3. System's Throughput (NCC-ARQ vs C-ARQ) (Packet Payload=1500 bytes)

Specifically, we can observe that NCC-ARQ outperforms the classic cooperative ARQ schemes under the same conditions (i.e. when both schemes operate under similar SNR values). However, it is worth noticing that NCC-ARQ outperforms C-ARQ even for worse SNR scenarios. To make it clear, observing the energy performance of the NCC-ARQ for the *medium SNR scenario* we can see that it clearly outperforms the C-ARQ under the *high SNR scenario*. Furthermore, comparing the *low SNR scenario* for NCC-ARQ with the *medium SNR scenario* for C-ARQ, we see that NCC-ARQ acts more efficiently in terms of energy when the channel conditions between the relay and the destinations are not good (i.e. when the packets need to be retransmitted three or more times).

Figure 6 shows the energy efficiency for both network coding-based and simple cooperative ARQ schemes using data packets of different size. The simulations have been conducted considering the *low SNR scenario* (i.e. low data rate between the source and the destination). In all cases we consider that one retransmission is needed ($E[r] = 1$) in order for the packets to be correctly received by the respective destinations. As it was expected, it can be observed that the bigger the data payload, the higher the energy efficiency of the protocol (up to 70%), since more bits are delivered in one transmission cycle. However, it has to be pointed that the gain we get in case of NCC-ARQ is significantly higher than the other schemes, since the delivered bytes in each transmission cycle are doubled because of the network coding techniques. It is also worth noticing that

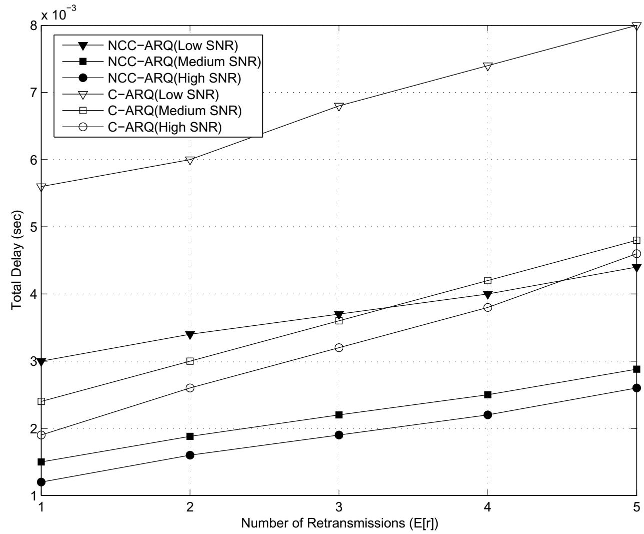

Fig. 4. Packet Delay (NCC-ARQ vs C-ARQ) (Packet Payload=1500 bytes)

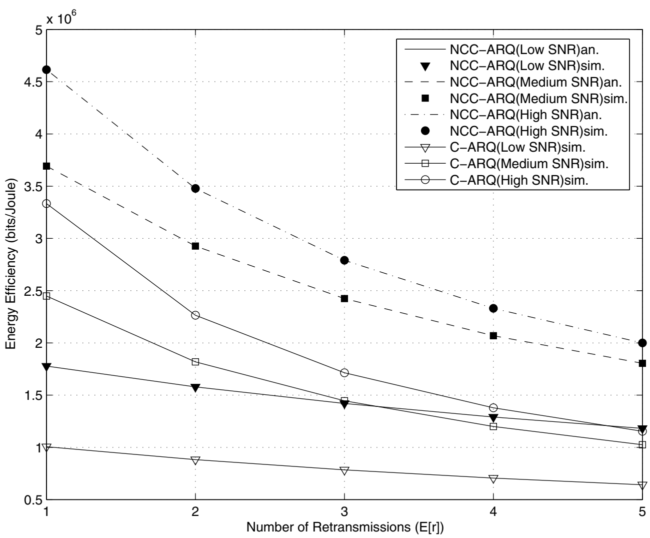

Fig. 5. Energy Efficiency vs Number of Retransmissions (NCC-ARQ vs C-ARQ) (Packet Payload=1500 bytes)

our protocol outperforms simple cooperative protocols in all cases, thus proving a better and more efficient approach in terms of energy management.

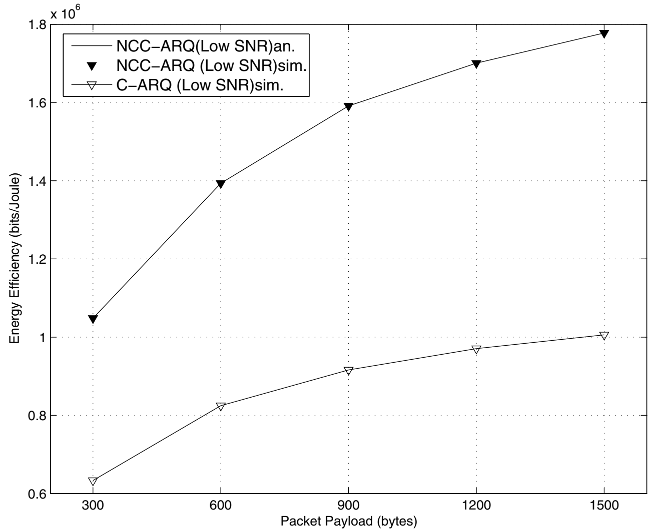

Fig. 6. Energy Efficiency vs Packet Payload (NCC-ARQ vs C-ARQ) (E[r]=1)

5 Conclusion

In this paper, an energy consumption model for a network coding-based cooperative ARQ (NCC-ARQ) scheme is presented. Compared to simple cooperative schemes, our protocol achieves significant enhancement in terms of power consumption, since it has been proven to be up to 80% more energy efficient, without degrading the offered Quality of Service.

Furthermore, we have shown that the energy efficiency is decreased with respect to the number of retransmissions, while we achieve better results by using bigger data packets. In order to optimize the energy management in the network, MAC schemes have to be combined with energy-aware routing solutions, while sleep mode for inactive nodes should be considered as an extra option. Our future research will be focused on such issues.

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