

Bit per Joule Achievable Rate of Cooperative Sensor Networks with Hybrid ARQ

Stefano Tomasin

Department of Information Engineering
University of Padova
via Gradenigo 6/B, 35131 Padova, Italy
e-mail: tomasin@dei.unipd.it

Abstract—Cooperation in wireless networks has been recently considered as a technique to increase the network throughput. However, for sensor networks with limited available energy, this benefit may come at the expense of a increased energy consumption due to the simultaneous transmission by many nodes. In this paper we consider the bit per Joule achievable rate (AR) as a performance measure of a cooperative wireless network, i.e. the bits transmitted per unit energy consumed by the entire network. For a network using carrier sense multiple access (CSMA) and hybrid automatic repeat request (HARQ) as error correction mechanism, we evaluate the bit per Joule AR for different cooperation configurations. The analysis includes the effects of path-loss and Rayleigh fading while as cooperative schemes we consider decode and forward, distributed space time coding and multiplexing coding.

I. INTRODUCTION

Cooperation among nodes of a wireless network, in the form of relaying or more elaborate distributed space-time coding, has been shown to achieve both multiplexing and diversity gain. Initial works on cooperation and relaying have been focused on exploring alternative techniques, such as amplify and forward (AF), decode and forward (DF) and compress and forward [1]–[3].

Integration of cooperation with hybrid automatic repeat request (HARQ) provides multiple retransmissions by the cooperator in the case of decoding failure at the destination. Similarly to cooperative HARQ, in coded cooperation retransmissions are limited to two. In [4] coded cooperation is investigated for multiple relays operating over orthogonal time slots for DF and AF, showing that a significant improvement of the energy-latency tradeoff is achieved when compared with conventional multihop protocols. The opportunistic selection of the relay with the best instantaneous link to the destination has been considered in [5]. Capacity bounds and power allocation for a wireless relay network with three nodes having transmit channel state information are derived in [6]. The diversity-multiplexing tradeoff of a relay network with a single relay and HARQ is derived in [7]. The outage probability of an HARQ cooperative protocol has been derived in [8], under the hypothesis of nodes operating on a single band in half-duplex mode with non orthogonal transmission. In this case, retransmissions by both relays and the source contain different redundancy bits relative to the same data packet.

Most literature has been focused on computing capacity

or throughput for cooperative networks. Still, when sensor networks are considered, other factors beyond throughput must be considered, in particular with respect to the energy constraints imposed by batteries and their duration. In [9] the minimization of energy consumption for a cooperative wireless sensor network is considered as the target for the optimization of modulation and transmission strategies, under suitable constraints on throughput and delay. It is shown that with cooperation a tremendous energy saving is possible for transmission distances larger than a given threshold and in some cases, cooperation provides both an energy saving and a delay reduction. In [10], power allocation is proposed to improve the efficiency of transmission while preserving energy.

In this paper we aim at comparing different cooperation strategies on a wireless sensor network in terms of bit per Joule achievable rate (AR), i.e. the maximum number of bits that a node can deliver for a unitary energy consumed by all nodes involved in the cooperation. The bit per Joule AR allows to compare different configurations where a variable number of nodes is active, each having an independent power constraint. It has been first introduced in [11] to evaluate the capacity of energy limited wireless networks, and is applied here to a HARQ cooperative network. Note that the bit per Joule ARQ does not account for circuitry energy consumption, while this could be a significant part of the overall energy expenditure for sensor networks.

We consider a network of half-duplex sensor nodes accessing the channel with carrier sense multiple access (CSMA) technique, thus avoiding interference. Beyond DF, we consider the use of randomized space-time codes for cooperation. While for the sake of clarity we consider Alamouti codes with two cooperators, the derivations can be easily extended to more elaborate systems comprising many relays, e.g. using the distributed space time block codes recently proposed in [12]. The outage probability of the distributed Alamouti code is evaluated for a system using HARQ for given nodes positions. In our HARQ scheme, the retransmissions relative to the same data packet may have different durations, thus implementing an efficient coding scheme with the rate adapted to channel conditions. In order to reduce implementation complexity we consider only two fixed durations, one for the the first transmission and the second for all forthcoming transmissions.

We then compare the Alamouti approach with both the DF technique, where at most one node is transmitting at any given time, and the multiplexing technique [8], where the relay retransmits together with the source and partially interferes with it. Opportunistic cooperator selection based on node distance [4] is also included in the analysis. The rest of the paper is organized as follows. We first introduce the system model in Section II, comprising the different cooperation schemes whose bit per Joule AR will be compared in Section III. Section IV shows some numerical results, using the bit per Joule AR as performance metric. Lastly, conclusions are outlined in Section V.

II. SYSTEM MODEL

We consider a sensor network where all nodes attempt to communicate to a common gateway node. To this end, a cooperative technique together with HARQ is employed by each node.

The transmission from each sensor to the gateway is affected by a) Rayleigh fading and b) path loss. Each sensor transmits at a fixed power which is attenuated by a factor d^κ in reaching a node at distance d , where κ is path-loss exponent. Due to Rayleigh fading, the received power for a given distance d is exponentially distributed. For quasi-static nodes, the channel does not change for the entire transmission of a packet. Although we consider frequency flat fading channels, extension to frequency selective fading can be obtained with the use of orthogonal frequency division multiplexing (OFDM), which is left for future investigation.

Interference among nodes is avoided by CSMA, where a node before transmission senses the channel and does not transmit if the channel is busy. Furthermore, we assume that a sensor uses exclusively the channel until the end of the packet transmission.

As in a conventional HARQ protocol, time is divided into frames, each comprising a data and an acknowledgment (ACK) slot. Data packet is first encoded and different portions of the coded packet are transmitted during the various frames. In the data slot, coded data are transmitted by the source sensor S and/or a cooperative sensor C , while in the ACK slot, the correct or wrong reception is reported by the gateway G . After at most $(N_{\max} + 1)$ unsuccessful frames, the packet is discarded. Frames have different durations. Let $\tau(n)$, $n = 0, 1, \dots, N_{\max}$ be the duration of the *data slot* within frame n , while ACK slots have a fixed duration τ_A . Let us also define the normalized (with respect to the duration of the first slot) duration of the first N retransmission frames as

$$\Delta(N) = \frac{1}{\tau(0)} \sum_{n=1}^N \tau(n). \quad (1)$$

Note that $\Delta(N)$ does not include the duration of frame $n = 0$, so that the overall packet duration after N retransmissions is $\tau(0)[1 + \Delta(N)]$.

In the following, for the sake of a simpler notation, we assume that frames after the first retransmission have all

the same duration, i.e. $\tau(n) = \tau$, $n = 1, 2, \dots, N_{\max}$. By adjusting

$$\eta = \frac{\tau}{\tau(0)} \quad (2)$$

we can tune the rate adaptation procedure. Let the normalized (with respect to the duration of the first transmission) duration of retransmissions be

$$\rho = \frac{\tau + \tau_A}{\tau(0)}. \quad (3)$$

A. Cooperative protocol

For each node a fixed cooperator sensor C is selected before frame $n = 0$. This selection may be either random or optimized. For the cooperator choice, we consider either a random selection or an opportunistic selection based on the distance with respect to the gateway, where the selected node minimizes the outage probability (including its probability of detecting the first transmission). In this selection procedure we consider only the distance, as in [4], without considering the instantaneous channel condition, as for example proposed in [5].

Cooperation is implemented as follows. If the selected sensor node C properly detects the first transmission of a packet, it can cooperate by re-encoding the packet and transmitting various sections of the coded packet. In particular, we consider three configurations for cooperation:

- **Decode and forward (DF)**: retransmissions are performed only by sensor C if it decoded the packet correctly, and by sensor S otherwise.
- **Multiplexing cooperation (MUX)**: retransmissions are performed simultaneously by both sensor S and sensor C without any coordination or symbol synchronization, if C decoded the packet correctly, and only by node S otherwise [8]. The MUX configuration benefits from both the retransmission of sensor S and the diversity of sensor C . Still, note that node G receives the superposition of two mutually interfering signals from sensors S and C .
- **Diversity cooperation (DIV)**: retransmissions are performed by both sensor S and sensor C simultaneously, if C decoded the packet correctly, and only by node S otherwise. In this case, simultaneous transmissions are performed by distributed space-time Alamouti code, so that no interference arises, and the receiver can exploit the diversity provided by the spatial transmission.

Figs 1 and 2 show the HARQ protocol operation in the case of successful decoding at the cooperator sensor, for the various considered techniques. In all cases, if the cooperator does not decode the first transmission, only the source sensor performs all HARQ phases.

III. BIT PER JOULE AR

In order to compare the performance of the various cooperation schemes, we consider the bit per Joule AR, defined as the AR normalized with respect to both the available bandwidth and the used energy, thus being measured in bit/J.

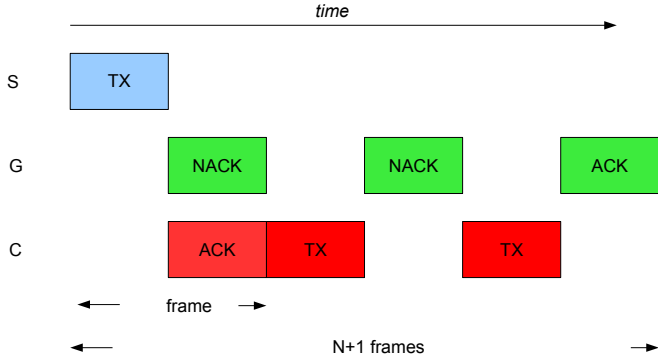


Figure 1. HARQ protocol operation for DF, in the case of successful decoding at the cooperator node.

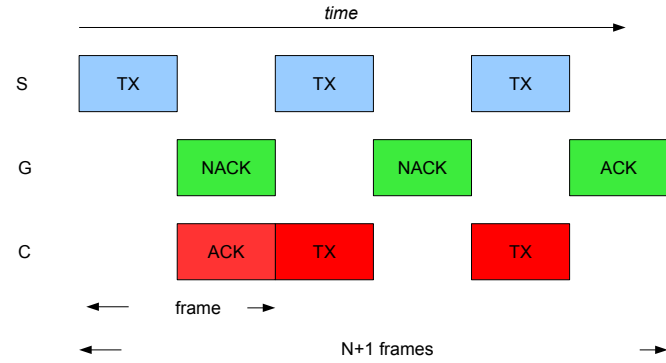


Figure 2. HARQ protocol operation for MUX and DIV, in the case of successful decoding at the cooperator node.

To obtain the bit per Joule AR, we consider the two events of cooperation and no cooperation, i.e. C being able or not to decode the first transmission. The cooperative event is denoted with \mathcal{E} , while the event of non-cooperative transmission is denoted with $\bar{\mathcal{E}}$. Let also $P[\text{succ } N = n|\mathcal{E}]$ be the conditioned average probability of a success transmission in exactly $(n+1)$ frames, provided that C decoded the first transmission. In the case of a non cooperative retransmission, let $P[\text{succ } N = n|\bar{\mathcal{E}}]$ be the conditioned average probability of a success decoding at the gateway in exactly $(n+1)$ frames.

Let β be the bit per Joule AR of the frame $n = 0$ (including both data and ACK slots). The bit per Joule AR of the HARQ protocol averaged over the number of HARQ retransmissions can be written as

$$C_J = \beta \left\{ P[\text{succ}, N = 0] + P[\mathcal{E}] \sum_{n=1}^{N_{\max}} \frac{P[\text{succ}, N = n|\mathcal{E}]}{\delta n \rho} + (1 - P[\mathcal{E}]) \sum_{n=1}^{N_{\max}} \frac{P[\text{succ}, N = n|\bar{\mathcal{E}}]}{n \rho} \right\}, \quad (4)$$

where δ is the number of active nodes in the cooperative retransmissions.

The success probabilities are obtained by the outage prob-

abilities. Let $I_C(n)$, $n = 0, 1, \dots, N_{\max}$, be the average (with respect to fading) outage probability after frame n , conditioned by event \mathcal{E} and for given distances among nodes. For $n > 0$ we obtain

$$P[\text{succ } N = n|\mathcal{E}] = I_C(n-1) - I_C(n). \quad (5)$$

Similarly, by indicating with $I_N(n)$, $n = 0, 1, \dots, N_{\max}$ the outage probability conditioned by event $\bar{\mathcal{E}}$ and for given nodes distances, for $n > 0$ we have

$$P[\text{succ } N = n|\bar{\mathcal{E}}] = I_N(n-1) - I_N(n). \quad (6)$$

For the first transmission we have

$$P[\text{succ } N = 0] = 1 - I_N(0). \quad (7)$$

In the following we derive $I_C(n)$ and $I_N(n)$ for the various cooperation strategies for given nodes distances. To this end, we assume capacity-achieving coding, so that the AR coincides with the Shannon capacity. Furthermore, we assume that node G performs single-user decoding. We indicate with $\gamma_{S,G}(n)$, $\gamma_{C,G}(n)$ and $\gamma_{S,C}(n)$ the signal to noise plus interference ratio (SNIR) at frame n between nodes S and G, nodes C and G, and nodes S and C, respectively, with $n = 0, 1, \dots, N_{\max}$.

Let R be the data bits per unit of frequency [bit/Hz] of the first transmission. In the absence of cooperation,

$$\gamma_{S,G}(n) = \gamma_{S,G}(0), \quad n = 1, 2, \dots, N \quad (8)$$

and we have [8]

$$I_N = P \left[\prod_{n=0}^N (1 + \gamma_{S,G}(0))^{\tau(n)} < 2^R \right] \quad (9)$$

$$I_N = 1 - e^{-\frac{(2^R/(\Delta(N)+1)-1)P_W}{P_0 d_{S,G}^{-\kappa}}},$$

where P_W is the noise power.

On the other hand, the cooperation event i.e. sensor C correctly decodes the first transmission is [8]

$$I_{\mathcal{E}} = P[\mathcal{E}] = P[\tau(0) \log_2(1 + \gamma_{S,C}(0)) \geq R] \quad (10)$$

$$= P \left[(1 + \gamma_{S,C}(0))^{\tau(0)} < 2^R \right]$$

$$= e^{-\frac{(2^R/\tau(0)-1)P_W}{P_0 d_{S,C}^{-\kappa}}},$$

where P_0 is the average received power at unitary distance.

A. Decode and forward

For the DF protocol, only one node is transmitting to G at any time, which may be either node S or node C. In particular, if the gateway G is not able to decode the first transmission, while sensor C has decoded it, node C will perform retransmissions, while node S will not be transmitting. For DF, we have $\delta = 1$ in (4).

Hence, in the case of cooperation, the SNIR of link C-G for $n > 0$ has probability density function (pdf)

$$f_{\gamma_{C,G}(n)}(a) = \frac{P_W}{P_0 d_{C,G}^{-\kappa}} e^{-\frac{P_W a}{P_0 d_{C,G}^{-\kappa}}}. \quad (11)$$

The bit per unit of frequency [bit/Hz] after N frames can be written as

$$R_{\text{DF}}(N) = \tau(0) \log_2[1 + \gamma_{\text{S,G}}(0)] + \sum_{n=1}^N \tau(n) \log_2[1 + \gamma_{\text{C,G}}(n)] \quad (12)$$

and the averaged conditional outage probability becomes [8]

$$\begin{aligned} I_{\text{C,DF}}(N) &= \mathbb{P} \left[(1 + \gamma_{\text{S,G}}(0))^{\tau(0)} \prod_{n=1}^N (1 + \gamma_{\text{C,G}}(n))^{\tau(n)} < 2^R \middle| \mathcal{E} \right] \\ &= 1 - e^{-\frac{(2^R/(\Delta(N)+1)-1)P_{\text{W}}}{P_0 d_{\text{S,G}}^{-\kappa}}} \\ &\quad - \frac{P_{\text{W}}}{P_0 d_{\text{S,G}}^{-\kappa}} \int_{x=0}^{(2^R/(\Delta(N)+1)-1)} e^{-\frac{b'_{\text{DF}}(x)P_{\text{W}}}{P_0 d_{\text{C,G}}^{-\kappa}}} e^{-\frac{xP_{\text{W}}}{P_0 d_{\text{S,G}}^{-\kappa}}} dx \end{aligned} \quad (13)$$

where

$$b'_{\text{DF}}(x) = \left[\left(\frac{2^R}{(1+x)} \right)^{1/\Delta(N)} - 1 \right]. \quad (14)$$

B. Multiplexing cooperation

For MUX cooperation, when sensor C is able to decode frame $n = 0$, it starts transmitting simultaneously to sensor S. The SNIR's now account for the mutual interference of transmissions of nodes S and C, when C is active. Note that in a MUX configuration, the total transmit power is doubled with respect to DF, since both S and C transmit at maximum power, there we have $\delta = 2$ in (4). This is a distinctive feature of cooperative systems with respect to a single link with nodes equipped with multiple antennas, where the power must be distributed among the antennas. In particular, for event \mathcal{E} we obtain, for $n > 0$,

$$\gamma_{\text{S,G}}(n) = \bar{\gamma}_{\text{S,G}} = \frac{P_0 d_{\text{S,G}}^{-\kappa}}{P_{\text{W}} + P_0 d_{\text{C,G}}^{-\kappa}} \quad (15)$$

$$\gamma_{\text{C,G}}(n) = \bar{\gamma}_{\text{C,G}} = \frac{P_0 d_{\text{C,G}}^{-\kappa}}{P_{\text{W}} + P_0 d_{\text{S,G}}^{-\kappa}}. \quad (16)$$

The bit per unit of frequency [bit/Hz] in the case of cooperation can be written as

$$\begin{aligned} R_{\text{MUX}}(N) &= \tau(0) \log_2[1 + \gamma_{\text{S,G}}(0)] + \\ &\quad \sum_{n=1}^N \tau(n) \{ \log_2[1 + \gamma_{\text{C,G}}(n)] + \log_2[1 + \gamma_{\text{S,G}}(n)] \} \end{aligned} \quad (17)$$

and the conditioned outage probability is

$$I_{\text{C,MUX}}(N) = \mathbb{P} \left[(1 + \gamma_{\text{S,G}}(0))(1 + \bar{\gamma}_{\text{C,G}})^{\Delta(N)} (1 + \bar{\gamma}_{\text{S,G}})^{\Delta(N)} < 2^R \right]. \quad (18)$$

Let us define

$$\xi'(x) = 2^{R/\Delta(N)} (1+x)^{-1/\Delta(N)} - 1, \quad (19)$$

$$b'_{\text{MUX}}(x) = \frac{1}{2}(1+x) [-(1 - \xi'(x)) + \sqrt{(1 - \xi'(x))^2 - \frac{4[x - \xi'(x)]}{(1+x)}}]^+, \quad (20)$$

where $[y]^+ = 0$ for $y < 0$ or y complex, and $[y]^+ = y$ otherwise. As shown in [8], the average outage probability conditioned by \mathcal{E} is

$$\begin{aligned} I_{\text{C,MUX}}(N) &= 1 - e^{-\frac{(2^R/(\Delta(N)+1)-1)P_{\text{W}}}{P_0 d_{\text{S,G}}^{-\kappa}}} \\ &\quad - \frac{P_{\text{W}}}{P_0 d_{\text{S,G}}^{-\kappa}} \int_{x=0}^{(2^R/(\Delta(N)+1)-1)} e^{-\frac{b'_{\text{MUX}}(x)P_{\text{W}}}{P_0 d_{\text{C,G}}^{-\kappa}}} e^{-\frac{xP_{\text{W}}}{P_0 d_{\text{S,G}}^{-\kappa}}} dx. \end{aligned} \quad (21)$$

C. Diversity cooperation

With DIV cooperation, upon correct decoding of the first transmission by node C, both S and C transmit simultaneously, using the Alamouti code 2×1 . For DIV cooperation, we have $\delta = 2$ in (4). Note that by using Alamouti there is no interference among the two transmissions, but the total transmit rate is halved with respect to the MUX case. In the case of cooperation, the bit per unit of frequency [bit/Hz] can be written as

$$R_{\text{DIV}}(N) = \tau(0) \log_2[1 + \gamma_{\text{S,G}}(0)] + \sum_{n=1}^N \tau(n) \log_2[1 + \gamma_{\text{S,G}}(n) + \gamma_{\text{C,G}}(n)] \quad (22)$$

and we have

$$I_{\text{C,DIV}}(N) = \mathbb{P} \left[(1 + \gamma_{\text{S,G}}(0)) \prod_{n=1}^N (1 + \gamma_{\text{S,G}}(n) + \gamma_{\text{C,G}}(n)) < 2^R \middle| \mathcal{E} \right] \quad (23)$$

Moreover, $f_{\gamma_{\text{S,G}}(n)}(x)$ is provided by

$$f_{\gamma_{\text{S,G}}(n)}(a) = \frac{P_{\text{W}}}{P_0 d_{\text{S,G}}^{-\kappa}} e^{-\frac{P_{\text{W}} a}{P_0 d_{\text{S,G}}^{-\kappa}}}, \quad (24)$$

and $f_{\gamma_{\text{C,G}}(n)}(x)$ is provided by (11). For the computation of the outage probability of DF we define the events of outage for cooperative and non-cooperative transmission, as well as the event for cooperation of the first transmission by the cooperator as a function of the S-G and C-G channel gains a and b as

$$\begin{aligned} \mathcal{C}_{\text{DIV}} &= \{(a, b) : (1 + a/P_{\text{W}})(1 + (a+b)/P_{\text{W}})^{\Delta(N)} < 2^R; \\ &\quad a, b \geq 0\}. \end{aligned} \quad (25)$$

In order to compute the integrals we derive the maximum value of b that gives outage as a function of a from (25) as

$$b_{\text{DIV}}(a) = \left\{ \left[\left(\frac{2^R}{(1+a/P_{\text{W}})} \right)^{1/\Delta(N)} - 1 \right] P_{\text{W}} - a \right\}^+. \quad (26)$$

By defining $x = a/P_{\text{W}}$ and

$$b'_{\text{DIV}}(x) = \left[\left(\frac{2^R}{(1+x)} \right)^{1/\Delta(N)} - 1 - x \right]^+, \quad (27)$$

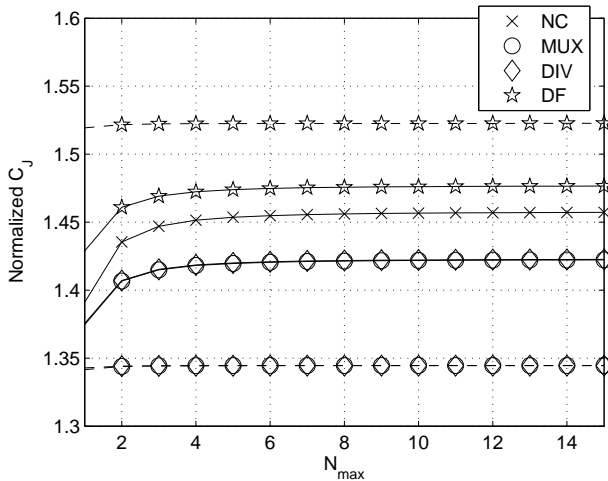


Figure 3. Bit per Joule AR as a function of the maximum number of retransmissions with $\rho = 1.1$ and both random cooperator selection (solid lines) and opportunistic cooperator selection (dashed lines).

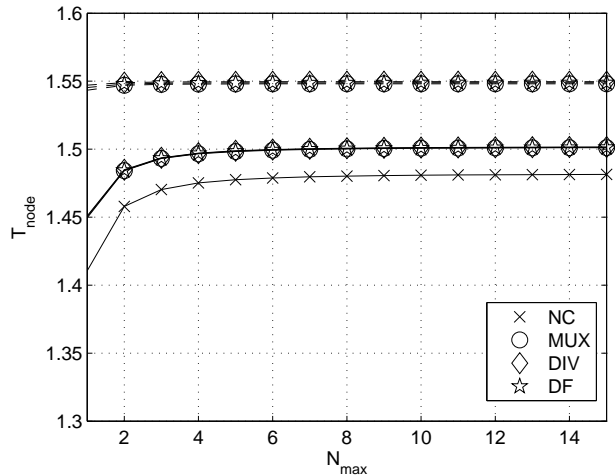


Figure 4. Throughput per node as a function of the maximum number of retransmissions with $\rho = 1.1$ and both random cooperator selection (solid lines) and opportunistic cooperator selection (dashed lines).

we can rewrite the probability of event \mathcal{C}_{DIV} as

$$I_{\mathcal{C},\text{DIV}}(N) = 1 - e^{-\frac{(2^{R/(\Delta(N)+1)} - 1)P_W}{P_0 d_{s,g}^{-\kappa}}} - \frac{P_W}{P_0 d_{s,g}^{-\kappa}} \int_{x=0}^{(2^{R/(\Delta(N)+1)} - 1) \frac{b'_{\text{DIV}}(x)P_W}{P_0 d_{c,g}^{-\kappa}}} e^{-\frac{xP_W}{P_0 d_{s,g}^{-\kappa}}} dx. \quad (28)$$

IV. NUMERICAL RESULTS

We assume that $\nu = 50$ sensors are uniformly distributed around the gateway on a ring having inner circle with radius $R_{\min} = 1$ and outer circle with radius $R_{\max} = 3$. Both the source and the gateway sensors are uniformly distributed in the ring. The path-loss exponent is $\kappa = 4$ and the average signal to noise ratio (SNR) at unitary distance is 30 dB. The overhead due to ACK slot transmission is 10% with respect to the first data slot, i.e. $\tau_A/\tau(0) = 0.1$.

As performance metric we consider the bit per Joule AR, normalized with respect to the bit per Joule AR of frame $n = 0$, i.e. in (4) we assume $\beta = 1$. We also evaluate the normalized (with respect to the AR of frame $n = 0$) average achievable throughput per node as

$$T_{\text{node}} = \sum_{n=0}^{N_{\max}} \frac{1}{(n+1)} P[\text{succ } N = n], \quad (29)$$

where $P[\text{succ } N = n]$ is the average probability of having a success in exactly n retransmissions, i.e., for $n > 0$

$$P[\text{succ } N = n] = P[\mathcal{E}]P[\text{succ } N = n|\mathcal{E}] + (1 - P[\mathcal{E}])P[\text{succ } N = n|\bar{\mathcal{E}}], \quad (30)$$

while $P[\text{succ } N = 0]$ is given by (7).

We first evaluate the average bit per Joule AR as a function of the maximum number of retransmission frames N_{\max} , with the average taken with respect to different nodes positions, generated with a Monte Carlo approach: for each set of sensors' (source and cooperator) positions, the bit per Joule AR

is computed with formulas derived in the previous Sections. For comparison purposes, we report also the performance of a non cooperative (NC) transmission, where $P[\mathcal{E}] = 0$ and all retransmissions are performed only by the source sensor. Performance of cooperating schemes with opportunistic selection based on the average outage probability are also reported, and corresponding acronyms are prefixed with O-.

Fig. 3 shows the normalized C_J for frames having all the same duration, i.e. $\tau = \tau(0)$, which yields $\rho = 1.1$. We observe that in this configuration cooperative schemes performing simultaneous transmissions with more nodes [MUX and (O-)DIV] are inefficient from an energetic perspective, as in most cases transmissions are successful in two frames for all considered techniques and therefore using only one sensor [NC and (O-)DF] is advantageous. Indeed, O-MUX is performing even worse than MUX, as the opportunistic cooperator choice yields a higher probability of cooperation (i.e. a high probability of simultaneous transmission) with a consequent higher probability of having two sensors consuming energy at the same time. The best performing technique, in terms of C_J , is O-DF as it provides efficient cooperation without requiring additional energy consumption. We can compare these results with the achievable throughput, as reported in Fig. 4, under the same parameter configuration. We note that according to a pure throughput metric the best technique is now the O-MUX and that all cooperative techniques outperform NC. Hence, if energy consumption is not an issue, cooperation is always advantageous.

We now evaluate performance in the case of short retransmission frames. In particular, we assume $\tau = 0.1\tau(0)$, which yields $\rho = 0.2$. Fig. 5 shows the bit per Joule AR as a function of the maximum number of retransmission frames N_{\max} for various transmission techniques. We observe that in this case all cooperative techniques outperform NC, since even with small frames cooperation provides a throughput

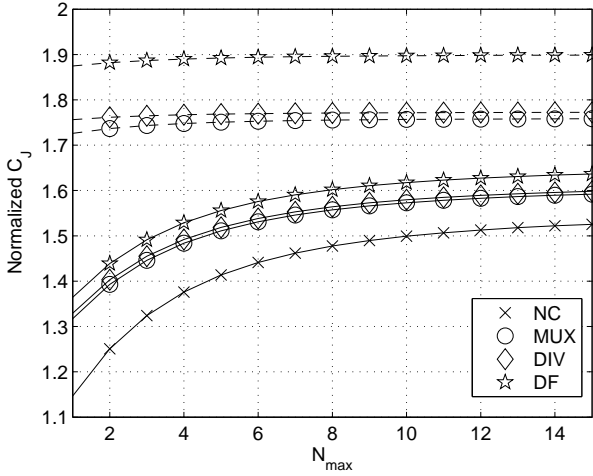


Figure 5. Bit per Joule AR as a function of the maximum number of retransmissions with $\rho = 0.2$ and both random cooperator selection (solid lines) and opportunistic cooperator selection (dashed lines).

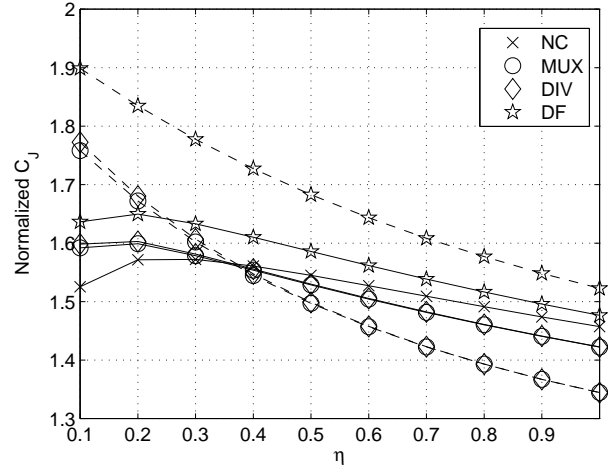


Figure 7. Bit per Joule AR as a function of η , with $N_{\max} = 15$ and both random cooperator selection (solid lines) and opportunistic cooperator selection (dashed lines).

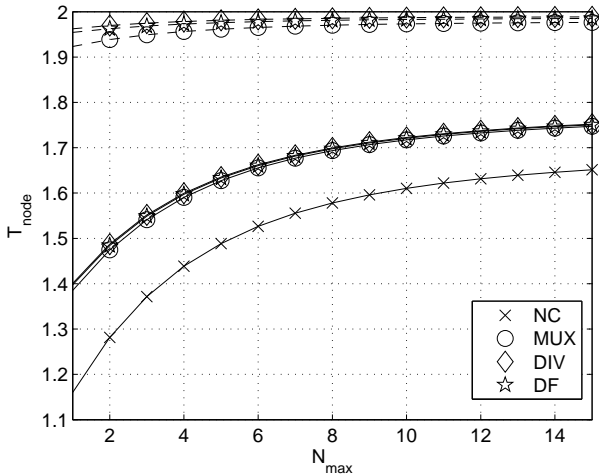


Figure 6. Throughput per node as a function of the maximum number of retransmissions with $\rho = 0.2$ and both random cooperator selection (solid lines) and opportunistic cooperator selection (dashed lines).

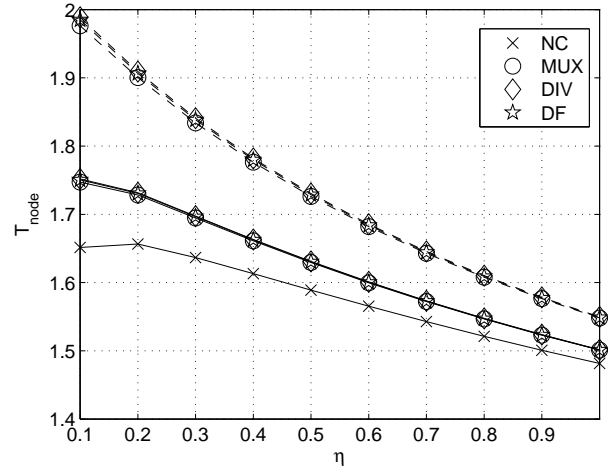


Figure 8. Throughput per node as a function of η , with $N_{\max} = 15$ and both random cooperator selection (solid lines) and opportunistic cooperator selection (dashed lines).

advantage (as shown in Fig. 6), so that the energy penalty incurred by simultaneous transmission by more sensors in the case of MUX and DIV is compensated by the higher success probability. The best performing scheme, in terms of C_J is still O-DF, as it opportunistically exploits channel conditions without increasing the energy consumption, although O-DIV has a very close performance to O-DF. Considering that O-DIV does not require extra signaling for deciding which sensor is transmitting from frame $n = 1$, we may prefer O-DIV for its simplified protocol with respect to O-DF. On the other hand, O-MUX has the further advantage of not requiring synchronization among sensors, although it has a lower bit per Joule AR.

Lastly, Fig. 7 shows the bit per Joule AR of various techniques as a function of η for $N_{\max} = 15$. We observe

that for small values of η , i.e. for small durations of retransmission frames, (O-)MUX and (O-)DIV cooperative schemes outperform the NC case, while both DF and O-DF have always a higher normalized C_J than NC. Indeed, for $\eta > 25\%$ NC outperforms O-MUX and O-DIV. On the other hand, the throughput comparison shown in Fig. 8 shows that for all values of η all the cooperative schemes outperform NC. We also observe that at small η both C_J and T_{node} are increasing, as the convergence to the maximum value is slow and N_{\max} is limiting the performance. For higher values of η , both C_J and T_{node} are decreasing as each retransmission yields a significant decrease of the effective code rate achieved by HARQ.

V. CONCLUSIONS

In this paper we have evaluated the bit per Joule AR of a cooperative wireless sensor network with various cooperative strategies and a HARQ protocol. We compared the bit per Joule AR with the throughput computed without any consideration of energy consumption, observing that the comparison among the various cooperative schemes is different with respect to the used metric. An important role is played by the duration of retransmissions in HARQ, which allows to tune the code rate adaptivity and determines the impact of energy consumption on the various cooperative schemes. In general, shorter retransmissions allow to achieve a higher bit per Joule AR, with a better exploitation of the cooperative strategies where more sensors transmit simultaneously. In particular, O-DIV and O-MUX where two sensors transmit simultaneously without coordination allow for a simpler protocol design.

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