Adaptive Medium Access Control for Distributed Processing in Wireless Sensor Networks

César Asensio-Marco†‡, *Member, IEEE,* and Baltasar Beferull-Lozano†, *Senior Member, IEEE*

***Abstract*—Signal and information processing tasks over Wireless Sensor Networks can be successfully accomplished by means of a distributed implementation among the nodes. Existing distributed schemes are commonly based on iterative strategies that imply a huge demand of one-hop transmissions, which must be efficiently processed by the lower layers of the nodes. At the link layer, general purpose medium access (MAC) policies for wireless communications usually focus on avoiding collisions. These existing approaches result in a reduction of the number of simultaneous transmissions, and an underutilization of the channel as a consequence. This leads to a decrease in the performance of the distributed tasks, since an efficient channel occupation is not generally accomplished. In this work, we propose a new MAC protocol that, besides focusing on the reliability of the communications, provides an efficient channel occupation. While the former has a direct impact on the energy consumption of usually battery powered devices, the latter affects the performance of the distributed task executed. We include both aspects in a global utility function that the nodes, relying just on local available information, aim to increase at every communication step. Furthermore, our proposal combines in a unique framework both unicast and broadcast scenarios. Through several simulation results, we show that our adaptive protocol outperforms the related literature.**

***Index Terms*—CSMA protocol, high traffic demand, energy efficiency, distributed computation, Wireless Sensor Networks**

I. INTRODUCTION

Wireless Sensor Networks (WSN) have emerged as an attractive technology due to their wide range of applications [1-3]. One of their most appealing characteristics is that, despite the limited capabilities of the individual devices in the network, these are able to accomplish complex signal and information processing tasks by means of cooperative algorithms [4]. These schemes involve iterative exchanges of information by one-hop wireless communications that are only discontinued when all the nodes obtain the desired result. Consequently, while the distributed task [5][6] is executed, a large number of wireless transmissions must be performed, which is the most energy demanding operation [7] in WSNs.

A major handicap of the devices in a WSN to satisfy such a high traffic demand is that these are generally battery powered. Then, after executing a certain number of distributed tasks, the batteries must be charged or replaced. Depending on the deployment scenario, this maintenance may involve an important associated cost, which can be significantly reduced by extending the lifetime of the devices. This can be accomplished by saving energy, for example, by avoiding packet losses due to wireless collisions.

Satisfying the traffic demand of the task being executed while avoiding collisions is the main purpose of a medium access control (MAC) protocol. A preliminary classification of MAC policies differentiates between schedule-based and contention-based protocols. Scheduled protocols divide the channel into time slots and assign each slot to one or several feasible nodes. These methods avoid collisions between nodes, at the price of either requiring a central entity or increasing the complexity of the operations and introducing certain traffic overhead. On the other hand, contention-based protocols involve competition for medium access in an asynchronous and random manner. Although collisions are not completely avoided, these protocols are decentralized and respond better to burst and irregular traffic patterns than scheduled protocols.

A. Medium access control for distributed processing

The design of a MAC protocol for handling high traffic, as the one generated by distributed signal and information processing tasks, entails considerations different from those of the general purpose protocols. First, the distributed nature of these tasks implies to discard scheduled protocols, even those specifically designed for traffic adaptation [8], since these generally rely on the existence of a centralized entity for the assignment of transmission slots. Moreover, at every iteration of the cooperative task, each node in the network always tries to exchange information with its neighbors in order to refine its local result. Hence, nodes never enter sleep mode until the task has been finished and the problem of optimizing the idle listening is not relevant here. For that reason, designs based on optimization of the preamble sampling [9] or low power listening [10] are not suited to this approach either. It is also important to notice that, in this setting, transmitted packets always contain the same amount of information, i.e. the payload is the current state of the node, and the intended receivers are always neighboring nodes. Accordingly, packets are always of the same size and no routing protocol [11] needs to be considered at MAC level. Finally, the statistical features of signal and information processing tasks, and the random nature of CSMA protocols, recommend a stochastic approach to appropriately solving the problem of medium access under high traffic demand, rather than a deterministic one. More

---

†Department of Information and Communication Technology, University of Agder, Norway. ‡I2SysBio, CSIC-UVEG, Valencia, Spain. Email:{cesar.asensio,baltasar.beferull}@uia.no

This work was supported by the PETROMAKS Smart-Rig grant 244205/E30, the SFI Offshore Mechatronics grant 237896/O30, the TOPPFORSK WISECART grant 250910/F20 and the IKTPLUSS INDURB grant 270730/O70 from the Research Council of Norway.

The material in this work was presented, in part, at IEEE GLOBECOM 2014 [17].

detailed considerations and assumptions specific to this setting are presented in the next section.

B. Related work

Traditionally, increasing the throughput has not been a priority of MAC designs for WSNs, which have focused on increasing the energy efficiency of the communications through the avoidance of collisions [12]. In this sense, the standard IEEE 802.15.4 employs a carrier sense multiple access with collision avoidance (CSMA/CA) mechanism to determine the channel occupancy by detecting any energy above a preset energy detection (ED) threshold. This simple mechanism presents low performance in the presence of heavy interference and irregular traffic. Other CSMA protocols have focused, similar to our work, on increasing the throughput of the network by adapting the carrier sensing [13][14][15]. The work in [14] aims at maximizing the spatial reuse of the wireless medium by dynamically adjusting the physical carrier sensing threshold depending on the network topology, the sensed power at reception and the data rate. Since this adaptation is performed in a global fashion, it means that any change in the network topology would require a new estimation of the threshold in a centralized manner. A decentralized protocol is presented in [15], following an information theoretical approach in order to improve the spatial reuse. Interestingly enough, it is claimed in [15] that under certain conditions, it is preferable to tune both the transmit power and the data rate, instead of the carrier sense threshold. However, it is not always possible to change dynamically the transmission power and data rate of the nodes. Besides, the work in [15] only considers a unicast scheme of communications, but not a broadcast one, which is more common for wireless networks. For a detailed survey on MAC protocols for WSNs check [16].

In contrast to these previous works, we propose a CSMA protocol following a stochastic methodology. Therefore, and given the random interference, fading and noises, we focus on obtaining the best response through multiple realizations of the distributed task, instead of considering a single realization. Our new protocol, in a complete distributed fashion, aims to achieve both a reduced number of collisions and a high throughput during the execution of a distributed task. Furthermore, extending our previous work in [17], a unique framework for both unicast and broadcast scenarios is proposed. Our design does not require the use of control packets and retransmissions, and relies exclusively on the carrier sensing of each node and the local information about its neighborhood. Then, every node decides to access the channel if and only if the transmission results in an increase of new proposed global cost function that captures both the reliability and the efficiency of the wireless communications.

The remainder of the paper is organized as follows. In Section II, we provide some background about the main concepts and formulate the problem in a formal way. In Section III, the proposed CSMA protocol is described in detail, together with the local computations that the nodes must perform. Simulation results are offered in Section IV. Finally, conclusions are drawn in Section V.

II. BACKGROUND AND PROBLEM FORMULATION

In this section, we explain in detail the formulation of our problem. First, we present the adopted interference model, which is a key concept that conditions all the subsequent design decisions. According to this model, several areas related to a given transmission are defined, as well as different ways to compute the number of receivers of an intended transmission. We also introduce formally the two concepts that we use to measure the performance of the inter-node communications, namely the packet reception rate and the throughput. Finally, the problem is formulated in terms of a global utility function that includes both performance metrics.

A. Interference model and transmission areas

We consider a network composed of a set $\mathbf{V}$ of N nodes, each one equipped with an omni-directional antenna, and arbitrarily deployed in a square area of L square meters following a uniform distribution. The nodes perform half-duplex communication using a common transmission power P_t. Each pair of nodes is linked by a single user channel affected by the corresponding fading. The work in [18] shows that, in practice, a simplified path loss model is usually enough to capture the essence of the fading effect. Therefore, the average power P_r that a node r receives from a transmitter node t is given by:

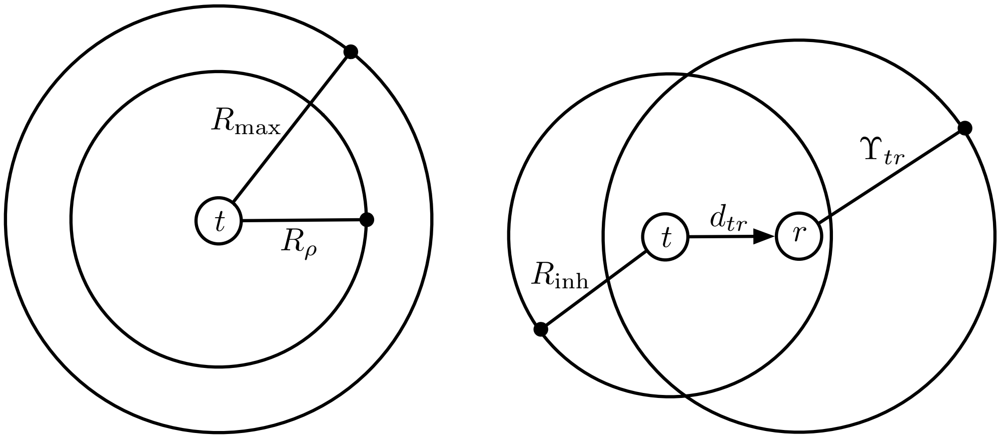
$$P_r = \frac{P_t}{d_{tr}^{\gamma}}, \tag{1}$$

where d_{tr} is the distance between both nodes and γ is the path loss exponent [21]. The amount of received power by a node during a radio signal transmission is called the received signal strength (RSS), and is measured in practice by the received signal strength indicator (RSSI). Since we are considering a single user channel between any two nodes, only one intended signal can be present in each collision domain. The rest of the concurrent transmissions are considered as interference, which we refer to as the joint received interference strength (JRIS). In the absence of activity, the measured RSSI gives the background noise power σ^2 existing in the channel. Furthermore, the signal to interference and noise ratio (SINR) expresses the quotient between the power of the desired signal and the sum of the background noise and the interference.

A key issue in a wireless network is the definition of when a transmission is correctly received by the intended destination. Because of its accuracy and since it is closely related to the physical layer, we adopt the physical interference model presented in [20], which states that the successful reception of a packet sent by a node t to a node r is accomplished if the SINR at r is above a specific threshold β. In practice, the value of β is chosen to guarantee a low bit-error probability. In a more formal way, the packet is correctly delivered from t to r if the following inequality holds

$$\text{SINR} = \frac{\frac{P_t}{d_{tr}^{\gamma}}}{\sum\limits_{i \in \mathbf{V}, i \neq t} \frac{P_t}{d_{ir}^{\gamma}} + \sigma^2} \geq \beta. \tag{2}$$

According to this model, a message may be correctly received even if there is one or various simultaneous transmitting



(a) (b)

Fig. 1. Example of the different areas considered in our model. (a) Transmission range $R_{\max}$ and intended transmission range R_ρ of node t. (b) Inhibition range R_{inh} of node t, and collision area Υ_{tr} centered at receiver node r and associated with the transmission from transmitter node t to receiver node r.

nodes close to t, as far as the inequality (2) holds. Unless otherwise stated, we assume that all the interference comes from a unique point, that we call *the virtual interferer I*. Therefore, and according to (1), if a transmitter node t senses a JRIS equal to ψ, the virtual interferer I is placed at the following distance from t

$$R_I = \left(\frac{P_t}{\psi}\right)^{\frac{1}{\gamma}}. \tag{3}$$

In the sequel, we introduce some definitions concerning the different areas that are associated to a transmission.

Definition 1. *The transmission range R_{max} is the maximum distance up to which a packet can be correctly received in absence of interference.*

By considering (1) and (2), $R_{\max}$ can be easily expressed as

$$R_{\max} = \left(\frac{P_t}{\sigma^2\beta}\right)^{\frac{1}{\gamma}}. \tag{4}$$

The correct reception at a node r, placed at the exact distance $R_{\max}$ from the transmitter node t, implies that no other transmission can be simultaneously scheduled in the entire network without causing collision. Then, for a given transmitter t, and in order to allow simultaneous transmissions, the links to be considered must be shorter than $R_{\max}$. Accordingly, we present the following concept, exploited in [17], [18] and [19]:

Definition 2. *The intended transmission range R_ρ of a node t defines the circular area that contains all the neighbors that node t aims to communicate with. In general, we have that $R_\rho < R_{max}$.*

Therefore, this intended transmission range can be expressed as

$$R_\rho = \rho R_{\max} = \rho\left(\frac{P_t}{\sigma^2\beta}\right)^{\frac{1}{\gamma}}, \tag{5}$$

with $0 < \rho < 1$. The value of ρ must be large enough to ensure that the network is connected, namely there exists a multi-hop path between every pair of nodes. This is a general condition for distributed processes to accomplish its target. It has been shown [20] that in order to ensure connectivity with high probability in a graph with random vertices uniformly and independently distributed, the lower bound $L\sqrt{\log N/\pi N} < R_\rho$ applies. Thus, from (5), we have that $L\sqrt{\frac{\log N}{\pi N R_{\max}^2}} < \rho < 1$. Both the transmission range $R_{\max}$ and the intended transmission range R_ρ are depicted in Fig. 1(a).

When a node t starts a transmission, and in order to prevent a collision, nodes around t may decide not to transmit. This concept leads us to the following definition:

Definition 3. *The inhibition range R_{inh} of node t is defined as the radius of the circular area that includes all nodes that are inhibited by the transmission of node t.*

The value of this radius is a design parameter of the protocol[1]. In our specific case, we derive the expression for it in Section III-C, after our protocol has been explained in detail.

Definition 4. *The collision area associated to a specific link between transmitter node t and receiver node r is the circular area of radius Υ_{tr} and centered at r, inside which no other node can transmit without corrupting the transmission from t to r.*

From (2), and considering that a collision occurs at node r if SINR $< \beta$, the following expression can be obtained

$$\Upsilon_{tr} = \left(\frac{P_t}{\frac{P}{\beta d_{tr}^{\gamma}} - \sigma^2}\right)^{\frac{1}{\gamma}} \approx \beta^{\frac{1}{\gamma}} d_{tr}, \tag{6}$$

where the approximation is obtained by neglecting the background noise σ^2.

The inhibition range R_{inh} corresponding to node t, and the collision area associated to the link between nodes t and r

---

[1] Although we are considering perfect circumferences, we are only interested in the average number of nodes inside them. Therefore, irregular shapes could be used with similar results, if the density of the nodes is maintained.

are represented in Fig. 1(b). This figure gives some insight into the main problems that affect carrier sense strategies. The *hidden terminal* effect is caused by nodes located inside the area defined by Υ_{tr}, but not contained in the area defined by R_{inh}, namely the nodes that can cause a collision to the packet from t to r, but that are not inhibited by the transmission of t. On the other hand, the *exposed terminal* problem affects the nodes inside the area defined by R_{inh} which are also outside the area defined by Υ_{tr}, that is, the nodes inhibited by t but which do not actually interfere with the intended transmission from node t to node r. The hidden terminal problem can be alleviated by increasing R_{inh}, but at the cost of inhibiting more nodes and increasing the exposed terminal. The effect of applying ρ and reducing the intended transmission range to R_ρ is to have smaller collision areas Υ_{tr} without increasing the inhibition range R_{inh}. Therefore, it results in a reduction of the hidden terminal effect, while allowing the same amount of simultaneous transmissions.

B. Degrees of a node

The number of neighbors that correctly receive a packet from a transmitting node t is what characterizes the efficiency and the reliability of the communications. This number of successful receptions is usually referred to as the degree of the transmitting node. Accordingly, we can define the intended degree of a node as the number of neighbors it attempts to reach with each transmission. Since, during a given transmission, several collisions may occur due to the presence of a specific interferer, the instantaneous degree of the transmitter is the exact number of nodes that correctly receive this specific transmission. This instantaneous degree depends on where the virtual interferer is exactly located, which is generally unknown by the transmitter node. Therefore, we introduce the concept of expected degree of a transmitter node conditioned to a given interference strength, which is the expected number of neighbors that will correctly receive the packet from this transmitter node t in the presence of this interference. This expected degree is computed by averaging all possible instantaneous degrees for the different positions where the virtual interferer may be located, given the specific interference strength sensed by node t.

More precisely, in a broadcast scenario the intended degree η_t of node t is the number of neighbors that t attempts to reach in each transmission, namely the number of nodes inside its intended transmission range R_ρ. The instantaneous degree $\tilde{\eta}_t(k)$ of a transmitter node t, at a given time instant k, with $\tilde{\eta}_t(k) \leq \eta_t$, is the real number of nodes that can correctly decode a packet from t at certain time instant k. If we denote by k a specific time instant, the instantaneous degree $\tilde{\eta}_t(k)$ depends on the position, denoted by φ_k, of the virtual interferer I at this time instant k. With a slight abuse of notation, we can write that $\tilde{\eta}_t(k) = \tilde{\eta}_t(\varphi_k)$. Finally, we denote by ψ_k the JRIS generated at node t by the virtual interferer I located at φ_k. Thus, if we average over all the possible positions of I that generate the interference strength ψ_k at node t, the expected degree $\bar{\eta}_t(\psi_k)$ can be expressed as

$$\bar{\eta}_t(\psi_k) = \mathbb{E}_{\varphi_k}\left[\tilde{\eta}_t(\varphi_k)|_{\text{JRIS}(\varphi_k)=\psi_k}\right]. \tag{7}$$

TABLE I
NOTATION USED FOR DEGREES AND COLLISIONS

Broadcast	Unicast	Description
η_t	1	Intended degree
$\tilde{\eta}_t(k)$	$\tilde{\eta}_{tr}(k)$	Instantaneous degree of node t
$\bar{\eta}_t(\psi_k)$	$\bar{\eta}_{tr}(\psi_k)$	Expected degree of t for an interference ψ_k
$\bar{\kappa}_t(k)$	$\bar{\kappa}_{tr}(k)$	Expected collisions of t for an interference ψ_k
η_I	1	Intended degree of interferer I
$\tilde{\eta}_I(k)$	$\tilde{\eta}_I(k)$	Instantaneous degree of interferer I
$\bar{\eta}_I(\psi_k)$	$\bar{\eta}_I(\psi_k)$	Expected degree of I for an interference ψ_k
$\bar{\kappa}_I(\psi_k)$	$\bar{\kappa}_I(\psi_k)$	Expected collisions of I for an interference ψ_k

Similarly, the expected number of collisions for a given ψ_k is $\bar{\kappa}_t(\psi_k) = \eta_t - \bar{\eta}_t(\psi_k)$.

Furthermore, the virtual interferer I is affected by a potential transmission of t, which would cause its intended degree η_I to be reduced to an instantaneous degree $\tilde{\eta}_I(k)$. It depends both on the interference power received from t, and the position of the neighbors that I is reaching at this slot k. We denote by ϕ_k this specific position, and by ψ_k the JRIS generated by t to I, which is the same received by t from I. Then, we can compute, similarly to (7), the expected degree of the interferer given an interference ψ_k from t, by averaging the degree of I over all the possible positions of its neighbors, for this specific ψ_k generated by t

$$\bar{\eta}_I(\psi_k) = \mathbb{E}_{\phi_k}\left[\tilde{\eta}_I(\phi_k)|_{\psi_k}\right]. \tag{8}$$

In the same way, we define as $\bar{\kappa}_I(\psi_k) = \eta_I - \bar{\eta}_I(\psi_k)$ the expected number of collisions caused to the interferer I by the possible transmission of t.

When a unicast scenario is considered, the intended degree of any transmission from t to r is always equal to one. We denote by $\tilde{\eta}_{tr}(k)$ the instantaneous degree of t, for the unicast transmission from t to r. Clearly, we have that $\tilde{\eta}_{tr}(k) = [0, 1]$. The expected degree $\bar{\eta}_{tr}(\psi_k)$ is computed similarly to (7), and the expected number of collisions is given by $\bar{\kappa}_{tr}(\psi_k) = 1 - \bar{\eta}_{tr}(\psi_k)$, with $0 \leq \bar{\eta}_{tr}(\psi_k), \bar{\kappa}_{tr}(\psi_k) \leq 1$. We denote by $\tilde{\eta}_I$ and $\bar{\eta}_I(\psi_k)$ the instantaneous and expected degree, respectively, of the virtual interferer, and by $\bar{\kappa}_I(\psi_k) = 1 - \bar{\eta}_I(\psi_k)$ the expected number of collisions caused by the possible transmission of t.

The different degrees related to a node explained along this subsection are summarized in Table III.

Finally, the average degree of the network is defined as the number of nodes inside the intended transmission range R_ρ when a uniform distribution of nodes is assumed

$$\bar{\eta}_{\text{avg}} = \pi R_\rho \frac{N}{L^2}. \tag{9}$$

C. Problem formulation

The main guideline for the design of the proposed CSMA strategy is to increase simultaneously the reliability of the communications and the throughput of the network, such that the traffic requirements of distributed signal and information processing tasks can be satisfied with a small number of packet losses.

We denote by T the duration of the distributed task, and by k each time slot in which T is divided. We consider the duration of each slot k to be, as maximum, equal to the transmission time of a packet. In this work, a node is considered to transmit at a specific slot k if the last byte of the packet is put in the channel during this time slot. By doing so, we guarantee that no node transmits more than one packet per time slot. Moreover, we denote by $\mathcal{T}(k)$ the set of nodes aimed to transmit simultaneously at time slot k. We define the number of sent packets $n_s(k)$ at a specific time slot k as the sum of the intended degree of all nodes transmitting at this time:

$$n_s(k) = \sum_{t \in \mathcal{T}(k)} \eta_t. \tag{10}$$

Accordingly, the total amount of packets sent during the T time slots is computed as

$$n_s(1:T) = \sum_{k=1}^{T} n_s(k) = \sum_{k=1}^{T} \sum_{t \in \mathcal{T}(k)} \eta_t. \tag{11}$$

Similarly, the number of correctly received packets $n_r(k)$ at a specific time k is defined as the sum of the instantaneous degree of all active nodes at time k

$$n_r(k) = \sum_{t \in \mathcal{T}(k)} \tilde{\eta}_t(k). \tag{12}$$

Again, the total number of correctly received packets during the T time slots can be computed as

$$n_r(1:T) = \sum_{k=1}^{T} n_r(k) = \sum_{k=1}^{T} \sum_{t \in \mathcal{T}(k)} \tilde{\eta}_t(k). \tag{13}$$

The expected efficiency of the network during the T time slots can be expressed as follows

$$U_1(T) = \frac{z \cdot \mathbb{E}\left[n_r(1:T)\right]}{s \cdot T} \text{ bit/second}, \tag{14}$$

namely the average number of correctly received bits per second during T time slots, where s is the duration of each time slot measured in seconds and z is the size of each packet measured in bits. Note that this expression can be viewed as the throughput of the network averaged along all the possible realizations of the distributed task. Clearly, this concept gives a notion about the efficiency of the communications, but does not consider the average number of sent packets that are needed to achieve this performance. Therefore, the same result can be attained with different associated rates of sent packets and packet losses. Then, our goal is to obtain a high value of $U_1(T)$ while as few packets as possible are sent on average during a specific number T of time slots. In this sense, the average number of correctly received packets divided by the average total number of sent packets

$$U_2(T) \triangleq \frac{z \cdot \mathbb{E}\left[n_r(1:T)\right]}{e \cdot \mathbb{E}\left[n_s(1:T)\right]} \text{ bit/Joule}, \tag{15}$$

gives an insight into the reliability of the communications during the experiment, where e denotes the total energy required to transmit a packet measured in Joules. This quotient can be seen as the packet reception rate (PRR) of the network averaged over all the possible realizations of the distributed task being executed. Considering all above, our utility function is expressed as:

$$U(T) = U_1(T)U_2(T) \text{ bit}^2/(\text{second} \cdot \text{Joule}), \tag{16}$$

that is, the product[2] of the average throughput multiplied by the average PRR. It becomes clear that the function $U(T)$ captures both the efficiency and the reliability of the network during the T time slots of the experiment. Note that the parameters z, s, T and e are determined by the hardware of the devices and the experiment being performed, so that these cannot be tuned or optimized. For simplicity and without loss of generality, we use $z = s = e$ in our experiments. Finally, the expression in (16) is directly applicable to a broadcast scenario, but also to a unicast scheme by particularizing $\eta_t = 1$ for all t.

Our main objective is to increase as much as possible and during the T time slots that the experiment lasts, the utility function defined in (16). This is accomplished by ensuring at each time slot k a high number of simultaneous transmissions with only a few collisions, in such a way that the throughput U_1 keeps growing with every new transmission while the packet reception rate U_2 remains as close to its maximum as possible. Then, the MAC policy proposed here is based on a continuous increase of the utility function along the T time slots. Accordingly, a node that senses an interference power ψ_k in the channel transmits if and only if, for this value of ψ_k, the transmission implies that $U(k) < U(k+1)$, namely an improvement of the utility function is ensured. The computation of the function U at both k and $k+1$ time slots involve expectations and knowledge about the whole network during the various time slots, and consequently it can not be exactly computed by the nodes in a distributed fashion. In the following section, we explain how each node can replace this global decision rule by a local one, which is based just on its available local information. This includes the measured power ψ_k in the channel, the number of nodes in the network N, the size of the deployment area L, and the distances to each neighbor d_{tr}. These distances can be estimated by means of several RSSI measurements performed during a previous training step.

III. DESCRIPTION OF THE ADAPTIVE PROTOCOL

This section is devoted to provide a detailed description of our proposed MAC protocol, which is designed in such a way that can be executed in a completely distributed manner. Our approach is a variation of the unslotted mode of the IEEE 802.15.4 standard, which defines a CSMA strategy with asynchronous wake intervals. According to this asynchronous strategy, when a node has a packet to send, it randomly choses an integer from a contention window (CW) interval following a uniform distribution, and waits for this time before attempting to transmit. When the timer expires, the node senses the channel and only transmits if the measured

---

[2] Alternatively, an additional parameter α to explicitly weight each term could be introduced: $U(T) = \alpha U_1(T) + (1-\alpha)U_2(T)$. Ideally, this multi-objective function would allow us to find the rest of pareto optimal solutions that are at same distance to the optimal operation point O than the solution obtained using the proposed product, see Section IV. B.

interference is below a specific threshold. This threshold is previously computed and is the same for all nodes.

In contrast, the present work proposes an adaptive and distributed method for each node to compute a set of thresholds, with the main purpose of allowing a high number of concurrent transmissions while as few collisions as possible occur. Accordingly, at each time moment k, each node makes its own decision about whether to transmit or not based on the measured interference ψ_k and other available local information. We first explain how the global decision $U(k) < U(k{+}1)$ can be mapped into a local rule that is computable by each node. Then, we show how each node can compute the different parameters involved in its own local decision rule. Finally, we describe the complete operation mode of the protocol.

A. Local decision rule

Before presenting the proposition that states the local decision rule for the nodes to increase the value of the utility function at each time instant k, we propose the following Lemma, which is used to show the main result

Lemma 1. *Given* $y(x) = \sqrt{(x+a_1)(x+a_2)} - x$, *with* $a_1, a_2 \geq 0$ *and* $a_1 > a_2$*, the following result holds:*

$$y(x) < \frac{a_1 + a_2}{2} \quad \forall x \geq 0. \tag{17}$$

Proof: Since $a_1 > a_2$, we have that

$$(a_1 - a_2)^2 > 0,$$

from which can be obtained the following inequality

$$\frac{a_1^2 + a_2^2}{4} + \frac{a_1 a_2}{2} > a_1 a_2.$$

For any $x \geq 0$, we can add the term $x^2 + 2\,(a_1 + a_2)\,x$ to both sides of the inequality while maintaining its correctness. After arranging terms, we have that

$$\left(\frac{a_1 + a_2}{2} + x\right)^2 > x^2 + (a_1 + a_2)\,x + a_1 a_2,$$

Taking square roots at both sides, it holds that

$$\frac{a_1 + a_2}{2} + x > \sqrt{(x + a_1)\,(x + a_2)}.$$

and the result in (17) follows.

■

Now, we are ready to present the proposition that defines the local rule for the node t to improve the utility function in the presence of the interferer I:

Proposition 1. *The utility function in (16) is improved at time* k *by the broadcast transmission of node* t *if, given an interference strength* ψ_k *at* t*, the following inequality holds*

$$\bar{\eta}_t(\psi_k) > \bar{\kappa}_I(\psi_k) + \frac{\eta_t}{2}. \tag{18}$$

Proof: If node t does not perform the transmission at time k, the utility function remains unchanged from k to $k+1$

$$U(k+1) = U(k) = \frac{\left(\mathbb{E}\left[n_r(1:k)\right]\right)^2}{\mathbb{E}\left[n_s(1:k)\right]}. \tag{19}$$

However, if node t transmits, the utility function at time $k+1$ becomes

$$\begin{aligned} U(k+1) &= \frac{\left(\mathbb{E}\left[n_r(1:k) + \tilde{\eta}_t(k) - \tilde{\kappa}_I(k)\right]\right)^2}{\mathbb{E}\left[n_s(1:k) + \eta_t\right]} \\ &= \frac{\left(\mathbb{E}\left[n_r^k\right] + \bar{\eta}_t(\psi_k) - \bar{\kappa}_I(\psi_k)\right)^2}{\mathbb{E}\left[n_s^k\right] + \eta_t}. \end{aligned} \tag{20}$$

Therefore, the transmission of node t improves the utility function as long as the expression (20) is larger than the expression in (19), or, equivalently, if

$$\bar{\eta}_t(\psi_k) - \bar{\kappa}_I(\psi_k) > \mathbb{E}[n_r(1{:}k)]\sqrt{\frac{\mathbb{E}[n_s(1{:}k)] + \eta_t}{\mathbb{E}[n_s(1{:}k)]}} - \mathbb{E}[n_r(1{:}k)]. \tag{21}$$

The second term in (21) is an increasing function in $\mathbb{E}[n_r(1{:}k)]$ and decreasing in $\mathbb{E}[n_s(1{:}k)]$, and since $\mathbb{E}[n_r(1{:}k)] \leq \mathbb{E}[n_s(1{:}k)]$, it attains a maximum for $\mathbb{E}[n_r(1{:}k)] = \mathbb{E}[n_s(1{:}k)]$. Thus, the previous condition becomes

$$\bar{\eta}_t(\psi_k) - \bar{\kappa}_I(\psi_k) > \sqrt{(\mathbb{E}[n_s(1{:}k)] + \eta_t)\,\mathbb{E}[n_s(1{:}k)]} - \mathbb{E}[n_s(1{:}k)].$$

By applying the inequality (17) from Lemma1 with $x = \mathbb{E}[n_s^k]$, $a_1 = \eta_t$ and $a_2 = 0$, we have that the right term of this inequality is upper bounded by $n_t/2$, hence the result in (18) follows.

■

Similarly, if a unicast scenario is considered, we can state the following result:

Corollary 1. *The utility function in (16) is improved by the unicast transmission from* t *to* r *at time instant* k *if, given an interference strength* ψ_k *at* t*, the following inequality holds*

$$\bar{\eta}_{tr}(\psi_k) > \bar{\kappa}_{Ij}(\psi_k). \tag{22}$$

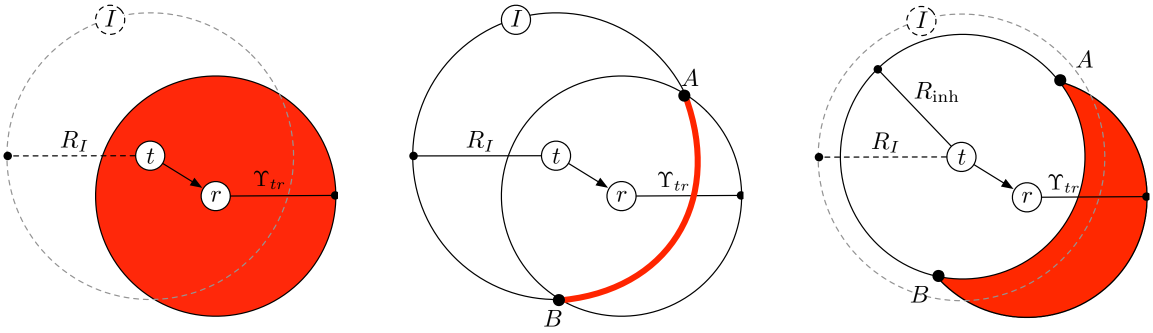
Proof: The proof is similar to the one used in (18) with the particularity that in a unicast scenario, $\eta_t = 1$. This particularity easily leads to $\bar{\eta}_{tr}(\psi_k) > \bar{\kappa}_{Ij}(\psi_k) + \frac{1}{2}$. Moreover, after a high number of iterations $k >> 1$, we have that $\frac{\mathbb{E}[n_s(1:k)]+\eta_t}{\mathbb{E}[n_s(1:k)]} \approx 1$, allowing us to approximate the right term of (21) by 0 and then the expression in (22) follows.

■

Every node t in the network knows its own intended degree. Then, local decision rules in (18) and (22) can be applied in a distributed fashion as long as node t can compute, just by using local information, its expected degrees and the expected number of collisions caused to the virtual interferer I. Next, we explain how node t computes both parameters using only the available local information.

B. Distributed computation of the required parameters

This section is dedicated to explaining how each node t can compute, in a completely local manner, the parameters needed to apply the local decision rules (18) and (22), namely, its expected degree in the presence of an interference ψ_k, and the expected number of collisions caused to the virtual interferer I that produces ψ_k.



(a) (b) (c)

Fig. 2. The three events included in the computation of the collision probability for a packet sent from node t to node r in the presence of the interferer I: (a) a node inside the collision area defined by Υ_{tr} decides to transmit after t has sensed the channel and before t starts the transmission, (b) the interferer is located inside the collision area defined by Υ_{tr}, (c) a node inside inside the collision area defined by Υ_{tr} and no inhibited by t decides to transmit during the τ time units after the transmission of node t.

1) Expected degree of the transmitter ($\bar{\eta}_t(\psi_k)$, $\bar{\eta}_{tr}(\psi_k)$): given an interference ψ_k, the expected degree of t for both broadcast and unicast transmissions are related as follows

$$\bar{\eta}_t(\psi_k) = \sum_{r:d_{tr}\leq R_\rho} \bar{\eta}_{tr}(\psi_k), \tag{23}$$

that is, the degree of t for a broadcast transmission is the sum of the degrees of all unicast transmissions to its neighbors inside the area of radius R_ρ. If we develop the expression for $\bar{\eta}_{tr}(\psi_k)$, we have the following

$$\begin{aligned}\bar{\eta}_{tr}(\psi_k) &= \mathbb{E}_{\varphi_k}\left[\tilde{\eta}_{tr}(\varphi_k)|_{\text{JRIS}(\varphi_k)=\psi_k}\right]\\ &= \sum_{\varphi_k} \tilde{\eta}_{tr}(\varphi_k)p(\varphi_k)|_{\text{JRIS}(\varphi_k)=\psi_k}\\ &= \sum_{\varphi_k^*} p(\varphi_k^*)|_{\text{JRIS}(\varphi_k^*)=\psi_k}\\ &= p_{tr}(\psi_k),\end{aligned} \tag{24}$$

where $p(\varphi_k)$ is the probability that the interferer is located at position φ_k, the third equality follows since in a unicast transmission $\tilde{\eta}_{tr}(\varphi_k) = [0, 1]$, and φ_k^* stands for any interferer position that allows the reception of the packet by r, that is, $\tilde{\eta}_{tr}(\varphi_k^*) = 1$. Finally, $p_{tr}(\psi_k)$ is the total probability that a packet from t reaches r in the presence of a virtual interferer I that produces an interference power ψ_k at t. For our particular setting, the probability $p_{tr}(\psi_k)$ can be expressed as follows

$$p_{tr}(\psi_k) = (1 - p_1)(1 - p_2)(1 - p_3), \tag{25}$$

where:

- p_1 is the probability that any node inside the area centered at r with radius Υ_{tr}, namely, the collision area of node r, decides to transmit after node t senses the channel but before the transmission starts (see Fig. 2 (a)).
- p_2 is the probability that the interferer I generating ψ_k is located inside the area centered at r with radius Υ_{tr} (see Fig. 2 (b)).
- p_3 is the probability that any node inside the area centered at r with radius Υ_{tr}, and outside the inhibition range R_{inh} of t, decides to transmit during the time that the packet from t to r remains in the channel (see Fig. 2 (c)).

For the computation of p_1, we first consider the probability that a single node i starts a transmission at a given moment, which is the combination of three events:

- The node has a packet to transmit. In the specific case of an iterative task, every node always has information to exchange with its neighbors, in order to refine it as soon as possible. Therefore, this probability is always equal to one.
- The timer based on the value of CW expires and the node i decides to sense the channel. From the work in [23], and particularizing for our specific scenario (no retransmissions, constant back-off window, packet discarding after channel sensing), it can be shown that the probability of this event is given by $\frac{2}{\text{CW}+1+2\tau\alpha_i}$, where CW is the size of the contention window, τ is the packet transmission time, and α_i is the probability that node i decides, after sensing the channel, that its own transmission improves the utility function. It depends on the interference measured by i, and on the final thresholds computed by i when this protocol is applied.
- The node i senses the channel and decides that its own transmission improves the utility function. This probability is directly given by α_i.

Therefore, and considering these three events, the probability that a node i starts a transmission at any time can be written as $\frac{2\alpha_i}{\text{CW}+1+2\tau\alpha_i}$. Then, the probability that this node i does not transmit during the time interval after node t senses the channel and before it starts the transmission is given by

$$\left(1 - \frac{2\alpha_i}{\text{CW} + 1 + 2\tau\alpha_i}\right)^{\min(\tau, t_{\text{turn}})},$$

where t_{turn} is the time for every node to turn around from listening to transmitting mode. If we extend this expression to all nodes inside the area of interest, we have that p_1 can be expressed as follows

$$p_1 = 1 - \prod_{i:d_{ri}<\Upsilon_{tr}} \left(1 - \frac{2\alpha_i}{\text{CW} + 1 + \tau\alpha_i}\right)^{\min(\tau, t_{\text{turn}})}. \tag{26}$$

The computation of the different α_i entails the previous knowledge of the adaptive thresholds that the MAC protocol aims to compute and centralized computations. Therefore, we apply a simplified model where node t assumes that $\alpha_i = \alpha$ for all i. The final choice of α is a design rule of the protocol. The more α approaches one, the more conservative the protocol is, that is, the PRR is prioritized over the throughput.

Moreover, since the nodes are deployed randomly but following a uniform distribution, the average number of nodes inside the inhibition area corresponding to the transmission from t to r is $N\pi\Upsilon_{tr}^2/L^2$. Therefore, we have that

$$p_1 = 1 - \left(1 - \frac{2\alpha}{\mathrm{CW} + 1 + \tau\alpha}\right)^{\left(N\pi\frac{\Upsilon_{tr}^2}{L^2}\right)\min(\tau, t_{\text{turn}})}. \quad (27)$$

The probability p_2 that the interferer I is placed inside the collision area of node r is given by the quotient of the circular arc between the points A and B (see Fig. 2 (b)) and the total length of the circumference of radius R_I. By applying some trigonometric relations, we have that:

$$p_2 = \begin{cases} 1 & u < -R_I, \\ \frac{1}{\pi}\text{arcos}\left(\frac{u}{R_I}\right) & |u| < R_I \\ 0 & u > R_I \end{cases} \quad (28)$$

where $u = \frac{R_I^2 + d_{tr}^2 - \Upsilon_{tr}^2}{2d_{tr}}$.

Finally, and regarding p_3, a collision may occur when any node inside the area centered at r with radius Υ_{tr} and placed at a higher distance from t than R_{inh}, is not inhibited by the transmission of t and decides to transmit during any of the τ time units after t starts the transmission. The value of R_{inh} is obtained and explained in (III-C). The area of these non-inhibited nodes is computed by subtracting from the collision area of r the intersection between itself and the circle defined by the radius R_{inh} (see Fig. 2 (c)). If we denote as H_1 this intersection area, we have that:

$$H_1 = \begin{cases} \pi\Upsilon_{tr}^2 & R_{\text{inh}} \geq \Upsilon_{tr} + d_{tr}, \\ \pi R_{\text{inh}}^2 & R_{\text{inh}} \leq \Upsilon_{tr} - d_{tr}, \\ \frac{1}{2}\left(\phi_1 R_{\text{inh}}^2 + \phi_2 \Upsilon_{tr}^2\right) & \text{otherwise} \end{cases} \quad (29)$$

where $\phi_i = \theta_i - \sin(\theta_i)$ for $i = 1, 2$, and:

$$\theta_1 = 2\text{arcos}\left(\frac{u_1}{R_{\text{inh}}}\right)$$

$$\theta_2 = 2\text{arcos}\left(\frac{u_2}{\Upsilon_{tr}}\right)$$

$$u_1 = \frac{R_{\text{inh}}^2 + d_{tr}^2 - \Upsilon_{tr}^2}{2d_{tr}}$$

$$u_2 = \frac{\Upsilon_{tr}^2 + d_{tr}^2 - R_{\text{inh}}^2}{2d_{tr}}$$

Given a uniform distribution, the number of nodes inside the area of interest is $\left(\pi\Upsilon_{tr}^2 - H_1\right)\frac{N}{L^2}$. Following the same reasoning as for the computation of p_1, the probability that any node inside this area decides to transmit during the τ time units that the packet remains in the channel is given by

$$p_3 = 1 - \left(1 - \frac{2\alpha}{\mathrm{CW} + 1 + \tau\alpha}\right)^{\tau\left(\pi\Upsilon_{tr}^2 - H_1\right)\frac{N}{L^2}}. \quad (30)$$

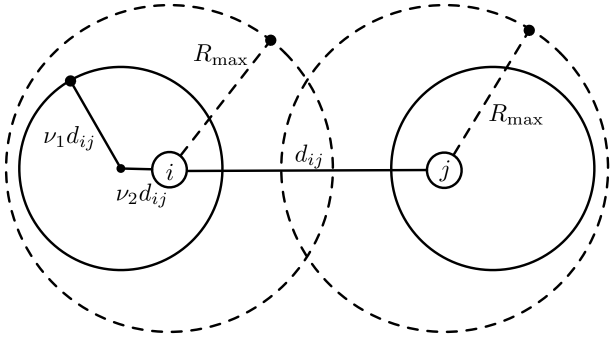


Fig. 3. When two nodes perform a broadcast transmission simultaneously, the areas containing the reached neighbors are reduced and displaced backwards according to Lemma III.2

2) Expected collisions of the interferer ($\bar{\kappa}_I(\psi_k)$, $\bar{\kappa}_{Ij}(\psi_k)$): for any node, the expected number of collisions is computed as the intended degree minus the expected degree of the node. We assume that, prior to the transmission of t, the virtual interferer I is reaching all its intended neighbors. Furthermore, we also assume that this intended degree is the average degree of the network $\bar{\eta}_{\text{avg}}$ for a broadcast transmission, and 1 for a unicast one. Therefore, node t only needs to compute, in the case it starts a transmission, the expected degree of the virtual interferer I. Node t cannot infer any information about the neighbor distribution of this virtual interferer. However, since the nodes have been deployed following a uniform distribution, from a statistical point of view we can state that the intended neighbors of the interferer I are uniformly distributed inside the area of radius R_ρ around it.

In a broadcast scenario, and in order to compute the expected number of neighbors that will still receive from the interferer I when node t starts its transmission, we make use of the following lemma:

Lemma 2. *Let us consider two nodes i and j, separated by a distance d_{ij}, and each one broadcasting to their neighbors using a common power P_t (see Fig. 3). The neighbors that correctly receive the packet from each transmitter are those located inside the respective circles of radius $\nu_1 d_{ij}$, centered in the straight line joining i and j, and backward of the respective transmitter at distance $\nu_2 d_{ij}$, where*

$$\nu_2 = \frac{1}{\beta^{2/\gamma} - 1}$$

$$\nu_1 = \sqrt{\nu_2(1 + \nu_2)}$$

Proof: We prove it for the neighbors of j. Since the transmission power is common to both nodes, the same result holds for i. According to the interference model expressed in (2), a neighbor r of j will correctly receive the packet in the presence of i as long as $\frac{d_{ir}^\gamma}{d_{jr}^\gamma} \geq \beta$, or equivalently

$$d_{ir}^2 \geq d_{jr}^2 \beta^{\frac{2}{\gamma}}. \quad (31)$$

By applying the cosine law between d_{jr}, d_{ij} and d_{d_ir}, and making use of (31), we have that the following inequality holds

$$d_{jr}^2\left(\beta^{\frac{2}{\gamma}} - 1\right) + 2d_{ij}d_{jr}\cos(\theta) \leq d_{ij}^2,$$

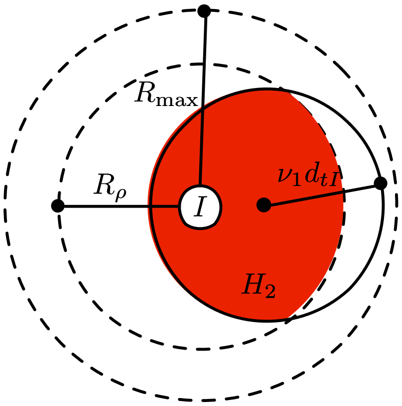


Fig. 4. The instantaneous degree of the interferer I when node t is transmitting broadcast at a distance d_{tI} from I is given by the number of nodes inside the area H_2. This area can be computed as the intersection between the circle defined by the intended transmission range R_ρ of I, and the circular area of radius $\nu_1 d_{tI}$, which involves the nodes receiving from I when t is transmitting.

where θ is the angle between the segments $\bar{ij}$ and $\bar{jr}$. If we move from polar to Cartesian coordinates by doing $x = d_{jr}\cos(\theta)$ and $y = d_{jr}\sin(\theta)$ the previous inequality can be written as

$$\left(\beta^{\frac{2}{\gamma}} - 1\right)(x^2 + y^2) + 2d_{ij}x \le d_{ij}^2.$$

After arranging terms, the previous expression becomes

$$\left(x + \frac{d_{ij}}{\left(\beta^{\frac{2}{\gamma}} - 1\right)}\right)^2 + y^2 \le d_{ij}^2 \left(\frac{1}{\left(\beta^{\frac{2}{\gamma}} - 1\right)} + \frac{1}{\left(\beta^{\frac{2}{\gamma}} - 1\right)^2}\right)$$

which is the formula of the circle proposed in Lemma III.2.

■

This lemma defines the area inside which the neighbors of interferer I still receive even in the presence of the transmitter t. However, the intended neighbors of I are those inside the area centered at I, and with radius R_ρ. Therefore, the intersection H_2 between those two areas defines the area containing the intended neighbors of I that receive in the presence of the transmitter t (see Fig 4). This intersection area H_2 is computed in the same way as (29), by simply substituting the appropriate distances as follows:

$$R_{\text{inh}} \longmapsto \nu_1 R_I, \;\; d_{tr} \longmapsto \nu_2 R_I, \;\; \Upsilon_{tr} \longmapsto R_\rho$$

Given that H_2 and for a uniform distribution of nodes throughout the network, the expected degree of the interferer I in a broadcast scenario is computed as

$$\bar{\eta}_I(k) = H_2 \frac{N}{L}^2. \tag{32}$$

For the case of a unicast transmission, if we develop the expression of the expected degree of I, we have the following

$$\begin{aligned} \bar{\eta}_{Ij}(k) &= \mathbb{E}_{\phi_k}\left[\tilde{\eta}_{Ij}(\phi_k)|_{\psi_k}\right] \\ &= \sum_{\phi_k} \tilde{\eta}_{Ij}(\phi_k)|_{\psi_k} p(\phi_k) \\ &= \sum_{\phi_k^*} p(\phi_k^*)|_{\psi_k} \\ &= p_{Ij}(\psi_k), \end{aligned} \tag{33}$$

where $\tilde{\eta}_{Ij}(\phi_k)|_{\psi_k}$ is the instantaneous degree of I in the presence of an interference ψ_k, for a unicast transmission, and when the destination j is located at ϕ_j. We denote by $p(\phi_k)$ the probability that j is placed at this specific location ϕ_k. The third equality follows since $\tilde{\eta}_I(\phi_j) = [0, 1]$. The value ϕ_j^* expresses any placement of j that allows its reception from I when t is transmitting. Finally, $p_{Ij}(\psi_k)$ is the probability that any node j located at a distance d_{Ij} from I can receive a packet from I when t is generating an interference ψ_k at I. Given the uniform distribution of nodes, we assume that the generic intended receiver j is located at a distance corresponding to the average of the uniform distribution, specifically $d_{Ij} = R_\rho/\sqrt{2}$.

The probability $p_{Ij}(\psi_k)$ is given by one minus the probability that the transmitter t is placed inside the area centered at j and with radius $\beta^{\frac{1}{\gamma}} d_{Ij}$, namely the inhibition area of j. This probability is computed in the same way that p_2 in (28), by substituting the following:

$$\Upsilon_{tr} \longmapsto \beta^{\frac{1}{\gamma}} R_\rho/2, \;\; d_{tr} \longmapsto R_\rho/2, \;\; R_I \longmapsto R_I$$

TABLE II
THE DIFFERENT ACTIONS PERFORMED BY THE TRANSMITTER NODE DEPENDING ON THE MEASURED POWER

JRIS	**Interferers**	**Action**
$\psi = \sigma^2$	0	Transmission
$\sigma^2 < \psi < \sigma^2\beta$	1	Decision rule
$\sigma^2\beta \le \psi \le N_0(1+\beta)$	> 1	Decision rule
$\sigma^2(1+\beta) < \psi$	> 1	No transmission

C. Description of the protocol

The key point of any CSMA/CA policy is the decision that each node makes after sensing the channel. Here we explain the different situations that arise regarding the measured interference ψ, and the action performed by the node in each case. The decision of the node is taken by considering just local available information, and by applying the decision rules explained in Section III-A. In this way, if the sensed RSSI corresponds to a packet that the node can decode, the node performs the reception and waits for a new random period before sensing again the channel[3]. Otherwise, the RSSI is considered merely interference, and depending on its value, the node makes the following decisions (see Table II):

1) If no energy is detected, that is, $\psi = \sigma^2$, no assumption about the presence or absence of an interferer can

---

[3] For the unicast scenario, if the packet is not intended for this node, we always consider that the packet is completely received before it is discarded.

be made. Nevertheless, it is assumed that a possible interferer would be far enough for the utility function to increase, and consequently node t always transmits.

2) If $\sigma^2 < \psi < \sigma^2\beta$, we assume that the interference comes from a unique point. In this case, node t applies its local decision rule, hence it evaluates either (22) for the unicast case or (18) for the broadcast case, and if the inequality holds, the node transmits. Otherwise, it waits for a random period before sensing the channel again.

3) If node t senses a signal strength such that $\psi \geq \sigma^2\beta$, and no packet can be decoded, we can infer that m signals exist in the channel, with $m > 1$. Without loss of generality, let I_1 be the nearest transmitting node and $I_2 \dots I_m$ the rest of the active nodes. Then, we have that

$$\psi = \sum_{i=1}^{m} \psi_i, \tag{34}$$

where ψ_k denotes the signal strength of the transmitting node I_k. Then, since no packet can be decoded, the following expression holds

$$\frac{\psi_1}{\sum_{i=2}^{m} \psi_i + \sigma^2} < \beta. \tag{35}$$

Therefore, combining expressions (34) and (35) and neglecting the background noise, the energy assignment in this case is given by

$$\begin{aligned} \psi_1 &= \frac{\beta}{\beta+1}\psi - \epsilon \\ \sum_{i=2}^{m} \psi_i &= \frac{1}{\beta+1}\psi + \epsilon \end{aligned} \tag{36}$$

for any $\epsilon > 0$ and such that $\psi_1 > \psi_i \; \forall i \neq 1$. If we consider the worst case, node I_1 is placed as close as possible to node t, such that the interference between them is maximized, but far enough to make t unable to decode its packet. This is done by fulfilling the equations in (36) and choosing the value of ϵ infinitesimally small, so that ψ_1 is maximized. Let us consider I_2 to be, among $I_2 \dots I_m$, the closest node to t. Then, two possible scenarios emerge.

- If $\sum_{i=2}^{m} \psi_i \leq \sigma^2$, it means that the distance between node t and I_2 is $d_{tI_2} \geq \left(\frac{P_t}{\sigma^2}\right)^{1/\gamma}$, and the rest of the $m-2$ nodes are located further away. In this case $\psi \leq \sigma^2(1+\beta)$, we neglect the $m-1$ nodes, and consider node I_1 to be the unique interferer, with an interference strength $\psi = \frac{\beta}{\beta+1}\psi$. Considering this interference, node t applies the local decision rule expressed in (18) and acts accordingly.
- If $\sum_{i=2}^{m} \psi_i > \sigma^2$, we cannot ensure node I_2 to be far enough to assume its effect negligible. Consequently, if $\psi > \sigma^2(1+\beta)$, we must consider, at least, two interferers. Since in this case the effect on the global utility function of a transmission from node t cannot be locally approximated, node t decides not to transmit. Then, the radius R_{inh} used for the computation of p_3 in Section III-B1 is given by $R_{\text{inh}} = \left(\frac{P_t}{\sigma^2(1+\beta)}\right)^{1/\gamma}$.

TABLE III
VALUES OF THE MOST RELEVANT SIMULATION PARAMETERS

Parameter	Value	Description
β	13	SINR threshold
N	200	Number of nodes in the network
γ	2.5	Path loss exponent of the simplified model
T	10000	Number of time slots of the experiment
σ^2	-100	Background noise power (dBm)
L	20	Side of the squared deployment area (m)
$z = s = e$	$z = s = e$	Hardware and experiment dependent

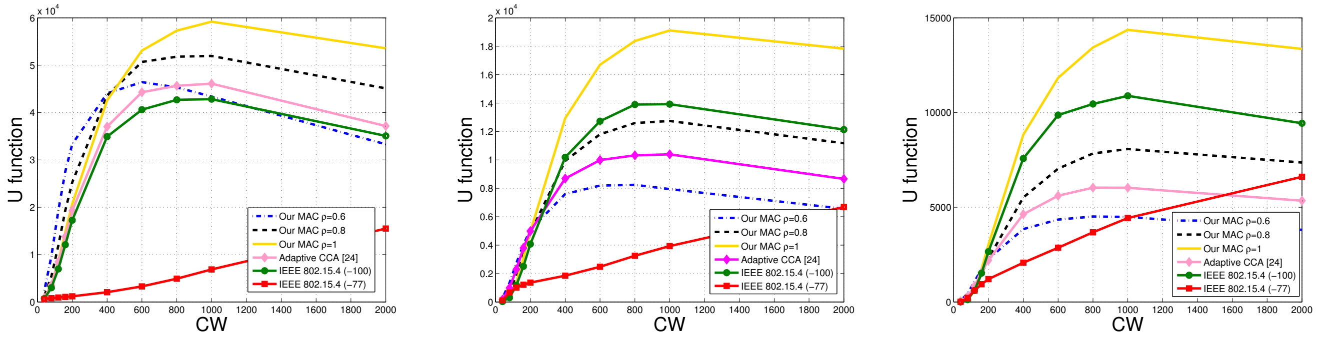
IV. SIMULATION RESULTS

In this section, several simulation results are presented in order to show the performance of our adaptive CSMA protocol under both unicast and broadcast communications. We compare our proposal with the unslotted mode of the standard IEEE 802.15.4 and the work in [24]. In both cases, acknowledgements and retransmissions where deactivated to favour its throughput. In the standard IEEE 802.15.4, nodes transmit after the timer expiration only if the measured JRIS is under a constant ED threshold of value -77 dBm or -100 dBm. As an interesting extension, the work in [24] adapts these ED thresholds according to the interference present in the channel. We have used Cooja [22] to simulate the behavior of the TelosB mote working with our proposed design and the related works considered. For every combination of parameters, we have performed 10 realizations of the experiment. The values of the parameters used are listed in Table III.

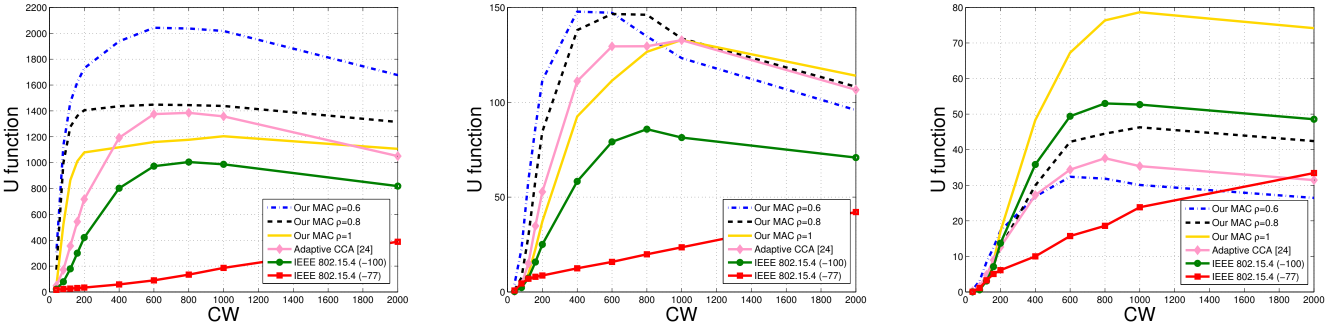
A. Evaluation of the utility function

Fig. 5 shows the value of the utility function introduced in Section II, as a function of CW, for our protocol, the unslotted IEEE 802.15.4 and the work in [24]. It can be seen that our protocol outperforms both protocols for almost all combinations of the parameters considered. For a fixed threshold of -77 dBm the channel is saturated very quickly: thus the occurrence of numerous collisions reduces its throughput drastically. As the size of CW grows and the concurrence in the channel decreases, it approaches the rest of the protocols. The results are clearly better for a fixed threshold of -100 dBm, since the PRR keeps high values due to the avoidance of concurrence in the channel. However, the lack of flexibility to increase the throughput under favourable channel conditions prevents this scheme from reaching the performance of our design. In the case of the work [24], the adaptation of the ED thresholds does not fit the requirements of irregular traffic, as the one generated by a distributed task, since the adaptation is made for an interference level in a time slot that could have changed completely in the next one.

In broadcast communications, our protocol reaches maximum utility values around CW $=$ 800ms for all the transmission powers evaluated. Regarding the parameter ρ, the best performance is obtained for $\rho = 1$, which indicates that the trend in a broadcast scheme is to cover large areas. In this case, the hidden terminal problem has less impact on the final result, since the reception of several other nodes compensates a possible collision. When unicast communications are considered, ensuring a correct packet reception becomes more



(a) Broadcast ($P_t = -15$ dBm) (b) Broadcast ($P_t = -5$ dBm) (c) Broadcast ($P_t = -1$ dBm)



(d) Unicast ($P_t = -15$ dBm) (e) Unicast ($P_t = -5$ dBm) (f) Unicast ($P_t = -1$ dBm)

Fig. 5. Evolution of the utility function for three different power transmissions: $P_t = -1, -5, -15$ dBms. The values of U are shown as a function of the contention window CW. Our protocol with $\rho = 0.6, 0.8, 1$ is compared with fixed threshold strategies, -100 dBm and -77 dBm.

relevant. The results depend on the transmission power and the corresponding areas created around the transmitter. For small values of P_t, it is possible to create multiple simultaneous unicast transmissions, but with a small SINR ratio. In this case, transmissions are protected by using small values of ρ, which implies larger inhibited areas. The opposite occurs for high transmission powers, where values of ρ close to 1 provide the best results.

Finally, Table IV shows the averaged results in terms of bit/s and bit/Joule of all possible parameter combinations for both unicast and broadcast communications. Our protocol increases the throughput between 40% and 250% with respect to the standard IEEE 802.15.4 and the work in [24], while maintaining similar energy efficiency.

TABLE IV
AVERAGED RESULTS OVER ALL COMBINATIONS OF THE PARAMETERS
P_t=[0, -1,-2,-5,-10,-15] AND CW=[50:2000]

	Broadcast		Unicast	
Protocol	bit/s	bit/Joule	bit/s	bit/Joule
Our MAC ($\rho = 0.6$)	4.8×10^4	0.54	1.7×10^3	0.62
Our MAC ($\rho = 0.8$)	5.7×10^4	0.52	1.5×10^3	0.59
Our MAC ($\rho = 1$)	8.1×10^4	0.47	1.1×10^3	0.45
Adaptive CCA [24]	6.1×10^4	0.43	1.2×10^3	0.47
802.15.4 (-100 dBm)	5.8×10^4	0.56	0.7×10^3	0.63
802.15.4 (-77 dBm)	4.4×10^4	0.11	0.5×10^3	0.09

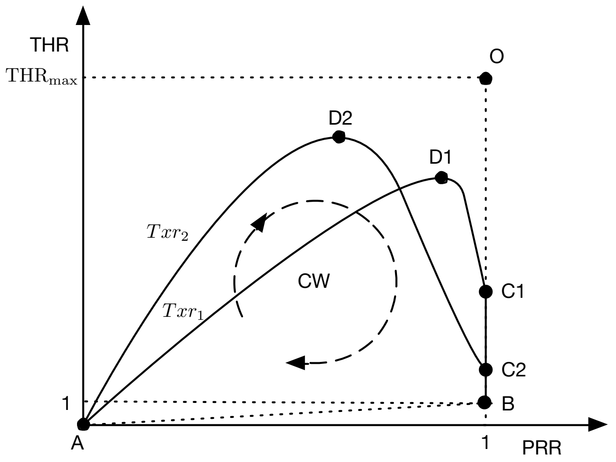


Fig. 6. Qualitative example of the operating regime of the IEEE 802.15.4 unslotted protocol, in terms of the packet reception rate and the throughput, as a function of the contention window size (CW), and for two different predefined transmission thresholds (Txr_1, Txr_2).

B. Operating regime of a CSMA protocol

The utility function presented in Section II C evaluates the number of correctly received packets together with the number of times each of these packets have to be sent before a successful reception occurs. To show clearly how this function captures simultaneously the PRR and the throughput of the network, we evaluate the performance of a CSMA protocol by studying the inter-dependence of both values. Fig.

6 qualitatively shows the operating regime, in terms of PRR and throughput, of a specific network (for a given deployment and specific transmission power), when a specific transmission threshold (Txr_1) is applied. When the CW is infinitely long, the number of sent packets is zero, and so are the PRR and the throughput (point A). After a first packet is sent and correctly received, both PRR and throughput become 1 (point B). From this point, as the value of CW decreases and as long as there are no packet losses, the value of PRR remains 1 and the throughput keeps growing (between points B and C1). If we continue decreasing CW, and due to the random nature of the CSMA strategy, some collisions usually appear. The throughput keeps growing until a maximum is reached (point D1) at the cost of reducing the PRR. From this point, a further decrease of CW causes a saturation of the channel: more collisions result in a reduction of both the PRR and the throughput. In the limit, as CW tends to zero, we approximate again point A. If the transmission threshold is changed (Txr_2), the operating regime has a similar shape, but this is characterized by its own operation points C2 and D2. Therefore, a CSMA protocol with a fixed predefined threshold works in some specific point of the operating regime curve, which is determined by the chosen value of CW. Furthermore, for a specific network, a maximum throughput $\Gamma_{\max}$ exists that can be attained without collisions (point O) by an optimal link scheduling strategy whose slot duration equals the packet transmission time. Although no CSMA protocol, due to its random nature, can reach this optimal point no matter what ED threshold strategy is used, its main purpose should be to work as close to this ideal point O as possible.

In Fig. 7 we plot the results of our experiments in the terms described before. It can be seen that the resulting shapes are similar to the ones in Fig. 6, and that higher values of the utility function imply smaller distances to the optimal point of the operating regime. As a matter of fact, our protocol obtains better operating regimes than both the standard IEEE 802.15.4 and the work in [24] for both unicast and broadcast schemes of communications. As expected, for a threshold of -100 dBm, better results are obtained when using small values of CW, while the opposite occurs for a threshold of -77 dBm. Note that the point (1,1) is not reached in these particular figures because we are using a maximum CW value of 2000, which is not large enough to reach the aforementioned point.

V. CONCLUSIONS

Throughout this work, we propose a reliable CSMA protocol suitable for both broadcast and unicast scenarios under high traffic demands in Wireless Sensor Networks. We first propose a utility function that considers jointly the packet reception rate and the throughput of communications. Based on this function, we propose a local indicator that nodes utilize to decide wether to transmit or not. Then, each node collaborates locally to increase the global utility function. Finally, we implement our CSMA protocol using a simulator and compare it with other related CSMA protocols based on ED thresholds. We show how our protocol outperforms them in terms of the utility function, presenting as a consequence better operating regimes in both broadcast and unicast scenarios.

REFERENCES

[1] Y. Hu, M. Dong, K. Ota, A. Liu and M. Guo. "Mobile target detection in wireless sensor networks with adjustable sensing frequency." *IEEE Systems Journal*, vol. 10, no. 3, pp. 1160-1171, 2016.

[2] L. M. Oliveira and J. J. Rodrigues. "Wireless sensor networks: a survey on environmental monitoring." *Journal of communications*, vol. 6, no. 2, pp. 143-151, 2011.

[3] V. C. Gungor and P. H. Gerhard. "Industrial wireless sensor networks: Challenges, design principles, and technical approaches." *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 4258-4265, 2009.

[4] C. Asensio-Marco and B. Beferull-Lozano, "Energy efficient consensus over complex networks." *IEEE Journal of Selected Topics in Signal Processing*, vol. 9, no. 2, pp. 292-303, March 2015.

[5] S. Mahfouz, F. Mourad, P. Honeine, J. Farah, and H. Snoussi. "Target tracking using machine learning and Kalman filter in wireless sensor networks." *IEEE Sensors Journal*, vol. 14, no. 10, pp. 3715-3725, 2014.

[6] C. Lu, A. Saifullah, B. Li, M. Sha, H. Gonzalez and Y. Chen. "Real-time wireless sensor-actuator networks for industrial cyber-physical systems," in *Proc. of the IEEE*, vol. 104, no. 5, pp. 1013-1024, 2016.

[7] C. Antonopoulos, A. Prayati, T. Stoyanova, C. Koulamas and G. Papadopoulos. "Experimental evaluation of a WSN platform power consumption," in *Int. Symp. on Parallel and Dist. Processing*, pp. 1-8, 2009.

[8] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves. "Energy-efficient, collision-free medium access control for wireless sensor networks." *Wireless Networks*, vol. 12, no. 1, pp. 63-78, 2006.

[9] S. Lim, S. Kim, J. Cho and S. An. "Medium access control with an energy-efficient algorithm for wireless sensor networks." *International Conference on Personal Wireless Communications. Springer Berlin Heidelberg*, pp. 334-343, 2006.

[10] J. Polastre, J. Hill, and D, Culler. "Versatile low power media access for wireless sensor networks." in *International conference on Embedded networked sensor systems*, pp. 95-107, 2004.

[11] M. Uddin, C. Rosenberg, W. Zhuang, P. Mitran and A. Girard. "Joint routing and medium access control in fixed random access wireless multihop networks." *ACM/IEEE Transactions on Networking*, vol. 22, no. 1, pp. 80-93, 2014.

[12] T. Kim, I. H. Kim, Y. Sun and Z. Jin. "Physical layer and medium access control design in energy efficient sensor networks: An overview." *IEEE Transactions on Industrial Informatics*, vol. 11, no. 1, pp. 2-15, 2015.

[13] L. Fu, S. C. Liew and J. Huang. "Effective carrier sensing in CSMA networks under cumulative interference. IEEE Transactions on Mobile Computing," vol. 12, no. 4, pp. 748-760, 2013.

[14] J. Zhu, X. Guo, L. Yang, S. Conner, S. Roy and M. M. Hazra. "Adapting physical carrier sensing to maximize spatial reuse in 802.11 mesh networks." *Wireless Comm. and Mobile Comp.*, pp. 933-946, 2004.

[15] T. Kim, L. Hyuk and J. C. Hou. "Improving spatial reuse through tuning transmit power, carrier sense threshold, and data rate in multihop wireless networks." in *Mobile Computing and Networking*, pp. 366-377, 2006.

[16] P. Huang, L. Xiao, S. Soltani, M. W. Mutka and N. Xi. "The evolution of MAC protocols in wireless sensor networks: A survey." *IEEE Communications Surveys and Tutorials*, pp. 101-120, 2013.

[17] E. Celada-Funes, D. Alonso-Roman, C. Asensio-Marco and B. Beferull-Lozano, "A reliable CSMA protocol for high performance broadcast communications in a WSN," *Global Communications Conference* (GLOBECOM), pp. 473-479, Dec. 2014.

[18] D. Alonso-Roman, E. Celada-Funes, C. Asensio-Marco and B. Beferull-Lozano, "Improving reliability and efficiency of communications in WSNs under high traffic demand," in *Wireless Communications and Networking Conference* (WCNC), pp. 268-273, April 2013.

[19] O. Goussevskaia, T. Moscibroda, and R. Wattenhofer. "Local broadcasting in the physical interference model," in *International workshop on Foundations of mobile computing*, pp. 35-44, 2008.

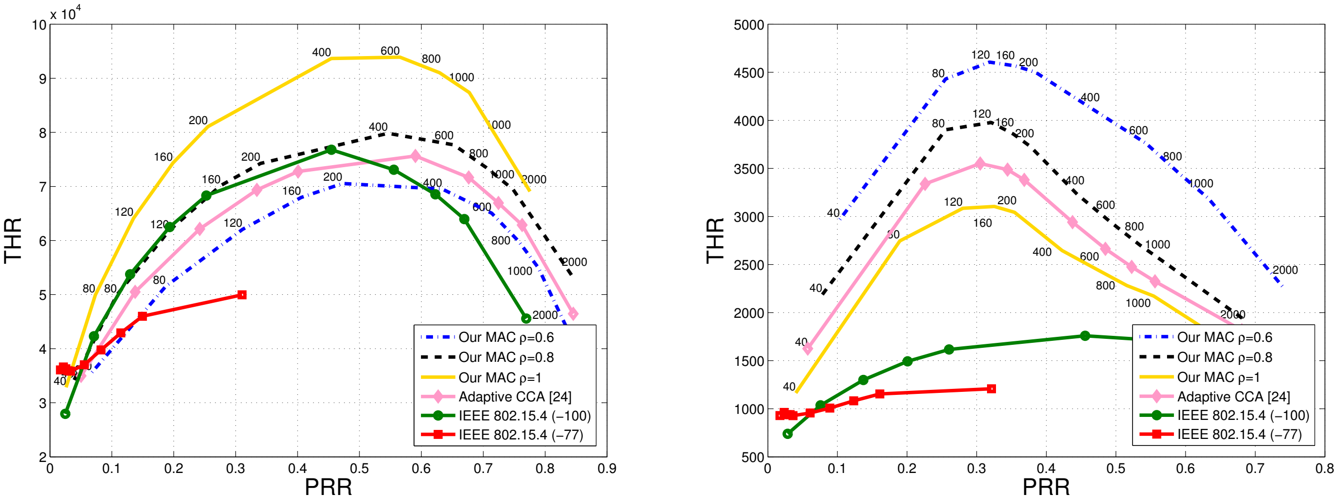
[20] P. Gupta, P.R. Kumar. "The capacity of wireless networks." *IEEE Trans. on Information Theory*, vol. 46, no. 2, pp. 388-404, March 2000.

[21] A. Goldsmith. "Wireless Communications." *Cambridge University Press*, January 2005.

[22] A. Dunkels, B. Gronvall, and T. Voigt. "Contiki- a lightweight and flexible operating system for tiny networked sensors," in *IEEE International Conference on Local Computer Networks*, pp. 455-462, 2004.

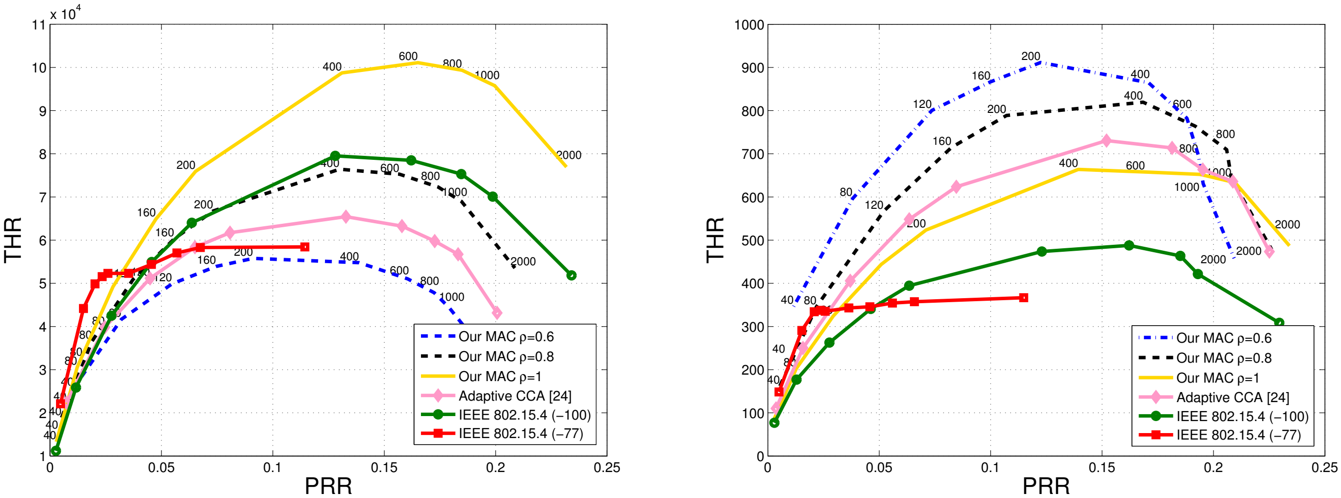
[23] P. Di Marco, P. Pangun Park, C. Fischione and K.H. Johansson. "Analytical Modelling of Multi-hop IEEE 802.15.4 Networks." *IEEE Trans. on Vehicular Techn*, vol. 61, no. 7, pp. 3191-3208, Sept. 2012.

[24] W. Yuan, J. P. M. Linnartz and I. G. Niemegeers. "Adaptive CCA for IEEE 802.15.4 Wireless Sensor Networks to mitigate interference," in *Wireless Communications and Networking Conference*, (WCNC), pp. 1-5, 2010.



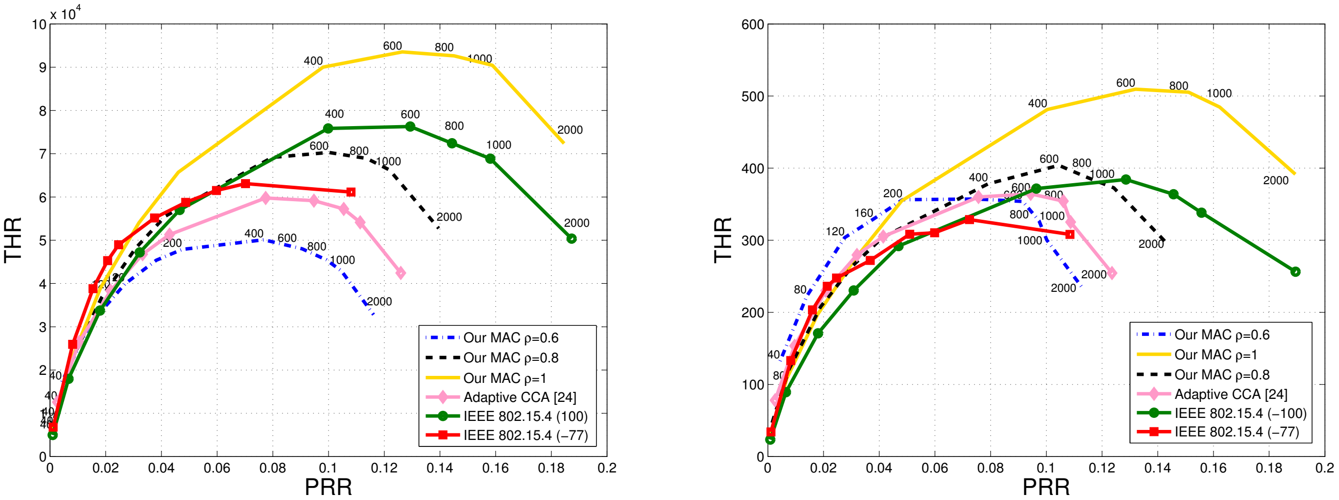
(a) Broadcast ($P_t = -15$ dBm)

(b) Unicast ($P_t = -15$ dBm)



(c) Broadcast ($P_t = -5$ dBm)

(d) Unicast ($P_t = -5$ dBm)



(e) Broadcast ($P_t = -1$ dBm)

(f) Unicast ($P_t = -1$ dBm)

Fig. 7. Maximum value of the utility function for the same three transmission power levels evaluated before. This figure has been generated by obtaining the value of CW that provides maximum utility value for the power level considered.

César Asensio-Marco received his B.S. degree in Computer Science and in Telecommunications from the University of Valencia, Spain, in 2006, and his M.Sc. in Electrical Engineering in 2008. He worked for five years as a research assistant in the Research Institute of Robotics in Valencia, Spain, participating in several national and international projects related with Information and Communication Technologies. In March of 2017, he received his Ph.D. degree from the University of Agder, Norway. Since then, he has been working as Postdoctoral Research Associate in the WISENET Lab, also in Agder. Currently he has joined the I2SysBio in Valencia, Spain, as a visiting professor, where he is involved in several projects for predicting the dynamics of Living Systems.

Baltasar Beferull-Lozano received his MSc in Physics from Universidad de Valencia, Spain, in 1995 (First in Class Honors) and the MSc and PhD degrees in Electrical Engineering from University of Southern California (USC), Los Angeles, in 1999 and 2002, respectively. In October 2002, he joined the AudioVisual Communications Laboratory, Department of Communication Systems, at EPFL, as a Research Associate, where he spent around three years. In December 2005, he joined the School of Engineering at University of Valencia as Associate Professor. Since August 2014, he is a Professor at the Department of Information and Communication Technology and (by courtesy) the Department of Engineering, University of Agder, Norway, where he leads the Intelligent Signal Processing and Wireless Networks (WISENET) Lab. He serves as a Senior Area Editor for IEEE Transactions on Signal Processing since 2016 and has also served as a member of the Technical Program Committees for several ACM & IEEE International Conferences. His research interests are in the general areas of distributed signal processing and communications for wireless sensor and communication networks, cross-disciplinary tools, data analytics and machine learning. At USC, Dr. Beferull-Lozano received several awards including the Best PhD Thesis paper Award in 2002 and the Outstanding Academic Achievement Award in 1999. He received the Best Paper Award at the IEEE DCOSS 2012 international conference. He has also received a TOPPFORSK Grant Award from the Research Council of Norway, 2015. He is a Senior Member of the IEEE.