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RESEARCH ARTICLE

Location-aided medium access control for low data rate UWB wireless sensor networks

Eirini Karapistoli*, Ioannis Gragopoulos, Ioannis Tsetsinas and Fotini-Niovi Pavlidou

Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Panepistimioupolis, 54124 Thessaloniki, Greece

ABSTRACT

This paper presents a distributed medium access control (MAC) protocol for low data rate ultra-wideband (UWB) wireless sensor networks (WSNs), named LA-MAC. Current MAC proposal is closely coupled to the IEEE 802.15.4a physical layer and it is based on its Impulse-Radio (IR) paradigm. LA-MAC protocol amplifies its admission control mechanism with location-awareness, by exploiting the ranging capability of the UWB signals. The above property leads to accurate interference predictions and blocking assessments that each node in the network can perform locally, limiting at the same time the actions needed to be performed towards the admission phase. LA-MAC is evaluated through extensive simulations, showing a significant improvement in many critical parameters, such as throughput, admission ratio, energy consumption, and delay, under different traffic load conditions. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS
wireless sensor networks; MAC protocols; ultra-wideband technology; IEEE 802.15.4a; call admission control

***Correspondence**
Eirini Karapistoli, Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Panepistimioupolis, 54124 Thessaloniki, Greece.
E-mail: ikarapis@ieee.org

1. INTRODUCTION

Wireless sensor networking is an emerging technology that assumes the deployment of large number of wireless nodes [1]. The driving force behind research in sensor networks is to develop systems that can operate unattended for years, a fact that calls for robust and energy-efficient solutions both at the hardware and software level. The IEEE 802.15.4 [2] standard and the industrial consortium supporting it, namely the ZigBee Alliance, is a valuable candidate for the energy-constrained wireless sensor networks (WSNs). It covers a large range of this technology's applications, varying from industrial monitoring, automation and control to connecting consumer electronics, many of which require location-awareness. Due to the importance of location-awareness, another standard for low-power wireless networks with extended application requirements and an alternative physical layer has been developed within the framework of the IEEE 802.15.4a Task Group [3]. The ultra-wideband (UWB) based physical layer standard is a spin-off to the IEEE 802.15.4 standard, having precision ranging capabilities, extended range, ultralow power consumption and robustness against interference and mobility.

UWB radio technology makes use of ultra-short pulses (<1ns) that yield ultra-wide signal bandwidth with instantaneous spectral occupancy in excess of 500 MHz. The IEEE 802.15.4a standard specifies two optional signaling formats based on IR-UWB and chirp spread spectrum (CSS). The IR-UWB system can use one out of three unlicensed UWB bands, whereas the CSS uses the unlicensed 2.4 GHz (ISM) band. For the IR-UWB option, there is an optional ranging capability, whereas the CSS signals can only be used for data communication. Since we investigate ranging for the proposed medium access control (MAC) protocol, we only focus on the IR-UWB option of the standard.

Various advantages result from the carrierless UWB technology, such as fine time resolution for accurate position estimation, feasible single chip architecture, highly secure transmissions, fading robustness and more [4]. What is worth mentioning, however, is that the very low transmission power of each node, which is determined by the FCC's emission regulations [5], appoints the use of the carrier sensing (CS) mechanism that is necessary for the CSMA/CA method of channel accessing, extremely difficult (one may perceive an ongoing transmission as noise, or *vice versa*). Hence, given the peculiar characteristics of the UWB radio technology, the MAC sublayer design should be revisited.

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In the traditional layered narrowband systems, such as in IEEE 802.15.4 protocol, MAC is achieved by temporally enforcing mutual exclusion between concurrent transmissions (no other communication is possible within the same collision region), either with a collision management protocol (unslotted CSMA/CA), or via a time-division-based scheme (slotted CSMA/CA). However, this is an over-cautious approach towards channel accessing. In fact, for UWB networks with low transmission power and large processing gain, instead of using a single data channel for transmissions, the use of multiple channels (spread by different time-hopping (TH) codes [6]) allows simultaneous transmissions in a neighborhood.

For a realistic UWB-based system, however, where the bandwidth is large but finite, uncontrolled simultaneous transmissions are not optimal [7], mostly because of the *near–far* phenomenon [8]. There are two main streams in the research of MAC protocols intending to alleviate this phenomenon, namely code (or channel) assignment and power/interference control. Code/channel assignment is necessary to allow multiple transmissions and avoid collisions, thus, increasing the system throughput. As orthogonal codes or channels may not be available all the time, power/interference control is necessary to guarantee quality-of-service (QoS) for the ongoing traffic flows. Yet, none of the existing UWB admission control proposals based on interference control, considered the inherent ranging support of the UWB signals. The adopted, by the 802.15.4a standard, localization protocol, utilizes UWB ranging information to define the power level and therefore the interference a potential transmission may introduce to ongoing transmissions in its vicinity. This transmission's admissibility can then be decided based on the measured interference. It is the above stated observations and inspirations that lead us to propose a location-aided MAC protocol for UWB sensor networks.

A preliminary design of a 802.15.4a-like MAC protocol was first presented in Reference [9]. In this article we describe several extensions we have made to this work. First, we have updated the core of the admission control function. Second, we have altered the way network resources are allocated towards the admission phase, using a threshold-based selection algorithm. Finally, we have tested the protocol's performance under both one-hop and multi-hop network topologies. As it will be shown, the results confirm our previous findings that the MAC protocol currently suggested by the IEEE 802.15.4a standard can be upgraded by exploiting the UWB PHY's ranging capability. The good characteristics of the protocol were confirmed via simulations, where significant gains in performance were witnessed in terms of increased network throughput, lifetime, as well as, reduced control overhead and connection latency.

To summarize, the contribution of the proposed MAC protocol is twofold:

- by taking advantage of the ranging support provided by the UWB signals, it amplifies the admission control strategy with location-awareness;
- based on ranging messaging, it vehiculates the local information about measured interference, authorizing the admission control to be implemented locally by every node, thus limiting the actions needed to be performed towards the admission phase.

The remainder of the paper is organized as follows: in Section 2 existing medium access methods proposed for UWB networks are outlined. In Section 3 we introduce several features of the underlying physical layer in order to provide a better understanding of the UWB LA-MAC protocol. In Sections 4 and 5 we present the proposed MSI-based admission control mechanism and a detailed description of the location-aided MAC protocol. Section 6 illustrates the obtained simulation results, followed by detailed reports. Finally, conclusions are given in Section 7.

2. RELATED WORK

Researchers are actively studying the UWB transmission technique and attempt to design specific MAC protocols that take advantage of the strengths of this new technology.

Cuomo *et al*. [10], were the first to explore the issue of admission control in UWB networks. Their proposal follows an interference margin (IM)-based approach. Relying on that principle, a distributed admission control function is obtained based on the evaluation of the interference generated by each potential new link over active links. The admissibility of a new link is determined by predicting its effect on the signal-to-noise-plus-interference ratio (SINR) characterizing each active link. Then, if the new link is admitted, its power or rate is adopted to the level of interference. However, this scheme implies a constant monitoring of all the peer-to-peer connections, thus, in a distributed UWB network it is far too complex for the power levels of all the existing links to be reconfigured when there is a call arrival/departure. Moreover, upon a new call admission/completion, each node needs to update and broadcast its IM value, appointing the associated overhead to be very high.

On a variation of the previous work, U-MAC [11], suggests a proactive method of assigning power and rates to the network nodes. It uses periodic HELLO messages to exchange local state information. Based on that information, a node can compute the interference levels and hence deduce the power and rate that it can assign to its own link. However, even though the periodicity of the hello messages is adaptive (based on the node stability), it may lead to a burst of hello messages when a new link causes state changes to a number of nodes. Moreover, the simulations were limited to a single hop case, although the authors mention that the scheme can be generalized to support multi-hop topologies, while no simulations exist to account for the induced overhead of the periodic HELLO announcement and the link set up latency. Again, the protocol does not address how to use UWB to facilitate channel accessing.

DCC-MAC protocol [12], on the other hand, based on the preliminary work presented in Reference [13], proposes to take advantage of the infrequent nature of collisions at the pulse level by using interference mitigation. The decoder declares the outputs of the receiver that are abnormally high as erasures (i.e., when a pulse collision occurs with a near-far interferer). The loss of information due to erasures is recovered by the error correcting code. At the cost of a small rate reduction, it alleviates the effect of one or several near-far interferers located within an exclusion region. The authors also propose a private MAC to resolve contention between multiple sources and a single destination. Still, this design may never achieve the high data rates of the other currently proposed protocols, because of the requirement for large pulse repetition periods (PRPs).

In Reference [14], the authors present a pure ALOHA access strategy appropriately tailored to the UWB physical layer. According to their findings, multiple access using a TH-IR scheme (a combination of common and transmitter-specific TH codes), implies that uncoordinated transmission of data has high probability of successful delivery due to MUI resistance of the UWB signals. In UWB^2, access to a destination is achieved through the RTS-CTS exchange at a common broadcast channel, while the subsequent data transmission uses the particular TH sequence proposed in the CTS packet. Yet, UWB^2 was evaluated through limited simulations where nodes were organized in single hop topologies not suited for WSNs.

In a second category, that of the TDMA-based MAC protocols that have been proposed for 802.15.4a-like UWB sensor networks, the work proposed by Jiang *et al.* [8] is the most representative one. Their protocol aims at an effective resource management scheme that relies on a frame transmission structure tailored to the UWB characteristics. While the proposed control message exchange procedure needs network-wide synchronization via beacon frames, the admission decision is distributed to the so called slot heads (similar to the idea of clusterhead in clustered networks). However, their work appears to be complex, while it may also lack scalability in large UWB networks.

Various other studies, are focusing on the enhancement of the existing narrowband WPAN MAC, namely the 802.15.3 [15] standard, to make it fit the UWB technology. These works include the complementary code-code division multiple access (CC-CDMA) MAC protocol [16], the positioning-enabled MAC (PAMAC) [17], as well as, the works in References [18,19]. Another such example, is the Ultra-wideband Concepts for *Ad hoc* Networking (U.C.A.N.) project [20], adding ranging and relaying features. All mentioned works, concentrated their research in proposing efficient slot assignment procedures that administer the piconet coordinator (PNC) with the admission control. Despite the fact that synchronization is relatively easy because of the piconet approach, this centralized concept works only for wireless personal area networks (WPANs). Hence their applicability is limited and non-scalable to large networks.

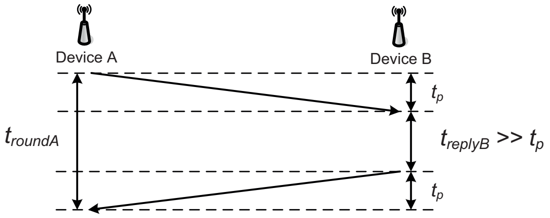

Figure 1. Exchange of message in two-way ranging [3].

Our work distinguishes itself from previous works in several significant ways. First, it presents a distributed location-aware admission control protocol, with the latter asset expected to prevail in typical 802.15.4a applications. Second, it fully exploits the UWB PHY's ranging support, which allows the easy and low complexity adoption of several basic ideas towards link admissibility. Third, the correctness of our proposal and validity of the incorporated mechanisms are verified by running a full-fledged simulator.

3. PRELIMINARIES

3.1. UWB ranging support

Ranging in 802.15.4a standard is an optional capability achieved through support of a number of specific PHY capabilities as well as defined MAC behaviors and protocols. In the UWB PHY option of the standard, the mandatory ranging protocol is the two-way ranging (TWR) depicted in Figure 1, which allows for ranging measurements based on the round trip delay between two stations, without the need for a common time reference [21]. In this scheme, the ranging-capable device A (RDEV) begins the session by sending a range request packet to device B. Then, device B waits a time $t_{\text{reply}B}$, known to both devices, to send a request back to device A. Based on that packet, device A can measure the round-trip time $t_{\text{round}A} = 2t_p + t_{\text{reply}B}$ and extract the one way time-of-flight t_p with respect to its own reference time.

Because of the large instantaneous bandwidth of the UWB signals and their reduced sensitivity to multipath propagation, accurate ranging estimations of less than 3 ns are feasible [3], corresponding to less than 1 m spatial uncertainty [22]. The two-way frame exchange described earlier, provides the initiator device with one-way position awareness. As it will be seen, this ranging dialogue, which precedes the actual DATA/ACK transmission so as to accompany the MSI announcements, represents an integral part of the LA-MAC protocol's functionality.

3.2. The frame structure

In IEEE 802.15.4a networks, devices communicate using the packet format illustrated in Figure 2. Based on that, we define two types of transmitted frames, namely *data frames* and *ranging frames*. Data frames are used in peer-to-peer

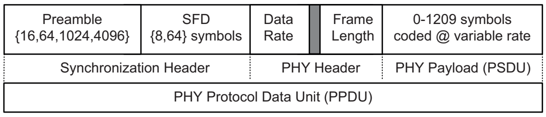

Figure 2. Illustration of the IEEE 802.15.4a packet structure (the gray portion indicates the ranging bit).

communications so that the nodes comprising the WSN can exchange gathered information, while ranging frames are utilized in support of the UWB ranging functionality and enable the requesting nodes to make ranging measurements based on the TWR technique. The packets used for ranging estimation are standard packets, with the only difference being the value of a specific bit in the PHY header (PHR) called the 'ranging bit', which is set by the transmitting PHY for frames intended for ranging. A UWB frame with the ranging bit set in the PHR is called a ranging frame (RFRAME). There is nothing else, beyond the ranging bit, that makes an RFRAME unique. FRAMEs can carry data or can even be acknowledgments.

4. ADMISSION CONTROL STRATEGIES

In this section, we present the generic MSI-based admission control strategy, and its location-aided alternative that the LA-MAC protocol implements. Prior to that, we introduce some notations and assumptions concerning the channel model:

UWB network: We consider an UWB wireless network covering a small area, where each node can hear any other node's transmission as long as it tunes to the transmission code and the received SINR exceeds a threshold.

Traffic requests: We first define a transmission session as a link, which is denoted by $l(s, r)$, between node s (the sender node) and node r (the receiver node). For the QoS traffic request that is defined in this study, we have $\{l(s, r), R_s\}$, where R_s is the bit rate requirement of node s.

Control channel: Besides having UWB channels for data transmission, we assume there is a control channel used to exchange control messages.

Path gain: Every node in the network is assumed to know the path gain to every other node in the network. Similar to Reference [23], we assume there is no fast fading, and the power at the receiver is attenuated due to path loss. As such, the path gain between the transmitter s and the receiver r of link $l(s, r)$ can be represented as $g_{sr} = d_{sr}^{-\alpha}$, where d_{sr} is the distance between these two nodes (obtained through the use of the ranging algorithm described in Section 3.1) and α is the path loss exponent, typically between 2 and 4. The above definition can be generalized to denote the path gain between any active transmitter and any receiver in the network.

4.1. MSI-based admission control

According to the analysis provided in Reference [6], the SINR at the receiver of link i, where the link quality is seen, is a linear function of the transmission rate:

$$\mathrm{SINR}_i = \frac{P_i g_{ii}}{R_i\left(\eta_i + T_f \sigma^2 \sum_{j=1, j\neq i}^{N} P_j g_{ji}\right)} \tag{1}$$

where P_i denotes the average transmission power of the transmitter of the ith link, g_{ji} the path gain between the transmitter of link j and the receiver of link i,[†] R_i is the bit rate of the ith link, η_i the background noise energy plus interference from other non-UWB systems, T_f the pulse repetition time, σ^2 is a parameter depending on the shape of the pulse and N is the number of nodes in the network.

In a following analysis performed by Cuomo *et al.* [10], the channel capacity for UWB networks is bounded by the SINR threshold, say γ_i. This means that the network QoS provisioning has to provide each link with a power/rate guarantee under the constraint of the required SINR threshold. In this study, we do not differentiate the services among the links, hence, this threshold is common to all links, i.e., $\gamma_i = \gamma, \forall i = 1, .., N$. It becomes apparent that in order to achieve successful transmissions, we should maintain the receiver-side SINR ratio over this threshold. Therefore, the following inequality should hold for the ith link to be performed:

$$\mathrm{SINR}_i = \frac{P_i g_{ii}}{R_i\left(\eta_i + T_f \sigma^2 \sum_{j=1, j\neq i}^{N} P_j g_{ji}\right)} \geq \gamma \tag{2}$$

An optimal solution, where all the potential new links could be dynamically admitted, would require a constant reconfiguration of powers/rates in order for the links to adapt to every network change, i.e., new link accesses or releases. However, since an *ad hoc* network is of concern, this would lead to increased complexity in the MAC implementation. Conversely, in LA-MAC, every node follows the $\{0, P_{\max}\}$ power strategy as suggested in Reference [23], which corresponds to the extreme choice of either zero or maximum power level transmission, while the assigned transmission rates are appropriately selected (see Section 4.2.2) so as QoS (i.e., SINR requirement) for the ongoing traffic flows are respected upon the new transmission joining the network.

Inequality (2) can be further analyzed. A term, denoting the maximum sustainable interference (MSI) each link can tolerate, is thus added:

$$\gamma = \frac{P_i g_{ii}}{R_i\left(\eta_i + T_f \sigma^2 \sum_{j=1, j\neq i}^{n} P_j g_{ji} + \mathrm{MSI}_i\right)} \tag{3}$$

[†] accordingly, g_{ii} represents the path gain between the transmitter and the receiver of link i.

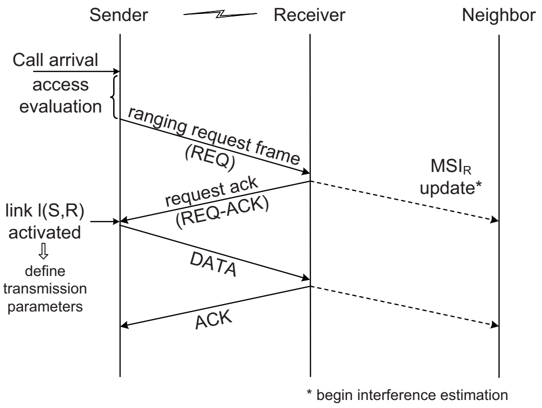

Figure 3. Signaling procedure in LA-MAC.

From Equation (3), we can extract the MSI_i value of the receiver of the ith link:

$$\mathrm{MSI}_i = \frac{P_i g_{ii}}{R_i \gamma} - \left(\eta_i + T_f \sigma^2 \sum_{j=1, j \neq i}^{n} P_j g_{ji} \right) \qquad (4)$$

This value is updated upon every other new link access/release or the receiver's own activity and should be kept nonnegative in order to satisfy the transmission accuracy of the link. To sum up, an efficient MSI-based admission control protocol should guarantee the aforementioned requirement by allowing only those transmissions to occur that do not violate the active MSI values.

4.2. Location-aided admission control

LA-MAC protocol requires the nodes to advertise their local states through ranging messages, a process which facilitates the interference and distance estimations taking place during the admission control. These messages are exchanged every time a link request is initiated from two communicating nodes. In particular, one RFRAME (namely REQ) is sent during the request phase and one during the response (namely REQ-ACK), with the latter acting as an announcement of the receiver's node MSI value. After collecting the receiver's node reply, the sender node selects the parameters of the new link (that are locally admitted) and immediately sets up the link. Figure 3 illustrates the control message exchange in LA-MAC.

A node other than the intended receiver, i.e., the sender of a potential new link, node j, upon receiving a ranging frame begins interference estimations. By overhearing this frame, this node learns and caches the instantaneous MSI value of the receiving node involved in the ith active link (say MSI_i). It also knows its location from previous TWR measurements and the antenna gain and transmission power as of hardware specification. Using the designated path loss model described by Shellhammer [3], the sender of link j can measure the UWB path loss in dB at some distance d and then calculate the power level of its own transmission at both the source P_j^s and the destination P_j^d of the ongoing delivery. Accordingly, based on that measurements node j estimates the produced additional interference, namely the AIF_j^s and AIF_j^d values, by using the expression:

$$\mathrm{AIF}_j^k = T_f \sigma^2 P_j^k g_{jk} \qquad (5)$$

where the k index corresponds to the sender s or the destination d of the ongoing transmission. Expression (5) may also be seen as the link's i MSI reduction due to the activity of node j. The admissibility of the link j can be decided such that the additional interference (due to the new admitted link) is limited within the MSI_s and MSI_d margins of the source and the destination of the active link i. Thus, the decision of whether node j should block its own transmission is made as follows:

$$\text{if } \left\{ \mathrm{MSI}_s - \mathrm{AIF}_j^s \geq 0 \right\} \text{ AND } \left\{ \mathrm{MSI}_d - \mathrm{AIF}_j^d \geq 0 \right\} \qquad (6)$$

then the call is admitted with QoS satisfaction; otherwise, the call is blocked (temporal exclusion case). Thereby, in LA-MAC, a non-receiver station (such as node j) will postpone its transmission when it determines that it will produce enough energy to disturb the ongoing delivery. What is more, it is noteworthy that the resulted admission control function considers the sender s of the ongoing delivery as well, in order to secure the node for the reverse communication direction (during ACK).

In general, when n links are active in the neighborhood, in order to ensure the transmission accuracy of all the links the transmitter of the new call request, node j, should check whether it can be assigned with the maximum allowed transmission power while not violating the MSI margins of all the existing links (i.e., the MSI of all active links should be kept nonnegative):

$$\text{for } P_j = P_{\max} \Rightarrow \min_{k \neq j} \left\{ \mathrm{MSI}_k - \mathrm{AIF}_j^k \right\} \geq 0, \forall k \qquad (7)$$

Even if the MSI value of one active link will become nonnegative, the call request should be rejected as otherwise it will corrupt this reception. Expression (7) represents the admissibility criterion of our protocol. As it can be seen, the resulted admission control function policies the concurrent transmissions allowing them to occur when possible. Since we assume that the nodes do not cooperate with each other, the distributed protocol can operate in an non-cooperative mode. In this mode, once a node starts to transmit, it will not change its transmission power or bit rate during the transmission.

4.2.1. The link state table.

Each node needs to keep track of other nodes' most recently advertised state information. In doing so, each node has a 'link state' table. In every record the node maintains the following information; neighbor's ID, estimated distance (from TWR measurements), neighbor's current MSI value, produced interference (AIF_{ij} indicator) and a timer that enables the owner of the table to properly update/remove the MSI entries according to accesses/releases of active interference sources. By using this timer, we ensure that the MSI estimate, once generated, is used until it becomes outdated.

Each node updates this table upon receiving an RFRAME. Such a frame is being exchanged during the link-request/link-response phase described before, and enables the communicating nodes to exchange MSI-related indices. The broadcasted information attached to each ranging frame varies depending upon the sender or the receiver of the link. For example, the sender node announces part of its link state table, the tuple $\{i, \mathrm{AIF}_{ji}\}$. A node overhearing this information, will need to re-calculate the MSI margin of node i by subtracting the AIF_{ji} value from the MSI_i one, and update the timer entry accordingly. Recall that the AIF indicator is seen as the link's i MSI reduction due to the activity of link j. Moreover, by this, the active neighbors are not required to broadcast again and again their MSI values upon a new link admission. It is apparent that this automated process allows for accurate interference report, while reduces the complexity at the MAC layer since information exchange is incorporated into just one ranging dialogue. On the receiver's side, the recipient node will have to report its current MSI margin only. By announcing its MSI value by means of the ranging response frame, the receiving node precludes other nodes from claiming access if its MSI were to be violated causing service degradation at this link's transmission. Having all this available information, each node can decide on its own link admissibility based on the criterion (7).

4.2.2. Resource allocation algorithm.

Rate assignments in LA-MAC take place at the sender node upon a ranging dialogue has been exchanged. Resource allocation involves using the link quality indications that reside in the received ranging frame, i.e., the receiver node's SNR estimate or equivalently the MSI estimate, given the dependency of these two metrics, to choose an admissible rate for the upcoming data transmission of link j, $R_j = R_{\mathrm{admitted}}$.[‡]

In UWB systems, the data rate is defined as $R = 1/(N_s T_f)$, where N_s is number of pulses used for transmitting one data symbol and T_f represents the pulse repetition time. The bit rate R can thus be altered by adjusting either the N_s or the T_f parameter. Despite the obvious flexibility, the admissible data rates supported by the IEEE 802.15.4a standard are the mandatory data rate of 851 kb/s and the optional data rates; 110 kb/s, 6.81 Mb/s, and 27.24 Mb/s (all resulting from a combination of the two aforementioned parameters) [24]. While the latter two data rates are not of the interest of a low rate MAC protocol, the 250 kb/s, 40 kb/s, and 20 kb/s ones, which are compliant with the IEEE 802.15.4 standard [2], are more suitable. Overall, the proposed rate allocation algorithm results in a $n = 5$ predefined set of admissible data rates.

We consider a threshold-based selection algorithm to enable local rate assignments. This means that we choose the rate heuristically by comparing the reduction each of the admissible data rates produces to the announced MSI_j margin. The highest data rate that satisfies the performance objective for the channel quality estimate, i.e., it keeps the MSI_j nonnegative, is the chosen rate.

In more details, let $R_1 > R_2 > \ldots > R_n$ be the set of the admissible data rates in decreasing order, and $\mathrm{MSI}(R_1) < \mathrm{MSI}(R_2) < \ldots < \mathrm{MSI}(R_n)$ the diminished MSI values in increasing order. Recall that R is inversely proportional to MSI according to Equation (4). The protocol would then choose the rate as follows;

$$R = \begin{cases} \max\{R_j\}|_{\mathrm{MSI}(R_j)\geq 0} & , j = 1, 2, \ldots, \text{ or } n \\ 0|_{\mathrm{MSI}(R_j)<0} & , \forall j = 1, 2, \ldots, n \end{cases} \qquad (8)$$

i.e., set R to the highest possible data rate, $\max\{R_j\}$, $j = 1, 2, \ldots,$ or n, given that it keeps the $\mathrm{MSI}(R_j)$ margin nonnegative. If this is not the case, i.e., $\forall j = 1, 2, \ldots, n$, $\mathrm{MSI}(R_j)$ is reduced to a negative value, then data rate assignment is not feasible, thus, set $R = 0$. From the above rate selection scheme, it becomes apparent that, link j maximizes its rate when there is no other active link in its vicinity.

5. HIGH-LEVEL PROTOCOL OPERATION

At this point we provide a high level overview of our protocol. The protocol implementation at each node can be represented by the finite state machine shown in Figure 4. Initially, a node is in the IDLE state. When a call request arrives from the upper layers, it enters the REQUEST state. In this state, it advertises its request to the intended recipient after evaluating the ambient interference levels (access evaluation phase). Towards this, it transmits the request by sending out a ranging frame over the control channel. If the request were to succeed (authorized request), the node enters the TRANSMIT state, switches to a dedicated channel and sends the data packet. After successfully completing the transfer, including the ACK reception, the node returns to the IDLE state. On the contrary, if the request were to fail (blocked request), the node enters the BACKOFF state and tries again at a later time. In case it fails to authorize its request after several attempts (dropped request), it returns to the IDLE state.

[‡] Note that control frames (ranging dialogues and ACK frames) are being transmitted at $R_{\mathrm{base\,rate}}$ instead.

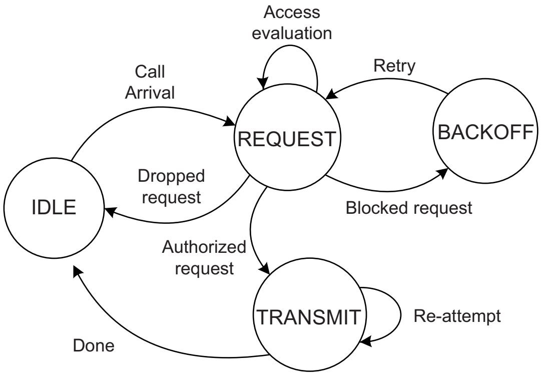

Figure 4. Depiction of the protocol's operations.

5.1. Detailed protocol description

Request Initiation: When a call request arrives from the upper layers, a node will notify the intended receiver by sending a ranging request frame (REQ) over the control channel. Our design mandates that the transmission of the request is to be initiated after the link state status of the sender's table authorizes it. This process is referred to as the 'access evaluation phase' and enables the requesting node to evaluate the ambient interference levels prior to initiating its transmission request. This timing requirement further implies that an in-progress transmitted ranging dialogue from two neighboring nodes, shall be completely received so as for the potential sender to make accurate interference predictions. After successfully transmitting the request, the sender node awaits for a response from its intended receiver. In the case that the link state parameters do not allow a request to be send, the sender node will have to wait for the corresponding timer entry to expire before re-initiating its request.

Acknowledgment of the Request: If the REQ packet is correctly received, the receiver will send a REQ-ACK packet (request acknowledgment) to the originating sender, turning on the ranging bit in response to its ranging request. If the REQ-ACK packet is successfully received by the sender, it completes a successful handshake and the sender can then begin the data transfer. In case the REQ-ACK packet cannot be decoded, the requesting node cannot accurately estimate whether its recipient is ready to receive a packet, and by adopting a conservative approach, it blocks its transmission.

Link Activation and Data Transfer: As already revealed, the reception of the REQ-ACK packet activates the link and enables the call originating node to proceed with the data transfer. The node enters the TRANSMIT state and proceeds to rate reconfigurations by invoking the rate allocation algorithm stated in Section 4.2.2. Accordingly, the power and rate of the upcoming data transfer are allocated as follows; $P_i = P_{\max}$ and $R_i = R_{\text{admitted}} = f(\text{MSI}_i)$. The node then transmits the data packet using a pair-specific TH code C_{ij}, which is unique for the sender-receiver pair $\{i, j\}$. This information resides in the PHY header of each packet (it is the rate that is mapped to a specific code) and enables the dynamic channel assignment at each node. Immediately after successfully receiving the data packet, the receiver sends an ACK packet (data acknowledgment) to the sender node. The admission control is kept suppressed during the ACK transmission, in accordance with the standard. If collisions or other factors corrupt the data packet, and the receiver is unable to correctly decode it, it does not issue an ACK back to the sender. The sender would then reattempt to transmit the packet up to a fixed number of times after which the packet is dropped. In light of a dropped packet, the node returns to the IDLE state. According to Reference [3], each node will attempt three times before notifying the higher layer of a link failure.

The BACKOFF State: In case (a) there were more than one REQ packets that collided or (b) the receiver is busy transmitting elsewhere, the sender node enters the BACKOFF state. To elaborate on case (a), if two (or more) nodes transmit their REQ packets to a common receiver at the same time, a collision will occur. The sender nodes after waiting for a *macACKwaitDuration* symbols, they conclude that a collision has occurred. They will then initiate their backoff timers and at the end of their backoffs they will re-attempt to initiate their request. In case (b), where the receiver is busy sending data, it does not receive the REQ packet. The sender will, as in the previous case, await for the REQ-ACK packet, which it does not arrive. The sender cannot distinguish this case from case (a) in which a collision occurs. Therefore, it enters the BACKOFF state and reattempts a request at a later time.

6. PERFORMANCE EVALUATION

6.1. The simulation model

In this section, we present a *ns*2 simulation-based study to evaluate the performance of the LA-MAC protocol for different parameters, such as the traffic rate, λ, and the number of nodes, N. Our simulation used the UWB PHY module developed by Merz *et al.* in Reference [25]. Modifications were made in order to comply with the functionalities described in the finite state machine of Figure 4. Towards this, we have set the transmit power to be static and we have suppressed the dynamic channel coding feature. We have also upgraded the code to account for the admission control function embraced by the LA-MAC protocol.

We compare the performance of the LA-MAC protocol to that of a proactive MAC, namely the U-MAC protocol. The different parameters of the U-MAC protocol were simulated as they appear in the literature [11]. As such, the maximum and minimum periods for triggering hello messages, $T_{\max}$ and $T_{\min}$, were set to 10 and 1 s respectively, while their size was 64 bits. The MSI threshold was kept equal to 10%, and the interference threshold equal to 50%. However, we had to restrict the transmission power and rate to comply with the 802.15.4a specifications. Towards this, $P_{\max}$ was set equal to -14 dBm, while the upper and lower limits for the rate were 851 and 20 kbps respectively. A third

Table I. Simulation settings.

Parameters	Values
α	2.4
σ^2	1.996×10^{-3}
η	2.568×10^{-17} mW/Hz
γ	7 dB
T_f, N_s	Adjustable
Maximum bit rate $R_{\max}$	851 kbps
Transmission power $P_{\max}$	−14 dBm (39.8 μW)
Poisson arrival rate λ	0.5–4.0 calls/s
DATA packet length L	161 bytes
Number of nodes N	From 5 to 25
Area size	20 × 20 (one-hop) 50 × 50 (multi-hop)

scheme is considered for comparison purposes as well. It is the IEEE 802.15.4a MAC protocol adopting the CCA Mode 4 (pure ALOHA access), where the UWB preamble sensing is disabled. It can be seen as a protocol implementing 'no admission control' rules, i.e., a packet is transmitted as soon as it becomes head-of-the-line, and in the figures' legend it is mentioned as NoAC-MAC. This is not the case for the LA-MAC and U-MAC protocols, since both assume a signaling and measurement phase before any transmission can start, towards verifying their respective admission criteria. What is more, the transmission parameters ($P = P_{\max}$ and $R = R_{\max}$) of the NoAC-MAC remain unmodified during the simulation period.

We have simulated an area of 50 m × 50 m with 25 nodes organized under one-hop topologies (nodes have overlapping radio ranges) and multi-hop topologies. Each node was characterized by a radio transmission range of 15 m and a radio interference range of 20 m. Two different types of traffic that are typical of sensor networks are considered in our study; a *peer-to-peer* and a *sink-type* application traffic [26]. The former case comprises of a set of connections which are constructed as pairs of stationary sender and receiver nodes, while the latter, represents traffic driven by data gathering applications where a sink located either at the corner or the center of the network, collects the relayed data for further processing. The traffic flows are generated based on a Poisson process (with rates λ varying from 0.25 calls/s to 4 call/s). Table I summarizes the main simulation settings. Each simulation is run for 3600 s and each point on the curves to be presented is an average of 50 simulation runs.

The protocols are compared in terms of the following performance metrics:

(1) Average network throughput: average number of bits transmitted by all network nodes over the simulation time.
(2) Call admission ratio: the ratio between the number of admitted links and the total number of link requests generated in the network.
(3) Average power consumption (accounts for the network lifetime extension): in order to calculate this metric we borrowed the chip-level energy-model described in Reference [7]. In this model, the energy consumption is represented by a vector $\overrightarrow{q} = [q_{tx}, q_{rx}, q_{ao}]$ consisting of three states: the q_{tx} that is defined as the cost of transmitting a pulse, q_{rx} that of receiving a pulse, and q_{ao} that of being in the active-off state (the cost for sleeping is fractional). The q_{ao} energy state occurs due to time hopping (when a node is between two pulse transmissions or receptions, energy is consumed only to keep the circuit powered up). In our analysis we used a scenario where a higher cost for reception and a lower cost for active-off is implied, i.e., $\overrightarrow{q} = [1, 5, 0.5]$.
(4) Average packet delay: is the average end-to-end delay of a packet from its birth up until correct reception at the destination. Given the above description, this metric also accounts for the link setup latency.

Next, we assume that all protocols can operate in a distributed manner, having no prior knowledge of the network topology, and that during tests they share the same network parameters and conditions.

6.2. Simulation results

6.2.1. One-hop topology.

For our first set of simulations, we varied the number of active links located within the one-hop neighborhood in order to verify the protocol's robustness to interference. We utilized parallel links, where the sender of a link is close to the receiver of the nearby link, thus making the near-far problem stronger. In this scenario, each sender node generates packets at a call arrival rate λ equal to 2 calls/s.

In Figure 5(a), the overall achievable throughput in the network is shown. As the number of nodes increases, MAC protocols with admission control outperform the NoAC-MAC. The performance of NoAC-MAC quickly drops as the number of interference sources increase, showing that the lack of admission control limits the potential number of coexisting links. What is more, in low load conditions (fewer nodes in the network), the throughput of LA-MAC is similar to that achieved by the U-MAC protocol. The gap starts to widen when the number of active links is above 6 and reaches a maximum of about 40% at very high interference conditions. This is not surprising, because nodes in U-MAC, by making periodic hello announcements so as to exchange local state information, increase the protocol's control overhead and negatively affect the network throughput. In LA-MAC instead, nodes stay updated about the neighbors' status by overhearing only the exchanged ranging dialogues that precede the actual data transfer, a fact that keeps the control overhead to the minimum.

Figure 5(b) shows the ratio between the number of admitted links and the total number of link requests generated in the network, with respect to the increase in the number of nodes. We can observe that the NoAC-MAC protocol's uncontrolled link admission (pure ALOHA access) leads to a narrow call admission ratio equal to 15% when the

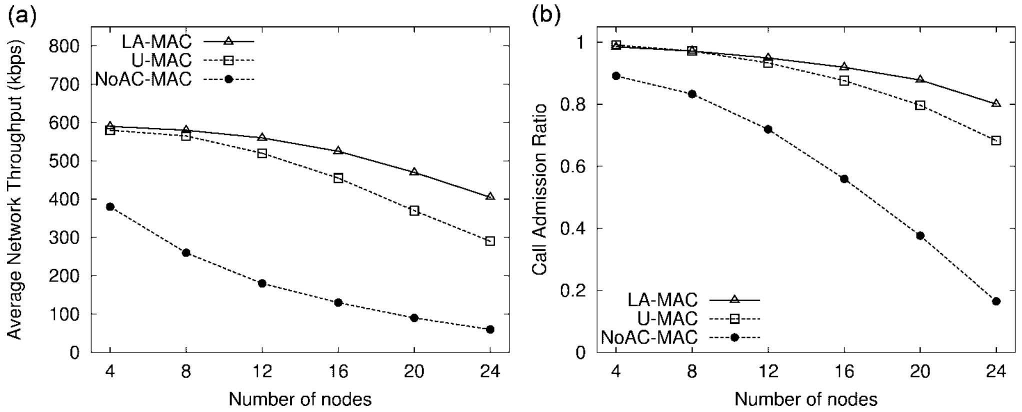

Figure 5. (a) Average network throughput and (b) call admission ratio with respect to increasing number of active links.

number of nodes is high. In low load conditions, the rest of the protocols seem to admit the same number of requests. This reveals that in lightly populated networks, LA-MAC and U-MAC protocols behave similarly. The increase in the number of nodes causes a drop in the number of concurrently admitted links for both protocols. In such conditions, LA-MAC achieves, however, a call admission gain of 12% when compared to that achieved by U-MAC. This happens because in U-MAC, as the link request rate grows, state changes occur more frequently, and as a result nodes have less accurate information about their neighbors' states, a fact that affects the admitted rate. All-in-all, our location-aided admission strategy, as opposed to the proactive one followed by the U-MAC protocol, makes a difference in the average admission ratio. Though it is not that big, it is indicative of the characteristics related to the protocols' admission control phase.

Next, we perform a network lifetime comparison between the simulated protocols taking into account the energy model described earlier. Once again we varied the number of nodes lying in the same neighborhood. From Figure 6(a) we can see that the protocols under test have nearly the same power consumption when the number of nodes is small. As expected, with further increment of this number, the power consumption of all the protocols grows, but our proposal maintains the examined metric at the lowest levels. The relative difference between LA-MAC's curve and that of the rest protocols steadily grows. In dense network conditions, i.e., 24 nodes, the difference is quite large and the average power consumption of the LA-MAC protocol is about 76 and 85% reduced, when compared to the U-MAC and NoAC-MAC protocols respectively. Besides to its low associated overhead (recall that there is no need for an extra mechanism to broadcast MSI values), this is also attributed to the fact that the protocol is less time consuming in processes such as packet retransmission and collision resolution. On the other hand, the periodic hello announcement in U-MAC increases the protocol's overhead and the time the nodes need to remain active in order to accommodate the requests, thus increasing the average power consumption at the nodes.

Simulation results concerning the measured packet latency are illustrated in Figure 6(b). In this figure the vertical axis represents the attainable average packet delay, whereas the horizontal axis resembles the number of nodes. We can see that the average MAC delay achieved by the LA-

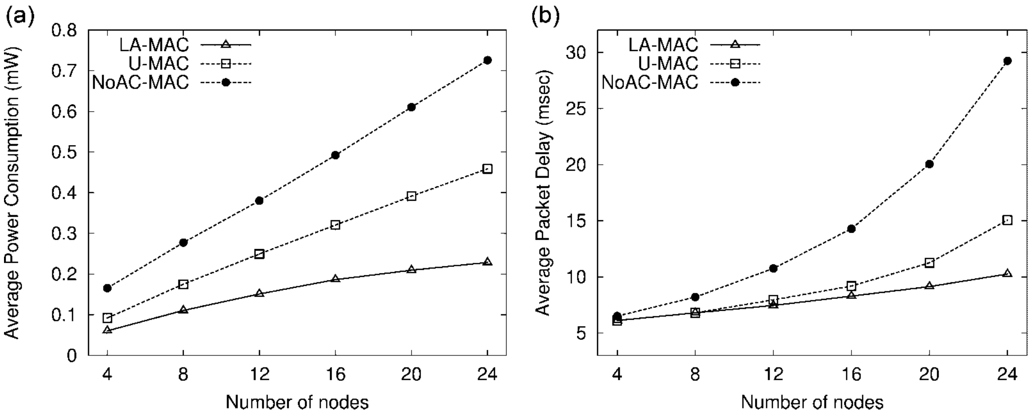

Figure 6. (a) Average power consumption and (b) average packet delay with respect to increasing number of active links.

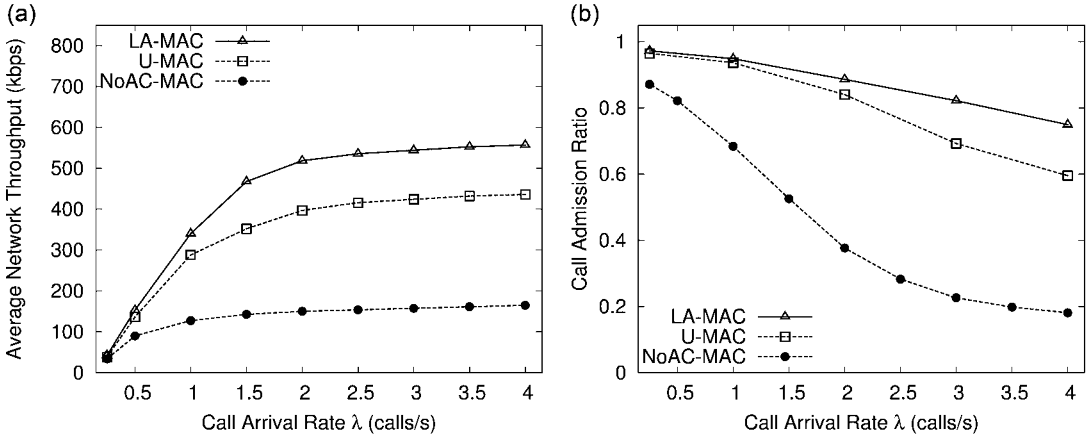

Figure 7. (a) Average network throughput and (b) call admission ratio over traffic load variations.

MAC protocol is a little bit higher than 6 msec when four nodes are active and that the delay does not surpass 11 msec in case of twelve active nodes. Overall we can observe that in LA-MAC nodes experience the lowest delay compared to U-MAC and NoAC-MAC. Concerning the latter protocol, when 16 or more nodes are present, the increased frequency of link requests causes a sharp rise in the protocol's average packet delay. Figure 6(b) also reveals the link setup latency of the protocols under test. In the LA-MAC protocol the preceded access evaluation phase can potentially add an extra delay overhead. This is true when the number of nodes is high. As such, the proposed protocol at highly loaded conditions presents an increased delay, yet, it remains the lowest one when compared to the rest of the protocols. On the contrary, in U-MAC there is an inherent increase in latency, since when a node sends an RTS, the link setup involves the node waiting for replies from the receiver and any other neighbor with conflict (i.e., nodes not agreeing with the link parameters) prior to initiating a data transfer.

6.2.2. Multi-hop topology.

The multi-hop topology consists of 25 nodes placed in a 5 by 5 grid with 15 m distance between adjacent nodes. We have chosen a radio range so that all non-edge nodes have four neighbors. In this testing scenario we applied a *sink-type* communication pattern, where nodes send packets to a single sink at the corner of the network. Wireless nodes have to resort to the routing protocol so as to deliver packets to the sink. A randomized shortest path routing scheme was used where next hop nodes are eligible if they have fewer hops to the destination. From these next hops, a random one is chosen. Thus, packets flow in the correct direction, but do not use the same path every time.

Figure 7(a) compares the overall network throughput of the protocols under test. When the call arrival rate is low, the throughput achieved by all protocols is similar, because fewer links are active simultaneously appointing the protocols' mechanisms to have minimal effect. As the call arrival rate increases, nodes in U-MAC require more bandwidth to make MSI announcements (recall that there are more frequent state changes occur due to the increase in the number of link requests). Though the periodicity of the hello messages in U-MAC is adaptive, it still results in an increased overhead that decreases the overall network goodput. LA-MAC instead, allows for local reconfigurations that require little information exchange among the nodes in the network and results in higher bandwidth efficiency. Thus, there is a growing gap in the throughput as arrival rates increase, and it appears to stabilize for rates above 2 calls/s when the total throughput achieved saturates, reaching its maximum value. Apparently, this is not the case for the NoAC-MAC that fails to deliver data above a saturated limit of few kbps.

Figure 7(b) depicts the ratio between successfully admitted and requested links as function of the call arrival rate. We can observe that the gap in the performance of these protocols steadily grows with the network load. LA-MAC admits almost the 75% of the requested links when the link request rate is high (equal to 4 *pps*), while the U-MAC protocol has a relatively lower admission ratio equal to 60% in such conditions. This indicates that nodes in U-MAC make less accurate local rate and power assignments due to a higher rate of change in the network state that hello messages cannot accompany, and as a result, the admitted rate drops sharply as the requested rate increases. This is not the case for the LA-MAC protocol that accompanies the changes in the network state more efficiently since nodes have up-to-date information about the ambient interference levels. LA-MAC ensures a stable ratio between the admitted and requested links for a link request arrival rate between 0.25 and 2. What is more, the achieved admission ratio of the LA-MAC protocol almost doubles that of the NoAC-MAC, highlighting the benefits of using admission control with the underlying UWB physical layer.

Following on, we examine the energy consumption of the simulated protocols by considering the energy model described in Section 6.1. The obtained results of Figure 8(a) are proportional to that of the previous scenario.

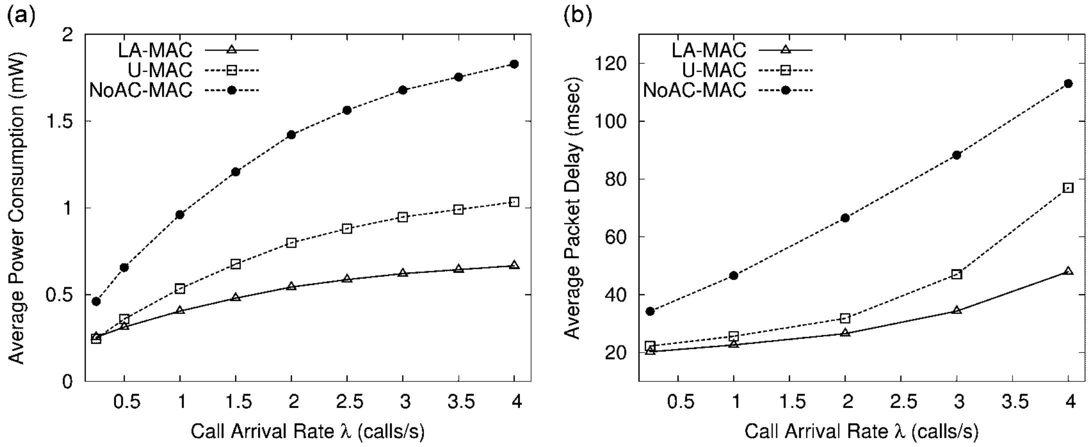

Figure 8. (a) Average power consumption and (b) average packet delay over traffic load variations.

LA-MAC once again outperforms the U-MAC protocol as well as the NoAC-MAC protocol, by demonstrating as high as 62 and 176% energy savings respectively, under frequent link requests. By this, the LA-MAC protocol ensures a longer-lasting operation of the deployed sensor network. The extension in lifetime comes as a result of the increased channel spatial reuse efficiency and the low overhead associated with the operation of the LA-MAC protocol, which minimizes the energy lost for MSI announcements and retransmissions toward collision resolution.

Simulation results concerning the measured end-to-end packet latency are illustrated in Figure 8(b). In case of the NoAC-MAC protocol, the lack of admission control cannot guarantee the immediate transmission at each hop, thus the protocol presents increased queuing delay and end-to-end delay. On the contrary, the concurrent nearby transmissions that the LA-MAC protocol wisely permits, enable nodes to more effectively forward data to the sink and make on-time deliveries. Simultaneous transmissions are a key factor in delivering delay-constrained content over multiple hops, an advantage that our protocol easily presents. This is not the case for the U-MAC protocol, especially under increased link requests (i.e., above 3 pps). The large waiting period for replies during the protocol's admission phase and the need for power/rate reconfigurations, negatively affect the link setup latency of the protocol.

7. CONCLUSIONS

In this paper we propose a novel MAC protocol that fits in the design framework of the IEEE 802.15.4a standard for low data rate UWB wireless sensor networks. It is a distributed MSI-based admission control protocol with dedicated procedures for location-aware interference estimation. The latter feature, enables the admission control to be implemented locally by every node, thus limiting the actions needed to be performed towards the admission phase. The good characteristics of the proposed protocol were confirmed via simulation experiments, where significant gains in performance were witnessed in terms of increased network throughput and lifetime, as well as, reduced control overhead and connection latency. Simulations also quantified the tradeoffs involved and the benefits of our location-aware admission control strategy. In the future, we intend to examine the performance of the LA-MAC protocol in greater depth, especially to quantify the impact of inaccurate location estimations on the probability of erroneously admitted links.

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AUTHORS' BIOGRAPHIES

Eirini Karapistoli received her Diploma (with honors) in Electrical Engineering from the Democritus University of Thrace in 2005. In July 2009, she obtained her Ph.D. Degree from the Aristotle University of Thessaloniki, Greece. Her research interests lie in the area of wireless communications, wireless ad hoc and sensor networks and optimization of communication networks. Her involvement with those research areas has led to the co-authoring of over five articles in peer-reviewed journals and more than 10 papers in international conferences. She has served as a regular reviewer for a number of international journals and conferences. Currently, she is working as a research associate at the Informatics and Telematics Institute (CERTH/ITI) of Thessaloniki. Since

2005, Dr Karapistoli has been involved in four projects, funded by the EC and the Greek Ministry of Research and Technology. Finally, she is a member of the IEEE and a member of the Technical Chamber of Greece.

Ioannis Gragopoulos received his Diploma degree from the Department of Electrical and Computer Engineering in Aristotle University of Thessaloniki in 1993 and his Ph.D. Degree from the same institution in 1999. He has worked in several telecommunication companies as a research and development engineer of computer networks, fleet management and global positioning systems as well as navigation. From 2004 up to now he has been working as a researcher (Grade D) at the Institute of Informatics and Telematics of CERTH. He has participated in various research programs and his interests focus in the field of wireless telecommunication networks and telematics and especially in wireless sensor networks, medium access, and routing protocols and in global positioning and navigation systems.

Ioannis Tsetsinas received his Diploma degree from the Department of Electrical and Computer Engineering in Aristotle University of Thessaloniki in 1997. He has worked in companies an engineer in computer networks and in research institutes as a research and development engineer of wired and wireless telecommunication networks. From 2004 up to now, he has been working as an associate researcher at the Informatics and Telematics Institute of CERTH. He has participated in various research programs and his interests focus in the field of wireless sensor networks, medium access protocols and navigation systems.

Fotini-Niovi Pavlidou received the Ph.D. degree and the Diploma in Electrical Engineering from the Aristotle University of Thessaloniki (AUTh), Greece, in 1988 and in 1979, respectively. She is with the Department of Electrical and Computer Engineering at AUTh engaged in teaching in the areas of Mobile communications and Telecommunications Networks. Her research interests are in the field of mobile and personal communications, satellite communications, multiple access systems, routing and traffic in networks and QoS studies for multimedia applications over the Internet. She is participating in many national and international projects (Tempus, COST, Telematics, IST) and she has been chairing the European COST262 Action on Spread Spectrum Systems and Techniques for Wired and wireless Communications. She has served as member of the TPC in many IEEE/IEE conferences and she has organized/chaired some conferences like, the IST Mobile Summit2002, the 6th International Symposium on Power Lines Communications-ISPLC2002, the International Conference on Communications-ICT1998, etc. She is a permanent reviewer for many IEEE/IEE journals. She has published more than 100 papers in refereed journals and conferences. She has served as guest-editor for special issues in many journals. She is a senior member of IEEE, currently chairing the joint IEEE VT&AES Chapter in Greece.

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