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A MAC protocol for low-rate UWB wireless sensor networks using directional antennas

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ABSTRACT

Ultra-wideband (UWB) is a key solution for wireless connectivity, characterized by ultra-low power consumption and a good degree of robustness to interference and multipath fading. Evidence of its significance, is its recent use in the IEEE 802.15.4a standard. UWB technology with joint consideration of directional antennas can benefit when compared to classical omni-directional antennas from the energy conservation viewpoint, which is of fundamental concern when it comes to wireless sensor networks (WSNs). However, exploiting directionality requires new approach in the design of a medium access control (MAC) protocol to be applied. In this work, idle nodes continuously rotate their receiving beams over 360° until a predefined *preamble trailer* is detected. The resulting scheme is a *directional ultra-wideband* MAC protocol, named DU-MAC, which deals effectively with the problem of deafness and the problem of determination of neighbors' location. Simulation-based studies will demonstrate the effectiveness of the proposed protocol in many critical parameters, such as throughput and network lifetime.

1. Introduction

Wireless communications based on UWB signals have attracted much attention both from standardization bodies and chip manufacturers. This air interface promises flexibility, increased data rate, an extended communication range, robustness against interference, and the ability of providing sub-meter ranging accuracy. Additionally, UWB allows for ultralow power communications, typically under −10 dBm, a property that is ideal for the energy-constraint sensor nodes. The recently released IEEE 802.15.4a standard [1], a spin-off to 802.15.4 [2], adopted this physical layer (PHY). The additional capabilities of this alternate PHY over its predecessor, are expected to enable significant new applications and market opportunities.

Most of the existing research on ultra-wideband sensor networks typically assumes the use of omni-directional antennas by all nodes, however, several drawbacks exist due to the omni-directional nature of transmissions. For example, the distribution of energy in all directions other than the intended direction not only generates unnecessary interference to other nodes, but it also decreases the opportunity to have simultaneous nearby transmissions. With directional communications, on the other hand, spatial reuse can be substantially enhanced by having nodes' transmitted energy concentrated only towards their destination's direction. Moreover, on the receiving side, directional antennas enable a node to selectively receive signals only from a certain desired direction, thereby increasing the signal-to-interference-plus-noise ratio (SINR).

When using directional antennas, a node may concurrently transmit in directions that do not interfere with ongoing transmissions. However, as shown in [3], there are inherent conflicts between these two characteristics of directional antennas that pose challenges in the design

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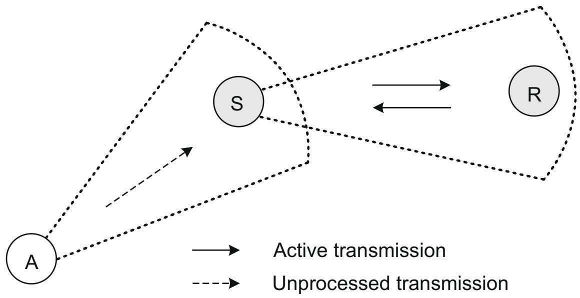

Fig. 1. A scenario illustrating the problem of deafness.

of MAC protocols. One such example is the well-known *deafness* problem depicted in Fig. 1. Node *A* (a neighbor of node *S*), unaware of *S* being in directional communication with another neighbor, attempts to communicate with *S* by sending a packet. Node *S*, being beamformed in a different direction, fails to hear the packet. Assuming congestion as the cause of failure, *A* backs off before attempting retransmission. If data packets are large, then *S* remains engaged in communication to *R* for a long duration, during which *A* may attempt multiple retransmissions (each retransmission preceded by an increasing backoff duration). When *S* finally completes its packet delivery and is ready to transmit a new one, it is highly likely that *A* would be counting down a larger backoff counter. Clearly, this results in a serious wastage of channel resources in unproductive transmissions and also in unfairness. Thus, the question of whether directional antennas improve the performance of a wireless network is not straightforward, but requires close examination of the issues involved in channel access.

While traditional MAC protocols that have been designed under the omni-directional assumption are no longer suitable for use over directional antennas, the proposed MAC should attempt to exploit both the benefits of directionality, namely *spatial reuse* and *higher communication range*. While spatial reuse is always a desirable property, the latter asset does not directly apply to WSNs. The battery-operated wireless nodes in a WSN mostly require energy minimizing mechanisms, in order to ensure a long-lasting operation without the need for replacement/recharging the battery [4]. Hence, the idea to form shorter possible links and therefore benefit from the power reduction is more attractive. Intuitively, with denser node distribution, as the one observed in most deployed sensor networks, one can decrease the transmission ranges without affecting the connectivity properties of the network [5–7]. The above stated observations and inspirations lead us to utilize *directional-omni* links amongst the nodes participating in the network, i.e. links whose communication range is limited within a sector of an omni-directional transmission range (detailed in Section 3.1).

In this paper, we introduce a novel UWB MAC protocol that provides efficient support of directional antennas with the underlying UWB physical layer, named DU-MAC. It replaces the omni mode operation with its directional alternative in which idle nodes continuously rotate their receiving beam over 360°, while forming directional-omni links in order to conserve energy. Moreover, the new protocol does not rely on the upper layers for beamforming information. As such, it does not assume the providence of neighbors' locations by a higher layer or by means of an additional hardware, such as GPS or a direction finding instrument. Nor does it need extra information for the beam rotation to take place, since it relies on a simple circular beam switching pattern. Finally, by using a simple yet effective scheme, the neighbors decide for their transmission differentiation in order to avoid deafness. To make the protocol simple in implementation, we fully exploit the characteristics of the underlying 802.15.4a physical layer.

The remainder of the paper is organized as follows. In Section 2, we discuss related work on medium access control protocols using directional antennas. We describe our antenna model in Section 3, together with features related to the underlying 802.15.4a standard. In Section 4, we provide a detailed description of the proposed DU-MAC protocol. Section 5 illustrates the obtained simulation results, followed by detailed reports. Finally, conclusions are given in Section 6, along with potential future directions.

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. Existing works include [8–12]. Most works based on Cuomo's et al. research [8] follow a maximum sustainable interference (MSI) admission control that adapts the power and/or rate of each link to the level of interference. DCC-MAC protocol [11] on the other hand, proposes to take advantage of the infrequent nature of collisions at the pulse level by using incremental redundancy and dynamic channel coding at the physical layer. Lastly, the UWB^2 protocol [12] embraced specific code assignment procedures for the transmitting-receiving pair to agree on the time-hopping sequence (THS) to be used during the actual data transmission. However, none of these works considered to jointly combine this technology with directional antennas so as to solve the link-layer scheduling problem. According to El Fawal [13] and Radunovic and Boudec [14], the performance of a MAC protocol that simply adapts its rate to the level of interference is constrained by the well-known *near-far* problem. The findings in our work suggest that a joint consideration of the time-hopping concept and the use of directional transmissions could greatly increase the performance of such an UWB MAC protocol.

Although substantial work has been done in the context of ad hoc networks [15–22], literature in the context of directional antennas to be used in UWB based networks is very limited. While the existing literature provided us with the basis for designing our proposed protocol, significant changes had to be made for various reasons. This way, characteristics that lead to inefficiencies were avoided and the protocol was accordant with the physical layer's updated guidelines, while having as a primary objective the energy conservation. Contrary to our protocol, research efforts in [15–18] employ different transmission ranges for the control and data packets, resulting in the *hidden terminal problem due to the asymmetry in gain* [19]. In addition, these protocols suffer from the *location information staleness problem* stated in [20], in which the gap between the cached information and the actual location, due to the elapse of time, renders the direction of transmission inaccurate. Furthermore, in most works, the authors assume the providence of neighbors' physical location by an upper layer or by means of a GPS, which is not always the case. Only in [21], a separate directional neighbor discovery is proposed to tackle this problem. Finally, these protocols do not incorporate a generally efficient functionality to inform a sender's and/or receiver's directional neighbors (the neighbors that are within directional reach) of the intended transmission so as to avoid the *deafness* problem described in [22].

Another interesting fact is that much of the work on medium access control has been done in the context of extending the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism introduced in 802.11 networks, to work with directional antennas. Their main innovation is the use of a directional network allocation vector (NAV), where the nodes defer those transmissions that are in (and around) the direction that received the request-to-send (RTS) or clear-to-send (CTS) packet. However, given the peculiar characteristics of the UWB physical layer (discussed in Section 3.2) and the lack of the ability to use carrier sensing, our design and research efforts are to introduce novel solutions specifically tailored to the underlying PHY.

3. Preliminaries

3.1. The switched sector beam antenna model

We have implemented a complete and flexible switched sector beam antenna module at the *ns*-2 simulator. The assumed antenna system operates in a *directional-omni* mode. This may be seen as a switched beam antenna model, whose coverage range is limited within a sector of an *omni* mode transmission (see Fig. 2). The idea behind this choice is that the proposed scheme applies for the energy-constrained sensor networks. Since energy conservation is of primary concern, one way to accomplish that is through power controlled directional transmissions. Hence, unlike *omni* mode transmissions (a node is capable of receiving signals from all directions with a gain of G^o), and *directional* mode transmissions (a node can point its beam towards a specified direction with gain G^d greater than G^o), in our proposal, we employ directional-omni links with $G^{do} = G^o$. This in turn, would roughly result in having as high as N_{beams} times lower radiated power when compared to an omni mode transmission:

$$P_{dir\text{-}omni} \approx P_{omni}/N_{beams}. \quad (1)$$

The antenna power adaptation and range limitation that the paper proposes taking into account the work in [5], is motivated by the fact that the unexploited directional gain should be beneficial for the battery-operated sensor nodes in terms of prolonging their lifetime and the network's as a whole.

Moreover, it becomes apparent that for the transceiver to perform a full rotation, i.e. to cover the whole region around it, it may need to carry out as many sequential beam switches as there are antenna beams. This is called *sweeping* (switching sequentially in all antenna beams). In this process, we assume that there is a slight delay in switching the beam in various directions. According to Yao and Feng [23] and Park [24], a 5.1 μs is needed in order to perform a beam switch. We call this the *beam switching time* (T_{beam_switch}), and adds to the protocol's overhead. The feeding network that is responsible for the electrical beam steering, i.e. for persistently rotating the receiving beam between the different sectors of the antenna module, achieves so by adjusting the on/off state of the RF MEMS switches. The latter are actuated via an external electrostatic field without requiring constant applied current, appointing the typical power consumption to be in the order of 40 μW per switching. This is a negligible amount of energy, which we did not consider in our energy cost analysis.

Fig. 2 illustrates the antenna model we consider in this work. Each node possesses multiple antenna elements/branches that are able to provide sectored radiation patterns. The shape of the directional footprint is assumed to be conical with the apex pointed in the desired direction. As we can see in this figure, the area around the node is covered by N non-overlapping beams. We number the antennas from 1 to N in a clockwise fashion. The node can transmit its signal to any of the N beams, concentrating the transmitted energy towards a specific direction. In the reception of a signal, the index of the beam that sensed the signal is cached at the receiver and may be used in the future for communicating back to the transmitter. Finally, even though each node is equipped with multiple directional antennas, there is only one radio transceiver per node, which can transmit and receive one packet at any given time.

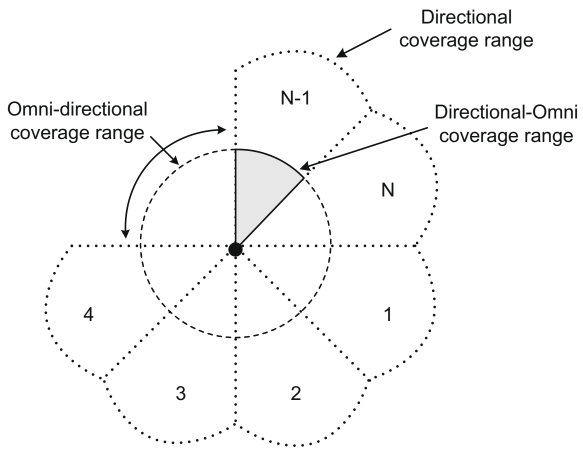

Fig. 2. The radiation pattern of a N-beam antenna system.

3.2. 802.15.4a Overview

Recently, UWB technology has received increasing recognition for its applicability to multi-user wireless communication networks. At the physical layer, the implementation of UWB transmissions can be achieved by pulse-based time-hopping (TH), where very narrow pulses (referred to as monocycles) are employed to convey information based on their positions and/or polarities [25]. In the IEEE 802.15.4a specification, the main difference with respect to this classical IR-UWB physical layer lies in the signal format of the data part. Instead of sending single pulses, a short, continuous burst of pulses with pseudo-random polarity and burst hopping is being sent. The burst hopping sequence therefore, provides for multi-user access, with the possible burst positions to be obtained through scrambling [1].

In 802.15.4a-like networks, devices communicate using the packet format illustrated in Fig. 3. Each packet, or PHY protocol data unit (PPDU), contains a synchronization header (SHR) preamble (preamble plus start-of-frame-delimiter (SFD)), a physical layer header (PHR), and a data field, or PHY service data unit (PSDU). With the clear channel assessment (CCA) modes available in this standard, and the very low, below the noise floor, power emissions, the physical carrier sensing is no longer a good indication of neighboring nodes competing to acquire access to the shared channel (recall that there is no carrier to sense with UWB communication) [26]. As a consequence, one possibility to emulate carrier sensing with IR-UWB, is to actively decode in order to detect an acquisition preamble at the beginning of each packet [13]. Given that the nodes need to detect a predefined sequence of symbols, this simplifies the acquisition process.

The acquisition preamble is constructed by repeating the preamble symbol N_{sync} times. The length-31 preamble symbol is drawn from a ternary alphabet $\{-1, 0, 1\}$, while the adopted preamble symbol repetitions by the standard are 16, 64, 1024, or 4096. For each respective number, the duration of the SHR preamble, corresponding to the 16.10 MHz mean pulse repetition frequency (PRF), is depicted in Table 1, while its mathematical expression is given by Eq. (2). In this study, we consider the short preamble with a 23.8 μs duration, for purposes of improved energy and delay efficiency, and in the rest of the paper we will refer to as the UWB *preamble trailer*. According to the CCA Mode 5 (namely the UWB preamble sense based on the SHR of a frame) [1], the latter represents the shortest CCA detection time for a compliant UWB to correctly report a busy medium:

$$T_{pre} = N_{pre} \times T_{psym} = (N_{sync} + N_{SFD}) \times T_{psym}, \tag{2}$$

where N_{pre} is the number of symbols in the SHR preamble (note that the SFD field adds eight symbols) and T_{psym} is the preamble symbol duration. To ensure that the receiver has enough time and will not miss the end of the sync part before the signal acquisition is over, we inserted a time margin (guard zone). From simulations, we observed that a T_{margin} equal to $T_{sync}/4$, is adequate for the above purpose.

Table 1
Timing requirements of the IEEE 802.15.4a standard.

Number of symbols in the SHR preamble (N_{pre})	Duration of the SHR (μs)
(short) 24	23.8
(default) 72	71.5
(medium) 1032	1025.4
(long) 4104	4077.7

As far as the channel access mechanism, we should note that the UWB physical layer made possible the use of the contention-less ALOHA access method (CCA Mode 4). This decision was based on the multi-user interference (MUI) robustness guaranteed by the UWB PHY that enables the ALOHA approach to provide satisfactory throughput in medium and lightly loaded networks, avoiding the additional access delay of the collision avoidance phase. In the pure ALOHA protocol, a device transmits as soon as it gets data without sensing the medium or waiting for a specific time slot. However, as it will be shown in Section 5, for a realistic UWB system where the bandwidth is large but finite, uncontrolled simultaneous transmissions (spread by different codes) are not optimal [13], appointing the need for novel practices of great importance when designing such networking protocols.

4. The DU-MAC protocol

4.1. Protocol's functionalities

The proposed MAC protocol aims to effectively overcome the limitations found in traditional directional MAC protocols. To take advantage of the increased spatial reuse efficiency obtained by the use of directional antennas, all transmissions in DU-MAC are directional, having a directional-omni coverage range. On the receiving side, the listening is also directional and rotational with a step equal to $360^\circ/N_{beams}$, i.e. the receiving beam stays in each antenna sector for time T_{pre} (equal to the extended CCA detection time) and then switches to the next consecutive beam until the hole region around the receiver is covered. Additionally, the DU-MAC protocol does not rely on prior availability of neighbors' location. In order to accomplish that, it employs a directional *blind discovery* mechanism to learn

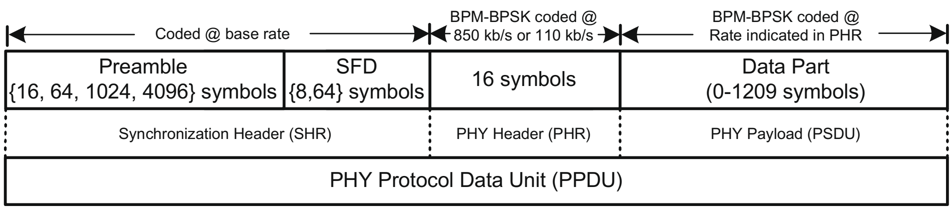

Fig. 3. Illustration of the IEEE 802.15.4a packet structure.

and cache information about the sectors where neighbors exist. It is important to note that the transmitter and the receiver do not need any information about each other's location. The circular transmission reaches the target node wherever it is located.

Summarizing, in order to handle the problems raised when directional antennas are employed, the proposed MAC protocol is able (a) to communicate directionally (in the interest of higher spatial reuse) and (b) to inform the surrounding neighbors about a communication (in the interest of addressing deafness). The three capabilities that have been added to the original IEEE 802.15.4a standard to enable directional communications are: beam caching, beam locking and unlocking, and a procedure for determining the neighbors' relative location. The following paragraphs describe each of these, finely tailored to the UWB PHY characteristics, features.

4.1.1. Beam caching

Beam caching refers to the process of a node storing beam-related information after the detection of a preamble trailer. More specifically, in the reception of a preamble, the index of the beam (b_i) that sensed the preamble from a neighboring node x is cached at the receiver y. This means that for the receiving node y, the tuple (x, b_i) serves as the signature of node x. If this information is available, a node shall switch to that specific sector beam b_i so as to transmit a packet to the respective neighbor; otherwise the blind discovery protocol that is described later, will be performed. Each node updates the cached beam information every time it receives a newer preamble trailer from a neighbor and invalidates the cache if it fails to get the ACK response from the neighbor after several attempts. This assumes that the failure to get the response is not due to a collision, but because the direction of transmission is inaccurate. According to Ref. [1], each node will attempt three times before notifying the higher layer of a link failure.

4.1.2. Beam locking and unlocking

In DU-MAC, nodes transmit preamble trailers to notify neighbors for an imminent data transmission. Whenever a node receives a preamble trailer from a neighbor, it deduces that a packet transmission will follow and thus it locks its beam pattern for the data reception towards the direction of the received power. The beam patterns at both sides are used for both transmission and reception, and are unlocked after the ACK frame transmission is completed, i.e. after the full DATA/ACK exchange. Note that the pattern locking at the receiver's side occurs after a preamble trailer is detected. Otherwise, idle nodes persistently rotate their receiving beams over 360°.

4.1.3. Determination of neighbors' location

In DU-MAC protocol, determining the neighbors' location does not mean finding the exact physical location of the nodes. Instead, it simply denotes the process of a node learning the sectors where its neighbors exist, so as to properly beamform its antenna to the respective sector when communication is needed. We have developed a directional *blind discovery* protocol to address this issue, which is in accordance with the discovery strategy supported by the 802.15.4a standard. As it will be shown, the proposed protocol slightly differentiates itself by applying the above strategy on each antenna beam. Before advancing with that, the description of this strategy follows; in a nonbeacon-enabled 802.15.4a network, nodes search for neighbors via active channel scan [1]. The MLME-SCAN.request primitive is used to initiate a channel scan and search for activity within the personal operating space (POS) of the scanning device. During active scanning, a short frame is sent out over the specified communication channel and responses are recorded. Note that for the UWB PHY, the preamble code appropriate to the specified channel is being scanned. According to the standard, the available length-31 preamble code sequences range from C_1 to C_8, with each UWB channel mandatorily having to support two of them (one during the discovery and one during data communication). In the analysis that follows, the preamble code chosen for communication during the discovery process is the code C_5, when the device implements the mandatory low band channel 3 and the code C_3, when it implements the mandatory high band channel 9.

In the directional version of this strategy, the active channel scan is applied to each individual antenna beam sequentially. This means that when a node initiates the blind discovery protocol, it transmits a preamble trailer at the very first antenna sector of Fig. 2, using the C_i code related to the UWB channel in use. After neighbors' responses are arrived, the node then switches to the next consecutive beam and repeats the above process. This is done until the 360° azimuthal plane is covered. All in-range neighbors that lie within the sector covered by the respective transmitting beam and that heard the preamble trailer, announce their presence by sending *hello* packets. Hello packets contain each node's cached beam information and act as a form of neighbor table announcement. The task of sending hello packets is performed after the completion of the preamble trailer transmission, during which each node uses a random delay to send its packet (required to avoid systematic collisions). At the same time, the transmitting node switches to receive mode in order to collect the hello packets. As responses are received, the sender node records them into a small neighbor table. As previously stated, this information is adequate for a node to initiate a directional transmission. If during the listening time it does not hear channel activity, it deduces that no neighbors exist in that sector. This information is used by the sweeping mechanism, which in turn ignores the sectors that do not contain neighbors during its circular scanning.

An issue requiring further discussion is for the case where two neighbors are busy, i.e. they both are in the middle of discovering their neighbors. Apparently in this case they will not detect each other. One can say that this scenario falls into the location information staleness problem stated at Takata and Watanabe [20]. To handle such occurrence and any other similar, DU-MAC protocol foresees the proactive or reactive execution of the blind discovery protocol. More specifically, we have investigated the optimization of the lifetime of the cached beam information and accordingly the scheduling of the next discovery round. Thereby, we propose that the blind discovery protocol runs either periodically or reactively depending on the application requirements. In the former case, the frequency with which a node performs neighbor discovery depends on the node density in its vicinity. If a node does not have any neighbor, it performs neighbor discovery more aggressively than in the case that it has many neighbors. In DU-MAC, if a node has at least one neighbor, it performs neighbor discovery every 10 min. The latter case instead, can be performed after a node assesses that it does not contain an updated neighbor list or can be part of a reactive routing protocol that runs on top of the network layer. During simulations, DU-MAC adopted only the first approach.

4.2. Data transmission phases

As already revealed, the new MAC protocol replaces the omni mode operation with its directional alternative, by having idle nodes to continuously rotate their receiving beam over 360°. Since a switched sector beam antenna model is implied, this means that the receiving beam stays in each antenna sector for time T_{pre} and then switches to the next consecutive beam until the hole region around the receiver is covered.

Suppose now that we have the topology shown in Fig. 4, and node S is willing to initiate communication with node R. In this case, S repeatedly transmits preamble trailers over the control channel[1] and towards the intended neighbor for time T_{rot} (step (a)). T_{rot} is the time required by an idle node to complete one full rotation and is given by Eq. (3). This constraint ensures that the intended in-range neighbor node will receive the preamble trailer at least once, unless it is busy transmitting elsewhere. Note that contrary to the agreement of the beam to be used for the communication between the two nodes, both nodes are every moment unaware of the beam in which each other listens. The separate sending of the preambles over each beam and for time T_{rot} would be unnecessary if only a node incorporated a method for predicting the antenna beam in which its neighbor is.

When the intended neighbor detects the preamble trailer, it aborts rotating and continues to point its receiving beam towards the direction of arrival (DoA) of the preamble trailer, in anticipation of a DATA from the sender (step (b)). During this time, the receiving node is locked in a "ready to receive" mode ignoring the reception of other packets. At the end of the preamble trailer transmission, nodes S and R are synchronized and are ready to carry out the DATA/ACK transmission. This transaction is performed using a dedicated channel, associated with the burst hopping sequence $h_{S,R}$ [1]. This effectively establishes a directional link, with minimal reliance on upper layers.

The above approach, however, does not solve the deafness problem by itself. For example, node A unaware of S being in directional communication with another neighbor, attempts to communicate with S by sending a DATA packet. However, node S being beamformed in a different direction, fails to hear the packet. Assuming congestion as the cause of failure, node A attempts retransmission. By this, unsuccessful transmissions unnecessarily flood the region covered by node's A sector beam. On the contrary, if a ready to receive acknowledgement transmission (RTR-ACK) preceded the actual DATA/ACK transmission (step (c)), node A would be able to understand if the intended recipient is "ready to receive", aborting its data transmission effort as otherwise (step (d)). According to Lal et al. [27], this polling mechanism, which is detailed in the next subsection, is a simple and effective trick to avoid the unavailing directional transmissions occurring due to deafness.

4.3. Avoiding deafness

Informing neighboring nodes and avoiding the deafness problem is of main concern when designing a MAC protocol that employs directional antennas. Within our proposal, deafness is remedied by the fact that "ready to receive" nodes send an acknowledgement packet at the end of the preamble trailer reception, indicating their readiness to receive packets. Hence, if the source node A does not receive an ACK from the recipient node S for at most *macAckWaitDuration* (54–120) symbols, it concludes that the single transmission attempt is not possible and it needs to be postponed. We should point out that the NACK indication that is issued in this case (step (d) in Fig. 4), means absence of ACK and is not actually send. NACK notifies the sender node that its potential receiver is not in a "ready to receive" state, forcing the sender node to backoff and reattempt its transmission later. Node A shall repeat the process of transmitting the data up to a maximum of *aMaxFrameRetries* times, equal to 3 [1]. If an acknowledgement is still not received, the MAC sublayer shall assume the transmission has failed and notify the next higher layer of the communication failure.

4.4. Timing requirements

At this point, we examine the T_{rot} timing requirement of the proposed protocol. As already revealed, time T_{rot} corresponds to time required to perform a full 360° rotation. This time depends on the SHR duration, the number of antenna beams and the beam switching time (introduced in Section 3.1), and it is formulated as follows:

$$T_{rot} = (T_{pre} + T_{margin} + T_{beam\_switch}) \times N_{beams}. \quad (3)$$

For example, for a four-sector beam antenna system, time T_{rot} is equal to 131 μs. We use the term *delay overhead* to refer to this extra TDMA-like overhead that the proposed protocol incurs to the traditional 802.15.4a MAC at the cost of using energy-aware directional links both at transmission and at reception. Simulation results would show that the spatial reuse gains emanating from the directional transmissions, compensate the delay overhead induced by the rotating mechanism of the DU-MAC protocol, and as a consequence, the TDMA-like access delay is efficiently mitigated.

We should also note that in case the network consists of heterogenous sensors, i.e. the beamforming capability is

[1] According to Ref. [1], the control channel can be supported by resetting the linear feedback shift register (LFSR) scrambler to the initial (zero) state.

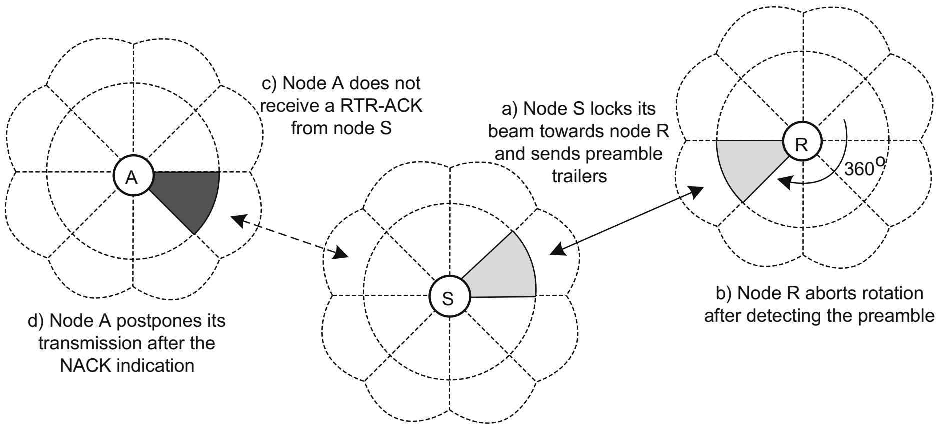

Fig. 4. Basic steps of the deafness-aware DU-MAC protocol.

not available to every single sensor, the proposed protocol is backward compatible to allow efficient communication among them. In doing so, it resumes to the original 802.15.4a omni mode standard with the following notable modification: time T_{rot} must be equalized to T_{pre}, since the single antenna element will radiate omni-directionally.

5. Performance evaluation

5.1. Simulation model

In this section, we present simulation-based studies to evaluate the performance of the DU-MAC protocol using the *ns*-2 simulator (version 2.29). So far, we have utilized the UWB physical layer coded in [28] (setting the transmit power to be static and suppressing the dynamic channel coding feature) and the directional antenna module from [29]. On top of that we have added the directional transmission/reception model that the DU-MAC protocol embraces, including its rotating mechanism, a variable number of antenna beams and gain equalization for the different number of beams in support of the directional-omni links. The timing parameters for the IEEE 802.15.4a have also been coded into the simulation framework [1]. We compare our MAC proposal to the omni mode 802.15.4a MAC adopting the CCA Mode 4 (ALOHA access). Finally, we should note that both protocols can operate in a distributed manner, assuming no knowledge of the network topology, and that during tests they share the same network parameters and conditions.

Wireless nodes adopting the proposed protocol are equipped with antenna arrays of $N = 4$ and 6 elements, resulting in a 90° and 60° beamwidth, respectively. Recall that the number of antenna beams, which is basically an application-related choice, has an impact on the delay overhead of our protocol (this delay is directly proportional to the number of antennas, Eq. (3)). Moreover, as previously stated, the directional gain for the switched sector beam antenna system is constrained through power control to provide directional-omni coverage range (no range extension). Hence, the approximate transmission range is 20 m and the radio interference range is 30 m, matching that of the IEEE 802.15.4a omni mode standard.

Sensor nodes are organized under one-hop (nodes have overlapping radio ranges) and multi-hop topologies (see Fig. 5). 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 [30]. The former case comprises a set of connections which are constructed as pairs of stationary sender and receiver nodes (Fig. 5a), 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 (Fig. 5b).

In the application patterns described above, all wireless nodes generate sensing data based on an exponentially dis-

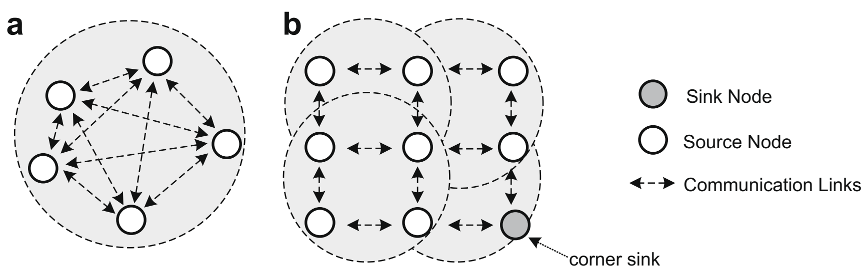

Fig. 5. A sample (a) one-hop topology and (b) multi-hop (grid) topology.

tributed inter-arrival time. The packet rate was varied from 0.25 packets per second (pps) to 4 pps (poisson traffic). With such inter-arrival times, the need for information transfer (sensing data and control data as well) is satisfied in a typical WSN [31]. Each data packet has a size of 127 bytes and is transmitted at 851 kb/s. Finally, each simulation is run for 3600 s and each point on the curves to be presented, is an average of multiple simulation runs.

We do not consider node mobility in our simulation scenarios. All graphical presentations that follow show average simulation results achieved by all nodes with a constraint of zero lost probability, which is the probability of no queued packets being dropped prior to being served. If a protocol starts dropping packets under certain conditions, the corresponding result entry is empty. The metrics we consider to evaluate the performance of the protocols are:

(1) Packet delivery ratio: is the ratio between successfully delivered and offered packets.
(2) Average transmission cost (accounts for the network lifetime extension): in order to calculate this metric we borrowed the energy-model described in [13]. In the used and referenced chip-level model of energy consumption, the PHY can transmit a pulse, receive a pulse, perform signal acquisition, be in an active-off state, or sleep. Accordingly, the energy consumption is modeled as a vector $\vec{q} = [q_{tx}, q_{rx}, q_{ao}]$ consisting of three states[2]: 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 (to account for the time-hopping, i.e. when a node is in between two pulse transmissions or receptions energy is consumed only to keep the circuit powered up). Since the same transceiver elements are used for signal acquisition and reception, the signal acquisition energy consumption is equal to q_{rx} (note that during the preamble acquisition no time-hopping is used), whereas the energy consumption for packet reception is a combination of q_{rx} and q_{ao}. The complete formula appears in [13]. In our analysis we used a scenario where a higher cost for reception and a lower cost for active-off is implied, i.e. $\vec{q} = [1, 5, 0.5]$.
(3) Average MAC delay: is the average end-to-end delay of a packet from its birth up until correct reception at the destination.

Next, we report the main performance results derived from the simulation analysis. The 90% confidence intervals of these metrics are within ±1%.

5.2. Simulation results

5.2.1. Simple scenarios

We begin by examining the behavior of the DU-MAC protocol under scenarios affected by hidden terminal and deafness problems. Two such scenarios are shown in Fig. 6 (solid lines indicate links and dotted lines indicate flows).

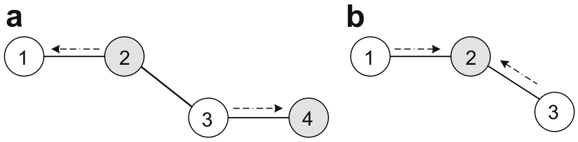

Fig. 6. Scenarios affected by hidden terminal and deafness problems.

As depicted in Fig. 6a, there are two active flows; the 2 → 1 and 3 → 4. The specified scenario can be seen as a near-far case for the reverse communication directions (during ACK transmission). For example, since nodes 2 and 3 are within range of one another, in the case of the IEEE 802.15.4a standard (simulated with omni-directional antennas), this causes node's 2 data transmission to sometimes collide with the ACK reception of node 3 or vice versa, resulting in lower aggregate throughput. Collisions are highly attributed to the ALOHA access scheme and the near-far problem that UWB transmissions are prone to. The directional communication in DU-MAC instead, is not affected by this. Nodes 2 and 3 communicate with nodes 1 and 4, respectively, by beamforming their antennas to different directions based upon the DoA information. As a result, the two flows benefit from the spatial reuse gains, since they do not face unintended receivers.

Table 2 shows the average data rate achieved by each flow in scenario 6a, for an offered load of 1 pps transmitted at 851 kb/s data rate. As expected, the overall throughput achieved by the proposed protocol in the scenario considered, is highly improved (almost doubled). From this table, we can also see that 802.15.4a has a fairness problem when compared to our protocol, where the communication resources are equally allocated. Indeed, in terms of resource sharing, we can see that the original 802.15.4a protocol does not provide balanced resource allocation under hidden terminal scenarios. This is mainly attributed to the omni-directional nature of transmissions that lead to congestion and disarrange the chance of the wireless nodes to win the next channel contention. On the contrary, a MAC protocol exploiting directionality at its communications, is capable of avoiding this shortcoming in a more fair manner, unless prolonged deafness is occurring.

In the scenario illustrated in Fig. 6b, DU-MAC protocol once again outperforms the 802.15.4a MAC thanks to its ability to handle deafness. Suppose that node 3, a neighbor of node 2, unaware of two being in directional communication with node 1, wants to communicate with node 2. Since node 2 is being beamformed in a different direction, it is not in a ''ready to receive'' mode, thus, it does not issue an acknowledgement back to the requesting node 3. This,

Table 2
Average data rates of different flows.

Flow	IEEE 802.15.4a (kb/s)	DU-MAC ($N = 4$) (kb/s)
2 → 1	467	719
3 → 4	334	698

[2] The cost for sleeping is fractional.

Table 3
Average data rates of different flows.

Flow	IEEE 802.15.4a (kb/s)	DU-MAC ($N = 4$) (kb/s)
$1 \rightarrow 2$	341	590
$3 \rightarrow 2$	232	571

prevents node 3 to perform an unnecessary data transmission and effectively avoids packet collisions. According to Table 3, there is a slight reduction in the throughput achieved by the DU-MAC protocol. Yet, the reduction is smaller compared to that of the ALOHA version of the 802.15.4a MAC. What is more, it is noteworthy the fact that the communication area, as seen by the sender nodes 1 and 3 in the case of the DU-MAC protocol, is limited to 90° beamwidth only (the blind discovery protocol identifies only one sector of interest), showing the adaptability of our proposal to the peculiarities of the topological area under test.

5.2.2. Single-hop topology

Thus far, we have analyzed the basic properties of our protocol in very simple scenarios. Our main goal of the *ns*-2 simulations, is to investigate whether our protocol works as expected under more realistic network conditions. For this reason, we simulate a network topology comprised of eight nodes randomly distributed in a 20 m $\times$ 20 m area. In Fig. 7, the overall achievable packet delivery ratio is shown with respect to traffic load variations. DU-MAC protocol operates effectively in all cases and regardless of the traffic conditions. The depicted metric always exceeds the 0.8 ratio, showing that directional communications positively acted upon increasing the number of concurrent transmissions. It can be seen that the proposed protocol under heavy load conditions (i.e. 4 pps), presents the least performance degradation in contrast to the original omni mode standard whose packet delivery ratio is highly reduced. In heavy load conditions, the packet delivery ratio of DU-MAC has a gain of 47% and 53% in the case of $N = 4$ and 6 antenna elements, respectively, when compared to 802.15.4a. In low load conditions, our protocol seems to have similar throughput to that of the 802.15.4a. This happens due to the fact that in lightly loaded networks, where the probability of collision is reasonably small, directional transmissions cannot actually benefit by the spatial reuse. Moreover, we see that by using $N = 6$ antenna elements, as opposed to $N = 4$ elements, makes a difference in the average delivery ratio. This is not surprising, because the average beamwidth when using $N = 6$ antenna elements is smaller than that when using $N = 4$ elements, hence, there is a greater potential for spatial reuse with $N = 6$ antenna elements.

Following on, from Fig. 8 we can see that under highly loaded conditions (i.e. 4 pps) DU-MAC reduces the energy cost at around 50% (for $N = 4$) and 61% (for $N = 6$), when compared to that of the 802.15.4a, thanks to the reduced power links that it employs. The two protocols under test have nearly the same power consumption when the offered load is very small. With further increment of the traffic, the power consumption of both protocols increase, but our proposal maintains the examined metric at the lowest

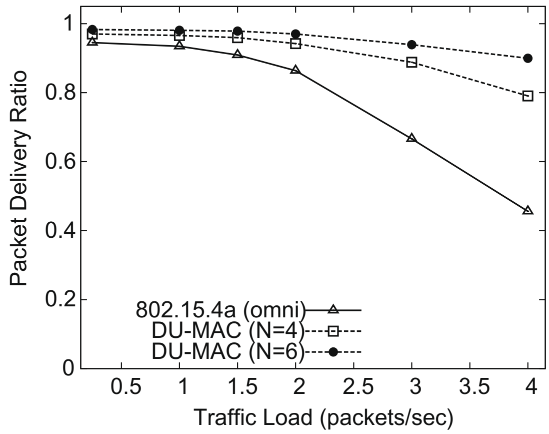

Fig. 7. Packet delivery ratio with respect to traffic load variations.

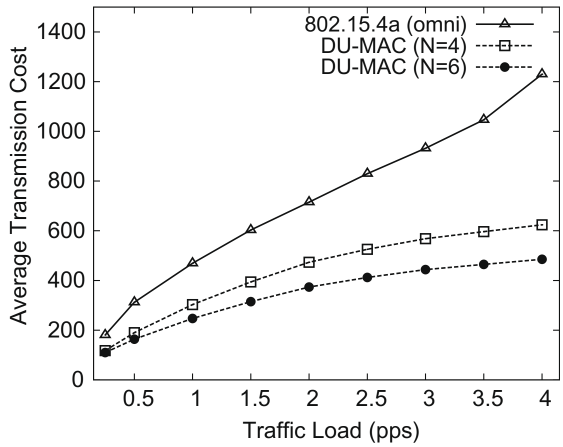

Fig. 8. Average transmission cost with respect to traffic load variations.

levels. DU-MAC by adopting reduced power links and directional-omni transmissions can preserve more energy when compared to the IEEE 802.15.4a omni mode standard, following the analysis illustrated in Section 3.1.

Simulation results concerning the measured packet latency are illustrated in Fig. 9. From this figure we can extract the delay overhead that is added by the rotating operation of the DU-MAC protocol. We already know that, in the proposed protocol the transmission of the DATA starts later than in the omni mode standard, due to the fact that the preceded preamble trailer transmission lasts T_{rot} time units. It is apparent that, the higher the number of beams the longer the full rotation lasts. As such, the proposed protocol at lightly loaded conditions presents an increased delay, in the order of 12.5% in the case of $N = 4$ and 30% when $N = 6$, compared to the 802.15.4a MAC. As the load increases, however, this extra overhead is quickly canceled by the increase of the throughput due to spatial reuse benefits.

5.2.3. Multi-hop topology

In this scenario, we focus on evaluating the performance of our protocol under scenarios where not all nodes

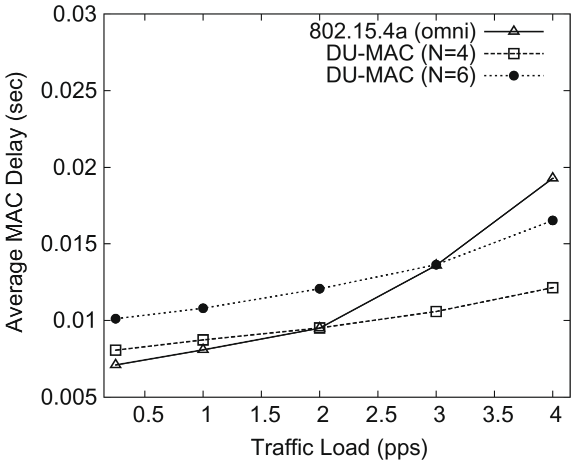

Fig. 9. Average MAC delay with respect to traffic load variations.

are within radio range of each other. The simulated multi-hop topology is visualized as a set of nine nodes placed in a 3 by 3 grid with 20 m distance between adjacent nodes. We have chosen this range so that all non-edge nodes have four neighbors to all their orientations. In this scenario, we applied a *sink-type* communication pattern, where nodes send packets to a single sink located at the corner of the network. Wireless nodes in this multi-hop environment, have to resort to the routing protocol in order to deliver a packet to a particular destination. 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.

Fig. 10 compares reliability in terms of delivery ratio. DU-MAC guarantees delivery at a 76% and 80%, when the offered load is high, while 802.15.4a has a relatively low delivery percentage, equal to 48%. That is because DU-MAC protocol is deterministic and guarantees high delivery in an ideal network, while 802.15.4a is a probabilistic scheme and does not guarantee full delivery. What is worth mentioning, is that the achieved delivery ratio of the DU-MAC protocol with $N = 4$ antenna elements, is close to that achieved by $N = 6$ antenna elements. This is something we attribute to the outcome of the directional neighbor discovery (i.e. the number of sectors where neighbors exist). In the simulated grid topology, this number is the same in the case of $N = 4$ and 6 antenna elements, thus the spatial reuse chances for both cases are the same.

Next, we perform a network lifetime comparison between the simulated protocols, taking into account the energy-model described earlier. Fig. 11 represents the average transmission cost of the protocols under test with respect to traffic load variations. The obtained results are proportional to that of the previous scenario. Our MAC proposal outperforms the ALOHA 802.15.4 MAC protocol by demonstrating as high as 50% longer lifespan (in the case of $N = 6$). The extension in lifetime is also attributed to the fact that our protocol is less time consuming in processes such as packet retransmission and collision resolution. Once again, the simulation results verified that the directional-omni transmissions employed in DU-MAC protocol, result in higher energy savings that ensure a longer-lasting operation of the deployed sensor network.

Finally, simulation results concerning the measured end-to-end packet latency are illustrated in Fig. 12. In this figure the vertical axis represents the attainable average MAC delay, whereas the horizontal axis resembles the traffic load variations. It is reasonable to state that in this multi-hop topology, nodes experience deafness when forward packets to next hop nodes, which in turn results in higher end-to-end delays. DU-MAC protocol with $N = 4$ antenna elements, however, succeeds in keeping the average end-to-end delay at low levels, especially when the offered load increases. This is not the case for the $N = 6$ antenna model. The unnecessary delay overhead in the case of $N = 6$ antenna elements, increases the overall end-to-end delay. Recall that the number of sectors where neighbors exist is the same in the case of $N = 4$ and 6 antenna elements, and $T_{rot|_{N=6}}$ is unnecessarily higher from $T_{rot|_{N=4}}$. As far as the delayed packet delivery that the omni mode 802.15.4a MAC protocol presents, it results from the larger silence region (omni-directional transmissions cover larger area, negat-

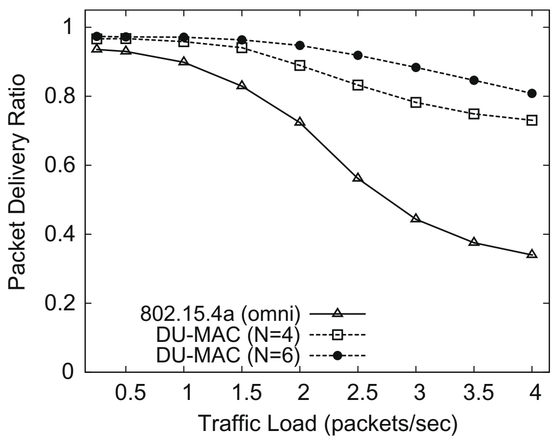

Fig. 10. Packet delivery ratio with respect to traffic load variations.

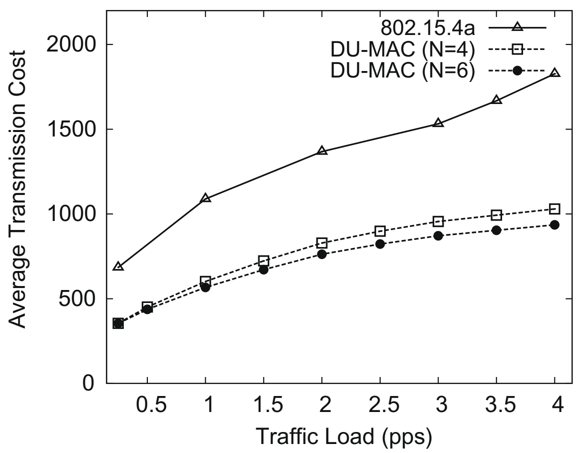

Fig. 11. Average transmission cost with respect to traffic load variations.

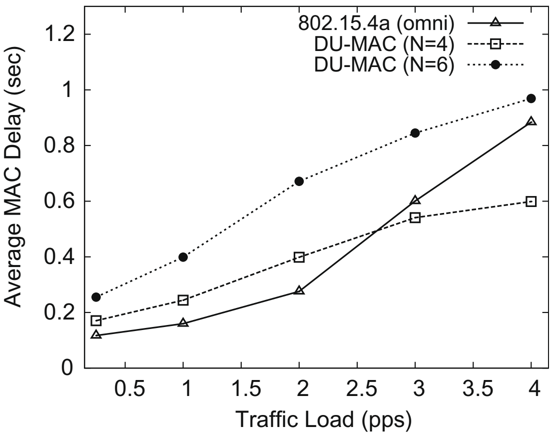

Fig. 12. Average MAC delay with respect to traffic load variations.

ing any spatial reuse gains) and from the long queuing delay due to packet retransmissions.

6. Conclusions and future work

In this paper, we propose a novel MAC protocol specifically designed for the energy-constrained WSNs, which augments the performance of the IEEE 802.15.4a standard by utilizing directional antennas. It is a distributed random access MAC protocol with dedicated procedures for power efficient directional-omni communications. Simulations demonstrated that the proposed protocol outperforms the IEEE 802.15.4a omni mode standard in terms of throughput and energy consumption, suggesting that it is beneficial to jointly utilize the UWB transmission technique with directional communication in shared wireless medium sensor networks. Finally, though the performance of MAC protocols using directional antennas is topology dependent, the different functionalities that the DU-MAC protocol embraces (i.e. beam caching, blind discovery, RTR-ACK), allow us to fully exploit the increased throughput attributed to the spatial reuse benefits of directionality. In the future, we intend to examine the DU-MAC protocol in greater depth, by finding a prediction mechanism based on a probabilistic model. In this scenario, beam hops would be probability-dependant, severely reducing the times that preamble trailers are sent, and subsequently minimizing the rotation phase prior to packet sending.

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