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On the influence of the hidden and exposed terminal problems on asynchronous IEEE 802.15.5 networks

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ABSTRACT

Hidden and exposed terminal problems are known to negatively impact wireless communications, degrading potential computing services on top. These effects are more significant in Wireless Mesh Sensor Networks (WMSNs), and, particularly, in those based on the IEEE 802.15.5 Low-Rate Wireless Personal Area Network (LR-WPAN mesh) standard, a promising solution for enabling low-power WMSNs. The first contribution of this paper is a quantitative evaluation of these problems under the IEEE 802.15.5 Asynchronous Energy Saving (ASES) mode, which is intended for asynchronous data-collection applications. The results obtained show a sharp deterioration of the network performance. Therefore, this paper also reviews the most relevant approaches that cope with these problems and are compatible with ASES. Finally, a set of these proposals is assessed to find out those more suitable for their potential integration with ASES, which constitutes the second major contribution of the paper.

1. Introduction

In the last few years we have witnessed the emergence of the Wireless Mesh Sensor Networks (WMSN) [1] technology. It consists of hundreds or thousands of autonomous, low-cost and small size devices which are usually deployed in a large area of interest to monitor events, acquire data from built-in or external physical sensors (e.g. temperature, humidity, pressure or gases), and process and transmit the significant information in the context of a pervasive service or application. These devices, nodes of the WMSN, are characterized by their limited memory allocation, reduced processing capacity and, above all, energy constraints. These may influence on the capabilities of the pervasive computing and the capacity of new services built on top. Another concern to take into consideration is the maximum transmission range of a commercial off-the-shelf WMSN device, usually restricted to be around one hundred meters in outdoor scenarios. Therefore, applications where source and destination (sink) are separated by distances higher than the maximum range need a path of intermediate nodes to connect them. In this sense, a reliable and efficient WMSN communication arises when there are different alternative paths between any source–destination pair. Among all the possible paths, an appropriate cooperation of network nodes will select the most suitable one assuring data transmissions with the best achievable network performance. In this framework the number of application domains of WMSNs is rising, comprising several fields of interest, such as the environmental surveillance, industrial automation and control, or precision agriculture.

Multiple work groups and standard organizations, such as Zigbee [2,3], IETF 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks) [4–6] or the HCF (Highway addressable remote transducer Communication Foundation) [7–9], have developed and issued specifications to adapt mesh capabilities to the traditional Wireless Sensor Networks (WSNs). Unfortunately, none of them have been able to integrate, into a unique solution [10], many of the functionalities that characterize a WMSN, such as selection of the best path toward destination, robustness to changes, asynchronous/synchronous communications, low power consumption, reliability or scalability. In this sense, the recent IEEE 802.15.5 Low-Rate mesh standard (henceforth IEEE 802.15.5) [11] emerges as an extension of Wireless Personal Area Network (WPAN) to efficiently support all the aforementioned mesh functionalities. To achieve this goal, IEEE 802.15.5 provides, in a single recommendation, distinctive features, in particular, an autonomous network formation and addressing scheme, a unicast/multicast/broadcast transmission model, two novel energy conservation mechanisms, a traceroute function and even mobility support, all of which facilitate the establishment and operation of a WMSN.

On the other hand, nodes equipped with batteries of limited capacity consume a large amount of their energy in different tasks associated to the communication and monitoring of large areas (e.g. network formation and maintenance, data acquisition, and routing). In particular, among all network nodes, those carrying out message retransmission tasks (i.e. listening to the physical medium to receive messages from

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neighbor nodes, and later dispatching them to the best neighbor in the path to the destination) are those demanding more energy. These devices, denoted as intermediate/relay nodes, usually operate in the active mode (ON) [3] what leads to restricting sharply the network lifetime (time interval since the network starts its operation until one or several nodes deplete their batteries, making the network operation unfeasible). Under these conditions, IEEE 802.15.5 provides the Asynchronous Energy Saving (ASES) operation mode [11–13], which assures data transmissions by means of an efficient energy-saving scheme to prolong the nodes' life. In ASES, nodes work according to a duty cycle (active/inactive periods), that is, they perform their transmission/reception of information during the cycle's active period (ON) and then switch to the inactive (sleep or OFF) mode to save energy.

As can be noted from the previous discussion, the IEEE 802.15.5 standard along with its ASES mode should be enough, a priori, to guarantee a reliable establishment and efficient operation of the WMSN, prolonging the nodes' and overall network's life. However, this desirable behavior is not accomplished. In wireless communications, one of the major concerns described in the specialized literature is the interference effect among nodes provoked by the so called hidden (HT) and exposed terminals (ET). In particular, the HT problem increases the number of message collisions and, as a consequence, the number of messages that must be retransmitted or simply discarded. On the other hand, the ET effect forces sender nodes to unnecessarily delay the transmission procedure. Under these premises, the hidden and exposed terminal phenomena imply extra energy consumption for transmitting a message. In the WMSN field, the large amount of network messages dispatched among nodes and, in many occasions, the high number and proximity of connectivity links, may cause a significant increase of HT and ET effects, affecting, in principle, negatively on the network performance.

To the best of our knowledge, there are no published works addressing the hidden and exposed terminal effects in the IEEE 802.15.5 standard. Therefore, the first contribution of this paper focuses on providing an accurate study on how the HT and ET problems affect WMSNs designed under the specifications of the IEEE 802.15.5 standard and particularly its ASES mode. To this end, a complete simulator has been programmed by using the well-known Network Simulator 2 (ns-2) [14] framework. The results obtained quantify the influence of the hidden and exposed terminal effects on the degradation of diverse figures of merit, showing that even the feasibility of the network is jeopardized. Analyzing these results, we review and discuss the most recent specialized literature that copes with the HT and ET problems, both on WSNs and on WMSNs. These works present different proposals intended to minimize the effects of these phenomena. Then, our second contribution concentrates on studying the feasibility of these proposals when they are integrated within ASES mechanism. As an additional contribution, a comparative evaluation of a group of relevant proposals is also provided. This helps us to figure out future efficient WMSN solutions where the HT and ET phenomena are mitigated and, consequently, the network fully exploited.

The rest of the paper is organized as follows. Section 2 outlines the ASES mode proposed on the IEEE 802.15.5 standard. Section 3 describes the principles of the hidden and exposed terminal effects. In Section 4, these interference effects are meticulously evaluated under the ASES mode, discussing the results obtained. In Section 5, the scientific WSN/WMSN literature about hidden and exposed terminal phenomena is reviewed, highlighting feasible proposals that can be aimed at reducing or eliminating them in the ASES mode. Section 6 evaluates a selected set of proposals. Finally, Section 7 concludes.

2. The IEEE 802.15.5 mesh standard and ASES mode operation

The IEEE 802.15.5 LR-WPAN mesh standard is a complete recommendation aimed at developing reliable and scalable WMSNs. In fact, IEEE 802.15.5 defines a novel communication layer comprising methods and functionalities which employ the physical (PHY) and medium access control (MAC) primitives of the IEEE 802.15.4 [15], the most commonly adopted standard in WSNs to perform one-hop/point-to-point topologies thanks to its simplicity and interoperability. Thereby, IEEE 802.15.5 takes full advantage of the IEEE 802.15.4 standard, incorporating new functions seeking to fulfill many requirements (such as multi-hop, robustness to changes, asynchronous/synchronous communications, low power consumption, reliability or scalability) of WMSNs appropriately. These new functions are divided by the IEEE 802.15.5 standard into two main groups: *mandatory*, which comprises the aspects related to the mesh network establishment and the unicast data transmission operation for every node [10,13]; and *non-mandatory*, including added-value features such as multicast and reliable broadcast communications, energy-saving mechanisms/modes, route tracing and mobility support for those applications that require them.

In order to deal with the energy concern, the IEEE 802.15.5 standard offers a non-mandatory solution consisting of maintaining the network nodes in a state of low-power operation (sleep state) most of the time, and waking them up periodically during a short time period to conduct the transmission/reception of information. The goal is to reduce the power consumption of the nodes and, therefore, to extend the duration of the batteries and the node's life. To this aim, time is divided into periodic time intervals denoted as *Wakeup Intervals* (*WI*), which, in turn, comprise (i) a period of activity, named *Active Duration* (*AD*), where nodes carry out the transmission of information, and (ii) a period of inactivity, called *Inactive Duration*, where nodes remain in the sleep state. The *WI* and *AD* are time intervals calculated according to the following expressions:

$$WI = meshBaseActiveDuration \cdot 2^{WO} \quad [\text{ms}], \quad \forall 0 \le WO \le 14 \tag{1}$$

$$AD = meshBaseActiveDuration \cdot 2^{AO} \quad [\text{ms}], \quad \forall 0 \le AO \le WO \le 14. \tag{2}$$

In Eqs. (1) and (2), *meshBaseActiveDuration* is a value fixed by the standard to 5 ms whereas *WO* and *AO* are the *Wakeup Order* and *Active Order* parameters, respectively. Based on this scheme, IEEE 802.15.5 specifies an energy-saving mode denoted as *Asynchronous Energy Saving* (ASES). In ASES, no network-wide synchronization is required, that is, the *ADs* of all the network nodes do not need to trigger at the same instant. Thus, to ensure a coordinated transmission between sender–receiver pairs, ASES provides a straightforward procedure, which allows the receiver to remain in its *AD* when the sender dispatches a data message (this issue will be explained in the next paragraphs). Thereby, ASES, together with the mandatory functions of the IEEE 802.15.5 specification, offers an efficient solution to support the majority of traditional WSN applications, extending its use to mesh topologies. In this sense, ASES mechanism ensures a long-life operation, while the mandatory functions satisfy significant requirements in mesh networks, such as scalability, robustness and reliability. All these benefits reveal that IEEE 802.15.5 and its ASES mode proves advantageous with respect to other WMSN proposals [3,5,8], which do not appropriately solve some of the aforementioned requirements [10]. These are the reasons why we focus on studying ASES in this research paper.

As shown in Fig. 1, under the ASES mode, every node broadcasts a *Wakeup Notification* (WN) message at the beginning of its *AD*, to announce its presence in the vicinity. Based on this approach, the data transmission process is as follows: node B (sender) transmits a data message to node A (receiver) only if node B has previously received the WN message from node A. WN messages include valuable information such as the receiver's *WO*–*AO* parameters, what allows the sender to estimate the duration of the receiver's *AD*. The result tells the sender if the receiver's *AD* is long enough to fulfill the transmission process. In this case, Fig. 1(a) shows how the sender transmits the data message using the well-known unslotted Carrier-Sense Multiple Access–Collision Avoidance (CSMA–CA) medium access mechanism (the complete transmission procedure in ASES is explained below). Once the data message

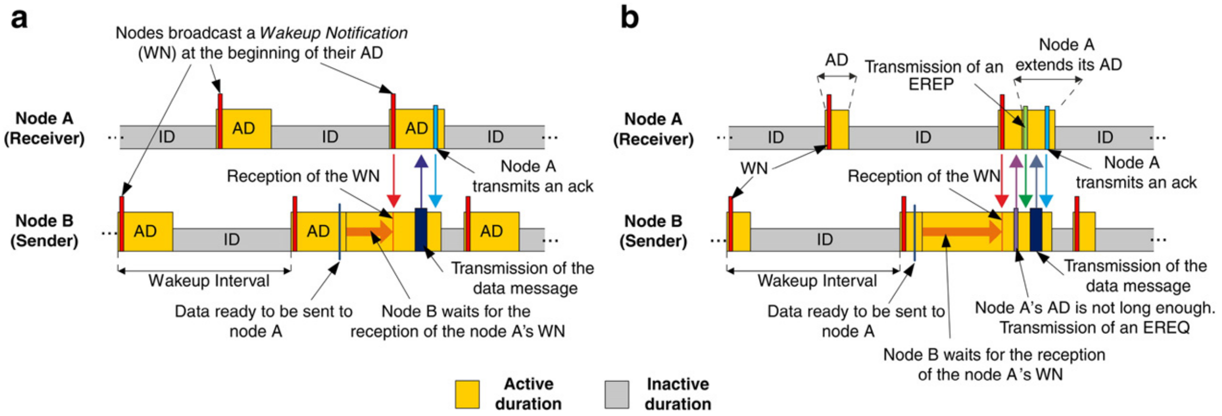


Fig. 1. Unicast transmission in ASES: (a) the receiver's *AD* is long enough to fulfill the data transmission; (b) the transmission of EREQ/EREP messages is required.

is transmitted, node A confirms its reception to B with an acknowledgement (ack). However, in the particular case that the duration the remaining receiver's *AD* (node A) is insufficient for accepting messages, Fig. 1(b) illustrates how ASES has the capability of increasing the length of the receiver's *AD*. In order to carry this out, the sender (node B) transmits an *Extension Request* (EREQ) message with the time requirements that it demands to perform the data transmission. Upon the successful reception of the EREQ, the receiver extends the duration of its *AD* and answers the sender with an *Extension Reply* (EREP) message. Now, the data transaction can be completed and the sender forwards its data message following the CSMA–CA rules.

Finally, as an additional feature, ASES allows data broadcasting. To this end, before transmitting the data message, a sender node broadcasts consecutive EREQ messages during a fixed interval to ensure that all its neighbors are active and able to fully receive data messages. Then, the sender broadcasts the data message.

On the other hand, data transmissions can be affected negatively because the wireless channel is error-prone by nature, including losses of the WNs, EREQ/EREP messages or acknowledgements sent by the receiver to confirm data messages. Under these conditions, to better understand the impact of these errors, the procedure followed by the ASES mode as regards the data transmission and reception processes is detailed by the pseudo codes described in Tables 1 and 2, respectively. Concerning the data transmission process, when a sender node is ready to transmit a data message, the mesh layer passes this operation down to the IEEE 802.15.4 MAC layer (lines 17 and 23 of the pseudo code written in Table 1), which is in charge of fulfilling the data transaction by means of the unslotted CSMA–CA algorithm. With this aim, the node contends for medium access and, if it is busy, the node defers its transmission a backoff time. This time takes a random value between 0 and $(2^{BE} - 1) \cdot 320$ μs, where *BE* is the backoff exponent parameter, an integer number whose value is in between the *macMinBE* and *macMaxBE* according to the CSMA–CA algorithm (being by default 3 and 5 respectively as established in the IEEE 802.15.4 standard). Once this backoff time expires, the node listens to the medium once more in an attempt to retransmit the message. In case it is busy again, the *BE* is increased by one unit and a new backoff time is calculated and applied to the message. Otherwise, if the medium is idle and the receiver node is active, the sender accesses the channel and transmits the message under consideration. However, the transmission may fail due to a collision with WN, data, EREQ/EREP messages or acks from hidden nodes. In this case, the node under study does not receive the *ack* from the receiver, which entails a new execution of the CSMA–CA algorithm (lines 51 to 57 of the pseudo code in Table 1). The goal is to delay the message one backoff time after which a new retransmission attempt is carried out.

The above procedure is repeated by the MAC layer unless one of the following cases occurs: (1) the message has been successfully dispatched; (2) the receiver's *AD* is too short to guarantee the feasible transmission of data (see lines 18 to 26 of the pseudo code presented in Table 1); and (3) a maximum number of failed attempts of retransmission, defined by the IEEE 802.15.4 standard as a configuration parameter called *macMaxFrameRetries*, is reached. In each case, the MAC layer reports the result of the transmission to the mesh layer. If this result is successful, denoted as case (1), the IEEE 802.15.5 mesh layer of the sender would continue with the transmission of a new data message. In case (2), the mesh layer belonging to the sender proceeds in accordance with the remaining time of the receiver's *AD*. Two possible options may arise. First, if the remaining *AD* is longer than 3 ms, the sender transmits an EREQ asking the receiver for extending its AD. If the latter can be accomplished, the receiver sends an EREP message back to the sender. Second, if the remaining *AD* is less than or equal to 3 ms and the number of retransmission attempts does not exceed the value of *meshMAXNumASESRetries*, the sender defers its transmission to the next receiver's *WI* (in its *AD*). In particular, if the first option fails (due to, for instance, loss of the EREQ/EREP messages or even the data message), the mesh layer runs second option. Finally, in case (3) the mesh layer of the sender executes second option above, that is, it postpones the transmission to the following *WI*. As it is observed, the *meshMAXNumASESRetries* parameter defines the maximum number of consecutive *WIs* in order to retransmit a data message through the mesh layer. In case this value is reached, *the data message is finally discarded*, and the mesh layer continues with the transmission of a new data message.

Finally, the pseudo code written in Table 2 illustrates the cases where a data message is discarded at a receiver node. As a premise, this procedure considers that the WN message has been previously transmitted by the receiver and delivered to sender/-s correctly, which is mandatory for future data transmissions in ASES mode. Going into detail, Table 2 shows as a data message that does not collide with other nearby transmissions is successfully received by the mesh layer of the receiver. In this case, the mesh level is in charge of forwarding the message to the next node or delivering it to the upper layers of the receiver (in the case the receiver under consideration is the destination of data). However, when two messages collide in the receiver, this acts as follows. Firstly, the PHY layer selects the message addressed to the receiver with the strongest power signal, discarding the other one. The reason is that the power of the selected signal may be high enough to obtain data successfully. Secondly, the PHY layer dispatches the data frame to the MAC one, which measures the link quality of the data frame, discarding it if this value does not exceed a predetermined threshold.

Table 1
Algorithm 1. Pseudo code for the transmission procedure at a sender node.

```
01: Procedure at mesh layer
02: ARC is the number (counter) of retransmission attempts at mesh layer in ASES (maximum
    meshMAXNumASESRetries)
03: begin
04:   for each data message k addressed to the neighbor (receiver) i do
05:     $ARC \leftarrow 0$
06:     Wait for the WN message from neighbor i for a time duration equal to one WI
07:     if no reception of WN (the waiting period has expired) then
08:       $ARC \leftarrow ARC + 1$
09:       if $ARC \geq meshMAXNumASESRetries$ then
10:         The message k is discarded
11:       else
12:         Go back to Step 06
13:       end if
14:     else
15:       Calculation of the remaining node i's AD (the unslotted CSMA-CA operation is included)
16:       if remaining node i's AD is long enough to transmit the full data message k then
17:         Deliver the message to the next lower layer, namely, the MAC layer (go to Step 31)
18:       else if remaining node i's $AD \geq 3$ ms then
19:         Transmit an EREQ message to the neighbor i, and wait for the EREP message from this neighbor.
20:         if transmission of EREQ fails or no reception of EREP (the waiting period has expired) then
21:           Go back to Step 08
22:         else
23:           Deliver the message to the next lower layer, namely, the MAC layer (go to Step 31)
24:         end if
25:       else
26:         Go back to Step 08
27:       end if
28:     end if
29:   end for
30: end procedure
31: Procedure at MAC layer
32: NB is the counter of retransmission attempts at MAC layer (maximum macMaxFrameRetries)
33: begin
34:   for each data message k from mesh layer and addressed to the neighbor (receiver) i do
35:     $NB \leftarrow 0$, $BE \leftarrow macMinBE$
36:     Delay for a random backoff time between 0 s and $(2^{BE} - 1) \cdot 320$ μs
37:     Run the Clear Channel Assessment (CCA) mechanism
38:     if physical medium is occupied (this status may be caused by an exposed node) then
39:       $NB \leftarrow NB + 1$, $BE \leftarrow \min(BE + 1, macMaxBE)$
40:       if $NB > macMaxFrameRetries$, this means that the MAC fails to relay the frame k (message k at MAC
          layer) then
41:         Report transmission failure to the mesh layer. End procedure and go back to Step 08
42:       else
43:         Calculation of the remaining node i's AD
44:         if remaining node i's AD is long enough to transmit the full data message k then
45:           Go back to Step 36 and perform a retransmission attempt
46:         else
47:           End procedure. Go back to Step 18
48:         end if
49:       end if
50:     else
51:       Deliver the data frame k down to the next lower layer, namely, the PHY layer, which is in charge of
          transmitting the message to the physical medium
52:       Wait for the acknowledgement (ack) from neighbor i
53:       if no reception of ack (the waiting period has expired) then
54:         It is assumed the frame k (or the ack) collided and was lost. Go back to Step 39
55:       else
56:         Confirm the successful transmission of message k to mesh layer
57:       end if
58:     end if
59:   end for
60: end procedure
```

3. Hidden and exposed terminal effects

The hidden and exposed terminal effects are two of the current major problems that restrict the full exploitation of the wireless communications [16]. In particular, the most noticeable concern is the HT effect, since it is associated to a significant increase in the number of message collisions. The hidden terminal effect occurs when two or more transmitters that are out of each other's coverage range, cause collisions at a receiver node which is within the coverage range of the transmitters. This problem is illustrated in Fig. 2(a) and Fig. 2(b). In particular, Fig. 2(a) shows sender nodes B (TX1) and C (TX2), which are nodes hidden to each other, and transmit simultaneously to receiver node A (RX) incurring a collision. This results in discarding both data messages. We refer to this type of collision as *primary*. In Fig. 2(b), sender nodes A (TX1) and D (TX2) are also nodes hidden to each other and transmit simultaneously to receiver nodes B (RX1) and C (RX2), respectively. Although messages are addressed to different receivers, only RX2, which is within the coverage range of both senders TX1 and TX2, experiences a collision. This is because RX2 receives the signals (data) from both senders simultaneously, while RX1 only receives the signal from TX1. As a result, RX2 discards both messages. We hereafter refer to this type of collision as *secondary*. In any of the above cases, the

Table 2
Algorithm 2. Pseudo code for the reception procedure at a receiver node.

```
01: Procedure at PHY layer
02: begin
03:    Detect incoming signal (frame) from physical medium
04:    if there is another frame which is being received by the node under study then a collision occurs
05:       if destination address included at PHY header of both frames matches the node's address under
          consideration or the broadcast address then
06:          Select the data frame with the strongest power signal
07:       else
08:          Select the data frame with destination address the node's address or the broadcast address
09:       end if
10:       Discard the frame that has not been selected
11:    end if
12:    Deliver the frame to the next higher layer, namely, the MAC layer (go to Step 15)
13: end procedure
14:
15: Procedure at MAC layer
16: begin
17:    Receive data frame from PHY layer
18:    if the link quality of the data frame received does not exceed a pre-defined threshold, this means that
       probably a collision occurred then
19:       Discard the data frame
20:    else
21:       if destination address included at MAC header matches the node's address (not broadcast) then
22:          Transmit an acknowledgement (ack) frame to the source of the data frame
23:       end if
24:       Deliver the data frame to the next higher layer, namely, the mesh layer
25:    end if
26: end procedure
```

retransmission procedure of the message (by means of the CSMA–CA algorithm) does not guarantee its correct reception at destination, since this procedure is also affected by the hidden terminal effect.

On the other hand, the exposed terminal effect arises when a sender node willing to dispatch information to a free-interfering receiver is forced by the CSMA–CA operation to unnecessarily delay its transmission procedure. The reason is that the medium is occupied by other transmissions carried out by sender's neighbors, although none of them interfere with the receiver. Under these conditions, despite of the fact that the sender node under study could transmit data to its intended receiver, the sender must defer its transmission (in accordance with the rules of the CSMA–CA algorithm) until sensing the physical medium free. The ET effect can be critical for time-sensitive applications, which, in addition, restricts the employment of part of the available network bandwidth. As an example, in Fig. 2(c) sender nodes A (TX1) and C (TX2), both in each other's coverage area, are nodes exposed to each other. At a certain instant of time, TX1 starts a data transmission to receiver B (RX1). In addition, TX2 has a data message for receiver D (RX2). However, when TX2 senses the wireless medium, it is being occupied by TX1, so TX2 triggers the CSMA–CA algorithm, delaying its own transmission.

As it will be shown in the next section, data messages are continuously affected by the hidden and exposed terminal effects thus jeopardizing the network operation. It should be noted that the IEEE 802.15.5 standard also implements the same unslotted IEEE 802.15.4 CSMA–CA mechanism, which is not designed to resolve these two shortcomings. That is, the IEEE 802.15.4 standard does not care about the high collision probability in multi-hop networks. In fact, these problems are emphasized, mainly, by the short range of the backoff time (determined by the *BE* parameter), which was fixed by the IEEE 802.15.4 standard in order to save energy. In this sense, the goal of the standard is to reduce the time spent in accomplishing the retransmission attempts [17,18], which involves a less power consumption in the transmission tasks. However, this operational mode, together with the hidden and exposed terminal effects, implies that the probability of retransmitting a message successfully is low. This is why retransmission attempts owing to hidden and exposed nodes will continuously be carried out in a very short time period, which, as a result, may provoke a high number of collisions (hidden terminal phenomenon) and a notable increase in the message delivery delay to the destination (both hidden and exposed terminal phenomena). Under these circumstances, the IEEE 802.15.4 is appropriate for network topologies such as star or simple cluster-tree (every node is one hop to its cluster-head), where the collision probability is much lower than in the mesh networks under consideration.

4. Performance evaluation of hidden and exposed terminal effects in the ASES mode

In order to assess the performance of the ASES mode including the hidden and exposed terminal phenomena, which, to the best of our knowledge, has not been evaluated yet, we conducted extensive computer simulations using the ns-2 [14] simulation platform. We have selected ns-2 because it is a network simulator widely accepted by the scientific community, which has already been verified and validated for different communication technologies, protocols and network topologies. For our evaluation, we start from the Zheng's simulator [19], the first approach to IEEE 802.15.5 that comprises the main mandatory functions related to the mesh network formation. Furthermore, in this same work [19], a novel routing protocol called Topology-guided Distributed Link State (TDLS) was proposed to select the best path between source and destination, since it is fully compatible with the unicast data forwarding mechanism defined by the IEEE 802.15.5 standard [11,13]. Therefore, our research is aimed at developing the entire ASES operation following the rules established by the standard, and then evaluating ASES according to the focus of our research: the study of the network performance under HT and ET effects.

To conduct a thorough evaluation of the network performance, we have considered the following metrics of interest: throughput (network utilization), retransmission overhead (percentage of data messages retransmitted), percentage of message losses (percentage of data messages, including retransmissions, that are definitely lost), latency (average delay of messages), message delivery ratio (percentage of messages delivered successfully) and energy consumption per bit (energy employed to successfully deliver a bit to the destination). We have set a layout composed of 100 nodes distributed in a regular 10×10 grid topology, where the distance between two consecutive

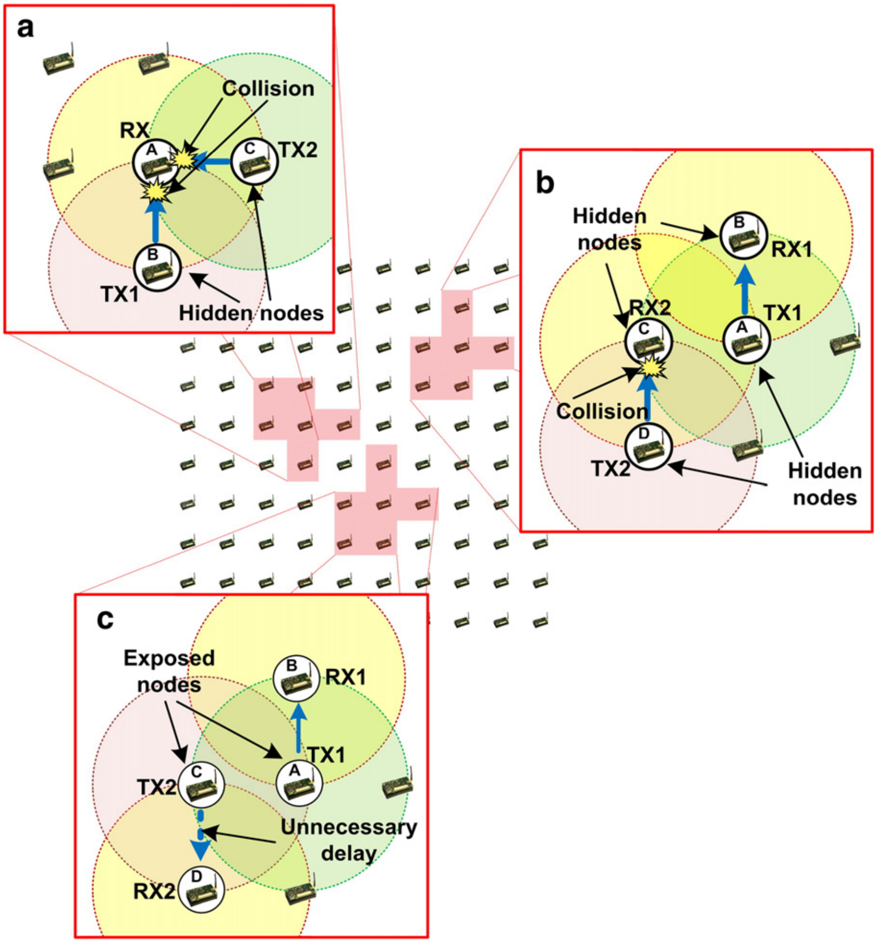


Fig. 2. (a) and (b) Hidden terminal effect; (c) exposed terminal effect.

nodes is 50 m. In order to maintain the simplicity on the node's transceiver as in traditional WSN deployments, all nodes are equipped with an omnidirectional antenna and the coverage range is configured to 60 m. Under these premises, a node can only communicate directly with its up, down, left and right neighbors in the grid. A free-space radio propagation model has been selected to characterize outdoor scenarios, which is a widely-used environment for simulating WSN applications. The purpose of this topology is to evaluate a representative case for the hidden and exposed terminal phenomena caused by transmissions from any node and to observe how they affect the communications in the vicinity.

In addition, two other relevant design aspects should be mentioned. Firstly, a Constant Bit Rate (CBR) traffic flow has been established between nodes 99 (source) and 0 (destination), both located at the opposite corners of the grid. Thus, a message sent by the source must be retransmitted by several intermediate nodes to reach the destination. Our grid scenario consisting of a source and destination pair provides a representative case of study for HT and ET phenomena, since it facilitates their observation in comparison to other transmission problems such as traditional medium access collisions or radio propagations errors (this issue is commented at Section 4.2 and illustrated in Fig. 5). The results obtained in this section can be extended to other WMSN layouts where, for instance, there exist several source nodes and/or destination nodes (sinks), or the mesh topology may be different from the grid one. Here, the study must consider aspects such as the average number of neighbors and the entire generated traffic in the network. Under these conditions, the HT and ET effects become a concern even more relevant (leading to significantly poorer results) than the presented in the following subsections. Secondly, the message size is 127 bytes at the PHY layer, the maximum size permitted by IEEE 802.15.4, sent at different transmission rates of 0.1, 1 and 2 messages per second, respectively operating at 2.4 GHz (nominal transmission bitrate of 250 Kbps). In the MAC layer, if a message does not reach an intermediate node/destination (the acknowledgement has not been received), the IEEE 802.15.4 CSMA–CA performs up to three retransmission attempts (*macMaxFrameRetries* is established to 3) of the data message, after which it is deferred to the next *WI*. The message queues at the nodes are considered unlimited to avoid the loss of messages due to their saturation.

Concerning the simulation of ASES mode, we have conducted our study setting different simulation scenarios which vary the values taken by the *Wakeup Order* and *Active Order* parameters. For each scenario, all network nodes are configured with the same values of the set *WO*–*AO*. Under this condition, we considered as representative values of the *WO* parameter those ranging from 3 to 9. Furthermore, the *AO* parameter is always less than *WO*, which implies dividing the *wakeup interval* into one *active* plus one *inactive duration*. Thereby, a node always switches to the sleep state to save energy regardless of the value of *AO*. If the sender node needs more time to finalize a data transaction, it transmits an EREQ message to extend the receiver's *AD* a time equal to 30 ms (default value of the standard). In addition, as it is indicated by the IEEE 802.15.5 standard, the *meshMAXNumASESRetries* is set to 2, therefore when a node is unable to deliver the data message to an intermediate node/destination within its current *AD*, an attempt is made to retransmit this message in the next *WI* (up to 2 consecutives *WI*). The remaining parameters of the ASES mode are set to their default values according to the standard. Finally, each simulation scenario is repeated 10 times with different random seeds and considering a 95% confidence interval.

4.1. Throughput

Throughput is one of the most relevant metrics for assessing WMSNs [1,20]. Throughput measures the amount of information per unit of time that reaches the destination, which is important to figure out the full exploitation of the network capacity. Observing Fig. 3, the variations of the throughput for different ASES configurations are motivated by two main aspects. Firstly, this metric is negatively influenced by wireless channel issues due to the hidden terminal phenomena. Hidden terminals may provoke an increase in data message collisions and the loss of ASES control messages (WN, EREQ and EREP). Secondly, the CSMA–CA mechanism is unable to solve the exposed terminals effect, so a sender that is ready to transmit a data message has to unnecessarily defer its transmission (at least one backoff time), although the receiver is fully available to receive messages. These results in the waste of one transmission attempt, what implies that the message has to be delayed for a future retransmission. However, this fact may be even more critical when multiple retransmission attempts for a same message occur. Under these circumstances, the data message should be discarded by the mesh layer in case the *meshMAXNumASESRetries* parameter is reached. Hidden and exposed terminal phenomena, individually or combined, may cause a sharp reduction in the throughput at destination. In this sense, this aspect is notably influenced by the transmission rate, as can be noticed in Fig. 3. At the lowest transmission rate considered, 0.1 messages per second, the throughput is almost constant for every value of the *WO–AO* parameters. The reason is that the network is barely loaded and the possible cases of hidden and exposed terminals are thus, very limited. The opposite effect occurs when the transmission rate increases to 1 or 2 messages per second. In these situations, the number of data messages that are dispatched through the network increases and, as a consequence, the HT and ET effects become more frequent.

According with the simulation results, the best throughput values for each transmission rate is achieved when $2 \leq AO < WO$, taking into account that for accomplishing this goal, *WO* should be in the range $4 \leq WO \leq 6$.

4.2. Retransmission overhead and messages lost

Following with the evaluation, Fig. 4(a) illustrates the retransmission overhead, an important concern related with the increase in the network traffic. To explain this issue, we need to examine jointly Fig. 4(a) and (b). The latter focuses on the percentage of data messages lost. As we pointed out at the beginning of this section, the grid topology offers a representative case that allows us to study the behavior of the HT and ET effects intensively. When a source node starts transmitting its traffic flow, the TDLS protocol routes each message by selecting the nearest intermediate nodes toward the destination. Nevertheless, in order to avoid the overload of the intermediate nodes chosen, TDLS balances the traffic load among some neighbors of the intermediate nodes under consideration by using the link with the best quality (according to the physical measurement of the Link Quality Indicator, LQI). Thereby, the increase in the number of nodes enhances the path redundancy of the network thanks to the generation of different source–destination paths. This guarantees a reliable data transaction, as well as a reduction in the cases of nodes bottleneck. Applied to the grid scenario under study, the TDLS protocol operation selects a high number of network nodes that guarantees path redundancy and efficient communications between source and destination. However, a large amount of these nodes forming the different source–destination paths might interfere with each other, in such a way that it would generate HT and ET effects.

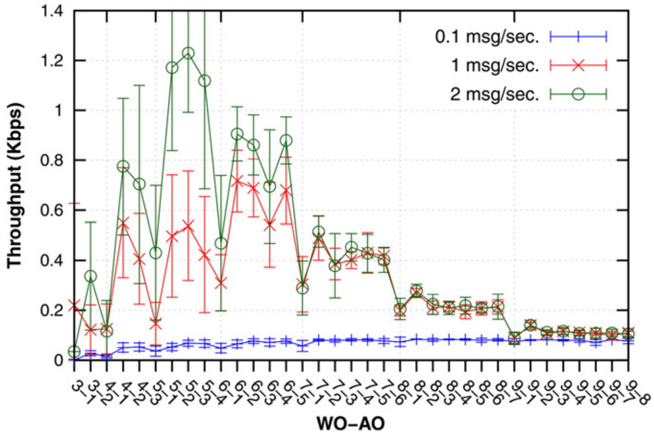


Fig. 3. Throughput as a function of the *WO–AO* parameters.

Under these circumstances, Fig. 4(b) shows failures in transmissions, mainly because of the hidden terminal effect (*primary* and *secondary* collisions). It leads to an appreciable increase in the number of retransmissions which also are prone to fail again because the problem of hidden nodes persists. This concern is depicted in Fig. 4(a). Comparing Fig. 4(a) and (b), we can observe that most of the messages lost (Fig. 4(b)) are due to the retransmissions (Fig. 4(a)), which in addition reveals that the retransmission mechanism of CSMA–CA does not avoid collisions by hidden nodes and, therefore, data are not forwarded successfully toward the destination. The rest of messages lost illustrated by Fig. 4(b) are usually owing to the exposed nodes. In particular, the number of unnecessary triggers of the CSMA–CA algorithm operation by the ET effect delays the delivery of the data messages at destination up to the point of provoking the discarding of these messages (maximum value of the *meshMAXNumASESRetries* parameter is reached). Observing Fig. 4(b), around 40% of the information dispatched is lost for *WO* values greater than 6, together with data rates of 1 and 2 messages per second. Furthermore, this percentage of messages lost is close to what was obtained for the retransmission overhead (illustrated in Fig. 4(a) for equal *WO* values and data rates) since, as we remarked before, most of the lost messages are retransmissions caused by the hidden terminal effect. In order to show in detail why the aforementioned retransmissions and losses take place, Fig. 5 represents the percentage of (a) retransmissions and (b) messages lost due to, mainly, HT and ET effects in the transmission and reception procedures for a data generation rate of 1 message per second.

Fig. 5(b) distinguishes between two groups of messages lost: group (1) illustrates the percentage of messages discarded at mesh layer of the sender, in accordance with the ASES operation, by the HT and ET phenomena. Group (2) represents the percentage of messages discarded at PHY/MAC layers at the receiver side (and, therefore, they are not delivered to the upper layers) motivated by the HT effect. Again, for a better understanding of these aspects, we examine Fig. 5(b) together with Fig. 5(a). Regarding group (1), as it was explained in Section 3, upon a failed transmission attempt by a sender mainly due to HT and ET phenomena, it proceeds as follows: (i) in the case that the receiver's *AD* is long enough (this information is computed from the receiver's *AO* and *WO* values, and the current time), the message is delayed a new backoff time for later retransmission; (ii) same case as (i), but the *macMaxFrameRetries* value is reached, so the MAC layer does not try the retransmission of the message again; and (iii) the sender estimates that the receiver node switched to the sleep state or the remaining receiver's *AD* is insufficient to transmit an EREQ message, so the data transmission is canceled. In cases (ii) and (iii), the MAC sublayer informs the mesh layer that the transmission failed. Under these circumstances, the sender triggers a new retransmission attempt into the *AD* of the next *WI*.

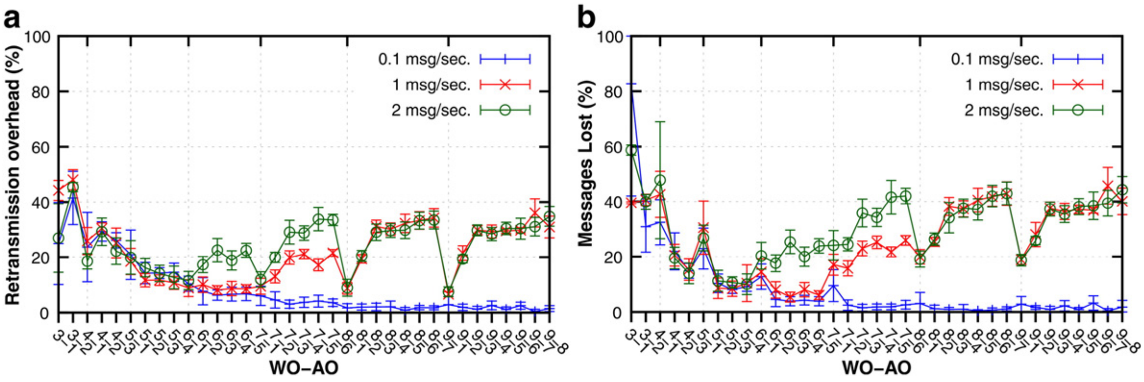


Fig. 4. (a) Retransmission overhead; (b) Percentage of message lost as a function of the *WO–AO* parameters.

However, in the case that the set of transmission/retransmissions exceeds the value of *meshMAXNumASESRetries*, data are finally discarded by the sender and, as a result, the message is *lost*. In order to illustrate why this occurs, Fig. 5(a) presents the main causes of message retransmission. In particular, Fig. 5(a) reveals that the majority of retransmissions are due to the HT effect, being the *primary* collision case the one affecting most negatively. This Figure also shows as a small percentage (almost 2% for any *WO–AO* configuration) corresponds to the typical collisions originated by the CSMA–CA operation (two or more nodes in coverage transmitting simultaneously) [17,21]. The reason of this low percentage is because the grid topology selected for our evaluation furthers mainly the hidden terminal phenomenon, reducing the number of collisions by CSMA–CA. Furthermore, Fig. 5(a) depicts the percentage of retransmission attempts due to the ET effect. This degrades, among other metrics, the throughput and the latency. All these retransmissions caused by the HT, CSMA–CA and ET phenomena may result in discarded messages when the *meshMAXNumASESRetries* value is reached, as shown in Fig. 5(b). In this sense, the $AO = 1$ value is a clear example explaining these concerns. In this case, the active period is too short, what implies that the values of backoff time calculated by sender nodes in the same coverage area, in many occasions, are also similar (due to the short value of the *BE*) and, therefore, sender nodes continuously contend for the physical medium although they transmit to different receivers (ET effect). Additionally, after the expiration of the backoff time and considering the short duration of the *AD*, the receiver cannot be active (surely it switched to sleep mode). It entails that those messages that were not transmitted must wait for their retransmission on the next *WI*. Within its *AD*, the same concern may arise, that is, similar backoff values among senders in coverage and short *ADs* in receivers may cause no retransmission of messages. The result is that most of the messages to be transmitted are discarded by the mesh layer when the *meshMAXNumASESRetries* value is reached. This short *AD* value also explains the low percentage of retransmissions when the *AO* is 1 for any transmission rate depicted in Fig. 4(a). Nodes are unable to access the medium (due to the backoff algorithm), so the messages are discarded when they are not transmitted in the next two consecutive *WI*. The loss of messages is also noticeable in scenarios where *WO* is fixed to 3 for any transmission rate. Unlike the previous case where the majority of messages are not dispatched to the medium, here, a large number of messages are discarded by collisions which are provoked, mainly, by HT effects along with the limited duration of *WI* (40 ms) and *AD* (10 ms for $AO = 1$ and 20 ms for $AO = 2$, respectively).

On the other hand, group (2), represented in Fig. 5(b), takes into account the messages retransmitted by sender nodes at MAC layer and discarded by receivers at PHY and MAC layers due to collisions caused by the HT phenomenon (mainly *primary* collisions). In detail, a sender node that successfully accesses the channel (even if this node was previously delayed a backoff time by the CSMA–CA algorithm) will transmit a data message to a receiver. It will most likely collide with another message (i.e. data, WN, EREQ, EREP) or ack which was dispatched by a node in the vicinity and which became a hidden node for this sender. In the receiver, both messages are received by their PHY layer. In the case that one or both messages do not have enough energy to excite the receiver's transceiver or to go above the power threshold imposed by the MAC layer, the messages are discarded. On the contrary, if some of the messages successfully exceed the thresholds imposed by the PHY and MAC layers, the message can be dispatched to the upper layers. Messages discarded by the receiver imply that the senders trigger the CSMA–CA algorithm (if the receiver's *AD* is long enough) or delay the data dispatched to the next *WI* in order to retransmit the

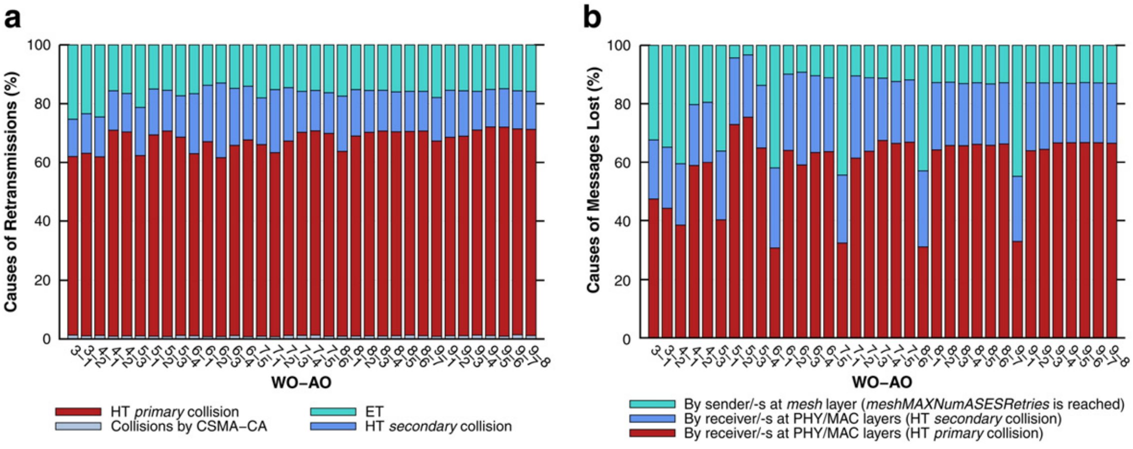


Fig. 5. Quantifying the different causes of (a) message retransmissions and (b) messages lost at 1 message per second rate as a function of the *WO–AO* parameters.

same messages again. However, they can be affected by the same problems, that is, these retransmitted messages may once more collide with other messages (data or control) sent by hidden nodes. In this sense, if the hidden terminal problem persists beyond two consecutive *WIs*, the sender station aborts the transmission and the message is discarded by the ASES operation. *This means that to account for a message lost at mesh level in the sender, several retransmissions discarded by the receiver at PHY/MAC layers are required*. This is the reason why the number of messages lost due to collisions (*primary* and *secondary* collisions) is significantly higher than that of those lost due to the ASES operation (group (1)).

4.3. Latency

Latency measures the average delay of messages since they are dispatched by the source until the instant they are delivered to the destination, including the time dedicated by all the intermediate nodes belonging to the source–destination path for accomplishing tasks such as the data processing, temporary storage in the node's memory or transmission/reception procedures, among others. Results are plotted in Fig. 6, revealing that the latency is mainly influenced by the values taken by *WO–AO*. A high *WO* value has a negative impact on the latency experienced by messages. In this case, sender nodes are forced to wait for the reception of one WN message when a new neighbor is selected to route data (TDLS operation), which may suppose a significant increase in the latency of future data messages (in the order of tens/hundreds of seconds more by each transmission). This effect also happens when *AO* is equal to 1 regardless of the value of *WO* because sender nodes can only transmit a single data message per each *WI*. As a result, data messages suffer different delays in each hop within the source–destination path, what involves an increase in the latency metric. Fig. 6 illustrates that the higher latency value is reached for *WO* equal to 9 (up to 350 s), being also remarkable the poor outcomes for any *WO* greater than or equal to 7. Comparing these cases, the different values for the latency are mainly because intermediate nodes require long time periods to dispatch data (e.g. in the case of $WO = 9$, this period is clearly greater than that for $WO = 7$), which increases the size of nodes' queues with new incoming messages. Although TDLS distributes the traffic among several intermediate nodes, after a long operation period, they become bottlenecks, continuously trying to access to the wireless channel. The result is that a large amount of nodes in the vicinity are contending, which makes the hidden terminal effect even worse.

Fig. 6 also shows that the latency for values of *WO* smaller than 7 are similar (approximately between 1 and 5 s) regardless of the transmission rate. Unlike the results obtained for $WO \geq 7$, in this case, the value of *WI* is short enough to avoid the accumulation of data messages in the transmission queues of the nodes (in particular, between consecutive *ADs*), thus allowing the prompt delivery of data to destination. Finally, the ET effects must be also considered in the calculation of the latency. As it was explained in Section 3, the ET phenomenon may produce continuous retransmission attempts of the same messages when they collide, provoking an undesirable increase in the latency.

4.4. Message delivery ratio

Fig. 7 shows the effects of the HT and ET for any *WO–AO* value and transmission rates of 0.1, 1 and 2 messages per second, where, in general, a poor percentage of messages delivered at destination is achieved. Only ASES configurations with a value of *WO* equal to 5 or 6 exhibit an acceptable operation, reaching 80% of the messages successfully delivered, but with the inconvenience of an important deviation in the confidence interval. This fact may represent a significant shortcoming for the final application because the network operation is unable to provide an accurate and reliable result, not only for the real message delivery ratio, but also for the remaining metrics. Regarding the results at a transmission rate of 0.1 messages per second, the hidden and exposed terminal phenomena are less frequent, mainly for values of *WO* starting from 7, so a higher percentage of messages reach the destination successfully. The message delivery ratio achieved is over 80%.

Observing globally Figs. 3–7, they also reflect that scenarios configured with values of *WO* greater than 6 and transmission rates of 1 and 2 messages per second achieve a poor network performance. As indicated, in these scenarios, the transmission of data messages is delayed longer time intervals due to the high values of *WO*, which in turn make the HT effect worse. Therefore, transmissions finally collide, increasing the number of later retransmissions and future messages lost. As a result, the throughput drops to values between 15 and 40% (0.1 and 0.5 Kbps respectively) of the data generated per node, and the number of messages lost, as well as the retransmissions, increase dramatically and the message delivery ratio decreases. Nevertheless, there is a relevant exception for scenarios where *WO* value ranges from 4 to 6. Here, the duration of the *AD* is large enough to allow the traffic to flow rapidly through the network, resulting in latency values between 1 and 5 s for the given scenario and transmission rates. Finally, in order to later compare with the proposals selected in Section 6, we take the configuration $WO/AO = 4/3$, since these values offer the best network performance, which in turn involves the greatest reduction of the HT and ET phenomena.

4.5. Energy consumption per bit

In order to study the effect produced on the energy consumption by the HT and ET phenomena, we have programmed the energy model of the MicaZ device [22,23] (see Fig. 8) in two scenarios. Both compute the behavior of an intermediate node operating in ASES mode but

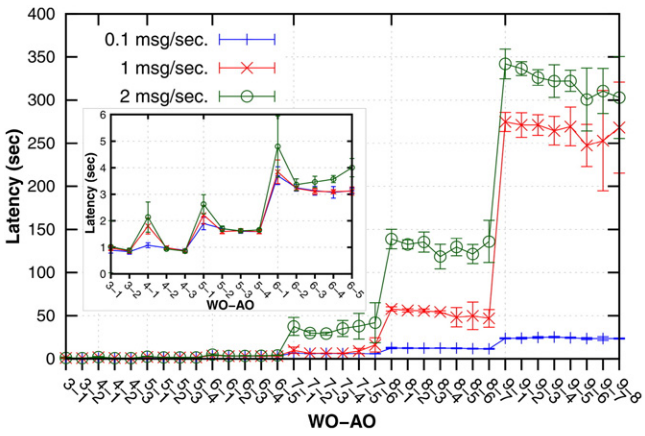


Fig. 6. Latency as a function of the *WO–AO* parameters.

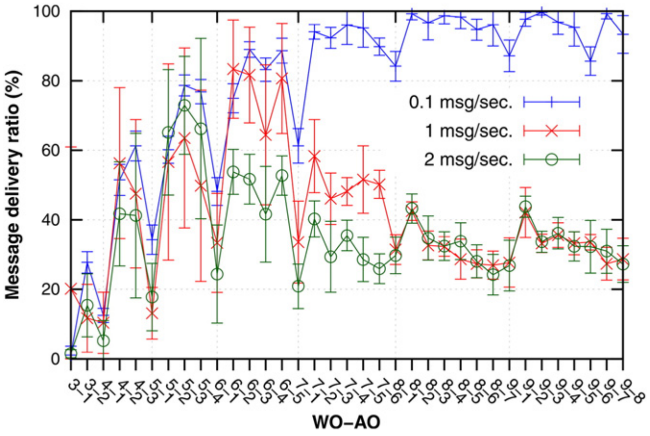


Fig. 7. Message delivery ratio as a function of the *WO–AO* parameters.

differing on the consideration or not of the HT and ET problems. In the first scenario, we implemented the energy scheduling of MicaZ as an additional functionality of the ns-2 simulation environment. This device is a widely deployed and referenced commercial WSN platform, which provides different power states, denoted as Transmission, Reception, Idle and Sleep (Fig. 8) to perform the duty-cycle scheme. In this scenario, we evaluate the energy consumption of an intermediate node under the hidden and exposed terminal effects. So, this setting computes the energy waste referred to, on the one hand, the reception of a message, and on the other hand, all the required attempts to retransmit this message to the next intermediate node or destination.

Facing the impossibility of implementing a mesh topology in ns-2 without considering HT and ET effects, we programmed a second scenario in MATLAB®. This scenario is also based on the MicaZ energy model and, therefore, it follows the sequence represented in Fig. 8. This model computes the energy consumption of an intermediate node under an ideal ASES scenario where the HT and ET problems do not arise. In order to fairly compare this ideal test with the simulation-based scenario, we implemented a case in MATLAB® in which nearly the entire *AD* of the intermediate node is required to receive a data message and dispatch it to the following intermediate node (or destination). As a result, a very short period (*inactive duration*) is used for sleeping.

On both scenarios, the energy consumption per bit has been calculated using the same throughput outcomes depicted in Fig. 3 for a transmission rate of 1 message per second. These results are plotted in Fig. 9. Observing this Figure in detail, we can deduce that the successful delivery of one bit involves a high energy cost due to the HT and ET effects (blue curve). Nodes cope with a high amount of message collisions and retransmissions, what noticeably increases the energy consumed per network node in comparison with the ideal case (red curve). The energy consumption, taking into consideration the HT and ET problems, experiences an increase from approximately a 30% to a 70% when *WO* is less than 8 (regardless of the value of *AO*), and up to 93% for the rest of situations. In particular, *WO* values equal or greater than 8 yield a very poor result for the metric under study, because nodes remain a large period in active mode for only achieving a very low throughput (see Fig. 3). By comparing both scenarios for the same intermediate node and throughput conditions, the conclusion is that HT and ET phenomena severely affect the energy efficiency. In particular, the worst result is obtained for $WO = 9$ (WI is 2.56 s) and $AO = 8$ (AD is 1.28 s) with a mean energy consumption per bit of 18 mJ/bit, around 85% greater than the ideal case.

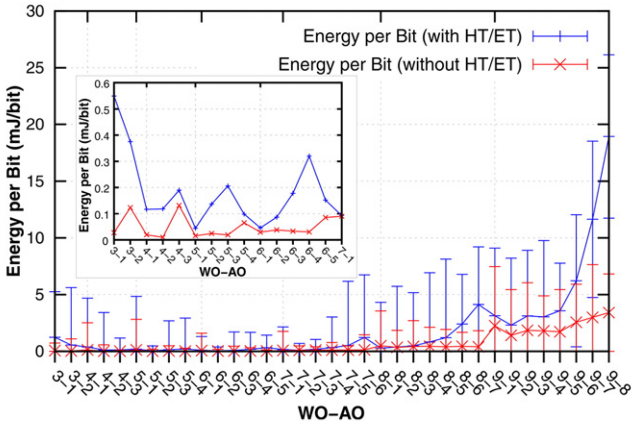
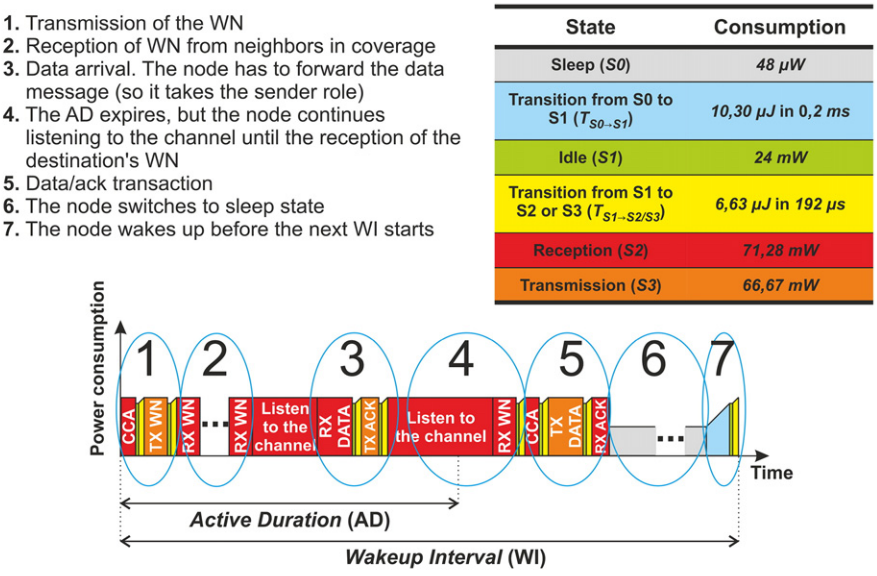


Fig. 9. Energy consumption per bit successfully delivered (at 1 message per second rate) as a function of the *WO–AO* parameters.

To sum up, collisions and message losses caused by the HT and ET effects are an important issue that jeopardizes the network and application performance, and therefore it needs to be appropriately addressed. It should be remarked that nodes are usually equipped with a single omnidirectional antenna, sharing the same wireless medium and having the same radio coverage, where no mechanism for interference avoidance exists. Thereby, as revealed by the results shown above, the exclusive use of CSMA–CA does not solve the hidden and exposed terminal problems. In this sense, the outcomes achieved from our evaluation are not unexpected, since neighboring nodes involved in data transactions will interfere with other communications in the vicinity. As a consequence, this notably degrades the network performance.

5. Proposals addressing the hidden and exposed terminal problems

Interference avoidance techniques including mitigation of the hidden and exposed terminal effects have been extensively investigated in wireless sensor networks [24–28]. The aim of this section is not to survey all the literature referred to WSN/WMSN that copes with these issues. Instead, it is only devoted to learn about those proposals compatible with the ASES mode of operation that, in addition, maintain the simplicity of design required by real WMSN devices.



1. Transmission of the WN
2. Reception of WN from neighbors in coverage
3. Data arrival. The node has to forward the data message (so it takes the sender role)
4. The AD expires, but the node continues listening to the channel until the reception of the destination's WN
5. Data/ack transaction
6. The node switches to sleep state
7. The node wakes up before the next WI starts

State	Consumption
Sleep ($S0$)	48 μW
Transition from S0 to S1 ($T_{S0\to S1}$)	10,30 μJ in 0,2 ms
Idle ($S1$)	24 mW
Transition from S1 to S2 or S3 ($T_{S1\to S2/S3}$)	6,63 μJ in 192 μs
Reception ($S2$)	71,28 mW
Transmission ($S3$)	66,67 mW

Fig. 8. ASES energy model of a single *WI* for an intermediate MicaZ node.

5.1. Time division multiple access protocols

Besides CSMA-based mechanisms, time division multiple access (TDMA) schemes are probably the most common technique employed for multiple access in traditional WSNs. This is because the number of collisions may be reduced or even fully eliminated thanks to the design of an efficient scheduling of the network activity [24]. To this end, in TDMA, each node reserves one or several time intervals called slots for its exclusive use (transmission and/or reception of data). This fact entails that any transmission or reception of messages is protected, a priori, from phenomena such as wireless interference or channel conflicts (due to, mainly, hidden and exposed nodes). However, a well-designed TDMA scheme must be associated to a tight synchronization. The reason lies in the fact that clock inaccuracy of devices (e.g. MicaZ introduces 40 μs per second [29]) may arise, what provokes that slots overlap with each other, causing interference and a significant reduction of the network performance. This circumstance is more noticeable as the network nodes density becomes higher, and the information generated by sender nodes placed far from the sink must be dispatched by several intermediate nodes. In this sense, a tight synchronization coordinates the operation of the intermediate nodes, solving the concerns caused by dynamic channel conditions such as nodes joining/leaving the network, node failures or mobility, among others.

Concerning ASES, it should be remarked that a TDMA scheme will be valid only if the ASES operation is preserved. Thereby, nodes must maintain the *WI*/*AD* procedure, being now mandatory to schedule transmissions within the *AD* through a TDMA process. The result would show how different nodes in coverage obviate channel conflicts and interference phenomena, thus guaranteeing the reliability of their transmissions. Nevertheless, this is achieved not only through the proper selection of a slot allocation mechanism that assigns non-overlapping slots to every node, but also by designing a robust TDMA protocol, able to suitably cope with crucial concerns typically encountered in such protocols, such as loss of synchronization or variable channel conditions. In this context, our interest is focused on the research works [30,31], since they consider different criteria for generating an efficient slot allocation and subsequent network operation that might be compatible with ASES, although increasing its complexity.

In [30], ROT (Receiver Oriented Time division multiple access) and MASM (Medium Access Scheduling Middleware) protocols are thought to eliminate the HT and ET effects in WMSNs by means of exchanging information among nodes placed within two-hops distance. In particular, ROT is the mechanism employed in the evaluation of the TDLS routing protocol [19]. In the research work conducted in [19], at the mesh network formation phase, each node calculates and adds to its routing table the time slot and the time slot cycle in which the node is able to transmit data to each one-hop neighbor individually. At the same time, each node includes its clock information in the messages transmitted during this phase to keep synchronization with neighbors. With this information, every node reserves a small guard time duration (GTD) within the slots calculated to estimate when to perform the re-synchronization process with each one-hop neighbor independently. As the authors support in works [19,30], this approach does not add network overhead in the synchronization process, since there is no need to share synchronization information frequently. Nevertheless, the main weakness of ROT is that it only focuses on preventing *primary* collisions, (Fig. 2(a)), obviating the *secondary* collision case (Fig. 2(b)) and the ET effect shown in Fig. 2(c).

To overcome these issues, all the aforementioned deficiencies are taken into account in MASM [30]. In contrast to ROT, MASM is a sender-oriented scheme. This means that the assigned slots are only used by sender nodes to perform the data transmission, and the remaining time is employed to listen to the transmissions from their neighbor nodes within their corresponding slots. In MASM, the slots assigned to every node are unique with regard to those assigned to two-hop neighbors, thus avoiding the hidden and exposed terminal effects completely. Nevertheless, this fact entails a tight synchronization of the entire network by means of periodic transmission of synchronization messages, thus increasing the network overhead. Applied to ASES, this approach would significantly increase the protocol complexity and degrade its energy efficiency.

5.2. Multi-channel access protocols

In Wireless Sensor Networks, multi-channel access protocols have been thoroughly investigated in order to reduce the interference phenomena and to increase the spatial reuse (multiple transmissions in a same interfering area thanks to the elimination of the exposed terminal phenomenon) by means of frequency channel switching. The work in [25] extensively surveys the major recent advances in multi-channel communications for WSNs. Unfortunately, an important concern arises in the diversity of proposals, mostly evaluated by means of computer simulation and very few through real test beds. Under these circumstances, we highlight several challenges that a well-designed multi-channel access protocol must satisfy accurately. These challenges have been grouped (according to different technical aspects) as follows: channel assignment (fixed or dynamic), coordination between nodes (both sender and receiver nodes tune to the same channel simultaneously to conduct the transmission), ET and HT problems, channel switching delay (switching duration in CC2420 radio transceivers is estimated in 200 μs [32,33]), broadcast support, or a new concern emerged by employing multi-channel switching, which is denoted as deafness (a sender node transmitting to a receiver node which is tuned to a different channel, so the receiver is unable to detect the incoming transmission).

In order to deal with the aforementioned challenges, Lohier et al. [33] proposed a multi-channel assignment protocol for IEEE 802.15.4. This approach can be considered as an extension of the Tree-based Multi-Channel Protocol (TMCP) [29], where each branch of a multi-hop tree topology is assigned a fixed channel by the root. Nodes belonging to a same branch are unable to switch to other channels different from the selected one (this fact makes communication among branches unfeasible). The goal is to increase the spatial reuse in the network. Nevertheless, the research in [29] employs CSMA–CA which, as it was mentioned, does not avoid the HT problems (*primary* collision case) in the same branch. Furthermore, because a fixed channel assignment is employed, the design offered in [29] is not flexible enough to adapt to dynamic channel conditions.

To overcome these shortcomings, the work in [33] allows all nodes of a same tree-branch to be configured to different channels. Every node employs one channel for transmission and a different one for reception. This means that a parent node exchanges information with all its children using the same channel, but this channel is different from the one employed with its parent. As a TMCP-based solution, collisions due to hidden nodes are not fully eliminated if two children nodes out of each other's coverage range (hidden) are transmitting simultaneously to the same receiver (parent). Moreover, CSMA–CA is unable to solve the deafness problem, which causes the loss of all messages transmitted by a parent to a node tuned to a different channel (i.e. its own parent's channel). Another feature introduced by [33] is that the root of the network periodically stops the execution of the application completely, and all nodes switch to a dedicated control channel to perform configuration operations for the re-assignment of channels. These operations may be motivated by different issues such as link failures (e.g. nodes leaving the network or external interference), or new nodes joining the network. This increases the energy consumption of nodes and, therefore, reduces the network lifetime. In any case, one of the major drawbacks of both works, [29,33], is related to the use of a tree-based topology, where a node may only dispatch information with its corresponding parent but never among neighbors in coverage area.

In the same context of relevant recent works about multi-channel access, a novel protocol close to the operation of ASES mode is presented in [34]. Under this protocol, called Efficient Multi-channel MAC

(EM-MAC), communications are conducted asynchronously following the same ASES procedure: a node periodically announces its neighbors that it is active during a short time interval through a broadcast notification message, in order to later switch to the sleep state. However, different from ASES, each time a node wakes up it computes and schedules, by means of a pseudorandom algorithm, a new interval for the active periods, and a new channel to receive the information. Thereby, if every node is able to operate, a priori, in a different time interval and channel, the number of collisions is reduced. Going into more detail, the receiver executes the pseudorandom algorithm to calculate its own seed value. This seed value is sent to the sender as an additional field within the notification message. Upon receiving the seed, the sender executes the pseudorandom algorithm in order to obtain beforehand the exact time and the channel on which the receiver wakes up. Therefore, for subsequent transmissions, the sender can activate its transceiver (ON mode) in the precise instant that it estimates the reception of the receiver's notification message.

Following with the work in [34] and in order to evaluate the EM-MAC protocol, the authors performed a real test bed using MicaZ devices, showing promising results in terms of the message delivery ratio. Moreover, this test bed presents two other main advantages: (i) the ability of nodes to adapt to dynamic channel conditions (e.g. channel overloaded) and, (ii) nodes do not require precise clock synchronization. Nevertheless, although EM-MAC reduces the HT phenomenon thanks to its multi-channel character, it does not completely solve the *primary* collision case, being this concern the main drawback of EM-MAC. This occurs when two or more hidden senders transmit to a common receiver. As the receiver's seed is known by the senders, they predict the same time instant and channel on which the receiver wakes up, thus, increasing the number of collisions. Test bed in [34] does not consider this concern, as only a few nodes are placed in such a way that they are in coverage area with each other. The result is only collisions produced by the usual operation of CSMA–CA (there are no hidden nodes). Therefore, work in [34] provides us with an incomplete performance evaluation of EM-MAC, because large-scale mesh networks (where the hidden terminal phenomena are usual) are not taken into account. Finally, data broadcast support is clearly inefficient in EM-MAC because the sender node needs to predict the wake-up instant and current channel of each neighbor, in order to later transmit its broadcast message to them individually (unicast).

The different channels allocated by the IEEE 802.15.4 PHY standard [15] can be fully exploited by multi-channel access protocols in order to improve the network performance in ASES. In this context, researchers/developers should avoid adding more complex radio hardware to the devices, what entails the degradation of the energy efficiency. Instead, we might take advantage of currently available low-cost and low-power radio transceivers, such as the traditional CC2420, or CC2530, which allow up to 16 non-overlapping channels with 5 MHz bandwidth each. Under this premise and concerning the research work in [33], the channel assignment method proposed might be extended to ASES. To this aim, the IEEE 802.15.5 mesh procedure should add the channels used by neighbor nodes in the routing tables. This has as a clear inconvenience the increase in the memory space per node. Nevertheless, this solution mitigates the exposed terminal effect, reducing the messages lost and consequently improving the latency and throughput performance metrics. In addition, other issues are left unsolved by [33], such as the ability to overcome HT effect or deafness. Regarding the novel approach followed in [34], it is fully compatible with ASES, however, this solution entails, a priori, important drawbacks in large-scale WMSNs. This is due to the fact that the usual EM-MAC operation does not completely eliminate the *primary* collision case.

5.3. Code division multiple access protocols

Code Division Multiple Access (CDMA) is one of the most commonly employed channel access methods in cellular networks (e.g. CDMA2000, W-CDMA), global positioning systems (GPS) and military applications, due to features such as spatial reuse and frequency reuse (simultaneous transmissions using different channels), interference robustness and security. CDMA-based schemes focused on WSN are usually categorized according to two well-known modulation techniques: frequency hopping (FH-CDMA) and direct sequence (DS-CDMA). FH-CDMA implements a different pseudorandom code for each frequency channel in which nodes operate. Thereby, the messages are de-/codified using the code assigned to each frequency channel. On the other hand, DS-CDMA assigns an orthogonal pseudorandom sequence to each node in radio coverage range, which enlarges the signal spectrum to the available bandwidth. The original message is obtained by correlating the incoming signal and the orthogonal sequence.

Regarding WMSNs operating under ASES mode, the use of CDMA would alleviate the HT and ET effects since pseudorandom codes facilitate the existence of multiple and simultaneous transmissions within the same vicinity. However, current CDMA techniques cannot be applied directly to these networks (where all nodes have the same role), since the design of these techniques is based on a central authority (base station) that controls and coordinates the access to the channel of the remaining network nodes, as in the case of cellular systems [35]. Additionally, analyzing the scientific literature [26,35–38], we identified other crucial requirements to take the exploitation of CDMA in WMSNs into account. Firstly, as in the multi-channel access protocols, one of the challenges of a CDMA scheme is to guarantee that both sender and receiver use the same pseudorandom codes aimed at selecting the same channel in FH-CDMA, or successfully extracting the information in DS-CDMA. Unfortunately, the number of available orthogonal pseudorandom codes is significantly smaller than the number of devices forming a large-scale WMSN due to restrictions of memory and processing on nodes. This leads to reusing the codes and assigning them efficiently to nodes. In particular, this assignment process should be performed carefully, so as to prevent several senders in coverage range from using the same codes and, therefore, from colliding with each other. Several research works are addressed to solve this issue [37,38] by conducting a code assignment process during the network formation procedure. This requires additional complexity in the protocol implementation, as well as an increase in the memory usage to store and access the codes from each neighbor node.

As a second requirement, the robustness to interference offered by CDMA is a feature achieved at the expense of additional complexity in the receiver. Regarding this issue, reception in a FH-CDMA scheme is more straightforward, since it does not need to avoid interfering signals from nearby transmitters. The only inconvenience is the time wasted and the energy consumed by switching to the corresponding channel (process executed by both sender and receiver simultaneously) to tackle the communications. However, in the case of DS-CDMA, since all nodes operate in the same channel and there is no central authority to control the channel access, a special receiver circuitry is required to eliminate all the interfering transmissions, that is, a specific hardware that captures the desired signal from the rest of possible concurrent transmissions. This statement introduces the concept of Multi-Access Interference (MAI) [36], also known as near-far effect, one of the major concerns in DS-CDMA systems, due to the significant degradation of the network performance. MAI arises when a receiver node receives multiple and simultaneous signals with similar power that collide with the desired incoming signal. In this case, the receiver node is unable to extract the signal under study and, therefore, to receive the information successfully. Unlike cellular networks, where MAI occurs only at the base station, all nodes of a WMSN must deal with this problem [35]. As a result, the number of retransmissions increases, and consequently more energy is consumed not only to transmit a data message (and later retransmissions in the event of collisions), but also on the receiver side, due to the overhead motivated by the multiple interfering transmissions and the later interference suppression.

Taking into account all the aforementioned premises and requirements, different works in WMSNs propose novel techniques based on CDMA to avoid the interference phenomena. Unfortunately, to the best of the authors' knowledge, there is an important lack of real WMSN implementations based on CDMA, most of the works being purely theoretical [39,40]. In this sense, we highlight two different proposals exploiting CDMA techniques [8,41], as well as the works in [39,42]. In particular, the first two solutions are provided by the industrial wireless mesh standards WirelessHART [7,8] and ISA SP100.11a [41,43]. WirelessHART was released in 2007 by the HART (*Highway Addressable Remote Transducer*) Communication Foundation (HCF) for implementing mesh networks on industrial sensing and control applications. This standard employs the IEEE 802.15.4 PHY layer together with a combination of (i) a FH-CDMA scheme where each data message is transmitted in a different frequency band, and (ii) a DS-CDMA scheme to fully exploit each band in every transmission. WirelessHART also develops a TDMA scheme at MAC layer [8], not only to schedule the access to the medium (minimizing collisions), but also to achieve certain requirements such as deterministic latencies and reliability. On the other hand, ISA SP100.11a was released by the International Society of Automation (ISA) also to provide a WMSN solution addressed to industrial environments. Many of its main features are inherited from WirelessHART, such as the use of DS/FH-CDMA schemes at PHY layer and a TDMA scheme at the MAC layer.

Unfortunately, both standards, WirelessHART and ISA SP100.11a, exhibit two important drawbacks. Firstly, as it was mentioned in the previous paragraph, they do not implement the whole IEEE 802.15.4 protocol stack, only the PHY layer, and provide their own design for the upper layers (proprietary software). This feature translates in the loss of compatibility and interoperability with the majority of WSN and WMSN implementations based on the IEEE 802.15.4, dominant standard in the WSN market. Secondly, their main benefits are the robustness to interference, reliability and deterministic latencies, which imply a serious increase in the computational overhead due to an additional stack implementation on simple WMSN devices. This fact increases the energy consumption and processing requirements, thus increasing the cost of the hardware compatible with these standards. For general purpose applications, we also want to draw attention to work in [42], which proposes a theoretical solution comprising DS-CDMA and TDMA techniques for cluster-tree networks. TDMA is employed to eliminate the inter-cluster interference and to schedule the data transmission within each cluster, whereas DS-CDMA aims at eliminating interference inside the cluster. The goal of work [42] is to minimize the energy consumption of nodes through an optimal schedule for transmission. To this end, the authors formulate an optimization problem based on minimizing the transmission power and transmission times within each cluster. The main weakness of this work is related with the cluster topology, where the information is managed and centralized by cluster-heads, i.e. special nodes which have more resources and capabilities than the remaining nodes of the cluster. This feature restricts the routing decisions, always conducted by these special nodes, what further limits the flexibility of these networks as regards mesh solutions. Furthermore, in the case of cluster-head's failure, the nodes belonging to the cluster will be disconnected from the network. This fact is opposite to the principles of a WMSN, where all nodes usually have the same capabilities, distributing the responsibilities and operations of the network among all their members.

Following with the line of solutions for cluster networks, the authors in [39] proposed a MAC protocol denoted as SN-MAC. As in [42], SN-MAC employs DS-CDMA and TDMA techniques. Nevertheless, unlike the study in [42], the design of SN-MAC is addressed to further reduce the interference phenomena thanks to the implementation of a Transmission Power Control (TPC) mechanism [35] together with a separate channel for transmitting control information (by means of *Request To Send* – RTS – and *Clear To Send* – CTS – messages). This protocol is assessed by means of ns-2 simulations in a random network composed of 200 nodes. The evaluation is performed in terms of latency, lifetime and throughput, assuming errors and retransmissions by the hidden and exposed terminal effects. Results show that those scenarios that implement SN-MAC protocol achieve better throughput and latency, at the expense of worsening the network lifetime. This is motivated by the increase in transmission power for RTS/CTS messages (including the associated overhead), the use of the TPC mechanism, and by the operation mode of DS-CDMA.

Summarizing, CDMA-based solutions for WMSNs are proprietary designs [7,41] or are in their early stages [39,42]. Regarding proposals [39,42], they lack real implementation or are poorly evaluated and, in addition, both are aimed at offering solutions based on cluster-tree topologies. All these concerns justify why the CDMA mechanism is not considered in the comparative study accomplished in Section 6.

5.4. Directional antennas

In recent years, different studies in directional antenna technology [27,44,45] have been conducted to obtain important benefits on multi-hop wireless networks, thus becoming an interesting research topic for WMSNs. In comparison with the traditional omnidirectional antennas, directional ones present significant advantages such as interference mitigation, increase in spatial reuse, higher network coverage and connectivity, energy consumption reduction, and an improvement in reliability, latency and throughput. Nevertheless, not all are benefits; directional antennas also have some drawbacks that cannot be ignored in the WMSN field under study. Firstly, the use of directional antennas increases the cost and complexity of the design, what comes up against the limitations of size, memory and processing resources of the WMSN devices. Regarding WMSNs, although a few prototypes have been implemented [45,46], there is a significant lack of existing hardware compatible with the strict requirements of WMSN devices. Furthermore, our interest is focused on directional antennas of a single beam, because the use of antenna arrays as in [45,46], implies a notable increase in the complexity, physical size (additional hardware is required) and the energy consumption per node.

Secondly, regarding directional antennas, a well-designed beamforming among different neighbor nodes can reduce interfering transmissions in the same neighborhood, decreasing the number of collisions and also alleviating the ET effect. As a result, the spatial reuse can be exploited more appropriately. Nevertheless, to reach this optimum beamforming design, it is necessary to overcome three noticeable concerns, namely: detection of incoming signals, deafness effect and HT phenomenon [27]. Detection of every incoming signal in directional antennas is not as straightforward as in the omnidirectional ones, due to the difference in radiation patterns. In the case of omnidirectional antennas, the pattern is uniform in all space directions, whereas in directional antennas the transmission/reception power is designed to be concentrated on a unique direction. Thereby, although transmissions can reach large distances (so less number of hops is required to deliver data to the destination) and the spatial reuse can be exploited more efficiently, a tight alignment between the direction of sender and receiver's lobes is mandatory. The goal is that both lobes point to the same direction in order to exchange information successfully and, as a consequence, to avoid data retransmissions and loss of messages. In the case of sensing the medium and detecting incoming signals, the receiver circuitry must continuously rotate the beam in all directions. After the detection of an incoming signal, the receiver stops the rotation and starts the reception of the message. Nevertheless, this procedure entails an important concern already discussed in the multi-channel subsection, the deafness effect. In directional antennas, this problem is due to the node's inability to detect incoming signals from any direction distinct from the main lobe's direction, that is, a receiver node may be involved in one transmission while, all information transmitted to this node from other directions is unavoidably lost. In these conditions, the implementation of a proper scheduling system or medium access control mechanism might solve this concern, as commented in the next paragraphs.

On the other hand, in order to route the information, an intermediate node can learn about the position of every neighbor node once it has been detected. Then, when this node has data to transmit, it rotates the antenna lobe to the direction where the receiver is placed at and dispatches the message. However, this operational mode is negatively affected by the hidden terminal phenomenon because all the antenna power is concentrated on one direction and, therefore, nodes are unable to sense if there are other nearby transmitters simultaneously dispatching messages to the same receiver. The result is the collision of the messages at the receiver node and hence, their subsequent retransmission or loss. For this reason, the access to the medium must be controlled with additional techniques such as the ones implemented in [44,47–50]. Finally, note that all these shortcomings (deafness and hidden effects) can be alleviated by using multiple beam antennas [45,46], but at the expense of extra complexity in the implementation and energy cost, as it was previously stated.

In order to handle these issues, two different solutions have so far been proposed in the open scientific literature with the aim of including a switching mechanism between directional and omnidirectional modes. These approaches are as follows: (i) using dedicated signals/flags to establish the switching sequence between omnidirectional and directional modes, and (ii) a temporal scheduling so as not to overlap both modes, that is, all network nodes learn about the time intervals operating with the omnidirectional mode (transmitting signals/flags) and the exact time instant when they switch to the directional mode to dispatch data. The first group of approaches opts for the employment of a set of antennas that are able to comprise a twofold functionality: they operate in an omnidirectional mode to listen to the incoming control signals (flags, namely, RTS/CTS signals or tones), which indicate that a node wants to transmit information; and then they automatically switch to a directional mode to receive the data or configuration messages from this node [48–50]. This operation mode seeks, a priori, to reduce the deafness problem. However, this stand-alone proposal requires taking advantage of other control mechanisms that ensure the successful access to the wireless channel so as to eliminate deafness completely and to reduce the HT phenomenon. In general, these control mechanisms are based on a contention-based protocol (e.g. CSMA–CA) plus the aforementioned transmission of RTS/CTS control signals [50] or pure tones [49]. In any of the above cases [49,50], these transmissions are done by dedicated omnidirectional antennas [50] or directional ones [49] moving sequentially on every direction within the node's range for the detection of those flags, and before selecting the direction to transmit data. Regarding the ASES operation, it may support, a priori, the switching between both configurations: omnidirectional antennas for broadcast messages (e.g. WN), and directional antennas for unicast ones (i.e. data). However, the feasibility of this mechanism for ASES is not yet clear because, in the case of omnidirectional antennas, the hidden and exposed terminal problems are not eliminated.

The second solution applied to switching between omnidirectional and directional modes looks for decreasing the deafness and hidden terminal phenomena by means of a mechanism based on scheduling the access to the medium of data messages and flags [47,48]. In particular, the work in [48] separates the control flag operations, which schedules the nodes' medium access, from data transmission tasks, and both are done in different consecutive periods. The main drawback of [48] is associated with the control functions which are performed exclusively through the transmission of RTS/CTS signals between sender and receiver, what entails increasing the network overhead. Furthermore, the use of this control mechanism based on RTS/CTS flags does not ensure that the hidden terminals and deafness effects are completely eliminated. This is because the flags are also affected by these same hidden terminal and deafness problems. In any case, this solution (RTS/CTS signals) was designed for approaches based on the IEEE 802.11 standard, whose network requirements are less restrictive than in the case of IEEE 802.15.4/802.15.5, so these signals cannot be directly applied to WMSN/WSN standards. For this reason, we should highlight the work in [47], where a theoretical study of the throughput and latency metrics including typical features of directional antennas and a temporal scheduling (obviating the transmission of RTS/CTS or tones) is carried out for multi-hop WSNs. Results are compared with the employment of omnidirectional antennas, showing that the design based on directional antennas significantly improves network performance. Nevertheless, the investigation in [47] lacks a complete study in simulated or real WMSN conditions. As a strong point, the solution based on temporal scheduling of the transmissions along with the omnidirectional and directional switching mechanism is fully compatible with ASES, but taking into consideration that broadcast/multicast messages are transmitted with the omnidirectional mode, while unicast messages are dispatched by means of the directional one. Moreover, to avoid the deafness and hidden effect on the omnidirectional case for transmitting broadcast, additional scheduling (whose goal is to generate exclusive time intervals) may be employed.

To sum up, the inclusion of directional antennas in the WMSN arena and, in particular, to be applied to the ASES mode, should be planned as in the case of the CDMA approaches, that is, in combination with a well-designed control access mechanism. In this context and taking the proposals discussed in this subsection into consideration, a temporal scheduling (data access to the physical medium in its exact time instant) is the most feasible solution. The reason is the greater simplicity of the temporal scheduling mechanisms in comparison with the other solutions which implement a complicated communication protocol and/or where an additional hardware must be included into the radio transceiver as well. Finally, although various theoretical studies show clear benefits of using directional antennas [27,44] to reduce the hidden terminals and deafness problems, this is a technology that needs to be implemented in the real devices to truly learn about its actual performance. To this end, the design and integration of their components (hardware and software) must fulfill the limitations and requirements of a wireless sensor device, in order to obtain a future exploitation of this technology in the WMSN field.

As final contribution of this section, Table 3 comparatively summarizes all the different technologies which mitigate the HT and ET problems and are to some extent compatible with ASES mode.

6. Comparison among proposals compatible with ASES

After reviewing the specialized literature, a comparative evaluation is accomplished following a twofold perspective. Firstly, we conduct a study in order to decide which approaches are the most suitable to be applied to ASES. To achieve this goal, different proposals/solutions based on TDMA mechanisms, channel multiplexing protocols and directional antennas techniques are evaluated and analyzed. However, CDMA-based proposals are not included in this study because, on the one hand, solutions [7,41] deal with proprietary implementations, which cannot be reproduced in the large-scale scenario planned here and, on the other hand, works [39,42] are theoretical studies based on cluster-tree topologies, which are out of the scope of our work specifically addressed to mesh networks. Therefore, the selected approaches are: ROT [19,30] and MASM [30] protocols from the TDMA alternatives, EM-MAC [34] referred to multi-channel solutions and finally, proposals [47,48] for the case of directional antennas. After this first study, we carry out a second comparison to stress the solutions selected in a more realistic scenario. Thereby, we aim to offer researchers, end users and developers some useful hints for future investigations and WMSN deployments.

Our first study is conducted by comparing the following metrics which are measured at the destination node, namely: (1) throughput, (2) message delivery ratio, (3) latency, and, (4) energy consumption per bit (following the model illustrated in Fig. 8). The rationale to select them is as follows: (i) to prove the feasibility of the proposals under

Table 3
Technology alternatives.

Proposal	Medium access mechanism	Goal	Use of dedicated control period/channel	Synchronization	Use of control messages or tones	Energy-saving support
ROT [19,30]	TDMA and CSMA–CA	Minimization of HT problem and latency	No	Synchronization with neighbors/vicinity	No	Duty cycle based on TDMA
MASM [30]	TDMA and CSMA–CA	Minimization of HT and ET problems, and latency	No	Centralized synchronization	Control messages, only for synchronization purpose	Duty cycle based on TDMA
MASN [33]	Multi-channel. fixed assignment of channels	Maximization of throughput	Dedicated control channel	No	No	No
EM-MAC [34]	Multi-channel. dynamic assignment of channels	Minimization of HT and ET problems, and other interference sources (e.g. Wi-Fi) Maximization of lifetime	No	No	No	Duty cycle
WirelessHART [7]	CDMA and TDMA	Minimization of HT and ET problems, and other interference sources (e.g. Wi-Fi) and latency Maximization of throughput	No	Network-wide synchronization (centralized by the Network Manager)	Control messages, only for synchronization purpose	Duty cycle based on TDMA
ISA SP100.11a [41]	CDMA, TDMA and CSMA–CA	Minimization of HT and ET problems, and other interference sources (e.g. Wi-Fi) and latency Maximization of throughput	No	Network-wide synchronization (centralized by the Network Manager)	Control messages, only for synchronization purpose	Duty cycle based on TDMA
Shu et al. [42]	CDMA and TDMA	Maximization of lifetime	Dedicated control channel	Network-wide synchronization (carried out by cluster-heads)	Control messages (*Channel Access Request*)	Duty cycle based on TDMA. Use of TPC mechanism
SN-MAC [39]	CDMA and TDMA	Maximization of throughput and lifetime	Dedicated control channel	Network-wide synchronization (carried out by cluster-heads)	Control messages (RTS and CTS)	Duty cycle based on TDMA. Use of TPC mechanism
Arora et al. [50]	Directional and omnidirectional antenna	Minimization of HT, ET and deafness problems	Dedicated control channel	Synchronization with neighbors/vicinity	Control messages (RTS and CTS)	Use of TPC mechanism
Dai [47]	Directional antenna	Minimization of HT and ET problems, and latency Maximization of throughput	No	Synchronization with neighbors/vicinity	No	Duty cycle based on TDMA
Rammohan et al. [49]	Directional and omnidirectional antenna	Minimization of HT	No	Synchronization with neighbors/vicinity	Control messages (RTS and CTS) and tones	No
Staniec et al. [44]	Directional antenna	Minimization of HT and ET problems	No	Synchronization with neighbors/vicinity	N/A	Duty cycle
Subramanian et al. [48]	Directional and omnidirectional antenna	Minimization of HT and deafness problems	Dedicated control period	Synchronization with neighbors/vicinity	Control messages (RTS, CTS and *Negative CTS*)	N/A

study with the aim of eliminating or alleviating the HT and ET problems (to this end the throughput in the Fig. 10(a) and the delivery ratio in Fig. 10(b) metrics are presented), (ii) to obtain a quantitative sketch about the energy cost of each proposal (illustrated in Fig. 10(d)), and (iii) to study the suitable operation of each mechanism to be integrated into ASES mode in a next future. In this sense, a figure of merit to consider is the latency (see Fig. 10(c)). A low latency reveals the appropriate operation of a solution, meaning that it may be rendered as feasible option to be implemented on the ASES mechanism. The evaluation is accomplished by testing the simulation framework provided in the work [19], by studying the simulation results developed in [47,48], and by solving the analytical expressions provided in [34]. In particular, [34] has been included in this discussion because its equations can be easily applied in a grid topology similar to the one shown in Section 4. Also, we include the ASES results for the configuration of $WO = 4$ and $AO = 3$, which offers the best network performance in accordance with the study done in Section 4. The objective is to compare the most significant ASES results with the ones obtained by identical configurations in terms of data generation rate (1 message per second), traffic pattern (CBR), topological layout (grid topology) and radio coverage range (60 m). Finally, for a fair comparison among the different proposals in this study, the duty-cycle schemes of all of them are adjusted to guarantee that most of the traffic generated in the network is delivered to the destination. The results of this evaluation are plotted in Fig. 10.

Thus, this first study is set to guarantee good outcomes referred to the throughput and message delivery ratio metrics for all the proposals analyzed, taking into consideration the same generated traffic than the ASES operation for $WO = 4, AO = 3$. To this purpose, the setup phase of each proposal requires a specific configuration of the duty cycle aimed at obtaining the expected throughput and message delivery ratio. Therefore, ROT and Subramanian et al. [48] mechanisms must be always in the ON mode (which has an adverse impact on the energy consumed per bit metric) while the active period of the duty cycle for the MASM solution is set to 50% and for Dai [47] and EM-MAC are 45% and 50%, respectively. In addition to the duty cycle, other design parameters must be configured in the directional antenna case, namely, the number of different phases to be employed by the antenna and the beamwidth. Regarding the number of phases, it depends on the selected topology (grid). Here, the number of neighbors in coverage range is a fixed value (4 nodes), which means that any network node requires four different phases to guarantee the appropriate communication with all

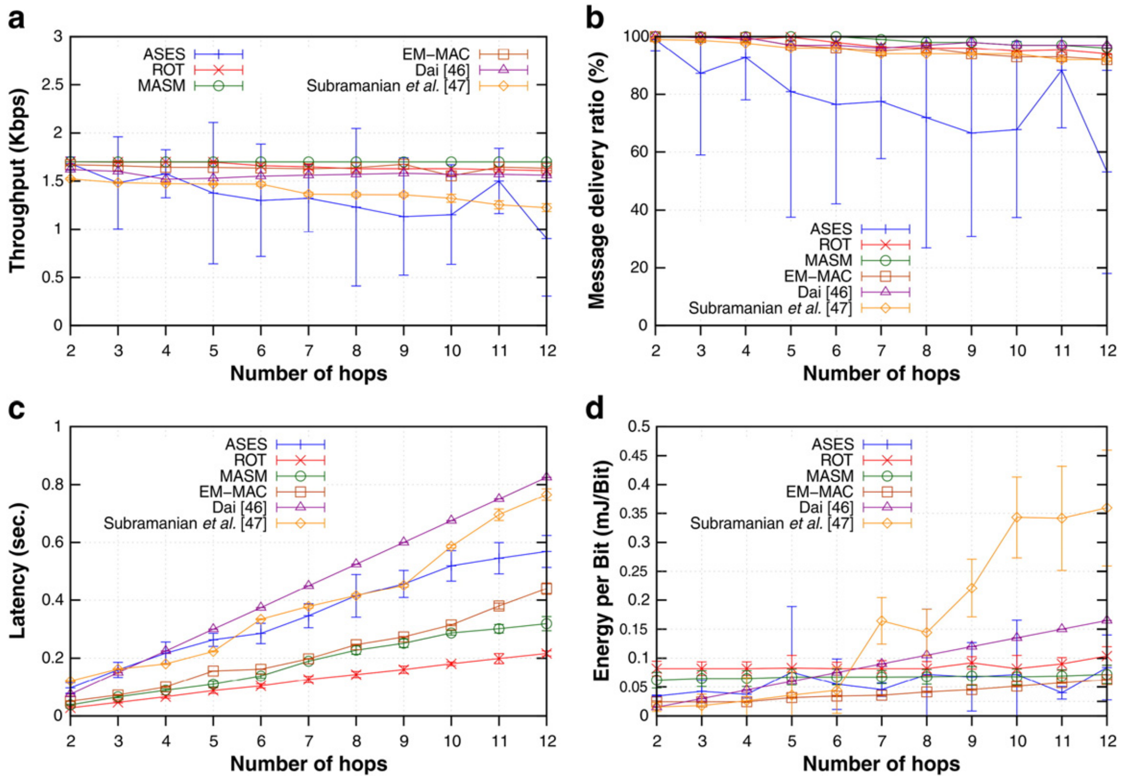


Fig. 10. (a) Throughput, (b) message delivery ratio, (c) latency, and (d) energy consumption per bit transmitted.

its neighbors. On the other hand, in order to reduce the complexity of the configuration, each one of the four phases has a beamwidth of 90°. In comparison with omnidirectional antennas, the configuration of these parameters (number of phases and beamwidth) consumes a quarter of the transmission energy waste. Concerning works in [47] and [48], our study calculates the entire figures of merit for the one-hop case transmissions, because these investigations do not offer mechanisms to fully mitigate the HT and ET effects when the transmission goes beyond one-hop.

Fig. 10(a) shows that the throughput obtained by all the proposals (with the exception of ASES mode) is reasonable in comparison with the generated traffic. However, as it was discussed in Section 4, ASES mechanism is not designed for dealing with these problems, what implies the worst results of all the approaches analyzed. In the case of the EM-MAC proposal, the achieved throughput is lower than the TDMA solutions, since EM-MAC does not absolutely solve all HT problems, in particular the *primary* collisions (Fig. 2(a)). Finally, proposals based on directional antennas lack a complete solution for the HT problems, since different senders aligned with a same receiver may interfere among them, degrading the throughput.

Message delivery ratio is depicted in Fig. 10(b). Obviating ASES, the rest of proposals obtain about 100% of success in message transmission when the number of hops is low (1–4), being slightly worst (over 90%) in the case of values around 10 hops. Concerning a higher number of hops, TDMA alternatives (ROT and MASM) offer a better behavior than the multi-channel or directional antennas approaches. In particular, for the maximum achievable throughput, MASM shows the best performance results, closely followed by ROT. The reason is that proposals based on multi-channel and directional antennas suffer a greater number of lost messages because they do not solve efficiently the deafness problems, and/or the HT and ET effects, as previously discussed. Observing jointly the throughput and message delivery ratio metrics, the selected proposals guarantee that most of the generated traffic reaches the destination, which in turn implies similar results in these metrics. This demonstrates that the operation modes of these proposals mitigate the HT and ET effects.

Following with the analysis, Fig. 10(c) illustrates the differences in the message latency for the set of approaches selected. Proposals based on directional antennas [47,48] exhibit higher delays to transmit information than the other ones. It is mainly due to the time required for carrying out the alignment procedure between transmitter and receiver antennas before transmitting data messages. Additionally, latencies are also conditioned by other issues, such as the time employed in retransmitting messages lost or the delay due to transmit RTS/CTS messages [48]. On the other hand, EM-MAC implements a multi-channel proposal which, a priori, increments the latency value as a consequence of the multiple channel switching. Nevertheless, once the same communication channel is set between sender/-s and a receiver, EM-MAC uses an asynchronous scheme for the medium access, which guarantees latency results comparable to the ones obtained by the TDMA approaches for the traffic model selected.

Finally, the energy consumed per bit is showed in Fig. 10(d). This Figure illustrates how the multi-channel solution achieves, on average, the best result in energy saving (less consumption than the other approaches and similar to the current ASES mechanism). This is due to the few control information that nodes must exchange with their neighborhood, referred to the assigned channel and the time instant in which the receiver wakes up. MASM and ROT proposals show a stable behavior, because both run the synchronization and transmission tasks (into their active periods) not taking into consideration the number of hops. In the case of directional antenna-based techniques, they consume more energy, for instance in switching passive transducers or in rotating the beam, what in turn represents a critical concern for resource-constrained WMSN devices. This issue also implies worse results than the remaining approaches regarding latency and ratio of successfully transmitted messages.

Once these proposals have been evaluated in a mesh topology, a second study is conducted in order to stress the set of selected approaches

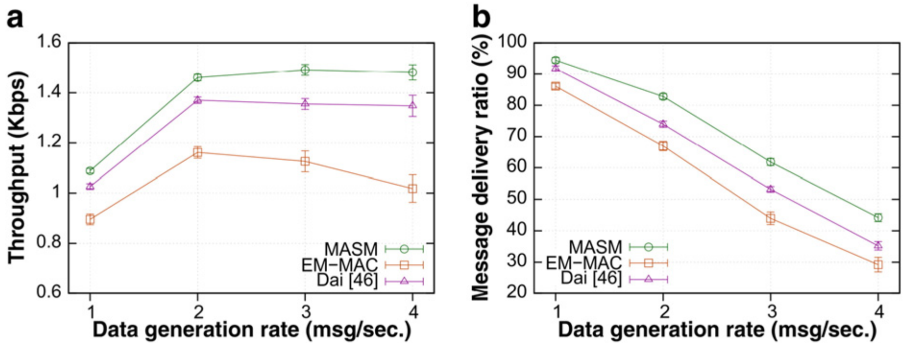


Fig. 11. (a) Throughput and (b) message delivery ratio for MASM, EM-MAC and Dai [47] as a function of the data generation rate.

in a more realistic scenario. In this regard, we assess the metrics of throughput and message delivery ratio for different data generation rates and under the premise that network lifetime is at least 5 months. This value is selected in accordance with our experience in WSN applications developed for the precision agriculture field [51,52]. In particular, we reproduce a complete agronomic cycle to monitor a melon (*Cucumis melo L.* variety) crop, where the network devices handle periodical measurements about different physical parameters such as the soil moisture, temperature and humidity. Under this condition, two approaches, ROT and Subramanian et al. [48], must be excluded from this evaluation since they force nodes to remain always in active mode (the duty cycle is 100%) and, therefore, they are unable to satisfy our lifetime constraint. Conversely, the remaining proposals, namely, MASM, EM-MAC and Dai [47], are configured with duty cycles of 20%, 25% and 22%, respectively, in order to operate during at least 5 months. Regarding the data generation rate, it ranges from 1 to 4 messages per second. The values of the remaining configuration parameters are the same as in our previous study, particularizing for the case of 12 hops between the source and destination.

Fig. 11(a) and (b) illustrate, for all proposals under study, the results of throughput and message delivery ratio as a function of the data generation rate. Going into detail, MASM and Dai are the solutions which offer the best results since both approaches are exclusively conceived to alleviate the HT and ET problems. Nevertheless, the delivery ratio and throughput drop for rates above 3 messages per second. This behavior occurs because the duty-cycle configuration satisfies the expected lifetime but affects negatively the throughput. Consequently, the message delivery ratio is restricted by the throughput achieved, so a lower value of this metric implies an increase in the number of messages lost. Furthermore, we can observe that MASM achieves better throughput values than Dai because, as Fig. 10(c) shows, the latter solution incurs the highest delay for the transmission/reception tasks. Finally, note that EM-MAC exhibits the worst results of the study because it does not fully mitigate the *primary* collision case of HT and the short duration of its duty cycle.

To sum up, these studies reveal that TDMA-based protocols, in particular, the MASM proposal, are the most appropriate techniques, in terms of throughput, message delivery ratio and latency to be implemented in ASES mode. Other proposals also mitigate the HT and ET problems, but offering a worse performance than MASM. However, the use of the TDMA mechanism is in conflict with one of the main basis of ASES operation mode: it does not require synchronization. Furthermore, the MASM operation involves considerable energy consumption as nodes must be synchronized, what restricts critically the network lifetime. Under these circumstances, channel multiplexing techniques such as EM-MAC are a competitive tradeoff approach, which handles the energy waste more efficiently, but degrading the rest of network metrics here studied, mainly for large-scale networks (more than 10 hops). Although directional antennas may sharply reduce the HT and ET effects, any solution based on this technique deteriorates the network performance. However, the use of directional antennas together with TPC mechanisms may be a well-suited solution in future designs, but assuming higher computational complexity.

7. Conclusions

To the best of the authors' knowledge, hidden and exposed terminal effects have never been evaluated for the recent IEEE 802.15.5 LR-WPAN mesh standard, a recommendation addressed to promoting newer and better applications in the WSN arena. In this line, a complete simulation framework was developed, that allowed us to deeply study the performance of WMSNs operating under the Asynchronous Energy Saving (ASES) mode, the most usual energy scheme to monitor physical parameters in the IEEE 802.15.5 standard. Our simulator assesses, in a grid topology, the interference effects produced by hidden and exposed terminals on several performance figures. In particular, we show how a simple transmission scheme consisting of a unique source and a unique destination is clearly affected and degraded by these types of interference, demonstrating and quantifying the importance of these phenomena on the normal operation of the ASES mode.

The degradation of the network performance caused by HT and ET also led us to review the recent specialized literature, seeking for feasible proposals that can mitigate these phenomena appropriately. These approaches must be aligned with the usual energy, processing and memory constrains of the wireless sensor devices and must be also compatible with the IEEE 802.15.5/ASES requirements (autonomous network formation and addressing, a unicast/multicast/broadcast transmission model, energy-saving mechanism, among others). Under these conditions, we overview and discuss in detail the most relevant WMSN works that deal with the HT and ET problems, classifying them into four groups of proposals, namely: time division multiple access protocols, multi-channel access protocols, code division multiple access protocols and use of directional antennas. In addition, a comparative evaluation of a group of significant proposals is performed, showing which of them are the most suitable to be developed together with the ASES mechanism. Then, we conclude that there is no approach that reduces the HT and ET phenomena and simultaneously satisfies all the IEEE 802.15.5/ASES requirements. From this knowledge, we aim to offer developers some useful hints in order to deal with the aforementioned issues. They should lead to minimizing or removing the hidden/exposed terminal problems, facilitating the definite penetration and expansion of the WMSNs in the consumer market. Our future work is aimed at filling this gap, proposing, designing and evaluating the most appropriate Mesh, MAC and PHY cross-layer solution for the success of WMSNs, in particular those based on the IEEE 802.15.5 standard. Additionally, this solution would include a novel analytical model seeking to provide a better understanding when it comes to mitigate or, ideally, eliminate HT and ET interference problems.

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