Comparison between Channel Hopping and Channel Adaptation for Industrial Wireless Sensor Networks

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Abstract: One of the differences between the new standard IEEE 802.15.4e, in comparison to the previous IEEE 802.15.4 standard, is the use of multiple channels. The Time-Slotted Channel Hopping (TSCH) mode employs channel hopping, and the Deterministic and Synchronous Multi-channel Extension (DSME) mode employs channel hopping or channel adaptation, during the contention free periods. When using the channel adaptation as the channel diversity technique, a pair of nodes communicate using the same channel while the channel quality is good enough in terms of signal-to-noise ratio. Thus, it is necessary to evaluate the quality of the links, in order to proper use this mechanism. In this paper, three different approaches, based on the DSME protocol, were implemented and evaluated through a simulation study. The first one (CH-DSME) is based on a simple channel hopping mechanism, the second one (CA-DSME) employs channel adaptation, and the third one is a novel hybrid approach (H-DSME), that uses both channel hopping and channel adaptation. The H-DSME outperformed the other two approaches for the scenario in consideration, which shows that the use of channel adaptation is better than channel hopping for the transmission of unicast packets, when the quality of the links are monitored continuously. However, for packets transmitted in broadcast by the coordinator, the use of channel hopping is a good alternative to deal with the spatial variation in the quality of the channels.

1 INTRODUCTION

The use of Wireless Sensor Networks (WSN), to implement monitoring and control systems in industrial environments, has some advantages when compared with the use of wired networks, such as low cost and high flexibility. However, it is necessary to deal with typical problems of wireless systems, such as electromagnetic interference (Lima-Filho et al., 2012), and industrial environment high attenuation, due to the presence of many objects and obstructions (Tanghe et al., 2008). Many industrial environments also present characteristics that make the wireless channel non-stationary, for long time periods, which can cause abrupt changes in the characteristics of the channel over time (Agrawal et al., 2014b).

To overcome these limitations, mechanisms that allow the network to self-adapt to the variations that occur in the link quality over time need to be implemented, such as adaptive routing (Gnawali et al., 2009) or dynamic channel allocation (Gomes et al., 2014). Other important aspect is the energy consumption and management, which is a key issue in industrial WSN, given network motes are usually powered by batteries. Some appropriate strategies, as energy aware geographic routing in lossy WSN, can be developed (Anastasi et al., 2009).

Some standards have been proposed in the last years with a focus on industrial applications, such as the WirelessHART and the ISA100.11a. Both WirelessHART and ISA100.11a are based on the physical layer of IEEE 802.15.4, but defines its own MAC layer. Instead of using CSMA/CA, as defined by the IEEE 802.15.4 standard, they use a MAC layer with Time Division Multiple Access (TDMA). By using TDMA, collisions are avoided and the power consumption can be optimized. They also use frequency hopping and blacklisting, to mitigate the problems related to interference and fading. However, without an adequate management of the blacklist, the com-

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munication performance may be lower for these standards (Petersen and Carlsen, 2009).

More recently, the IEEE 802.15.4e standard was released. The goal of this standard is to propose solutions for applications that require high reliability, such as industrial applications (Guglielmo et al., 2016). Five modes of operation are defined, that is: Time-Slotted Channel Hopping (TSCH), Deterministic and Synchronous Multi-Channel Extension (DSME), Low Latency Deterministic Network (LLDN), Asynchronous Multi-Channel Adaptation (AMCA), and Radio Frequency Identification Blink (BLINK). However, only the modes TSCH, DSME, and LLDN have been explored in the literature until recently. In general, the modes of the IEEE 802.15.4e are based on TDMA or frequency hopping to reduce collisions and mitigate the effects of interference and fading, and to satisfy the requirements of industrial applications in terms of reliability and determinism.

One of the main differences between the new standard IEEE 802.15.4e in comparison to the previous IEEE 802.15.4 standard is the use of multiple channels. The TSCH mode employs channel hopping. When using this mechanism, the nodes usually switch to a new channel before each transmission, which makes the network more robust against problems that affect only a subset of the channels. However, if a proper management of the blacklist is not made, the network performance can be significantly degraded (Grsu et al., 2016). In the DSME mode, channel hopping can also be used in the contention free periods. It is also possible to use a channel adaptation mechanism instead of channel hopping. When using channel adaptation, a pair of nodes communicate using only one channel during a large time period. A channel switch only occurs when the channel in use starts to present low quality. Thus, a procedure is necessary to evaluate the quality of the links continuously, in order to use the channel adaptation mechanism properly. The implementation of this procedure is not defined by the standard.

In this paper, the performance of three different approaches for channel diversity, based on the DSME mode of the IEEE 802.15.4e standard, were evaluated. The first one is based on a simple channel hopping mechanism, the second one employs channel adaptation, and the third one is a novel approach that uses both channel hopping and channel adaptation. The simulations were performed using the Castalia simulator, which is an event-driven simulator for WSN. A realistic channel model was used, which includes the effects of fading, shadowing, and the non-stationary characteristics of the channel in industrial environments. When using this model, which was first described in (Gomes et al., 2015b), it is possible to observe the performance of the protocols, considering the non-stationary behavior of the wireless channel in industrial environments. This simulation model was also used in (Gomes et al., 2016) to evaluate link quality estimators for industrial WSN.

2 IEEE 802.15.4e STANDARD

In networks that use the IEEE 802.15.4 standard, it is difficult to establish strict latency boundaries, due to the CSMA/CA protocol used in the MAC layer, since the access to the communication medium occurs in a distributed and random way. Hidden and exposed terminal problems can also affect the performance of the network, making it even more unpredictable. The MAC protocols defined by the IEEE 802.15.4 use a single channel for communication, which is a single point of failure, and increases the number of collisions in the network. Due to these limitations, the new standard IEEE 802.15.4e was proposed, for applications with more stringent requirements of reliability and determinism.

Five modes of operation are defined by the standard, but only modes TSCH, DSME, and LLDN have been more extensively studied until recently (Guglielmo et al., 2016). Modes TSCH, DSME and LLDN use TDMA as the channel access method, which allows to reduce the number of collisions, and increases the determinism of the network, since each node has specific time slots allocated to it, and the access can be done without contention. Besides, it is possible to reduce the energy consumption, since the nodes can sleep during time slots in which they are not transmitting or receiving packets. Modes TSCH, and DSME also employ multichannel communication and three types of topology (star, mesh or tree), while the LLDN define only star networks that use a single channel to communicate. However, some works have proposed the use of a tree topology and multiple channels in LLDN networks (Patti et al., 2014; Patti and Bello, 2016).

In the next sub-section more details about the DSME mode are provided, since the protocols proposed and evaluated in this paper are based on this mode.

2.1 The Deterministic and Synchronous Multi-channel Extension Mode

The DSME mode is the most complex and flexible mode of the IEEE 802.15.4e standard (Guglielmo et al., 2016). It extends the beacon-enabled mode

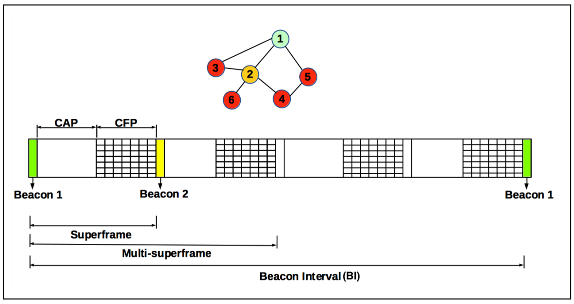

Figure 1: Example of a superframe structure for a DSME network.

of the IEEE 802.15.4, which is based on a superframe structure, that is managed by the network coordinator. The coordinator sends beacon frames to delimit two consecutive superframes. The main differences between the beacon-enabled mode of the IEEE 802.15.4 and the DMSE mode is that the DSME mode allows the use of a higher number of Guarantee Time Slots (GTS), and allows communication using multiple channels during the contention free period. Thus, multiple nodes can transmit simultaneously during the same GTS in different channels, increasing the overall WSN throughput.

Figure 1 shows an example of a superframe structure defined according to the DSME mode of the IEEE 802.15.4e standard (802, 2012). Each superframe is composed by a Contention Access Period (CAP), and a Contention Free Period (CFP). Different from the beacon-enabled mode of the IEEE 802.15.4, there is no inactive period. In the CAP, the nodes can access the communication medium using CSMA/CA or ALOHA (Guglielmo et al., 2016). The beacon frames, referred in the standard as Enhanced Beacons (EB), delimit the superframes. The EB frames are transmitted using the same channel, defined in the starting process of the network (802, 2012), which is also used in the CAP period.

Multiple superframes can be grouped inside a multi-superframe, and multiple multi-superframes can be grouped inside the same Beacon Interval (BI). This time structure is configured using some parameters, that is: *macSuperframeOrder* (SO), *macMultisuperframeOrder* (MO), and *macBeaconOrder* (BO), in which $0 \leq \mathrm{SO} \leq \mathrm{MO} \leq \mathrm{BO} \leq 14$. The parameter SO defines the size of the superframes, MO defines the size of the multi-superframes, and BO defines the BI. In the example shown in Figure 1 the parameters $\mathrm{MO} = \mathrm{SO} + 1$, and $\mathrm{BO} = \mathrm{MO} + 1$. Each superframe has 16 time slots. Thus, the value of SO defines the duration of each slot. Optionally, the number of CAP can be reduced in a multi-superframe, through a mechanism called *capReduction*. When the *capReduction* is enabled, only the first superframe in the multi-superframe has the CAP.

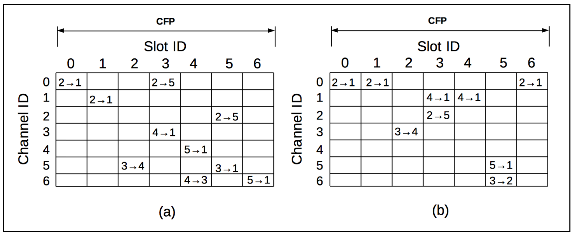

Figure 2: Channel diversity mechanisms defined for DSME networks.

In the DSME networks there are three types of nodes: PAN coordinator, coordinator, and end node. The PAN coordinator sends a EB every BI. The coordinator is the sink node for some of the network nodes. A coordinator sends a beacon at least once per multi-superframe, in the beacon slot, in order to register its presence in the network (Alderisi et al., 2015). In Figure 1, Node 1 is the PAN coordinator, Node 2 is a coordinator, and the remaining are end nodes. The coordinators can forward packets from end nodes that do not reach the PAN coordinator directly. In the same network multiple coordinators nodes are allowed.

The DSME mode defines two types of channel diversity, that is: channel hopping, and channel adaptation. Figure 2 shows two examples of scheduling for the CFP period, using channel hopping in (a), and channel adaptation in (b). When using the channel hopping, the nodes receive packets in different channels depending on the channel offset of the node, the slot ID, the superframe ID, and the sequence number of the EB sent by the coordinator. For example, in the example illustrated in Figure 2(a), Node 1 receives a packet using Channel 0 in the first time slot, using Channel 1 in the second time slot, and so on. The nodes that receive packets inside the same superframe need to have different channel offsets, in order to avoid collisions.

When using channel adaptation, a fixed channel is allocated for a given time slot inside the superframe, and a given pair of nodes. For example, in the example illustrated in Figure 2(b), Channel 0 was allocated for the communication from node 2 to node 1, in all slots. The channel is only changed if the allocated channel starts to present bad quality. The standard does not define how to select the communication channels when using channel adaptation (Guglielmo et al., 2016). In this paper, an algorithm to estimate the link quality is proposed, and used to implement the channel adaptation mechanism.

Another interesting characteristic of the DMSE is the possibility of using group acknowledgment (GACK), in which two time slots of the multi-superframe are allocated for the GACK frames (G1 and G2). The coordinator uses G1 to acknowledge all packets received until the G1 time slot. The G2 is used to acknowledge all packets received after the G1 time slot and before the G2 time slot. If the GACK is not used, all packets transmitted to the coordinator are acknowledged individually (802, 2012). With this mechanism, a node can retransmit a lost packet inside the same multi-superframe, if one slot before the G1 and other slot between G1 and G2 are allocated to the node.

2.2 Related Research

Some authors have proposed mechanisms to improve the performance of IEEE 802.15.4e networks, through the use of dynamic channel allocation or dynamic configuration of the blacklist for TSCH networks. In (Grsu et al., 2016) an experiment was performed to analyze the performance of a TSCH network inside an aircraft cabin, with external interference caused by Wi-Fi networks. In the experiments described in (Grsu et al., 2016) the Packet Error Rate (PER) was 35%, when using the 16 available channels, due to interference problems. In general, when fewer channels were used, the performance was better, as the interference is lower. For example, when using only one channel, the less affected by the interference sources, the PER was 5%. However, a mechanism is needed to estimate the quality of the channels and to dynamically configure the blacklist.

In (Du and Roussos, 2011; Du and Roussos, 2013) the use of adaptive frequency hopping for TSCH networks was proposed, in order to avoid using channels affected by interference sources. In this approach, two time slots in each cycle are used to perform readings of RSSI values, in order to identify interference sources. Based on these measurements, the blacklist is updated to avoid the channels with a high level of interference. In (Du and Roussos, 2013) experiments were conducted considering different sizes for the blacklist. It was observed that the higher the size of the blacklist, the better the communication performance. This result corroborate the results presented in (Grsu et al., 2016). However, this type of behavior only occurs if an adequate monitoring of the quality of the channels is performed, in order to properly configure the blacklist in real time. One limitation of the approach presented in (Du and Roussos, 2011)(Du and Roussos, 2013) is that only interference problems are considered. Other aspects that can affect the quality of the links are not considered, such as shadowing and fading. Besides, the channel quality monitoring is performed by all nodes and using time slots that could be used for communication, which incurs in a high overhead, and in an increase of latency.

Some authors have proposed the use of techniques for channel diversity and multi-channel communication based on the IEEE 802.15.4e standard for LLDN networks, which use originally only one channel. In (Patti et al., 2014) a multi-level and multichannel protocol based on the LLDN mode, called the MC-LLDN, was proposed. The goal is to increase the scalability of the network through the use of a multi-level topology, data aggregation, and multi-channel communication. The drawback is that the channels are allocated to the sub-networks in a static way. Thus, it is not capable of dealing with the variations that occur in the channel quality over time. The protocol described in (Patti and Bello, 2016) is an evolution of the MC-LLDN, called PriMuLa, which incorporates adaptive channel selection. One limitation of the proposed protocol, which is due to the characteristics of the LLDN, is that a same channel is allocated to all nodes in the sub-network. However, spatial variations in the channel quality can occur, as well as asymmetry problems. In the approaches developed for the present paper, the channel quality is assessed in a per-link basis, as well as the channel allocation.

The experiments described in (Jeong and Lee, 2012) and (Lee and Jeong, 2012) evaluated the performance of the DSME mode in comparison to the beacon-enabled mode of the IEEE 802.15.4. The experiments verified that, in some scenarios, the throughput of the IEEE 802.15.4e DSME network can be 12 times higher than the IEEE 802.15.4 beacon-enabled network, and with a lower energy consumption, due to the use of a TDMA-based medium access. In the experiments frequency hopping was used, and no dynamic management of the blacklist was employed. In (Lee and Jeong, 2012) the influence of interference caused by Wi-Fi networks was evaluated, but other problems that can affect the channel quality in industrial environments, such as shadowing and fading, were not considered.

In (Capone et al., 2014) simulation studies to verify the performance of DSME networks are described, and some enhancements to optimize the energy consumption are proposed. However, the paper focuses mainly on energy consumption, and did not consider in the experiments the problems that can affect the channel quality, such as interference and fading. Besides, although in the simulations described in (Capone et al., 2014) the channel adaptation mechanism was considered, the details about the implementation of this mechanism are not provided.

In (Alderisi et al., 2015) a comparison between DSME and TSCH in process automation scenarios is described. Simulations were performed to verify the delay, reliability, and scalability of each mode. The TSCH presented better results for small networks, with up to 30 nodes. For larger networks, with more than 30 nodes, the DSME presented better results. The simulations described in (Alderisi et al., 2015) used realistic parameters for the log-normal shadowing, but the effect of fading and the non-stationary characteristics of the wireless channel were not considered. In addition, only the channel hopping mechanism of the DSME were analyzed. The simulation model used for the present paper considers more aspects that can affect the channel quality, that is: shadowing, fading, asymmetry, and the non-stationary characteristics of the channel in long time periods. Besides, a comparison between channel hopping and channel adaptation is performed.

In (Juc et al., 2016) a comparison between TSCH and DSME is described, in terms of energy consumption and performance. In the scenarios under consideration, the energy consumption of DSME was slight better than TSCH, as well as the performance. For applications that send less data, the TSCH under-utilize the bandwidth, due to the fixed size of the time slots. In the experiments described in (Juc et al., 2016) only channel hopping was considered, and without group ACK. In the present paper, channel adaptation are also considered, as well as group ACK.

3 PROPOSED DSME-BASED PROTOCOLS

In this paper, three approaches for the DSME mode are implemented and evaluated, called CH-DSME, CA-DSME, and H-DSME. The CH-DSME is based on the channel hopping mechanism, and without blacklist. Most papers, described in Section 2.2, evaluated the DSME with this type of channel diversity. In (Capone et al., 2014) the channel adaptation mechanism was considered, but the details about the implementation of this mechanism were not provided. The CA-DSME is based on the channel adaptation mechanism for the CFP periods of the superframes. An algorithm to estimate the quality of the links is used to decide when a channel switch is needed. The H-DSME is a hybrid approach that uses channel adaptation in the CFP periods, and channel hopping for the beacons, and GACK frames.

This paper focuses in channel diversity techniques. Thus, to simplify the analysis at this point, a star topology was considered. In future works, the extension of the proposed approaches for tree and mesh networks, and considering a larger number of nodes, will be studied.

3.1 CH-DSME

Figure 3 shows the frame structure implemented for the CH-DSME. A network with 10 nodes, and star topology was considered, in which nine end nodes (Node 1 to Node 9) are connected, and transmit packets directly to the PAN coordinator (Node 0), and only one transmission occurs in each time slot. In Figure 3 the numbers in the time slots indicate the ID of the end node that performs a transmission in each time slot. The *capReduction* was enabled, and thus only the first superframe has the CAP.

Each node has two time slots to transmit packets. The first one is before the first GACK (G1), and the second one is placed between G1 and the second GACK (G2). Thus, if the transmission in the first attempt fails, the end node can try again, using other channel, inside the same multi-superframe. The second time slot of each node is used only for retransmission. If the first transmission occurs successfully, the second time slot is not used. The beacons, and GACK frames are always transmitted using the same channel (Channel 0 in Figure 3). For transmission of data packets, the channel to be used in a given time slot i is determined using

$$c(i) = (i + j \times l + macChannelOffset + BSN)\%16,$$

where j is the superframe index, *macChannelOffset* is the channel offset of a receiver node, *BSN* is a sequence number of the beacon sent by the PAN coordinator. The value of l is equal to 15 if CAP reduction is enabled and j is not equal to zero, or 7 otherwise. In the implementation built for this paper, the *macChannelOffset* is equal to the ID of the receiver node. All the 16 channels were considered, thus the value of $c(i)$ is an integer between 0 and 15, which represents the channel identification.

3.2 CA-DSME

The CA-DSME also uses the frame structure shown in Figure 3, but with a different channel diversity mechanism. In CA-DSME all nodes transmit to the coordinator using only one channel, without channel hopping. All the nodes use the same channel at the beginning. Since only one transmission occurs in each time slot, the end nodes can use the same channel in the transmissions. In scenarios with more than one transmission at the same time, the channels need to be allocated in order to avoid collisions. A channel switch only occurs when the channel of a given link starts to present bad quality, and only the channel of the affected link is changed.

When using channel adaptation in the CFP periods, it is possible to pick good channels for all links, if

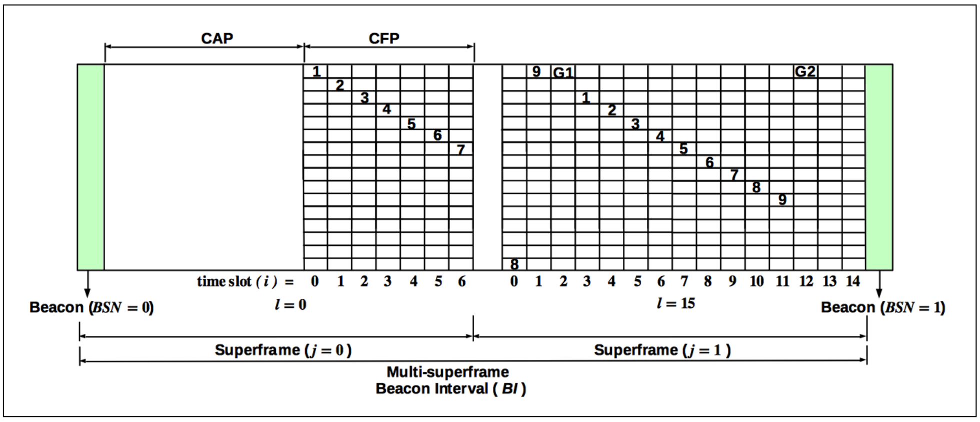

Figure 3: The time structure used in the simulations.

the link quality estimator is able to quickly and accurately estimate the link quality. The experiments described in (Du and Roussos, 2013; Grsu et al., 2016) showed that by using only one channel, the network performance is higher than using a channel hopping mechanism with a larger set of channels. However, the channels to be used need to be properly chosen.

Since the nodes try to retransmit a lost packet only once, and inside the same multi-superframe, it is possible to calculate the Packet Reception Rate (PRR), using the information obtained from a set of received packets. The Algorithm 1 was used to calculate the Packet Reception Rate of each link, in which each packet has an ID (a sequence number that identifies the packet) and the information about in which slot it was received, that is, before G1 (slot 1) or after G1 (slot 2). If the same packet is received twice due to a fail in the reception of G1, only the first received packet is put on the packet list to be analyzed by the algorithm. This algorithm also considers that the second time slot is used only for retransmission.

Using the Algorithm 1 the coordinator calculates the PRR for each link using a window of N packets. A threshold can be defined for each link, in order to trigger the channel switch procedure. In the implementation built for this paper, $N = 10$, and a threshold equal to 0.9, for all nodes, were used. Each new PRR value obtained using the Algorithm 1 is combined with the last calculated value using an Exponentially Weighted Moving Average (EWMA) filter with history control factor $\alpha = 0.3$, to make the calculated PRR more stable over time. Higher values for α can make the estimator more stable, but the reactivity becomes smaller.

Algorithm 1: Algorithm to calculate the Packet Reception Rate.

Input: a list of packets *packet_list* with N packets, and the expected id for the first packet in the list fp_{id}
Output: the Packet Reception Rate (PRR)

$fail\_cont := 0$
for each *packet* in *packet_list* **do**
  if $packet.slot = 1$ **then**
    $fail\_cont := fail\_cont + 2 \cdot (packet.id - fp_{id})$
  else
    $fail\_cont := fail\_cont + 2 \cdot (packet.id - fp_{id}) + 1$
  end if
  $fp_{id} := packet.id + 1$
end for
PRR $:= \frac{N}{N + fail\_cont}$
return PRR

In the beacon frame, there is a bitmap to indicate to each node if it needs to perform a channel switch. When the PRR calculated for a given link is below its threshold, the coordinator sets the corresponding bit on the bitmap to 1. When the node receives a beacon indicating the need of a channel switch, it switches to the next channel, in a round-robin fashion. While the coordinator does not receive a packet in the new channel, it continues to send the beacon with the bit equal to 1 in the bitmap. After receiving the first packet in the new channel, the coordinator clears the bit. Since the beacon frames are always sent using the same channel, if the transmission of a beacon fails, the nodes can wait for the next beacon to re-synchronize.

A mechanism to identify deep fading problems was also implemented. As the coordinator needs to receive data packets to calculate the PRR using the Algorithm 1, when the link between a given end node and the coordinator enters in a deep fading state, no packets can be received while the channel remains in that state. Thus, when the coordinator does not receive packets from a given end node during a long period, it starts the channel switch procedure for that node. In the implementation built for this paper, the coordinator starts a channel switch procedure when no packet is received from a given end node during 10 consecutive BI.

In both CH-DSME and CA-DSME the channel used to transmit the beacons and the GACK frames is a single point of failure. In these protocols, it is possible to deal with problems that affect the quality of a subset of channels through channel hopping or channel adaptation, but they are not capable of dealing with problems that affect the channel used to transmit the beacons and the GACK frames. Thus, in this paper a new hybrid approach is proposed (the H-DSME), which is better explained in Section 3.3.

3.3 H-DSME

The beacon and GACK frames are transmitted in broadcast mode to all the end nodes connected to the coordinator. Therefore, the channel used to transmit these frames needs to present good quality for all links between the coordinator and the end nodes. However, spatial variations in the channel quality can occur. The coherence length is used to quantify the maximum change in distance that will result in the channel being highly correlated. In experiments described in (Watteyne et al., 2010), it was verified a coherence length of 5.5 cm for IEEE 802.15.4 radios operating in the 2.4 GHz band. Thus, two nodes positioned more than 5.5 cm apart from each other, and using the same channel, can be considered uncorrelated, and thus the channel can present high quality for one node, and low quality for the other.

Although the use of only one channel during a large time period can be advantageous for the CFP periods, as explained in Section 3.2, it may be difficult to guarantee a good qualify of service for all end nodes when using only one channel for the transmission of beacons and GACK frames. Thus, the H-DSME uses channel adaptation for the CFP periods (in the same way of CA-DSME), and channel hopping for the transmission of beacons and GACK frames. The channels are used in a round-robin fashion to transmit the beacons and GACK frames. Using this mechanism, the end nodes do not remain disconnected for a large time period, when one channel begins to decrease its quality regarding the coordinator link.

The IEEE 802.15.4e standard defines that the channel used in the set-up of the network needs to be used to transmit the beacons and for the transmissions in the CAP period (802, 2012). However, the modification to use multiple channels can be done with no interference with the other parts of the protocol.

When dynamic addition of nodes is considered, the nodes that want to join the network need to listen in some channel during up to 16 BI. If no beacon is received, the node can start to listen in another channel during other 16 BI. When only one channel is used to transmit the beacon frames, as defined originally by the standard, the node listens in one channel during only one BI. However, if the end node doesn't know the channel used to transmit the beacons a priori, in some cases it will be necessary to wait for multiple BI (16 in the worst case) until a beacon is received. In addition, if the channel in use to transmit the beacons presents a very low quality for the link between the coordinator and the new node, the delay to join the network can be very high. This aspect will be better evaluated in future works.

To accommodate the use of channel hopping in the transmission of the beacons, it is necessary to have a mechanism to maintain the network synchronized in case of failures during the reception of a beacon. To do this, a timer is used in the end nodes to identify that a beacon has been lost. The coordinator sends a new beacon for each BI, thus the timer is configured to expire after a time equal to $\mathrm{BI} + \frac{\mathrm{SD}}{16}$ ms, where $\frac{\mathrm{SD}}{16}$ is the duration of a time slot. The values of BI and SD depend on the values of the parameters BO and SO, respectively. If a node receives a new beacon before the timer expires, the timer is reseted. Otherwise, the node switches the channel, and waits for the next beacon, which maintains the synchronization.

4 EVALUATION METHODOLOGY

The wireless channel can be considered as stationary for a short term, despite the moving parts around the transmitter and the receiver. However, the properties of the channel can change significantly over time due to changes in the topology of the environment, which are not considered in the distributions used to model the fading. This may require the recalculation of the distribution parameters, since these parameters may become obsolete over time (Agrawal et al., 2014b).

A characterization of the wireless channel in industrial environments was performed for a long term (20 hours) in (Agrawal et al., 2014a). The experiment demonstrated that abrupt changes in the channel characteristics can occur when the channel is analyzed for a long time, and differences on the mean value of the received power are observed, although the transmitter and receiver remain static. For example, in the experiment described in (Agrawal et al., 2014a), the received power varied about -55 dBm during seven hours, and after this period the mean value of the received power changed abruptly to -46 dBm. An experiment described in (Olofsson et al., 2016) also presented similar behavior, showing the special nature of these environments.

To allow the simulation of protocols for industrial

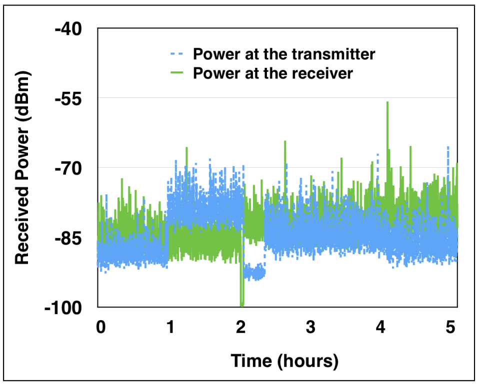

Figure 4: Asymmetry and temporal variations in the received power.

WSN, it is necessary to use a model that takes into account the channel characteristics for a long period of time. In a previous article (Gomes et al., 2015b), a simulation model was developed, which includes the effects of fading, log-normal shadowing, and the non-stationary characteristics of the channel. In this model, different channels can present different characteristics, since the channels defined by the physical layer of the IEEE 802.15.4e are uncorrelated in frequency. Experiments described in (Amzucu et al., 2014) have demonstrated that changing the communication channel can lead to a difference of up to 30 dB in the received power, in an office environment. Experiments described in (Watteyne et al., 2010), in an office environment, showed that for distances greater than 6.5 m between transmitter and receiver, even the adjacent channels are uncorrelated.

In the current implementation, two instances of the model are used to model the wireless channel in the two directions of a link, to capture the asymmetry. In the model, abrupt changes in the channels characteristics can occur. A mean time of change is defined for the model, which is used to define the value of a parameter p, the probability that a change in the characteristics of the channels occur. Thus, it is possible to simulate environments that remain unchanged for a long period of time and environments that present frequent changes in the topology. The simulation result obtained using the model is compatible with results from experiments performed in industrial environments (Agrawal et al., 2014b) (Gomes et al., 2015a) (Olofsson et al., 2016).

Figure 4 shows the reception power at a receiver (obtained from received packets) and a transmitter (obtained from received ACKs) during five hours of simulation to test the model. It is possible to notice the abrupt changes that occur in the channel characteristics over time, and the asymmetry between the two directions of the link.

Table 1: Parameters used in the simulation.

Area	60 x 60 meters
Physical layer	IEEE 802.15.4
Bit rate	250 $kbit/s$
Simulation Time	7200 s (2 hours)
Transmission power	0 dBm
Packet transmission rate	1 packet/s
Mean time of change	40 minutes

Table 2: Position of the nodes in the simulations.

Node ID	Coordinates (X, Y, Z)	Distance to the coordinator (node 0)
0	(-8.13, 7.66, 2)	-
1	(-14.53, 2.66, 2)	8.12 meters
2	(-22.83, 8.91, 2)	14.75 meters
3	(-12.25, -19.79, 2)	27.76 meters
4	(16.66, -11.84, 2)	31.54 meters
5	(-12.46, -15.26, 2)	23.33 meters
6	(-1.93, 1.65, 2)	8.63 meters
7	(-13.60, -20.99, 2)	29.17 meters
8	(22.60, -5.45, 2)	33.41 meters
9	(-15.30, 9.73, 2)	7.46 meters

To evaluate the performance of the three approaches, five replications of the experiment were made. Table 1 shows the parameters considered in the simulations for each replication. For the lognormal shadowing model the values of $n = 1.69$, $d_0 = 15$ m, $L(d_0) = 80.48$ dB, and $X_\sigma = 6.62$ dB were used. These values were obtained from experiments in an industrial environment described in (Tanghe et al., 2008). The mean time of change defines the average time between two changes in the characteristics of the channel.

To perform a fair comparison, for each replication the same seed was used to evaluate each approach, and different seeds were used for different replications. Thus, the three approaches were evaluated considering the nodes positioned at the same position and with the same channel characteristics during the replications. The positions of the nodes are shown in Table 2.

The frame structure used in the simulations is shown in Figure 3. Table 3 shows the values of the parameters that were used to configure the frame structure. In this configuration, the SO is equal to the BO, thus each BI has only one multi-superframe. Each multi-superframe has two superframes, in which only the first one has the CAP. With this configuration, the beacon interval has approximately 0.246 s, which is enough to accommodate the application implemented for the simulations, that transmits one packet per second.

Table 3: Parameters of the frame structure.

macBeaconOrder (BO)	4
macMultisuperframeOrder (MO)	4
macSuperframeOrder (SO)	3
Time slot duration	7.68 ms
capReduction	enabled
Group Ack	enabled

5 RESULTS

Four metrics were used to evaluate the approaches, that is: the Packet Reception Rate (PRR) at the application layer, the PRR at the MAC layer, the delay, and the maximum time between the reception of two consecutive packets. The PRR at the application layer considers the relation between the packets received and transmitted without considering the number of retransmissions at the MAC layer, while the PRR at the MAC layer considers the retransmissions. The delay is the time between the transmission of a packet and the reception of the packet at the application layer. The maximum time between the reception of two packets was analyzed to investigate the time in which the nodes remain disconnected due to low channel quality.

Figure 5 shows the PRR at the application layer for the nine end nodes. The averages and confidence intervals were calculated considering the data obtained from all replications. For the nodes positioned further apart from the sink node, the PRR was smaller when using CH-DSME and CA-DSME. When using the H-DSME the PRR at the application layer was almost 100% for all nodes. When using CH-DSME and CA-DSME, most errors occurred due to failures in the transmission of the beacons.

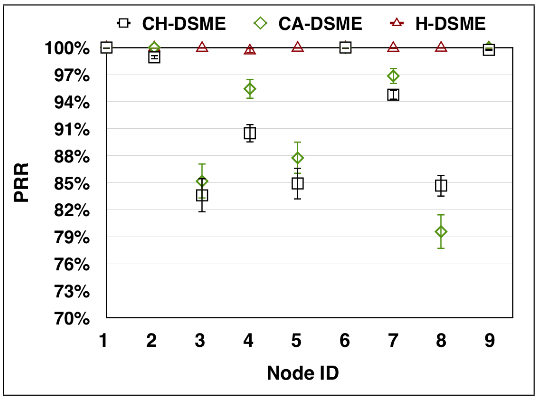

Figure 5: PRR at the application layer.

In general, the performance of the CA-DSME was better than the CH-DSME, except for the End Node 8. This shows that in most cases the use of only one channel during a larger time period provides a better quality than the use of all available channels with channel hopping. However, in scenarios in which the quality of the link between the coordinator and the end node for beacon transmissions is very low, the channel adaptation mechanism implemented for this research can delay a long time to perform the channel switch. This was the case of the End Node 8. When using H-DSME the channel adaptation mechanism was more reactive, since multiple channels are used to transmit the beacons, which eliminates the single point of failure.

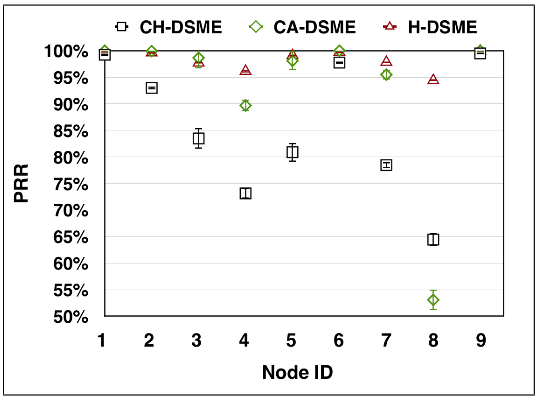

Figure 6: PRR at the MAC layer.

Figure 6 shows the PRR at the MAC layer. A transmission of a data packet in the MAC layer only occurs when a beacon is received at the end node. Thus, the failures in the beacon transmissions do not influence the PRR calculated at this layer, since only the transmissions of data packets from the end nodes to the coordinator are considered. It is worthy to note that when using CH-DSME the PRR at the MAC layer is significantly lower.

Since in the evaluated protocols two attempts are possible per packet, and in the CH-DSME different channels are used in each attempt, in most cases the packet is delivered at the application layer. However, when more retransmissions are needed the energy consumption of the end nodes can increase significantly. Again, the End Node 8 was the only exception, and the PRR was lower for the CA-DSME than for the CH-DSME for this end node. Even both CA-DSME and H-DSME use channel adaptation, the PRR at the MAC layer for the H-DSME was higher, since the channel adaptation mechanism was more reactive when using channel hopping for the beacons, as observed also in Figure 5.

Figure 7 shows the cumulative distribution function of the delay. Since the beacon period is approximately 0.25 seconds, 93% of the packets were transmitted with a delay lower than 0.25 seconds, and 99% of the packets were transmitted with delay lower than

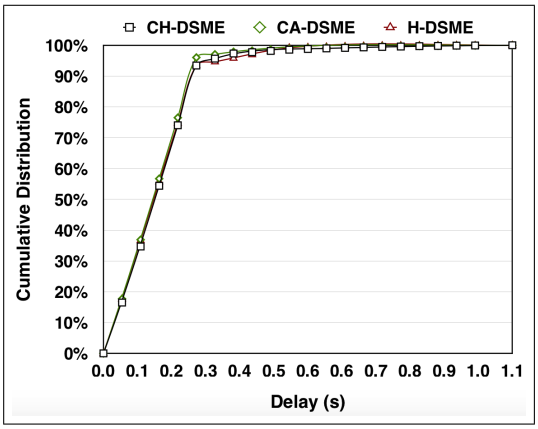

Figure 7: Delay at the application layer.

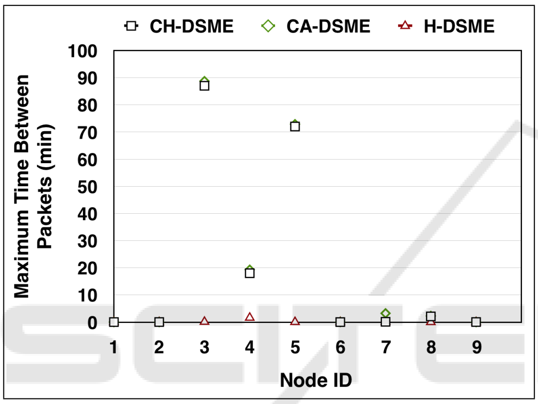

Figure 8: Maximum time between the reception of two consecutive packets.

0.5 seconds, which corresponds to two beacon intervals. Since the three evaluated approaches use the same superframe structure, the delay distribution was very similar. However, the delay is only computed for the delivered packets, and does not account for lost packets.

Figure 8 shows the maximum time lapse between the reception of two packets, which represents the maximum time interval in which a node remains disconnected. Since CA-DSME, and CH-DSME use only one channel for beacon transmissions, sometimes this channel can present low quality, for some nodes, during a long time period, due to a deep fading. The same channel can present good quality for other nodes, due to the spatial variation in the channel quality.

When using CH-DSME and CA-DSME, End Nodes 3, 4, and 5 presented long disconnection times (88, 29, and 72 minutes) due to problems in the channel used to transmit the beacon frames. Since the H-DSME uses channel hopping to transmit the beacons, this protocol is more robust against deep fading problems that affects only some channels. Besides, it is possible to deal with the spatial variation in the quality of the channels. For the H-DSME the maximum time of disconnection was 1.6 minutes, for the End Node 4.

As an example of the implemented channel adaptation mechanism, Figure 9 shows the reception power for End Node 8 in the first hour of simulation of the first replication, when using the H-DSME. In the charts, some moments in which the channel switch procedure is triggered are highlighted. It is possible to notice the difference in the characteristics of the different channels when the channel switch occurs.

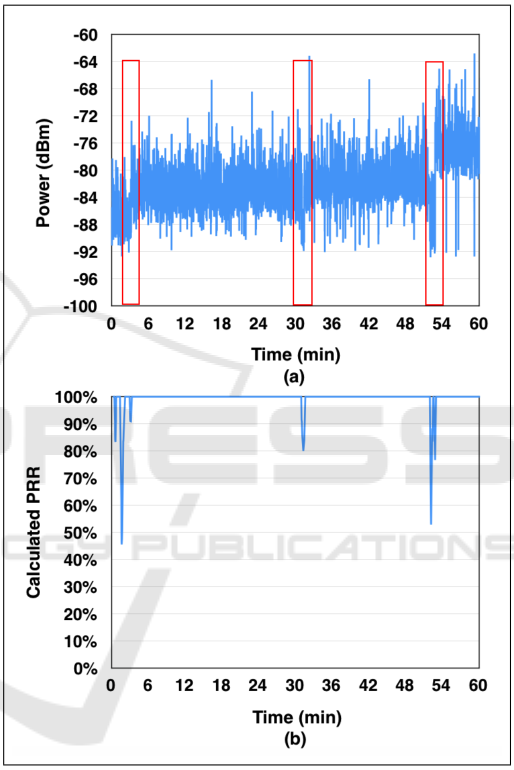

Figure 9: Received power at the End Node 8 in (a) and the calculated PRR using the Algorithm 1 (b), using H-DSME.

Sometimes, the channel switch procedure is triggered several times in a short time interval, until the node picks a good channel. For example, between 1.38 and 3.13 minutes, the End Node 8 switched its channel five times. However, when the End Node picks a good channel, it can remain for a long time using the same channel. In some cases, as demonstrated in the experiments described in (Agrawal et al., 2014a), the channels can maintain the same characteristics during several hours before an abrupt change in its characteristics occurs. In the simulations a threshold of 0.9 was defined. If the application supports lower thresholds, the channel switch procedure is triggered less often.

6 CONCLUSIONS

This paper presented a comparison between channel hopping and channel adaptation for industrial WSN. Three protocols, based on the DSME mode of the IEEE 802.15.4e standard, were implemented and evaluated using a realistic simulation model. This model permitted to observe the performance of the protocols, considering the non-stationary behavior of the wireless channel in industrial environments.

A novel hybrid approach (H-DSME), that uses channel hopping for the transmission of beacons and ACK frames, and channel adaptation for the transmission of data packets, was proposed. The results showed that the use of channel adaptation is better than channel hopping, when the quality of the links is monitored continuously by the network coordinator.

Since the beacon frames and ACK frames are transmitted in broadcast mode to several nodes, it is difficult to guarantee that a single channel will present good enough quality for all nodes. Thus, the use of channel hopping to transmit the frames is a good alternative to deal with the channel spatial variation in quality.

The H-DSME outperformed the other two approaches. In the performed simulations, even for nodes that were positioned further apart from the coordinator, and even considering the variations in channel quality over time, the PRR at the application layer was almost 100% when using the H-DSME, and the number of retransmissions was also reduced. Besides, 99% of the packets were delivered with a delay smaller than 0.5 s, which corresponds to two beacon intervals, and the maximum time of disconnection of the nodes was only 1.6 minutes.

This paper describes an analysis of the use of channel adaptation to implement industrial WSN based on the DSME mode. However, the algorithm used to estimate the channel quality considers that all the operation of the transmitter is predictable, that is, only one retransmission is allowed, and there is a slot dedicated to transmissions, and other slot dedicated only for retransmissions.

A more flexible use of the time slots, for example, the use of two transmissions of different packets in the same multi-superframe, and the use of a variable number of retransmission attempts, can lead the algorithm to present a low accuracy, unless more information obtained at the end nodes are provided to the coordinator, such as the average number of transmission attempts per packet.

Other aspect to be considered is the overhead caused by the algorithm. Experimental studies will be performed to investigate if the continuous monitoring of the quality of the links is viable using low-cost sensor nodes. The use of dedicated nodes to monitor channel quality, as proposed initially in (Gomes et al., 2014), as well as the use of estimators based on physical layer metrics, will be studied. Experiments considering different network topologies will also be performed.

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