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Experimental Assessment of IEEE 802.15.4e LLDN Mode Using COTS Wireless Sensor Network Nodes

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ABSTRACT The use of Wireless Sensor Networks in industrial environments imposes critical requirements such as low latency, high reliability, and robustness. To address these constraints, the IEEE 802.15 Task Group 4e developed the amendment IEEE 802.15.4e with three new MAC operation modes: TSCH, DSME, and LLDN. This paper aims to assess the feasibility of implementing the LLDN operation mode in low-cost commercial nodes and their capacity to meet industrial applications' timing and reliability requirements. LLDN services were implemented in COTS nodes using C programming language with Atmel provided stacks. In order to validate this implementation, a set of experimental scenarios was conducted and the measurement results were compared to simulation results available in the state of the art.

INDEX TERMS IEEE 802.15.4e, LLDN, MAC, real-time systems, wireless sensor network.

I. INTRODUCTION

IoT technologies enable the transformation of data into information and knowledge, which can be used in different production planning and control sectors, becoming an essential pillar for Industry 4.0. In this regard, wireless sensor networks (WSN) are considered adequate infrastructures for implementing last-link communication for smart IoT devices.

IEEE 802.15.4 [1] is the *de facto* communication standard for WSN nodes by specifying medium access control (MAC) and physical (PHY) layers that provide low-rate and low-power wireless communication. However, this standard has not adequately addressed critical requirements of industrial IoT applications such as low latency, high reliability and robustness.

IEEE 802.15.4e amendment [2] was proposed to meet these issues, including three MAC operation modes: Time Slotted Channel Hopping (TSCH), Deterministic and Synchronous Multi-channel Extension (DSME), and Low Latency Deterministic Network (LLDN). TSCH mode allows time-slotted and channel-hopping medium access, mitigating the effects of collisions, multipath fading, and interferences, aiming at deterministic latency with high network throughput. DSME mode supports frequency multiplexing and adopts a beacon-enabled multi-superframe structure comprising a flexible Collision Free Period (CFP), allowing pairs of nodes to allocate collision-free Guaranteed Time Slots (GTS) for their point-to-point communication.

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Although TSCH and DSME improve systems reliability and scalability, low latency communication is one of the challenges to be overcome in industrial applications. In order to meet stringent low latency communication requirements, the LLDN MAC service is timeslot-based and assumes a star topology. The timeslots can be either reserved for a single node or a shared-group timeslot, in which nodes contend for the medium using a simplified Carrier Sense Multiple Access (CSMA) algorithm to send messages within the timeslot.

Furthermore, the superframe may be divided into four distinct groups of timeslots whose sizes can be adjusted to best suit each application. Because of this customization and a newly defined MAC frame of 1-octet, LLDN can achieve short and deterministic latencies required by the industry [2].

Many studies address the feasibility of using these IEEE 802.15.4e MAC services in industrial applications [3]–[9], but few with implementation in COTS-based prototypes, and among these, only using DSME and TSCH modes [4]–[6], [10]. The MAC behavior of the LLDN mode was designed according to strict time constraints imposed by industrial environments, such as 10 milliseconds latency with up to 20 nodes [2], [11]. Thus, performing real experiments allows us to assess these temporal characteristics, in addition to analyzing the feasibility of using commercially available WSN nodes to ensure the proper functioning of the LLDN mode in an industrial WSN.

This paper aims to carry out an analysis of the feasibility of implementing the LLDN mode of the IEEE 802.15.4e protocol in low-cost commercial nodes, assessing compliance with the requirements imposed by the industrial environment as well as identifying possible improvements in the mode of operation and hardware limitations.

This paper is structured as follows: Section II presents state-of-the-art approaches for the LLDN MAC operation mode; Section III briefly describes the LLDN MAC operation mode; Section IV describes an implementation of LLDN in low-cost nodes; and Section V presents the experimental evaluation. Finally, conclusions are drawn in Section VI.

II. RELATED WORKS

The works presented in this section were selected after an extensive literature review in the IEEE Xplore, Science Direct, Scopus, and Willey databases, which initially selected 113 papers (57 from indexed journals). The selected works cover improvements in LLDN MAC mode operation, such as network design [12]–[14], configuration of relay timeslots [15], [16], channel evaluation [17], association process [18], [19] and multi-hop feasibility [15], [20], [21].

In [12] a delay bound model is presented, using network calculus in order to predict the worst-case timing performance of LLDN. The authors concluded that LLDN is best suitable for low latency and dense applications. In [13], the same authors used this model to further analyze the network throughput, varying the arrival rate and delay in the function of number of timeslots and active nodes. They concluded that the delay of LLDN is proportional to the number of timeslots and nodes.

There is no definition for the number of retransmission timeslots that should be used in an LLDN network. In this way, [15] and [16] proposed different methods to optimize retransmission timeslot usage. In [15], the authors proposed a novel retransmission mode, where LLDN devices that have a poor communication link with the coordinator have their message retransmitted by a static and mains powered retransmission node. The approach is validated through a probabilistic analysis and showed an improvement in network reliability and power consumption. To maximize the retransmission timeslots available in the LLDN superframe, Willig *et al.* [16] proposed four schemes. They presented simulation assessments comparing their proposed schemes with the LLDN standard.

To address the problem of collisions due to simultaneous channel assessment or hidden terminals, the authors in [17] proposed a new channel access mechanism. The mechanism is similar to CSMA-CA. However, a new signal is defined to act as a preamble to sense the medium and identify if any other node is performing CCA. Thus, collisions are avoided in the case of two nodes starting the CSMA-CA at the same time. This method requires all nodes to have a second antenna as one of them is dedicated to listening to the intended signal. The authors also presented a Markov model to analyze and to optimize the number of retransmissions timeslot. Both analytical and simulation assessments were presented, showing better performance over the standard in terms of throughput, energy consumption, delay, and reliability.

In [18], the authors analyzed the LLDN and identified a set of limitations that influence the network survivability. The main problem found was the single-channel operation, which increases the collision rate, complicating the association process. The authors concluded that it is necessary to allocate channels dynamically for the uplink timeslots, keeping the management and the bidirectional timeslots to a single channel.

In [19], in order to decrease the Configuration State time and increase its reliability, the authors proposed the use of Reserved Management Timeslots. They also proposed Downlink Reserved Timeslots, if the bidirectional slots are enabled, and an approach to defining the size of each type of timeslot. Through mathematical analysis, the results demonstrated that the modifications increase the determinism in the Configuration State and lower the worst-case latency of the Online State.

In [22], a MAC emergency communication scheme is proposed on the LLDN to incorporate emergency communications. A mechanism to enable emergency data requests is presented, where emergency nodes can request immediate access to transmit. When a request is accepted by the coordinator, a message is broadcast, and the scheduled communication is stopped until another message is broadcast advertising the end of the emergency period. A mathematical model is presented for the network with the proposed enhancement and the paper conclude that the approach enables a reduction in message delivery delay up to 90% compared to the standard LLDN for emergency enabled nodes.

A Markov chain model of LLDN mode during an association process is presented in [20]. From this model, the authors proposed the mobility-aware LLDN (MA-LLDN) based on two principles: defining the notion of the passive beacon used by the proxy coordinator and modifying the LLDN superframe. They presented a detailed analysis of the network and concluded that the proposed MA-LLDN model was able to reduce the dissociation by 75% and increase the coverage area through the channel hopping mechanisms.

In [15], it is presented a modification in the standard topology named as a Extended Topology Mode (ETM) with a goal of enabling nodes outside the range area of the coordinator node to send their data. In the proposal, a relay node is allowed to send two data packets simultaneously through opportunistic coding. In a retransmission timeslot, the relay of the ETM nodes can send at the same time the beacon for the outside device, and the previously received data packet to the coordinator. The authors presented a mathematical analysis of energy consumption and of the probability of losing messages to both methods and compared them with the LLDN standard.

In [21], the authors proposed the priority-aware multichannel adaptive framework to solve problems such as the low scalability of the network. A novel message is proposed, consisting of a priority field and a payload. This communication is based on a hierarchical topology so that multiple sub-networks can work in parallel. After receiving the beacon from the LLDN coordinator, each sub-coordinator switches to its respective channel, sends a beacon to all nodes in its channel, and receives their messages. In the respective timeslot, the sub-coordinator changes back to the LLDN coordinator channel and sends the received messages by highest priority. The authors presented an analysis of the response time, scalability and reliability of their proposed framework.

In [23], an optimized LLDN extension is proposed for nodes with radios with Ultra-Wideband (UWB) technology. Despite the proposal not being compatible with the LLDN mode, the paper presents an interesting implementation in COTS nodes with UWB transceivers.

Analyzing the state of the art of the LLDN operation mode, there are several works that presented mathematical analyses of the protocol [12]–[15], [17], [19]–[22] or simulation assessments [15]–[18], [21]. To the best of our knowledge, the study in this paper is the first that provides an experimental assessment of the complete LLDN mode (including existing overheads in its internal state changes) using COTS WSN nodes. None of the analyzed works showed a real experiment in WSN that address the feasibility of implementation in low-cost devices under the requirements imposed by the industrial environments. Therefore, this paper will contribute to the state of the art by filling this gap.

III. LLDN OVERVIEW

The industrial automation domain usually consists of a large number of devices to monitor and control factory production [11]. Many of these devices are allocated to robots, machinery, and transport equipment, where it may be necessary to use low-cost wireless sensor nodes. In these application scenarios, saving energy is not an essential issue, but they invariably require low latency. The LLDN mode was specifically designed to meet strict time requirements. Features like 10-millisecond latency capacity, TDMA-based access, and retransmission timeslots ensure a deterministic and robust network beyond the critical time requirement of industrial applications [15], [21].

This section describes the LLDN MAC operation mode, including the network topology, different configurations of the superframe, and the transmission states of LLDN.

A. NETWORK TOPOLOGY

The LLDN mode assumes a star topology, in which a PAN coordinator node is responsible for the configuration and maintenance of the network. Two types of messages are defined: (i) uplink messages forwarded from nodes to the coordinator; and (ii) downlink messages sent by the coordinator. In typical scenarios, nodes with only sensors can send their data to the coordinator through uplink timeslots, whereas actuator nodes, in addition to sending their data, can also receive signals for actuation through downlink timeslots.

B. SUPERFRAME

The LLDN superframe was designed with a minimized and static structure [24]. Its period is determined according to the number of nodes already associated after Discovery and Configuration transmission states. In the Discovery transmission state, new devices scan different channels until they detect an LLDN coordinator advertising a Discovery state. After that, a serie of messages is exchanged to ensure communication between the node and the coordinator. The Configuration transmission state is responsible for allocating timeslots to nodes and adjusting the superframe size.

The superframe structure is based on a TDMA method. Each timeslot may have an assigned node, which is the only device allowed to transmit in that timeslot. It is also possible to share a timeslot with multiple devices (shared group timeslot). In these shared group timeslots, devices transmit their messages using a simplified CSMA-CA algorithm.

Figure 1 show two examples of superframe, Group Acknowledgment (GACK) timeslot disabled and enabled, Figure 1a) and Figure 1b) respectively, highlighting the four types of timeslots:

- **Beacon timeslot**: It is reserved for the LLDN coordinator, and is always situated at the beginning of a superframe. The beacon frame is responsible for synchronizing devices, announcing to nodes the start of a superframe. It also contains important information such as an auxiliary security header, the presence of a GACK timeslot, and the direction of the bidirectional timeslots.
- **Management timeslots**: It is comprised of two management timeslots per superframe, one for uplink and other for downlink, allowing nodes to transmit and receive management commands. These timeslots are implemented as a shared group timeslot and their size is specified in the beacon frame, being optional.
- **Uplink timeslots**: They are reserved for unidirectional communication from nodes to the LLDN coordinator. Each timeslot can be either a dedicated timeslot or a group shared timeslot. These timeslots are also responsible for retransmitting previously lost messages.

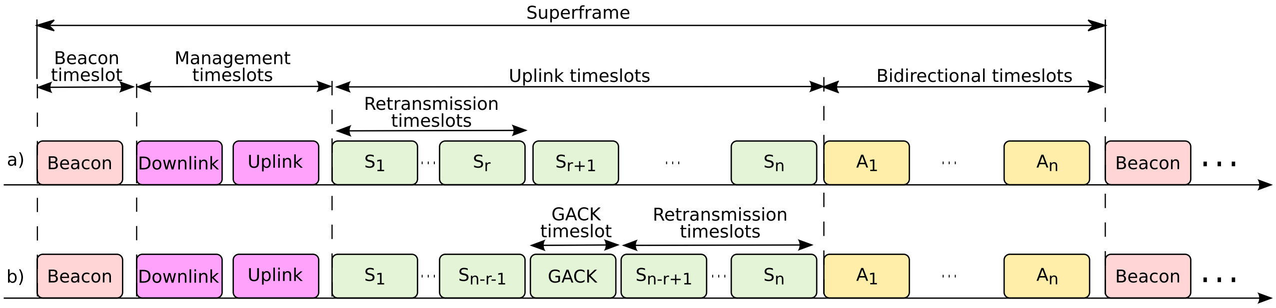

FIGURE 1. **Superframe in Online state: a) with Group ACK disabled and b) with Group ACK enabled.**

- **Bidirectional timeslots**: Localized at the end of a superframe, they can be used either as uplink or downlink timeslots. They are optional in the Online state and are not present in the Discovery and Configuration states.

LLDN defines a bitmap to the coordinator acknowledge messages. Each bit represents a slot in uplink timeslots, indicating the correct reception of the previous message. A superframe can be configured in two ways: Group ACK timeslot enabled and disabled. With the Group ACK timeslot disabled, Figure 1a), the acknowledgment bitmap is sent into the beacon frame payload. A predefined number of timeslots is reserved at the beginning of the uplink timeslots for retransmitting messages (S_r) not received by the coordinator in the previous superframe. After all S_r messages, from $S_r + 1$ to S_n where S_n represents the total number of uplink timeslots, nodes are able to transmit their messages.

Figure 1b) illustrates the case when the Group ACK timeslot is enabled; here, a separate frame containing the acknowledge bitmap is sent in a dedicated Group ACK timeslot, before the retransmission timeslots. The main advantage of the GACK timeslot is the shorter time required to retransmit a data packet. Considering the GACK timeslot, the total number of transmission timeslots is: $S_{n-r-1} = S_n - S_r - 1$. The implementation, presented in Section IV, has been done configuring the superframe with enabled GACK timeslot to take advantage of this shorter time required for retransmissions.

In the case of uplink transmission in bidirectional timeslots, the acknowledge mechanism is the same as described above. However, for downlink transmission, it is necessary that the next superframe uses bidirectional timeslots in uplink mode, so that each node can send an acknowledgment frame to the coordinator.

C. TRANSMISSION STATES

LLDN networks operates through three transmission states: Discovery, Configuration, and Online states. The Discovery state is responsible for the discovery and association of new devices. The next stage is the Configuration state, in which new associated devices are properly configured. Finally, the Online state allows data packets to be transmitted.

The coordinator is responsible for changing the transmission states, which are advertised to all devices operating in the same channel through the transmission state bits of the Low Latency (LL) Beacon frame. As shown in Figure 2, Discovery and Configuration can be restart as needed, to ensure the proper number of new nodes associated and right network configuration. In Online state, the coordinator can change to the Discovery state, reconfigure the network by going through the Configuration state or continue in the current state.

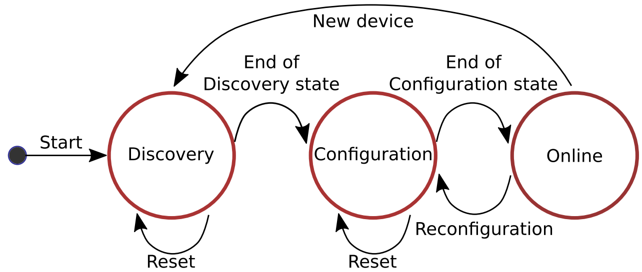

FIGURE 2. **LLDN transmission states.**

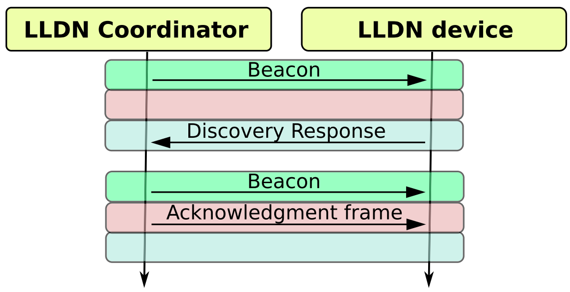

FIGURE 3. **Discovery state (rectangles represents beacon, downlink, and uplink management timeslots, respectively).**

In Discovery transmission state, the superframe consists of one beacon timeslot and two management timeslots, one downlink, and one uplink (Figure 3). New devices search in different channels until they find an LL Beacon frame on the Discovery state. After receiving the beacon and synchronizing with the superframe, the device sends a Discovery Response frame with three parameters: MAC address, timeslot duration and uplink/bidirectional type indicator. In the next superframe, the coordinator shall send an acknowledgment frame to each device. Devices that receive the acknowledgment must wait until the beginning of the configuration state; if an acknowledgment was not received, they continue sending Discovery Response frames until the coordinator changes the transmission state to Configuration. The state is changed to Configuration if the coordinator did not receive a Discovery Response frame within 256 seconds [2].

From Discovery to Configuration state, the type of superframes doesn't change (Figure 4). Devices upon receiving a beacon indicating the Configuration state, send a Configuration Status frame in the management uplink timeslot until they receive a Configuration Request frame. The Configuration Status contains information about the current configuration of the device, such as the complete and short MAC address of the node, required timeslot duration, uplink/bidirectional type indicator, and assigned timeslot, if the node was previously associated. The Configuration Request frame contains the new configuration of the device; the information received includes the full and short MAC address, transmission channel, the existence of management frames, timeslot duration, and assigned timeslot. Finally, all nodes that received the Configuration Request frame are now ready for the Online state and send an Acknowledgment frame to the LLDN coordinator.

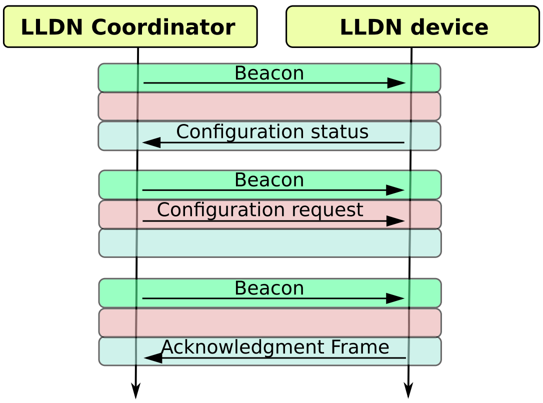

FIGURE 4. Configuration state (rectangles represents beacon, downlink, and uplink management timeslots, respectively).

As a new node must go through Discovery and Configuration states for a complete association, in the experimental evaluation presented in Section V, the time analysis measures all results after both stages.

IV. EXPERIMENTAL SETUP

This section presents the software, hardware, the necessary configuration and performance metrics used to assess the implementation of LLDN in low-cost nodes.

The set of experiments used fifteen nodes built with WM100-Duino boards [25].

This type of node features an ATMEGA256RFR2 chip that combines an AVR microcontroller and an IEEE 802.15.4 compliant 2.4 GHz RF transceiver in a single integrated circuit. It has an RF with a link budget of 103.5 dBm, 32-bit MAC symbol counter, true random number generator, and antenna diversity support. The radio was configured to promiscuous mode with O-QPSK PHY modulation, as specified by the standard IEEE 802.15.4 [1]. Other parameters used in the boards are presented in Table 1.

TABLE 1. Radio parameters used in experiments.

Data rate	Symbols per Octet (SO)	Seconds per Symbol (SS)
250 Kbps	2	0.000016 s

The LLDN MAC operation mode was implemented using C programming language with the Atmel Studio 7.0 IDE. The implementation was divided into three components: Application, Services, and Physical (PHY). Figure 5 shows the relationships between the components. The physical component is composed of drivers and codes that control physical aspects of the microcontroller, such as the radio module and timers. The code for this component was made available by Atmel through its IDE. The service component is an abstraction between the physical and the application component. In this part, the LwMesh stack was used as a base, which was modified to properly process the frames defined by the LLDN MAC operation mode. Finally, the application component is where the network's operation was programmed, according to the LLDN protocol. Two applications were developed, one for the coordinator and other for the nodes. The project with the implementations carried out can be found in the repository at [26].

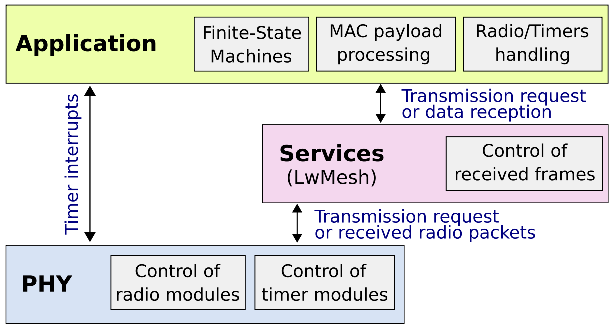

FIGURE 5. Implementation components.

In all experiments, the nodes were deployed five meters from the coordinator in a direct line of sight. This study was divided into two stages. First, the different parameter settings for the Association, Discovery, and Configuration states were tested to evaluate the average association time of a node. In the second stage, the Online status operation was evaluated.

A. PERFORMANCE METRICS

To assess the performance of the LLDN's operation, the following metrics were used: the Packet Error Rate (PER), Packet Loss Rate (PLR), and Success Rate (SR). The PER metric (Equation 1) represents the percentage of packets that are not received in the transmission attempt (Rx_t) and S_{n-r-1} is the total number of packets that are expected to be received in each superframe. The PLR metric (Equation 2) is the percentage of packets that are not received in both the transmission and retransmission attempts ($Rx_t + Rx_r$). From these equations, it is possible to determine the success rate (SR) in each case, which represents the percentage of packets successfully received in the transmission attempt or considering both transmission and retransmission attempts.

$$PER = \frac{Rx_t}{S_{n-r-1}} \times 100 \tag{1}$$

$$PLR = \frac{Rx_t + Rx_r}{S_{n-r-1}} \times 100 \tag{2}$$

B. COORDINATOR APPLICATION

Figure 6 illustrates a simplified form of the state machine present in the coordinator's application. Each state on the machine represents a beacon configuration to be sent; for example, 1st Discovery represents the first beacon in the Discovery state. In a simplified way, ignoring the Group ACK mechanism, the machine is always updated after sending the beacon frame. This is done in such a way that at the end of every superframe, the next beacon is ready to be sent.

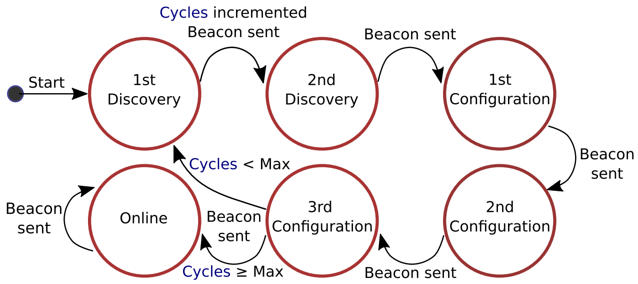

FIGURE 6. Simplified PAN coordinator state machine.

To control the superframe period, a hardware timer was used, without using the abstraction layer provided by the LwMesh stack, to increase accuracy and facilitate synchronization between all nodes. The coordinator is responsible for configuring the superframe, and two different configurations were defined, one for the Online operation state and other for the Association states.

C. APPLICATION IN NODES

Node operations are totally controlled by the reception of messages from the coordinator and interruptions by timers. The application operation in each node can be seen in the flowchart of Figure 7. Upon receiving any beacon, the node assesses whether the state of the beacon is consistent with its current state. If the node is associated and receives a beacon indicating the start of a superframe in the Online state, it calculates the periods for the superframe, for the GACK frame timeslot, and for its reserved timeslot. The calculations for the superframe period and management uplink timeslot are also performed when the node is disassociated and receives a beacon from the association states.

Upon receiving a Group ACK, the node verifies whether its message was received by the coordinator. In negative case, an algorithm is used to determine which retransmission timeslot is appropriate for its use. As in experiments is assigned just one retransmission timeslot for each associated node, the number of uplink timeslots may be calculated as $S_n = 2 \times S_r + 1$ (see Figure 1).

D. TIMESLOT SIZE

Frames are processed using the LwMesh stack, and this software inserts delays in receiving and transmitting messages. These delays were measured using a hardware counter, counting intervals of 16 μs. The transmission time (Ttx), that is

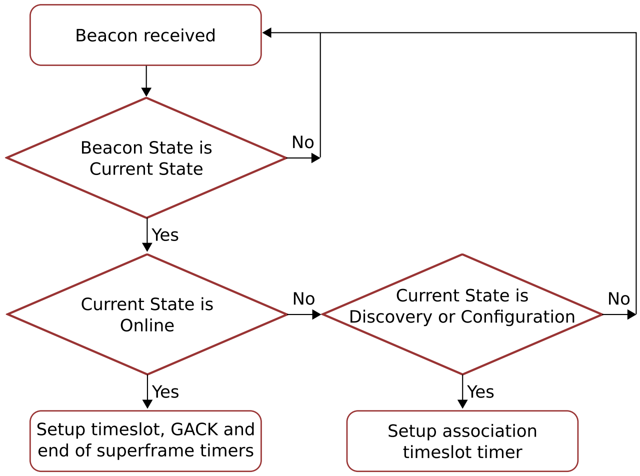

FIGURE 7. Simplified flowchart for application in the nodes.

the time needed for a transmission request of the application layer to reach the radio buffer for sending, was measured as $Ttx = 0.816\, ms$. The reception time (Trx) was also measured, evaluating the period required for a message from the radio reception buffer to reach the application; $Trx = 0.352\ ms$ was obtained. For the Online state, it is also necessary to consider a time for the application to process the message; approximately, $Tapp = 2\ ms$.

These three parameters have direct connection with the timeslot size (Tts), which must respect the limitations of the LwMesh stack and application, represented by Equation 3.

$$Tts \geq Ttx + Trx + Tapp \tag{3}$$

Assuming PHY layer operating at 2450 MHz with O-QPSK modulation, as defined in IEEE 802.15.4 standard [1], Equation 4 may be used to calculate Tts [2]:

$$Tts = (p \times sp + (m + n) \times sm + IFS)/v \tag{4}$$

where p is the number of octets of a PHY header, sp is the number of symbols per octet in the PHY header, m is the number of octets of a MAC overhead, n is the maximum expected number of octets in a data payload, sm is the number of symbols per octet in a PSDU header, v is the symbol rate, and Interframe Space (IFS) is a constant dependent on frame payload.

The Tts is applied to all timeslots, except the beacon timeslot. The uplink and bidirectional timeslots have the same Tts size, and the management timeslots are multiples of Tts, varying from 1 to 7 times Tts.

Based on the IEEE 802.15.4e amendment [2], and according to equations 3 and 4, the timeslot size Tts is assumed as 3.168 ms. This value is enough for frames with payload up to $n = 70$ and will be used in the whole experimental evaluation presented in the next section.

V. EXPERIMENTAL EVALUATION

This section is divided into two subsections, addressing the association process and Online state. In the first, the impacts of parameter values and comparisons between the experimental results and the mathematical analysis results of [19] are presented. The Online state section discusses the configuration setup used in the superframe, as well as comparisons between the experimental results with the simulation results by [15]. Finally, this paper present a discussion about the the implementation feasibility of the Online state.

A. ASSESSMENT OF ASSOCIATION PROCESS

An association cycle is assumed as comprised of one Discovery state followed by one Configuration state. In both states, the superframe is composed of one beacon timeslot and two management timeslots; one is used for downlink and another for uplink.

The number of nodes and the size of the management timeslots were varied to assess their impact on the association time. To vary the size of the management timeslots, the parameter Number of Base Timeslots per Management Timeslot (NBTMT) present in the Flag field of the *LL Beacon Frame* was used [2]. The number of nodes asking for association was varied from 4 to 12 and the NBTMT parameter from 2 to 5. More than 100 repetitions were performed for each experiment to obtain the average association time value.

In cases where NBTMT value was equal to or greater than 3, it was observed an excessive association time per node The shortest time for a node association was measured when NBTMT was equal to 2. In this configuration, it was confirmed that the coordinator continued to receive one message per superframe and it was concluded that with the reduction of the superframe period, it is possible to increase the number of cycles without excessively impacting the total association time, ensuring a better association rate.

In Dariz *et al.* [19], the authors carried out an analysis by Monte Carlo simulation on the behavior of LLDN in the Configuration state. Nevertheless, we performed the association time analysis considering the nodes' total time to associate the network, measuring together the Discovery and Configuration states. Fortunately, it is possible to calculate these times separately. Equations 5 to 7 allow the calculation of time for the Configuration state, where tCF is the time for the Configuration state, tD is the time for the Discovery state and tC is the time of a cycle.

$$tCF = 1.5 \times tD \tag{5}$$

$$tC = tD + tCF, \quad tC = \frac{tCF}{1.5} + tCF \tag{6}$$

$$tCF = 0.6 \times tC \tag{7}$$

Equation 5 comes from the principle that the Configuration state has 3 superframes and the Discovery state 2. In experimental case with NBTMT = 2, it was measured that approximately 10 nodes managed to associate in $tC = 598$ ms. From Equation 7, it is calculated that $tCF = 358.8$ ms. The result found by Dariz *et al.* [19] is that 10 nodes managed to pass through the Configuration state in 328 ms. It may be observed that the results of experimental evaluation using COTS nodes, with all associated hardware and software overheads, were close to the Monte Carlo simulation results, with a difference of 30.8 ms.

TABLE 2. Online state configuration.

Parameter	Value
LL-Beacon packet length (BLength)	14 bytes
LL-Data packet length (DLength)	11 bytes
LL-GACK packet length (ALength)	11 bytes
Number of time slots	19
Number of nodes	8
Number of retransmission slots	8
NBTMT	2
Superframe size	66.52 ms

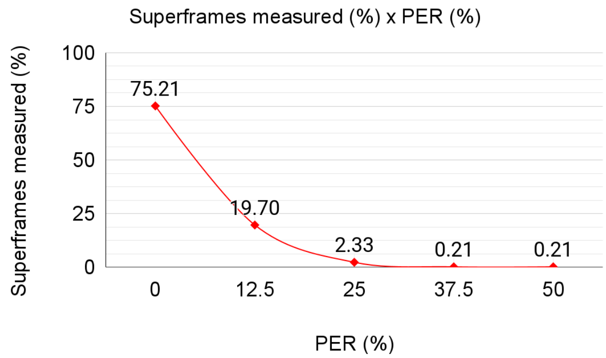

FIGURE 8. Percentage of superframes with PER values out of 472 superframes.

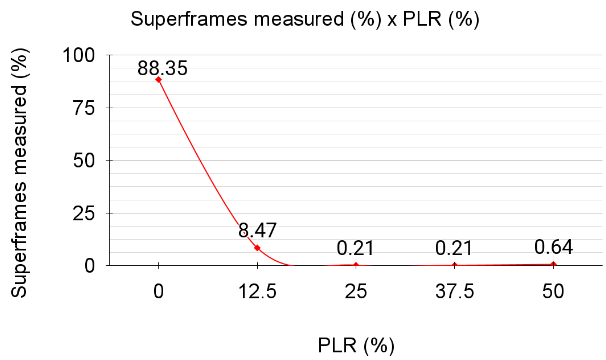

FIGURE 9. Percentage of superframes with PLR values out of 472 superframes.

B. ASSESSMENT OF ONLINE STATE

In order to compare the experimental scenarios with the simulations performed by Berger *et al.* [15] on the standard LLDN protocol, the network was configured according to Table 2.

It is possible to assess the performance of the network in terms of success rate and the impact of the retransmission mechanisms on the LLDN operation mode. All measurements were performed by the coordinator node. At the end of each superframe, the number of messages received by the PAN coordinator were evaluated, and the PER and PLR were calculated.

Figures 8 and 9 show the results. In both, the x-axis shows the metric value, and the y-axis shows the percentage of superframes that achieve the indicated packet loss rate or packet error rate, considering 472 consecutive superframes.

Assuming only the transmission attempt, it was observed that in 75.21% of superframes, the PER value was equal to zero, i.e., all transmitted messages were successfully received in 355 superframes. In 19.7% of superframes, it was observed that $0 \leq PER \leq 12.5$. The average value of PER was equal to 5.4%, with an error of ±1.36%.

In the case of PLR, 88.35% of superframes present a PLR equal to zero, indicating that in 417 of the superframes, all nodes successfully transmitted their messages in transmission or retransmission attempts. The average value of the PLR is 2.96%, with an error of ±1.11%.

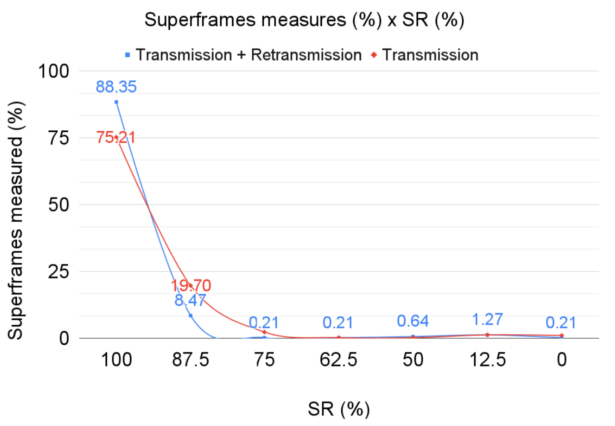

FIGURE 10. Comparison between the SR only in transmission and in transmission plus retransmission over 472 superframes.

Figure 10 shows a comparison between the SR in the transmission step and in the transmission plus retransmission step. In both cases, the overall SR of the network centralized on a value of 100%. The impact of the retransmission mechanism of LLDN is most visible in cases where only one message was lost in the transmission step ($SR = 87.5\%$). Almost 20% of the superframes measured had one message lost in the transmission stage; however, close to half of these superframes show that the message was later received in retransmission timeslots. This is clear because of the decrease of 11.23% of superframes with one message lost and the increase of 13.14% of superframes where no message was lost while considering both transmission and retransmission attempts as successful.

Figure 11 shows the relation between PER and PLR in the experiments we carried out and in the simulations carried out by Berger *et al.* [15]. To find the relation in the experiments, the PLR values were averaged given a determined PER value. One difficulty at this stage of the experiment was to acquire a number of samples relevant to different PER values. Figures 8 and 9 show the distribution of PER and PLR values. This stage of the experiments validated the current implementation of the protocol since the success rate of the network is similar to the simulations. It is possible to observe in Figure 11 that both the theoretical and the experimental curve approach a line when the PER value is high. The slightly higher PLR in the experiments may be due to the simulations' optimistic approach of [15] that does not account for software and hardware issues such as oscillator clock drift or software overheads.

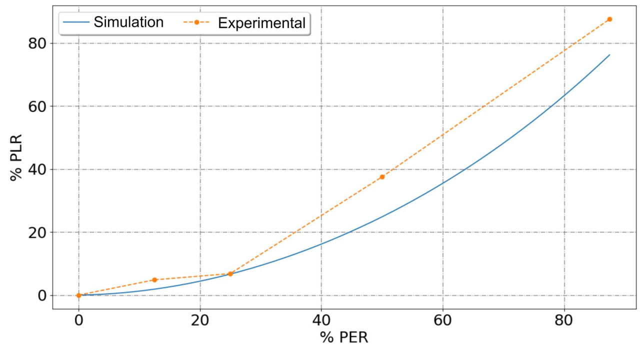

FIGURE 11. Plot of a given PER and an estimated PLR.

VI. CONCLUSION

This paper carried out an implementation of the LLDN MAC operation mode in low-cost commercial nodes, showing the feasibility of using this protocol. The LLDN operation mode was assessed both in the association and in the operation states. For the states, comparing the experimental results with the mathematical analyses performed by Daris *et al.* [19], we have reached very similar times and the difference is totally justified, given the difficulties generated by the hardware. For the state of operation, we encountered great difficulty in synchronizing the devices. It was necessary to control all timers in the application layer, increasing the period of the final superframe to incorporate the delays resulting from this. However, the behavior of the network's retransmission mechanisms was similar to the behavior in simulations made by [15], which can be seen as a good indication that, once the synchronization problems are solved, the LLDN is a viable protocol to be implemented in low-cost nodes.

As future work, we can highlight improvements that can be made in the LLDN MAC operation mode. The association process can be improved by reducing the number of superframes required in the Discovery and Configuration states. In the Discovery state, the Acknowledgment Frame can be transmitted before the Configuration Status messages from the Configuration state. Similarly, the Acknowledgment Frame of the LLDN devices can be transmitted one superframe before, just after the Configuration Request messages. By decreasing the number of Superframes, the total time of each cycle also decreases, ensuring a faster association. Further analysis on the impact of the number of retransmission timeslots over both the reliability and communication latency is also a topic for future work.

REFERENCES

[1] *IEEE Standard for Low-Rate Wireless Networks*, Standard IEEE 802.15.4, IEEE Standards Association, IEEE Computer Society, New York, NY, USA, Dec. 2015.

[2] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)—Amendment 1: MAC Sublayer*, Standard IEEE 802.15.4e, IEEE Computer Society, New York, NY, USA, Apr. 2012.

[3] M. R. Palattella, N. Accettura, L. A. Grieco, G. Boggia, M. Dohler, and T. Engel, "On optimal scheduling in duty-cycled industrial IoT applications using IEEE802.15.4e TSCH," *IEEE Sensors J.*, vol. 13, no. 10, pp. 3655–3666, Oct. 2013.

[4] G. Alderisi, G. Patti, O. Mirabella, and L. L. Bello, "Simulative assessments of the IEEE 802.15.4e DSME and TSCH in realistic process automation scenarios," in *Proc. IEEE 13th Int. Conf. Ind. Inform. (INDIN)*, Cambridgeshire, U.K., Jul. 2015, pp. 948–955.

[5] V. Sempere-Payá, J. Silvestre-Blanes, D. Todolí, M. Valls, and S. Santonja, "Evaluation of TSCH scheduling implementations for real WSN applications," in *Proc. IEEE Int. Conf. Emerg. Technol. Factory Automat. (ETFA)*, Berlin, Germany, Sep. 2016, pp. 1–4.

[6] D. Geng, J. Chai, X. Li, and L. Zhao, "Research and implementation of a self-organizing network dynamic timeslot channel allocation mechanism," in *Proc. 3rd Int. Conf. Comput. Sci. Netw. Technol. (ICCSNT)*, Dalian, China, Oct. 2013, pp. 635–640.

[7] M. R. Palattella, N. Accettura, X. Vilajosana, T. Watteyne, L. A. Grieco, G. Boggia, and M. Dohler, "Standardized protocol stack for the Internet of (Important) Things," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 1389–1406, 3rd Quart., 2013.

[8] M. G. Asuti and P. I. Basarkod, "Modeling and analysis of priority and range-based-deterministic and synchronous multichannel extension—Guaranteed time slot allocation in IEEE 802.15.4e medium access control protocol," *Trans. Emerg. Telecommun. Technol.*, vol. 32, no. 11, p. e4323, Nov. 2021.

[9] N. Choudhury, R. Matam, M. Mukherjee, and J. Lloret, "A performance-to-cost analysis of IEEE 802.15.4 MAC with 802.15.4e MAC modes," *IEEE Access*, vol. 8, pp. 41936–41950, 2020.

[10] G. Cena, C. G. Demartini, M. G. Vakili, S. Scanzio, A. Valenzano, and C. Zunino, "Evaluating and modeling IEEE 802.15.4 TSCH resilience against Wi-Fi interference in new-generation highly-dependable wireless sensor networks," *Ad Hoc Netw.*, vol. 106, Sep. 2020, Art. no. 102199.

[11] D. De Guglielmo, S. Brienza, and G. Anastasi, "IEEE 802.15.4e: A survey," *Comput. Commun.*, vol. 88, pp. 1–24, Aug. 2016.

[12] H. Kurunathan, R. Severino, A. Koubaa, and E. Tovar, "Worst-case bound analysis for the time-critical MAC behaviors of IEEE 802.15.4e," in *Proc. IEEE 13th Int. Workshop Factory Commun. Syst. (WFCS)*, Trondheim, Norway, May 2017, pp. 1–9.

[13] H. Kurunathan, R. Severino, A. Koubaa, and E. Tovar, "IEEE 802.15.4e in a nutshell: Survey and performance evaluation," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1989–2010, 3rd Quart., 2018.

[14] M. Anwar and X. Yuanqing, "IEEE 802.15.4e LLDN: Superframe configuration for networked control systems," in *Proc. 33rd Chin. Control Conf. (CCC)*, Nanjing, China, Jul. 2014, pp. 5568–5573.

[15] A. Berger, M. Pichler, W. Haselmayr, and A. Springer, "Energy-efficient and reliable wireless sensor networks—An extension to IEEE 802.15.4e," *EURASIP J. Wireless Commun. Netw.*, vol. 2014, no. 1, pp. 1–12, Aug. 2014.

[16] A. Willig, Y. Matusovsky, and A. Kind, "Retransmission scheduling in 802.15.4e LLDN—A reinforcement learning approach with relayers," in *Proc. 26th Int. Telecommun. Netw. Appl. Conf. (ITNAC)*, Dunedin, New Zealand, Dec. 2016, pp. 63–69.

[17] P. K. Sahoo, S. R. Pattanaik, and S. L. Wu, "Design and analysis of a low latency deterministic network MAC for wireless sensor networks," *Sensors*, vol. 17, no. 10, pp. 1–24, Sep. 2017.

[18] Y. Al-Nidawi, H. Yahya, and A. H. Kemp, "Impact of mobility on the IoT MAC infrastructure: IEEE 802.15.4e TSCH and LLDN platform," in *Proc. IEEE 2nd World Forum Internet Things (WF-IoT)*, Milan, Italy, Dec. 2015, pp. 478–483.

[19] L. Dariz, G. Malaguti, and M. Ruggeri, "Performance analysis of IEEE 802.15.4 real-time enhancement," in *Proc. IEEE 23rd Int. Symp. Ind. Electron. (ISIE)*, Istanbul, Turkey, Jun. 2014, pp. 1475–1480.

[20] Y. Al-Nidawi, H. Yahya, and A. H. Kemp, "Tackling mobility in low latency deterministic multihop IEEE 802.15.4e sensor network," *IEEE Sensors J.*, vol. 16, no. 5, pp. 1412–1427, Mar. 2016.

[21] G. Patti and L. L. Bello, "A priority-aware multichannel adaptive framework for the IEEE 802.15.4e-LLDN," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6360–6370, Oct. 2016.

[22] M. A. Imran, S. Hussain, and Q. H. Abbasi, *Multiple Access and Resource Sharing for Low Latency Critical Industrial Networks*. Hoboken, NJ, USA: Wiley, 2020, pp. 47–64.

[23] A. Lubken and M. Drobczyk, "Maximizing throughput in deterministic and low latency intra-spacecraft UWB sensor networks," in *Proc. IEEE Int. Conf. Wireless Space Extreme Environ. (WiSEE)*, Oct. 2019, pp. 35–40.

[24] B. Bitencort, R. Moraes, P. Portugal, and F. Vasques, "AdapTA: Adaptive timeslot allocation scheme for IEEE 802.15.4e LLDN mode," in *Proc. IEEE 14th Int. Conf. Ind. Informat. (INDIN)*, Jul. 2016, pp. 304–309.

[25] G. Budke, "Wireless module IEEE 802.15.4/Zigbee WM-100-DUINO," UFSC, Florianópolis, Brazil, Tech. Rep. 01/2021, Mar. 2021. [Online]. Available: https://gfbudke.wordpress.com

[26] G. Pereira, "IEEE 802.15.4e LLDN with LwMesh," UFSC, Florianópolis, Brazil, Tech. Rep. 01/2019, 2019. [Online]. Available: https://github.com/guilhermetpereira/802.15.4e-LLDN-with-LwMesh

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