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***Abstract* — The IEEE 802.15.4e amendment provides different modalities over which Wireless Sensor Networks (WSNs) can be deployed, even with strict requirements in terms of latency and determinism; still, there seems to be room for improvement. This paper proposes two enhancements for IEEE 802.15.4e LLDN mode: (1) allowing a reduced and more predictable configuration time and (2) focusing on the worst-case latency for high-priority traffic. A comparison with standard LLDN is then performed and evaluated, either through Monte Carlo simulations or analytically.**

***Keywords* — 802.15.4e, safe communication, real time, determinism.**

I. Introduction

Wireless Sensor Networks represents a broad and increasingly important field of application, such as weather monitoring, smart grids of sensors for home and industrial automation, health monitoring and robotics. IEEE 802.15.4 standard [1] is designed to fulfill the typical requirements of WSNs, thanks to key features such as low data rate and low duty cycle, which make it well suited for battery-powered systems. The fairly new IEEE 802.15.4e amendment [2] is intended to extend the field of application of IEEE 802.15.4 to industrial applications, that feature strict requirements in term of determinism, low latency and robustness to harsh RF environments through the definition of new MAC operating modes. As later discussed more thoroughly, the amendment focuses on creating a time-slotted and/or multi-channel communication to reduce or overcome some of the unpredictable latencies that common CSMA/CA introduces. This is essential for industrial domains, such as factory and process automation as well robotics and logistics. This paper proposes some modifications to the amendment to further improve the promptness of configuration and the worst-case latency of communications, in order to achieve higher determinism and efficiency in the bandwidth usage (which is a major constraint for this kind of WSNs.). The remainder of the paper is organized as follows: section II refers to the existing literature and detail the goals of our work; section III describes relevant characteristics of the LLDN MAC behavior; section IV and V focus on the improvements for the configuration phase and the optimization required in order to achieve a lower latency; section VI compares the modified configuration phase and the worst-case latency for real-time traffic with LLDN. Section VII concludes the paper and describe the future directions of the research.

All the research results presented in this paper have been achieved in the research activities developed in the project "FACTOry Technologies for HUMans Safety", acronym "Factothums", a project financed by National Research Council of Italy – C.N.R. – in the Factory of Future financing program..

II. Related Work

Though most of the research work regarding bandwidth reservation in IEEE 802.15.4 done so far has focused on the Guaranteed Time Service (GTS) mechanism described in section 5.1.1.1 of [1], evaluating either allocation schemes such as in [3], modified superframe structures [4], or both as described in [5]; no analysis has been done so far specifically for the 802.15.4e modalities. Some theoretical analysis has been done through Markov Chain models for both saturated [6] and unsaturated [7] traffic conditions, in order to analyze and model the performance of slotted CSMA/CA mechanism. A first analysis regarding CSMA/CA parameters has been done in [8]. Furthermore, a comprehensive analysis of CSMA/CA performance at varying parameters has been done in [10].

Reference [2] describes additional operating modes, such as DSME and TSCH. Rather than focusing on low latency, they focus on channel diversity and mesh topologies.

III. Overview of the IEEE 802.15.4 LLDN

The LLDN mode is a beacon-enabled mode where all communications span over a set of time-slots, be them shared or reserved. LLDN is designed to work in a star topology network, with a PAN coordinator (PANc) and n nodes, as illustrated in Fig. 1a. In shared time slots, access is provided through an *ad-hoc* slotted CSMA/CA mechanism as described in section 5.1.1.4.4 in [2], other than a RTS/CTS procedure as described in 5.1.1.6.6 of [2],

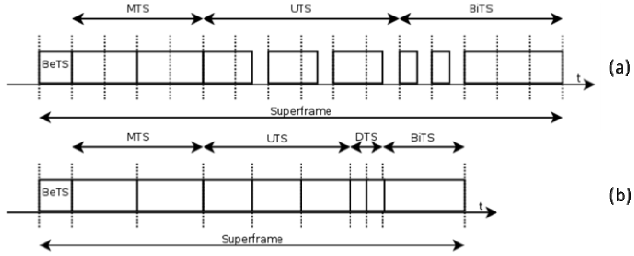

Fig. 1. a) describes the standard IEEE 802.15.4 LLDN superframe format; b) describes the proposed modified superframe format.

and are signaled by the PANc with a CTS Shared Group packet at the beginning of the slot. In reserved time slots access is provided without CSMA/CA, nor any RTS/CTS procedure.

A. Superframe structure

The length of each time-slot is multiple of a base time-slot (BTS), whose quantity and length is contained in the beacon packet. There can be four types of slots: Beacon time slot (BeTS), Management time slots (MTS), Uplink time slot (UTS), Bidirectional time slot (BiTS). The BeTS contains the beacon sent from the PANc to allow synchronization and to signal the current configuration. MTSs are reserved for management data, may not be present in every superframe, can encompass up to 7 BTSs and are at maximum 2, one for uplink and one for downlink. The UTS are reserved timeslots, used for data sent from a device to the PAN coordinator. A number of Uplink timeslots can be reserved for the retransmission of packets from the previous superframe which have not been acknowledged. A separate Group Acknowledge slot can also be reserved as an UTS to send acknowledgments, from the PAN coordinator to the devices, in addition to the beacon fields. These two last optional Uplink timeslots kinds will not be considered in the tests done. BiTS are shared time slots, placed at the end of the superframe, are used for bidirectional communication of non-management data between the PANc and the various devices. Their direction is fixed within each superframe and specified in the beacon.

B. Operating states

The life-cycle of a LLDN-enabled network is visible in figure 34a of [2]. Initially, PANc creates a new network by sending beacons indicating Discovery State; then each device can announce its presence and the duration and type of the required timeslots to the PANc. In Configuration State, each node sends its current timeslot configuration to the PANc, along with the extended and short MAC address in a Configuration Status packet. The coordinator then replies with a Configuration Request packet, in which it indicates some information, later specified, useful for correct management of the superframe. The node accepts the configuration with an ACK frame in the next Management timeslot. After every device has been configured, the PANc signals the Online State. After every superframe indicating Discovery or Configuration, a PANc can transmit a beacon indicating that every device must reset their discovery or configuration state. In Discovery and Configuration States, only MTSs are present, while in Online State all of the four types of slot can be used.

IV. Modifying the Configuration State

The configuration state, as described in the previous section, has the disadvantage to eventually last a long time to be completed. Provided that in Configuration State each node has to go through the fixed Configuration process (i.e. Configuration Status/Request/ACK) and the PANc already knows which devices are present in the network, the different approach that the paper deals with considers the chance to reduce the time required for the configuration process using Reserved Management Timeslot (RMTS) instead of shared timeslot. As tests will show, the time required to complete the Configuration process results: (1) deterministic and linearly dependent solely on the number of devices involved; (2) up to six fold faster. Assuming a RMTS for each device, the total configuration time can be computed as two superframe cycles; in the first one, each node sends the Configuration Status packet, while, in the second one, the PANc sends the Configuration Request to each device and receive the corresponding ACK, as described at sec. 5.1.9.3 of [2]. Each device can obtain its RTMS either explicitly (i.e. in the ACK payload in Discovery State) or implicitly through an algorithm based on its MAC address and some parameters included in the beacon. An approach like the one adopted in [9] could be used as a starting point.

V. Modifying the Worst-Case Latency

Considering a scenario where every device must be able to send and receive high-priority data as well as low-priority one. If each device has one reserved time slot for uplink and one for downlink, the worst case latency is equal to the superframe duration. A limitation of the LLDN mode is that it offers only reserved uplink slots, while the only downlink slots are BiTS. So, as there is no explicit concept of reserved downlink, the determinism of communication may suffer, in case of frequent downlink transmissions. To overcome this limitation, the approach described defines Downlink Reserved time slots (DTS), as an optional but relevant component of the superframe. Another aspect that seemed limiting for such applications with the requirements listed above, is that every UTS and BTS is built over a fixed number of base timeslots. This might be flexible enough for most applications, as the unused time for all timeslots in a superframe is a small percentage of the superframe duration, however this kind of flexibility is not enough when we have the requirements listed above. Moreover, as the beacon timeslot must always fit into one base timeslot, if many outgoing packets are shorter than the beacon, a sensible waste of time and bandwidth can occur. The proposed solution tries to optimize the superframe duration, as depicted in Fig. 1b, without any optimization algorithm to compute the BTS length, at the price of a slight overhead in the beacon.

A. Optimized Timeslot Description

The main idea for optimizing the superframe is to describe the slot size in a punctual way for every time slot in a superframe. These information will replace the Timeslot Size and number of Base Timeslots in the beacon payload of standard Superframe. Holding this assumption, there can be two possible approaches:

- adding Number of TimeSlots and Timeslots Durations fields for UTS, DTS and BiTS and Timeslots Duration for BeTS and MTS (since their number is known for the Online State) fields, using 8 bytes in the beacon. This approach is referred as BeTStyp;
- add a field Number of Data TimeSlots and a field Timeslots Duration for UTS, DTS and BiTS and two

fields Timeslots Duration for BeTS and MTS. This will sum to n+3 bytes in the beacon, where n is the sum of the number of UTS, DTS and BiTS in a superframe. This approach is referred as BeTSall.

The first approach works well if traffic requirements are different for uplink and downlink and for high and low priority data, but still has limited flexibility in the case where there are different slot requirements for a same type of slot. The second approach adds a greater overhead in the beacon but provides the flexibility necessary to efficiently handle different classes of traffic.

B. *Time slot allocation*

With an optimized superframe, the slot allocation algorithm is much simpler since it is not necessary to compute the optimal BTS length, and can be summarized as follows:

- in the configuration state, the PAN coordinator collects the slot requirements in term of number of bytes to be transferred for each node;
- when the PAN coordinator has the knowledge af all the time slots that must be available in a superframe, decide a schedule of the time slots simply allocating the time slots in the same order of which they are received in configuration state and sends to each node the duration and offset of the required time slot;

The number of computations required to obtain the schedule will depend solely on the number n of nodes and the number of slots n_i required by each node for a total of $\sum_{i=0}^{n} n_i$ operations, with polynomial complexity.

VI. Analytical and Simulation Results

Throughout this chapter, a theoretical comparison between standard and modified LLDN is done, for both Configuration State and worst-case latency. A PHY operating at 2.5 GHZ with O-QPSK modulation, as described in chapter 10 of [1], is assumed. When expressing a time slot length in bytes, the following formula (from 5.2.2.5.2 of [2]) is considered to compute the duration [sec] of the time slot:

$$T = (p \cdot sp + (m + n) \cdot sm + IFS) / v \quad (1)$$

Where p is the number of octets in the PHY header, m is the number of octets in the MAC header, n is the number of octets in the MAC payload, sp is the number of symbols per octets in PHY header, sm is the number of symbols per octets in PSDU, IFS is the interframe space which minimum is SIFS symbols if $m+n \leq 18$ and LIFS symbols if $m+n > 18$ and v is the symbol rate (SIFS and LIFS are respectively short and long interframe spaces, described in 8.1.3 and PHY dependent). For the PHY considered, p=6 octets, sp=2 sym/octet, sm=2 sym/octet, SIFS=12 sym, LIFS=40 sym, v=62500 sym/s. Furthermore, it is assumed that there are no hidden node in the CSMA/CA, i.e. each node can listen to the transmissions of every other node and the communication channel is ideal (i.e. errorless and with null propagation delay).

A. *Configuration state*

To compare the proposed configuration scheme with the standard LLDN configuration scheme, one has to consider that all slots are composed by BTSs, as imposed by LLDN mode. The slot length will be equal to the length required by the greater packet among the beacon, the Configuration Status, the Configuration Request and the ack. As IEEE 802.15.4e amendment does not specify the format of the packets Configuration Status/Request, they will be defined, to compare the standard approach with the proposed one, as follows:

- 1-octet length field with the Command Frame ID;
- 1-octet length field with configuration sequence number;
- 8-octets length field with the extended MAC address;
- 2-octets length field with the short MAC address;
- 1-octet length field with the type of the required slot in Configuration Status packet, and the indication of the channel used in Configuration Request packet;
- 1-octet length field with the length of the required slot in Configuration Status packet, and the number of MTS for Online State in Configuration Request packet;
- 1-octet length field with the type of the assigned slot;
- 1-octet length field with the length of the assigned slot.

The comparison assumes that, at the beginning of the Configuration State, a device has no slots assigned and it is requesting one UTS to the PAN coordinator. A minimal LLDN MAC Command frame header is also assumed.

1) *Standard Configuration*

Rather than developing a variant of the Markov Chain model suited for the combination of CSMA/CA and the RTS/CTS procedure, numerical results are obtained through a statistical characterization of the configuration time by means of Monte Carlo simulation, based on the specifications of the IEEE 802.15.4e amendment [2]. Management Timeslots are assumed to be equal to 7 BTSs, which is the maximum allowed by LLDN.

2) *Modified Configuration*

For this scheme, the overall configuration time can be computed as:

$$T_c = 2 \cdot (1 + 2 \cdot n) \cdot T(BTS) \quad (2)$$

where T_c is configuration cycle time and n is the number

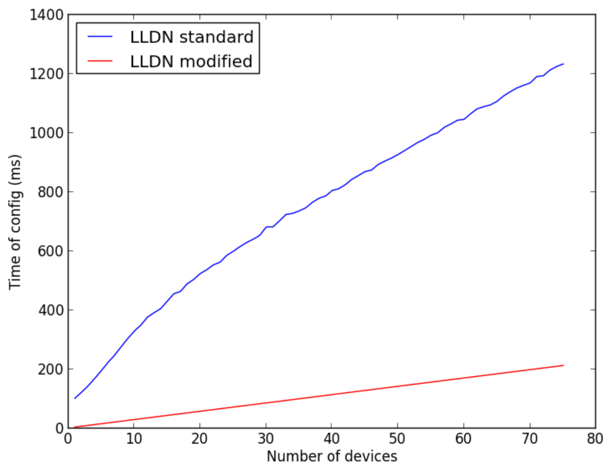

Fig. 2. Configuration time plot, highlighting the time taken for procedure adhering to the standard (Monte Carlo simulations) and with the proposed modified approach (deterministic)

of devices. It is assumed that each device can detect its RMTS, so no additional parameters must be added to the beacon in Configuration State.

3) Discussion

Fig. 2 plots the overall time required for the configuration of *n* nodes, both for standard and modified LLDN. The modified LLDN performs significantly better than standard LLDN, in terms of determinism and Configuration State duration, because there is no CSMA/CA involved. It is interesting to note that, for standard LLDN, the configuration time initially grows rapidly, but it settles down to a linear trend after a certain number of nodes are considered. This can be motivated by the stochastic nature of the backoff time in the modified CSMA/CA algorithm: if the number of nodes is relatively small, the probability that a shared slot is used to transmit its maximum allowable number of packets (considering the Clear Channel Assessments and the RTS/CTS packets) is also small, because the number of backoff slots actually used will cover the whole range of available backoff slots with low probability. Increasing the number of nodes, this probability increases and asymptotically tends to 1. Such behavior is confirmed by simulations with up to 200 nodes.

B. Worst-Case Latency

Comparing the standard solution with the proposed one, some traffic classes and their requirements have been defined, as well as superframe structures has been re-elaborated. These requirements concern the number of bytes in MAC payload for every traffic class. The traffic classes that must be considered in a superframe are four: uplink high-priority, uplink low-priority, downlink high-priority, downlink low-priority. High-priority traffic shall be sent in dedicated timeslots. The conditions imposed, in addition to the ones already specified, are:

- high-priority traffic in both uplink and downlink for each node, specified as $slot_{up}$ and $slot_{down}$. If there is no ambiguity, both requirements can be specified as $slot_{rt}$;
- low-priority traffic in both uplink and downlink, specified as $slot_{up\_nonrt} = slot_{down\_nonrt} = slot_{nonrt}$. A total of 2 shared time slots shall be considered, one for uplink and one for downlink;
- minimal MAC overhead, no security header, no sequence number, so there is 1 byte of mac header and 2 bytes of mac footer,
- no ACK for high-priority traffic, ack is present for low-priority traffic;
- no Management Slots in Online State;

1) Standard superframe

In order to satisfy the downlink requirements, either a single or double superframe can be considered. In a single superframe, the four traffic classes should be assigned as follows: uplink high-priority to dedicated UTSs, downlink high-priority to dedicated BiTS, low-priority to shared BiTS. In this case, also there can be no consecutive superframes in which BiTSes are set as DTS, to avoid the case in which no low-priority traffic can be sent in the uplink direction. However the worst-case latency for the high-priority downlink traffic doubles w.r.t. the one for high-priority uplink traffic, which may not be fit in into the requirements of some applications. A different approach could be to consider two superframes, one for uplink traffic and the other for downlink traffic, both composed only of bidirectional timeslots: part of the BiTSes will be reserved for every device for high-priority traffic and the remaining are shared timeslots for low-priority traffic. This way the worst-case latency becomes the total duration of the two superframes, and is the same for uplink and downlink traffic. The base timeslot size can also be different in the two superframes. A naïve algorithm for the search of the optimum BTS length w.r.t. the superframe length has been implemented performing an exhaustive search, that is:

$$\begin{gathered} BTS = \min_{B}\left(len(\text{superframe})\right) \\ B = [slot_{beacon}, \dots, \max(slot_{beacon}, \\ slot_{up}, slot_{down}, slot_{nonrt})] \end{gathered} \tag{3}$$

The total cycle time can then be computed, for the case with a single superframe, as:

$$T_c = (1 + n \cdot mu + n \cdot md + 2 \cdot ms) \cdot T(BTS) \tag{4}$$

while, with two superframes, as:

$$\begin{gathered} T_c = (1 + n \cdot mu + ms) \cdot T(BTS_{up}) + \\ + (1 + n \cdot md + ms) \cdot T(BTS_{down}) \end{gathered} \tag{5}$$

where *n* is the number of nodes, *mu* is the number of BTS for each UTS, *md* is the number of BTS for each DTS, *ms* is the number of BTS for a shared BiTS.

2) Modified Superframe

With an optimized superframe, all requirements can be fulfilled in a single superframe, having all four traffic classes in their corresponding time slot type. The total cycle time can be computed as follows:

$$\begin{gathered} T_c = T(beacon\_slot) + n \cdot (T(slot\_up) + \\ + T(slot\_down)) + 2 \cdot T(slot\_nonrt) \end{gathered} \tag{6}$$

TABLE 1: NUMERICAL RESULTS FOR STANDARD AND MODIFIED LLDN.

Nodes	*Bytes Reserved*	*Bytes Shared*	*STD 1sf*	*STD 2sf*	*MOD BeTSall*	*MOD BeTStyp*
10	1	2	16.2	16.8	13.2	12.2
20	1	2	31.6	32.3	24.1	22.5
30	1	2	48.1	49.1	35	32.8
40	1	2	66.4	67.2	46.0	43.5
2	10	2	5.6	5.8	4.6	4.6
2	30	2	7.4	8.1	6.7	6.8
2	50	2	8.7	9.4	8.1	8.0
2	70	2	10.0	10.6	9.3	9.3
2	1	10	6.0	6.4	4.6	4.5
2	1	30	7.4	8.1	6.7	6.7
2	1	50	8.7	9.4	8.0	8.001
2	1	70	10.0	10.9	9.3	9.2
15	10	10	26.4	27.2	27.8	26.5
15	10	30	29.6	30.45	30.1	28.9
15	10	50	31.2	32.1	31.3	30.0
15	10	80	32.8	33.6	33.2	31.9

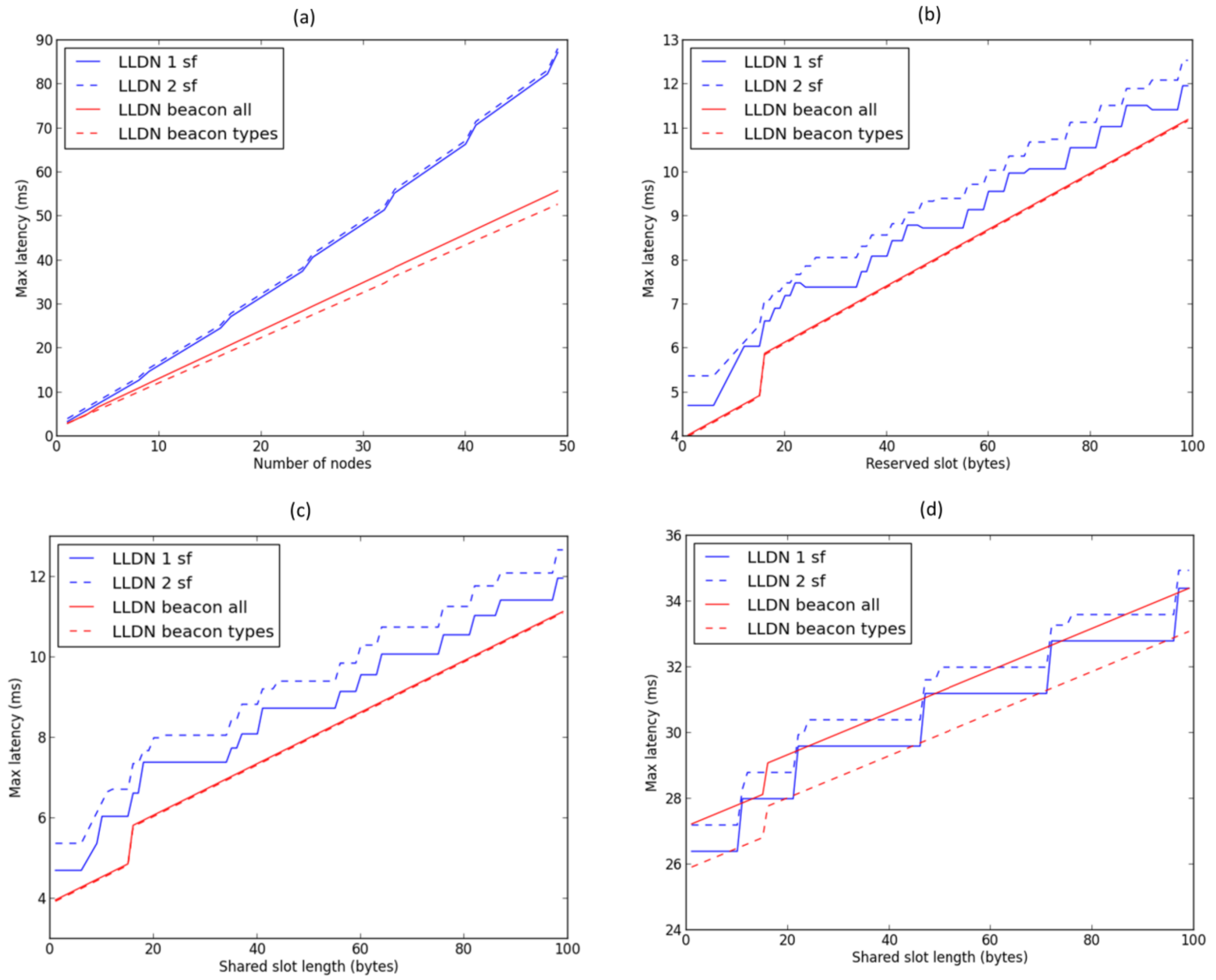

Fig. 3. In subfigures (a) $slot_{rt}$=1, $slot_{nonrt}$ =2, in (b) n=2, $slot_{rt}$ =1, $slot_{nonrt}$ =2,in (c) n=2, $slot_{rt}$ =1, in (d) n=15, $slot_{rt}$=10. Standard LLDN is plotted with blue lines for single and double superframe, while modified LLDN is plotted with red lines, for different beacon formats.

Where the length of BeTS can be given by either of the modification in section.

3) Discussion

In Fig. 3, some theoretical results are shown. In Fig. 3a the modified LLDN significantly outperforms standard LLDN with the increase of the number of nodes. The regular steps on standard LLDN are given by the increase of the BTS, since increasing the nodes also increase the beacon length because of the increment in the Group ACK field; the increase ratio is also different. Fig. 3b shows the maximum latency w.r.t. the required length for one type of reserved time slot, while keeping the other fixed; it is worth noticing that the dynamics are the same for UTS and DTS, with the exception of the standard LLDN with 1 superframe, in which case the worst-case latency for downlink traffic is double w.r.t the uplink traffic. In this case, Fig. 3b always represents uplink high-priority traffic. When the slot length exceeds 15bytes, the switch from SIFS to LIFS is observable with a sensible step. In Fig 3c and 3d the maximum latency w.r.t. shared slot length is depicted; while in Fig. 3c modified LLDN still performs better than standard LLDN, in figure 5d the separation between standard and modified LLDN is not absolute, and for some values standard LLDN performs the same or better than modified LLDN. This is given by the added bytes in the beacon slot for modified LLDN.

In Table 1 some numerical result are shown. The gap between standard and modified LLDN is of the order of 2-3 ms with varying traffic requirements; this means that given the traffic requirements and the maximum latency for high-priority traffic, more nodes can be added to the network with modified LLDN. A great improvement is obtained w.r.t. the number of nodes, with a maximum latency difference of up to 20 ms with 40 nodes.

VII. Conclusions

Ultimately, the results demonstrate that the modifications to the standard allow an increase of determinism in Configuration state and lower the worst-case latency in Online state. This would lead to a more confident use in industrial environments, in applications that have such requirements. Future fields of research can encompass many directions. The analysis presented through this paper w.r.t. worst-case latency can be extended to the more general case with different traffic and timing requirements among the nodes. For instance, if different classes of devices are considered, with relative common attributes, such as repetition time and packet size, the evaluation of the feasibility and the algorithmic formulation of the scheduling of the packets in one or more superframes seems interesting and worth further research. This algorithm would assign a number of slots to every device class. While the optimization of BTS duration has been analyzed in order to compare the standard LLDN with the modified LLDN presented in this paper, a deeper analysis would allow to better understand the characterization of LLDN w.r.t. throughput, latency and bandwidth utilization in the aforementioned traffic hypothesis.

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