A proposal for enhancement towards bidirectional quasi-deterministic communications using IEEE 802.15.4

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***Abstract* — The IEEE 802.15.4e amendment provides different ways 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 an enhancement for IEEE 802.15.4e LLDN mode, focusing on the worst-case latency for high-priority traffic. An analytical comparison with standard LLDN is then performed and evaluated.**

***Keywords* — IEEE 802.15.4e, Industrial Automation, Human Robot Interaction, LLDN, Localization, Real Time Traffic, WPAN, WSN.**

I. INTRODUCTION

WIRELESS Sensor Networks represent 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] represents as one attractive solution for 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 the worst-case latency for high-priority traffic. This is essential for industrial domains, such as factory and process automation as well as Machine to Machine communication. The paper proposes a modification to the amendment to further improve the worst-case latency of high-priority communications, in order to achieve higher determinism and efficiency in the bandwidth usage (which is a major constraint for this kind of WSNs.).

The research described in the paper was developed within the financed project FACTOTHUMS of the Factory Of Future Italian Public Financing Call.

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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 Slot (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.

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* devices, 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], and is 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.

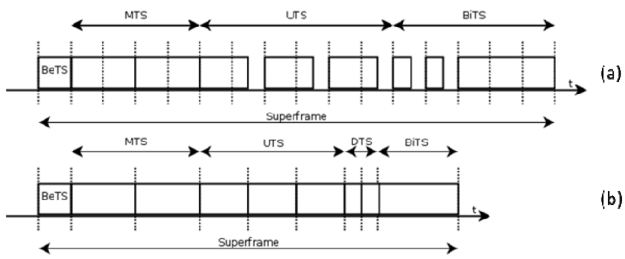

Fig. 1. a) describes the standard IEEE 802.15.4 LLDN superframe format; b) describes the proposed modified superframe format.

MTSs are reserved for management data. The UTS are reserved timeslots, used for data sent from a device to the PAN coordinator. BiTS are shared time slots, placed at the end of the superframe, 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. It then replies with a Configuration Request packet, in which it indicates some information, 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 Worst-Case Latency

Considering a scenario as described in [6] regarding safety critical transport protocols, 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. 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 for every type of time slot. 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 each 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 case 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.

V. Analytical and Simulation Results

Throughout this chapter, a theoretical comparison between standard and modified LLDN is done, for 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:

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

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 $m+n \le 18$ 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 the communication channel is ideal (i.e. errorless and with null propagation delay).

A. 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 redesigned. These requirements concern the number of bytes in MAC payload for each packet 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 downlink, 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 with respect to 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 first approach for the research of the optimum BTS length in terms of superframe length has been implemented performing an exhaustive search and is shown below:

$$\begin{aligned} BTS &= \min_{B}(len(\text{superframe})) \\ B &= [slot_{beacon}, \ldots, \max(slot_{beacon}, \\ &\quad slot_{up}, slot_{down}, slot_{nonrt})] \end{aligned} \quad (3)$$

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

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

while, with two superframes, as:

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

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:

$$\begin{aligned} T_c &= T(slot_{beacon}) + n \cdot (T(slot_{up}) + \\ &+ T(slot_{down})) + 2 \cdot T(slot_{nonrt}) \end{aligned} \quad (6)$$

where $slot_{beacon}$ can be given by either one of BeTSall or BeTStyp approach.

3) Discussion

In Fig. 2, some theoretical results are shown. In Fig. 2a 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. 2b shows the maximum latency in terms of 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 doubles the uplink traffic. In this context, Fig. 2b always represents uplink high-priority traffic. When the slot length exceeds 15 bytes, the switch from SIFS to LIFS is observable with a sensible step. In Fig 2c and 2d the maximum latency varying shared slot length is depicted; while in Fig. 2c modified LLDN still performs better than standard LLDN, in figure 2d 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 as a function of number of nodes, with a maximum latency difference of up to 20 ms with 40 nodes.

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

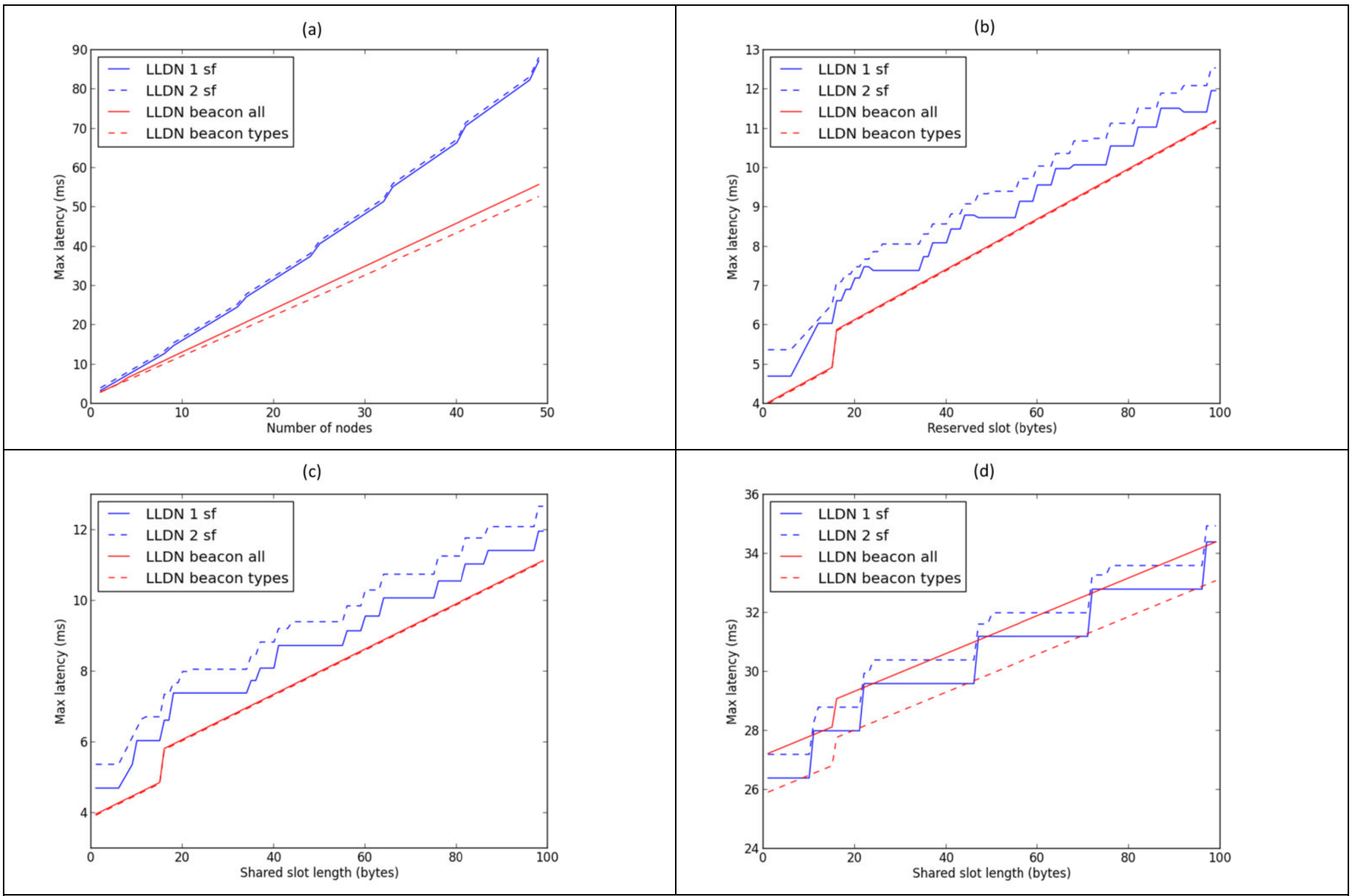

Fig. 2. In subfigures (a) $slot_{rt}$=1, $slot_{nonrt}$=2, in (b) n=2, $slot_{rt}$=1, $slot_{nonrt}$=2, in (c) n=2, $slot_{rt}$=1, in (d) n=15, $slot_{rt}$=10. In all subfigures, standard LLDN is plotted with blue lines for single and double superframe, while modified LLDN is plotted with red lines,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

VI. Conclusions

The theoretical results demonstrate that the modifications to the LLDN mode described in 802.15.4e standard lowers 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 about worst-case latency, presented through this paper, 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 packets scheduling 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 thorough analysis would allow to better understand the characterization of LLDN in terms of throughput, latency and bandwidth utilization in the aforementioned traffic hypothesis.

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