Introducing multi-level communication in the IEEE 802.15.4e protocol: the MultiChannel-LLDN

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Abstract

The Low Latency Deterministic Network (LLDN) protocol is defined in the IEEE 802.15.4e, which is an amendment to the IEEE 802.15.4 standard specifically devised to support the requirements of industrial applications. The LLDN provides a TDMA-based medium access mechanism in which the network cycle time grows linearly with the number of nodes. As a result, to offer low cycle times to applications requiring a high number of nodes, the LLDN specifications suggest to create multiple networks operating on different channels by embedding multiple transceivers in the coordinator. However, such an approach entails high costs and increases the design complexity. Moreover, the LLDN protocol foresees a star topology that limits the network area coverage. This paper proposes a novel approach, called a MultiChannel_LLDN, based on a hierarchical network structure in which nodes communicate on different channels at the same time. The approach supports a high number of network nodes while maintaining short cycle times without the need for multiple transceivers in the coordinator and also provides backward compatibility with the standard LLDN. The paper presents the MultiChannel_LLDN and comparative performance assessments.

1. Introduction

In recent years Wireless Sensor Networks (WSNs) have been adopted in many industrial domains, such as process automation, manufacturing, energy management applications, etc. The IEEE 802.15.4-2011 standard [1] was not specifically devised for such application domains, as it does not provide the properties of determinism and robustness to interferences that these domains strongly require [2]. Hence, some specific protocols for industrial communication were developed on top of the IEEE 802.15.4 physical layer (e.g. WirelessHART [3] and ISA100.11a [4]).

Since 2012, an amendment to the IEEE 802.15.4-2011 standard, named the IEEE 802.15.4e [5], is available. It defines additional MAC profiles for the IEEE 802.15.4-2011 to better support the requirements of industrial applications. In particular, the IEEE 802.15.4e specifications define three MAC sublayers: the *TimeSlotted Channel Hopping* (TSCH), the *Deterministic and Synchronous Multi-channel Extension* (DSME), and the *Low Latency Deterministic Network* (LLDN).

The TSCH protocol provides a time-slotted and frequency hopping communication mechanism suitable for the process automation domain.

The DSME profile is based on a multi-superframe approach and is suitable for general industrial domains. Each multi-superframe consists of multiple superframes which provide both contention-access periods (CAP) and contention-free periods (CFP). Moreover, the DSME provides channel diversity and channel hopping mechanisms to increase the robustness to interference.

The LLDN protocol is specifically devised for industrial applications requiring low latency such as, those found in manufacturing, in robotics, etc. The LLDN protocol provides a star topology and a TDMA-based medium access mechanism that allows for predictable communication latencies.

According to the LLDN profile, time is divided in cycles, called superframes, that repeat one after the other in a regular way. The superframe consists of several timeslots and each node has assigned one or multiple timeslots in which it is allowed to transmit.

The time required to complete a cycle is called cycle time, which corresponds to the duration of a superframe. Thanks to the TDMA-based medium access mechanism of the LLDN protocol, all nodes are allowed to transmit data within a cycle time. When the number of nodes grows, the superframe length increases and the cycle time increases too.

In the case of applications requiring short cycle times (i.e., lower than 50ms), the specifications in [5] suggest to create multiple networks (operating on different channels) with multiple transceivers embedded in a single coordinator. However, such a mechanism entails high costs and limits the network coverage, as multi-hopping is not allowed due to the star topology.

This work aims to improve the scalability of the LLDN profile allowing a high number of network nodes while maintaining low cycle times (i.e., in the range of 50-100 ms), without using multiple transceivers in the coordinator node. The approach here proposed, called a MultiChannel-LLDN (MC-LLDN), foresees a hierarchical organization, i.e., a two-level network in which nodes communicate on different channels at the same time. The two network levels consist of one higher level network (HLN) and multiple networks at the lower level, called sub-networks. A novel operating role for a node is defined, hereon called a network sub-coordinator, that acts as the coordinator for its sub-network and as an end node for the HLN. The MC-LLDN approach allows to achieve lower cycle times, larger radio coverage and higher throughput than plain LLDN.

The paper is organized as follows. Sect. II presents related works. Sect. III provides an overview on the LLDN protocol, while Sect. IV describes the Multi-Channel - LLDN. Sect. IV-A provides a tuning algorithm for the network configuration. In Section V the MultiChannel-LLDN is assessed and compared to the standard LLDN. Finally, Sect. VI concludes the paper and provides hints for future works.

2. Related work

The IEEE 802.15.4e [5] standard is obtaining a growing interest from both academia and industry [6]–[10].

In [11] a comparative assessment between the IEEE 802.15.4 standard and the IEEE 802.15.4e-DSME profile in terms of frame error rate, under the influence of IEEE 802.11b wireless LAN interference, is presented. The results show that the IEEE 802.15.4e-DSME network tolerates the 802.11 interference better than the IEEE 802.15.4 network. In [12] a traffic-aware scheduling algorithm able to support emerging industrial applications requiring low latency and low power consumption for the TSCH profile is presented. In [13] the feasibility of the DSME approach is analytically derived in terms of throughput and verified by simulations.

In the literature, some works addressed possible enhancements of the LLDN protocol aimed at introducing traffic class distinction for supporting quality of service differentiation. The work in [9] proposes to append n+3 bytes to the beacon frame, where n is the overall number of timeslots in a superframe, in order to embed the information needed for handling different traffic classes. However such an approach increases the beacon frame overhead. The work in [10] addresses cycle time reduction by aggregating in a single frame the beacon and all data frames sent to every sensor and actuator. However, the approach proposed in [10] uses a modified version of the LLDN on the IEEE 802.15.4a IR-UWB PHY, which provides higher data rates (up to 27.24 Mb/s) than the IEEE 802.15.4 2540 MHz PHY (250 Kb/s). Moreover, to realize these improvements the beacon frame has to be adapted and, consequently, all the network nodes must implement such a mechanism. This is a limit, as the use of specifically designed devices entails higher costs and does not allow for reusing existing hardware.

Both the works [9] and [10] show that the cycle time grows linearly with the number of nodes. This is natural as, according the LLDN profile, each new node requires at least one additional timeslot and, consequently, the superframe length grows, thus increasing the cycle time too.

In [14] the performance of the IEEE 802.15.4e protocol is evaluated in a typical automation scenario.In [15] several multi-channel approaches had been presented. In [16] a Multichannel Superframe Scheduling (MSS) algorithm for IEEE 802.15.4 networks, that exploits a multichannel approach to allow multiple clusters to schedule their superframes simultaneously on different radio channels, was proposed. The multichannel was adopted in [17] for the needs of wireless sensor networks supporting precision farming applications.

The MMS foresees a cluster-tree network topology, i.e., a hierarchically structured network in which the end nodes are grouped into clusters. Each cluster is ruled by a coordinator that periodically generates beacon frames to synchronize the nodes of its cluster and performs channel switching to synchronize with the PAN coordinator. The common aspect between the MSS in [16] and the MC-LLDN here proposed is that coordinator nodes switch between different networks that operate at different levels of the network hierarchy and on different channels. However, as it will be discussed in Sect. IV, unlike the MMS approach in [16], the MC-LLDN here proposed does not perform channel switch between one superframe and the next one, but within the superframe, by exploiting the TDMA medium access mechanism. This way end nodes are allowed to transmit cyclically without inactive periods, as required by the applications that need short cycle times.

3. The Low Latency Deterministic Network (LLDN)

The LLDN protocol provides a star topology in which nodes transmit using a Time Division Multiple Access mechanism. According to the LLDN protocol the network is managed by the PAN coordinator, which is responsible for the network configuration and node synchronization.

The time is divided in cycles, called LLDN superframes, and each superframe is also divided in equally-sized timeslots. The superframe structure is shown in Fig. 1. In the first timeslot, the PAN coordinator transmits the beacon frame, which is needed for node synchronization and contains informations about the structure of the superframe (e.g., timeslot size, number of timeslots, etc). Moreover, a field of the beacon frame can be used to transmit the group acknowledgement (i.e., a bitmap indicating the timeslots in which messages were received in the previous cycle), thus allowing the retransmission of corrupted messages. As shown in Fig.1, the beacon timeslot may be followed by two optional management timeslots which are used for the transmission of network configuration messages.

The other timeslots are assigned to nodes for data transmission. In particular, the uplink timeslots are reserved for the end node transmissions to the PAN coordinator, while in the bidirectional timeslots both the end nodes and the PAN coordinator can transmit. Generally timeslots are assigned to a single node, so addressing is implicit, as the timeslot in which a node can transmit is known a priori. The IEEE 802.15.4e standard allows a maximum of 254 timeslots excluding the beacon and the management ones. In the case a timeslot is assigned to multiple nodes, a CSMA/CA algorithm, defined in the standard, has to be used for accessing the medium. In order to minimize the overhead introduced at the MAC layer, the LLDN frames are composed of a single-byte header, the payload and two bytes of *Frame Check Sequence* (FCS).

The IEEE 802.15.4 standard [5] defines the duration of a timeslot as a function of the maximum frame length transmitted by a node (i.e., the sum of the number of bytes of the physical and the datalink overhead and the data payload). Such a timeslot duration (T_{ts}), for the 2450 MHz PHY, in the standard [5] is defined as in formula (1)

$$T_{ts} = \frac{(p \times sp) + (m+n) \times sm + IFSPeriod}{v} \quad (1)$$

where

p	is the number of bytes of the PHY header (6 bytes).
sp	is the number of symbols per byte in the PHY (2 symbols per byte).
m	is the number of bytes of the MAC overhead (3 bytes for a LLDN-Data frame).
n	is the maximum expected data payload (in bytes).
sm	is the number of symbols per byte in the physical data unit (2 symbols per byte).
v	is the symbol rate (62500 symbols/s).
IFSPeriod	is the interframe time. Such a value is equal to $\begin{cases} \textit{macMinSIFSPeriod} \text{ if } (m+n) \leq \textit{SIFS}_{Max} \\ \textit{aMaxSIFSFrameSize} \quad \text{otherwise} \end{cases}$

where

- *macMinSIFSPeriod* [1] is the short interframe time (12 symbols);
- $\textit{SIFS}_{Max}$ is equal to *aMaxSIFSFrameSize* [1], i.e., 18 bytes;
- *macMinLIFSPeriod* [1] is the long interframe time (40 symbols);

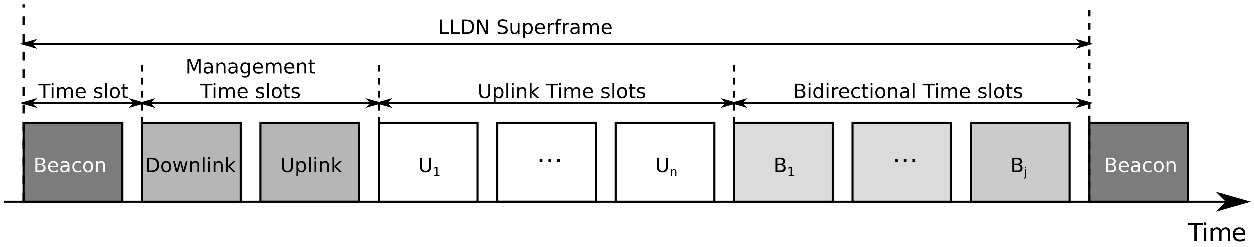

Figure 1. LLDN Superframe structure

Formula (1) shows that:

- The timeslot length grows proportionally to the maximum expected data payload (n), because in formula (1) the values of p, sp, m, sm, and v are constant, while *IFSPeriod* depends on n which in turn depends on the application;
- The time overhead for each timeslot is *macMinSIFSPeriod*$/v = 480\mu s$ for short frames, i.e., those with $(m + n) \leq 18$ bytes, and *macMinLIFSPeriod*$/v = 928\mu s$ for long frames values.

The duration of a superframe (corresponding to the cycle time) is calculated as in Formula (2)

$$T_s = T_{ts} \times N \tag{2}$$

where N is the overall number of timeslots in the superframe.

Formulas (1) and (2) show that the number of nodes and the maximum expected data payload significantly influence the network timing and scalability. In fact, considering that each node is assigned a single timeslot, N is equal to the number of nodes plus 1 timeslot for the beacon transmission (i.e., $N = 1 +$ *NumberOfNodes*). For instance, considering a network with 100 end nodes that periodically transmit 8-byte data, the minimum superframe duration, calculated using formulas (1) and (2), is equal to $74.336ms$. In order to avoid network saturation nodes cannot transmit with a period shorter that the superframe duration.

The IEEE 802.15.4e [5] standard in the case of a large network requiring low cycle times recommends to add multiple transceivers in the PAN coordinator so as to create multiple networks operating on different channels. However, such a solution entails increased complexity and higher costs. For this reason, this work presents a solution to the scalability problem of LLDN protocol that is able to support a high number of nodes without affecting the network cycle time.

4. The MultiChannel–LLDN

While the LLDN standard only supports the star topology, the MC-LLDN mechanism here proposed provides a two-level network in which different sub-networks operate at the same time on different channels. The rationale behind this choice, as it will be explained in the following, is manifold. First, the cycle time will be shortened, thanks to the existence of multiple sub-networks, as there is no need for a large superframe issued by the PAN coordinator with one timeslot for each node. Second, there is no need for embedding multiple transceivers in the PAN Coordinator. Finally, the two-level network allows for a larger coverage, as coordinators act as relay nodes for the end nodes belonging to their sub-network.

In the MultiChannel-LLND approach the timeslot length is the same for all the superframes in the Higher Level Network (HLN) and sub-networks (SNs). Synchronization is performed as follows. A beacon is sent from the PAN coordinator for synchronizing all the sub-coordinators and the end nodes that do not belong to any sub-network. In turn, each sub-coordinator sends a beacon frame to synchronize the end-nodes belonging to its sub-network.

In Fig. 2, node 1 is the PAN coordinator and schedules the superframe in channel X, while nodes 2 and 3, i.e., the sub-coordinators, schedule their sub-superframes on channels Y and Z, respectively. In this way the sub-networks can operate in parallel on different channels. Each sub-coordinator switches between the channel of the HLN, i.e., channel X in Fig. 2, and the channel related to the sub-network, i.e., channels Y or Z, in fixed timeslots. The channels X, Y, and Z are chosen far enough so as to avoid interference between parallel transmissions.

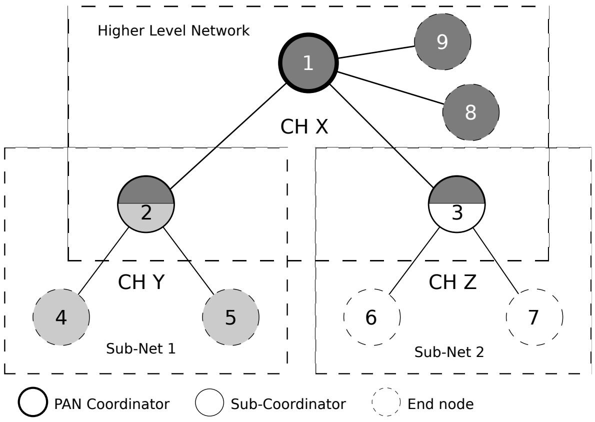

Figure 2. Network topology

Fig. 3 shows the scheduling for the network in Fig. 2, where each superframe is composed of 5 timeslots (1 for the beacon transmission and 4 uplink timeslots). In timeslot 0, the PAN coordinator transmits its beacon on channel X, while sub-coordinators 2 and 3 receive it on the same channel. In timeslot 1, both nodes 2 and 3 switch to the channels of their sub-networks (i.e., channel Y for node 2 and channel Z for node 3) and transmit the beacon frame. The channel switching time is negligible compared to the $IFSPeriod$ defined in Section III.

The MC-LLDN approach allows the interoperability with standard LLDN nodes. In fact, the end nodes and the PAN coordinator do not need any modification and the sub-coordinator nodes can be easily implemented with some modification to the MAC layer of standard nodes for the following functionalities:

- Channel switching between timeslots. Such a functionality is easy to implement, as the IEEE 802.15.4 PHY layer already provides primitives for channel switching.
- Beacon reception from the HLN and beacon transmission for the sub-network.
- Data aggregation algorithms.

In the other timeslots the sub-coordinators receive data from the nodes of their sub-networks with the exception of timeslot 3 for node 2 and timeslot 4 for node 3, in which the sub-coordinator switches to channel X and transmits the data collected from its child nodes to the PAN coordinator. In the case of messages between the PAN coordinator and an end-node, the sub-coordinator operates as a relay node (i.e., it receives the frame from the PAN coordinator and forwards it to the end node in the timeslot assigned to that end node).

The number N of timeslots that have to be provided for each superframe, in the case each node transmits a single message, depends on the number of sub-networks and the number of nodes for each sub-network (taking the maximum among all the considered sub-networks). It can be calculated as in Formula (3)

$$N = max_{i=0....SN}(L_{HLN}, L^i + 1) \tag{3}$$

where SN is the number of sub-networks, L_{HLN} is the number of nodes in the HLN and L^i is the number of nodes in the i-th sub-network (including the sub-coordinator).

As far as data aggregation is concerned, two operating modes are possible. Either sub-coordinators

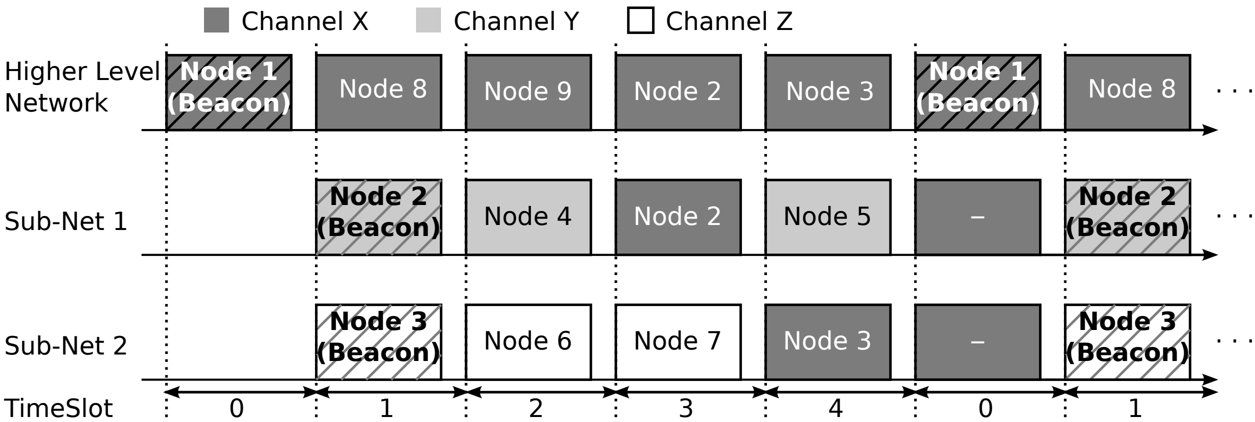

Figure 3. TimeSlot/Node assignment for a) the HLN, b) the Sub-Network 1, c) the Sub-Network 2

collect all the data received from the end nodes of their sub-network and concatenate them in a single bigger frame or, if the application foresees data processing and aggregation, process the data and create frames with aggregate values (e.g., the mean of the samples or other kind of processed data). Timeslots are equally-sized according to Formula (1) taking into account the maximum size of the data payload of a frame. For example, according to the first aggregation mechanism, such a maximum size is the sum of all the largest frames sent by each end node.

Thanks to the data aggregation performed by the sub-coordinators, the protocol overhead can be significantly reduced, so that the cycle time can result shorter than the one achieved with the standard configuration and the data generation periods of nodes can be shorter too.

The sub-coordinator nodes introduced in MC-LLDN may coexist on the same network with the standard IEEE 802.15.4e PAN coordinators and end devices, thus maintaining the backward compatibility with the IEEE 802.15.4e-LLDN standard. In fact, if a standard LLDN node joins the network, one of the following options may occur:

- The standard LLDN node is configured to work as a standard LLDN end device that sends messages to the PAN coordinator. In this case, the node sees each MC-LLDN sub-coordinator as an end device that sends messages to the PAN coordinator. As each node transmits during the timeslot it is assigned, no conflicts or collisions occur.
- The standard LLDN end node is configured as a member of one sub-network. In this case the node can only communicate with the other end-nodes of the same sub-network and with the MC-LLDN sub-coordinator, which plays the role of the PAN Coordinator in the sub-network.

Conversely, if a MC-LLDN sub-network joins the LLDN network (provided that the sub-coordinator of the sub-network has a time slot assigned in the superframe) the other nodes of the network will see the MC-LLDN sub-coordinator as a ordinary standard LLDN end node. This is because the MC-LLDN end nodes communicate on different channels and the MC-LLDN sub-coordinator acts as an end device for the standard LLDN network.

The number of sub-coordinators and the number of nodes determine the number and the length of the timeslots, hence the cycle time. In fact, with reference to Fig. 2, with a fixed number of end nodes N, a network with a low number of sub-networks requires long timeslots in the superframe, due to the data aggregation performed by the sub-coordinator. In fact, each sub-coordinator sends aggregate data whose length depends on the number of end nodes in the sub-network. Considering a given number of end nodes, reducing the number of sub-networks means increasing the number of end nodes per sub-network and, consequently, increasing the length of the aggregated data sent from the sub-coordinators. However, a network with too many sub-networks requires a high number of timeslots in the superframe, as for each sub-network a single timeslot has to be reserved. In order to find the optimal configuration that provides the shortest cycle time, a suitable algorithm is here proposed.

4.1.Calculation of the optimal number of sub-networks to achieve the shortest cycle time

With a given number of nodes and a maximum expected data length that each node can transmit, the aim of the algorithm is to find the optimal number of sub-networks required to obtain the shortest cycle time. The following assumptions are made:

- Each node transmits a single frame once per cycle.
- Sub-coordinators aggregate the frames received from their sub-network nodes and transmit the aggregated data to the PAN coordinator once per cycle.
- In the configuration phase, end nodes deployment has to be performed so as to make it possible an even distribution of nodes among the sub-networks.

These assumptions are not restrictive and usually hold in typical WSN scenarios.

Under these assumptions, if the maximum expected data length of the end nodes, in bytes, is M, then the maximum expected length of a data frame payload (n) can be calculated as in Formula (4)

$$n = \left\lceil \frac{\mathit{numOfNodes}}{\mathit{numberOfSubnets}} \right\rceil \times M \tag{4}$$

and the overall number of timeslots in each superframe is calculated as

$$N = \mathit{max}\left(\mathit{numOfSubnet}, \left\lceil \frac{\mathit{numOfNodes}}{\mathit{numOfSubnet}} \right\rceil\right) + 2 \tag{5}$$

Formula (5) takes the maximum between the number of sub-networks and the number of nodes for each sub-network, so that all the nodes have a dedicated timeslot. Moreover, other two timeslots are added: The first is to allow the beacon transmission of the PAN Coordinator and the second is for the beacon transmission of sub-coordinators.

Using formulas (4) and (1) it is possible to calculate the timeslot length as a function of the number of sub-networks. Hence, the cycle time (T_s) can be calculated as a function of the number of sub-networks too.

An example of the cycle times values obtained varying the number of sub-networks in a network with 100 nodes and $n = 8$ bytes is shown in Fig. 4. The shortest cycle time is achieved in a network with 10 sub-networks.

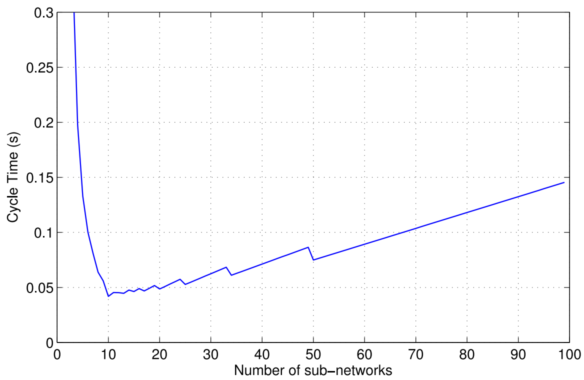

Figure 4. Cycle Times varying the number of sub-networks

If *Net_M* is the sub-network with the highest number of nodes and N_{max} is such a number, the timeslot size depends on N_{max}. If N_{max} is less than *NumOfSubnet* then adding a new sub-network increases the number of timeslots by one. Nevertheless, the introduction of a new sub-network decreases the number of nodes in each sub-network, thus contributing to reduce the timeslot size.

Algorithm 1 calculates the cycle time by varying the number of sub-networks from 1 to $\lceil numOfNodes/2 \rceil$ sub-networks. A higher number of sub-networks is not considered here, as there is no advantage in designing sub-networks consisting only of the sub-coordinator and a single child node. The algorithm returns the number of sub-networks which minimizes the cycle time.

Algorithm 1 Choosing the number of sub-networks

```
minCycleTime ← {99} //just for initialization purposes
numOfSubnet ← 0
for all S ∈ [1, ⌈numOfNodes/2⌉] do
    tCT ← calcCycleTime(numOfNodes, S, n)
    if tCT < minCycleTime then
        minCycleTime ← tCT
        numOfSubnet ← S
    end if
end for
return numOfSubnet
```

5. Simulation scenarios and results

The performance of the MC-LLDN mechanism was assessed through simulations. A simulation model was developed using the OMNeT++ [18] simulation tool and the inetmanet-2.0 framework [19].

The simulation model was evaluated observing the behavior of a simple network and comparing the cycle times calculated with Formula (2) with those obtained through simulation. The simulation parameters of the physical layer are shown in Table I.

Table 1. Simulation parameters of the physical layer

Phy layer parameter	Value/range
TxPower	1 mW
Sensitivity	-85 dBm
PathLossAlpha	2
Sensing area	100m × 100m
Nodes position	uniform(100m,100m)

The PAN Coordinator is placed in the center of the sensing area, so that the maximum distance between the PAN Cordinator and the end-devices is 50m. In this way all nodes are able to communicate with each other. The only random parameter (i.e., the node position) does not influence the measured values, hence there is no need to repeat simulations with different seeds.

The packet loss due to transmission errors is not evaluated in this work, as the same retransmission policy is adopted in both the MC-LLDN and in the plain LLDN standard. The performance indicators here assessed are:

- The cycle times (obtained as in Formula (2)).

- The maximum workload that can be generated by nodes without saturating the network (i.e., when the data generation period for each node is equal to or greater than the cycle time), and the respective throughput.
- The mean and maximum end-to-end latency.

5.1.Cycle times assessment

The cycle time was assessed by varying the number of nodes in the network from 3 to 100. Each node transmits data packets to the PAN coordinator. The size of each data packet is 8 bytes. Consequently, in Formula (2) the n value is equal to 8 bytes.

In the case of standard LLDN the end nodes are connected directly to the PAN coordinator, so a superframe of ($numOfNodes + 1$) slots is scheduled, while in the case of MC-LLDN the number of sub-networks is set according to the algorithm presented in Sect. IV-A. Fig. 5 shows the results obtained, in terms of number of sub-networks, adopting Algorithm 1.

The trend shown in Fig. 5 does not linearly increase, as the algorithm takes into account the slot size as well as the number of slots. For instance, assuming 21 nodes in the network, there are several possibilities, as follows:

- three sub-networks with seven nodes;
- seven sub-networks with three nodes;
- six sub-networks, three with four nodes and three with three nodes

and so on. Here, for the sake of brevity, only the three cases mentioned above are considered. The number of slots required for each of the above mentioned sub-network configurations is computed according to Formula (5). Moreover, the duration of each timeslot is also computed too using Formulas (4) and (1).

The first configuration has 9 timeslots. Each timeslot has a duration equal to 2.72ms and the cycle time is 24.48ms. The second configuration also has 9 timeslots. Each timeslot is 1.696ms long and the cycle time is 15.264ms. The third configuration has 6 timeslots. Each timeslot is 1.952ms long and the cycle time is 15.616ms.

The cycle times obtained as a function of the overall number of nodes are shown in Fig. 6. As shown in the figure, the the cycle time of the standard LLDN grows linearly with the number of nodes and is equal to $74.34ms$ with 100 nodes, while the cycle time of the MC-LLDN grows slowly with a stepped trend and reaches $41.86ms$ with 100 nodes. As far as the maximum value of cycle time is concerned, adopting the MC-LLDN approach instead of the standard LLDN an improvement of 44.07% is obtained.

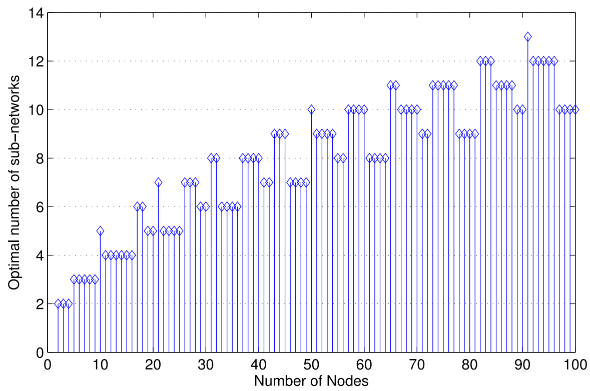

Figure 5. Optimal number of sub-networks varying the number of nodes

However, the graph shows that with up to 21 nodes the standard LLDN is the most convenient choice, as the relevant cycle time values are shorter than the ones of the MC-LLDN approach. However, when the number of nodes is 22 or higher the MC-LLDN offers shorter cycle times than the standard LLDN. Furthermore, 21 nodes are a small value for typical industrial monitoring applications.

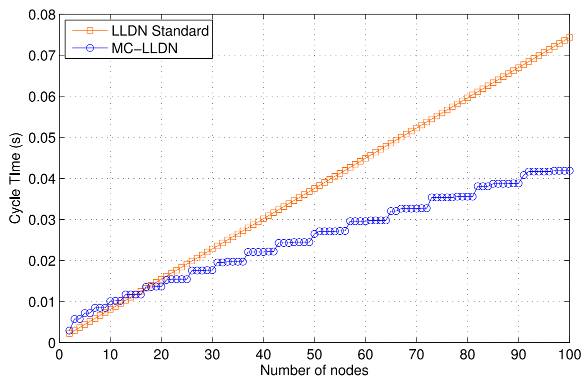

Figure 6. Cycle Times varying the number of nodes

5.2.Throughput and workload assessment

In order to assess the maximum network workload that can be supported and the throughput obtained at the PAN coordinator, a network scenario in which nodes transmit 8-byte data to the PAN coordinator was deployed.

The maximum network workload that can be supported, obtained at the application layer as a function of the number of nodes, is calculated as follows

$$wkl(numOfNodes) = \frac{8 \times 8 \times numOfNodes}{T_s} bit/s \quad (6)$$

while the throughput is determined as the number of bits received by the PAN coordinator from the start of the transmission of the first bit of a data frame until the reception of the last bit. Multiple simulations were executed by varying the number of nodes. The number of sub-networks for the MC-LLDN approach was chosen according to the Algorithm 1 presented in Sect. IV-A. The network configuration parameters for the MC-LLDN are shown in Table II, while those for the standard LLDN are shown in Table III.

Table 2. Network configuration parameters for the MC-LLDN

numOfNodes	*numOfSubnets*	$T_{ts}(ms)$	$T_s(ms)$
20	5	1.952	13.664
40	8	2.208	22.080
60	10	2.464	29.568
80	9	3.232	35.552
100	10	3.488	41.856

Table 3. Network configuration parameters for the standard LLDN

numOfNodes	$T_{ts}(ms)$	$T_s(ms)$
20	0.736	15.456
40	0.736	30.176
60	0.736	44.896
80	0.736	59.616
100	0.736	74.336

Simulation results comparing the maximum workload and the throughput of both protocols are shown in Fig. 7.

Results show that the MC-LLDN outperforms the standard LLDN protocol in terms of the maximum throughput achieved. In particular, with a number of nodes below 20 the difference between the two protocols is not significant, as the cycle times are short for both protocols, while such a difference grows if the number of nodes increases. In fact, in the case of 100 nodes the MC-LLDN supports workload values, at the application level, higher than 150 kb/s, while the standard LLDN supports at most workload values around 86 kb/s. Such a result is due to the reduction of the cycle time in the case of MC-LLDN, that allows to handle higher workloads without saturating the network.

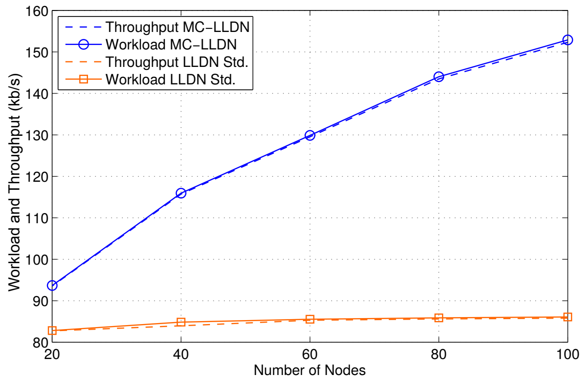

Figure 7. Comparison of the workload and throughput

5.3.End-to-end latency assessment

With the same network parameters of the simulation shown in Sect. V-B the maximum end-to-end latencies were assessed.

In Fig. 8 simulation results of the maximum end-to-end latencies at the application layer obtained by varying the number of nodes are shown.

Fig. 8 shows that the maximum end-to-end latency of the MC-LLDN is slightly higher than that obtained with the standard LLDN. The same trend was obtained for the mean end-to-end latency. This is natural, as in the MC-LLDN two hops are needed to reach the destination. However, in the MC-LLDN approach the reduction of the cycle times compensates for the latency increase introduced by two-hop transmissions. Moreover, the maximum end-to-end latencies grow in the same way as in the standard LLDN. Similar results were also obtained, with the same network configuration, for the mean end-to-end latency.

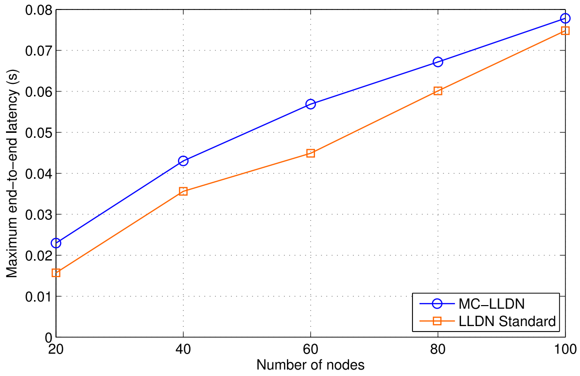

Figure 8. Max. End-to-end latency

6. Conclusions and Future work

In this work a novel mechanism, named MultiChannel-LLDN (MC-LLDN), that provides support for parallel multichannel transmissions over IEEE 802.15.4e LLDN network was proposed. The envisaged mechanism allows a high number of nodes in the network while maintaining low cycle times, as it allows for multiple nodes transmitting in parallel on different channels. The MC-LLDN approach maintains the backward compatibility with the IEEE 802.15.4e-LLDN standard. Moreover, the paper also presented an algorithm to set the optimal number of nodes for each sub-network.

The MC-LLDN mechanism was assessed by comparing the results in terms of cycle times, the workload supported and the latency with those obtained using the LLDN standard. Results show that when the number of nodes increases (20 in the scenario here addressed) the MC-LLDN protocol is able to support higher workload values than the standard LLDN while maintaining comparable end-to-end latencies.

For instance, in the case of 100 nodes, the workload that can be transmitted without saturating the network is 75% higher compared with the standard LLDN, while the maximum end-to-end latency achieved by the MC-LLDN only increases of 1%.

Future work will address the implementation of the protocol on COTS devices (e.g., TelosB devices) and an analytic assessment of the MC-LLDN approach. As far as the implementation of the protocol is concerned, all the modifications, including the data aggregation algorithms and channel switching, can be realized via software without requiring customized hardware. In fact, existing COTS products can be easily programmed to implement the functions needed by the MC-LLDN protocol.

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