Computer Communications 192 (2022) 57–65

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

LoRa support for long-range real-time inter-cluster communications over Bluetooth Low Energy industrial networks

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ARTICLE INFO

Keywords:
Real-time communications
Bluetooth Low Energy
LoRa
Low Power Wide Area Networks (LPWANs)
Industrial wireless networks

ABSTRACT

Industrial monitoring and control applications typically require real-time communications between a large number of nodes distributed over the plant. For the sake of network manageability and to reduce the overall network workload, wireless nodes are organized in clusters, which typically encompass neighboring nodes that frequently exchange data with each other. However, different clusters also cooperate to realize distributed applications and this raises the need for enabling communications between multiple clusters spread over large areas in the plant. This paper presents LoRaBLE, a long-range communication protocol that leverages the Long Range (LoRa) technology to provide inter-cluster communications over Bluetooth Low Energy networks with bounded delays, so as to meet the time constraints of real-time industrial traffic flows. The paper presents the design of LoRaBLE and a proof-of-concept implementation on a lab testbed made up of commercial-off-the-shelf devices.

1. Introduction and motivation

The Industry 4.0 vision drives to the introduction of novel communication and computation technologies that are aimed at reducing operational costs in industrial manufacturing systems by automating a large number of processes that involve sensors/actuators, mobile robots, edge/cloud computing, and autonomous vehicles [1,2]. Such a scenario requires the deployment of a large number of wireless networks able to connect a high number of devices, often distributed over wide areas. To reduce the overall workload on the network, the nodes that frequently communicate with each other can be grouped into clusters, which typically include nearby nodes.

However, distributed applications entail the need for inter-cluster communications, which can involve clusters that are far from each other. Providing bounded delays to long-range real-time inter-cluster communications is not trivial. In this context, this work proposes a solution to support long-range real-time inter-cluster communications that leverages two popular communication technologies, i.e., Bluetooth Low Energy (BLE) and LoRa (Long Range). The choice of BLE [3] is motivated by two main reasons. First, BLE is a short-range technology that nicely fits intra-cluster communications. Second, it is possible to guarantee bounded message delays in BLE networks with a star topology by configuring the parameters of the BLE master–slave connections using the methods proposed in [4]. However, for inter-cluster communications, multi-hop mesh operation would be needed to extend the network coverage, but, in large networks, the end-to-end delay values achievable by BLE through multi-hop approaches are neither bounded [5] nor low [6], as the maximum end-to-end delay grows with the number of hops that a message traverses to reach the destination [7].

For this reason, in this work a long-range wireless technology, i.e., LoRa, comes into play [8] to enable communications between multiple BLE clusters spread over large areas in the plant. The rationale behind the choice of the LoRa technology is twofold. First, LoRa enables long-range robust communications between low-cost devices. Second, LoRa [9] offers a variety of physical layer parameters that can be configured to meet the diverse needs of different applications.

This work proposes LoRaBLE, a novel protocol for long-range real-time wireless communications that allows to interconnect, through LoRa links, a number of BLE clusters [10] statically organized offline, i.e., at the network design time. In the literature [8,11,12] it was suggested that merging the features of BLE and LoRa for long-range communications can provide easy deployment, low deployment and maintenance costs, and independence from telecom operators. However, to the best of our knowledge, no previous work addressed a way to combine BLE and LoRa so as to guarantee bounded delays over long-range communications. LoRaBLE, instead, provides inter-cluster communications with bounded delays. In particular, LoRaBLE is intended for soft real-time applications, with cycle times [13] in the order of tens of seconds.

To the best of our knowledge, LoRaBLE is the first approach in the literature that is able to provide with real-time guarantees the communications between two LoRa end nodes, where a LoRa end

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https://doi.org/10.1016/j.comcom.2022.05.026
Received 10 March 2022; Received in revised form 29 April 2022; Accepted 24 May 2022
Available online 2 June 2022
0140-3664/

node represents the master of a LoRaBLE cluster. As a matter of fact, the approaches that have been proposed in the literature so far, such as [13–15], are able to provide bounded delays to time-constrained communications from a LoRa end node to the LoRa sink, but not between a LoRa end node and another LoRa end node. Consequently, LoRaBLE fills a gap as far as real-time communications over LoRa networks are concerned.

This paper describes in detail the LoRaBLE design and presents a proof-of-concept implementation to show both the LoRaBLE feasibility on commercial-off-the-shelf devices (COTS) and its performance, in terms of packet loss ratio, deadline miss ratio, and end-to-end delay.

The paper is organized as follows. Section 2 deals with related works. Section 3 recaps LoRa/LoRaWAN. Section 4 presents the LoRaBLE design, while Section 5 describes the proof-of-concept implementation and the experimental results obtained. Section 6 provides a discussion on LoRaBLE coverage and scalability. Finally, Section 7 gives conclusions and hints for future work.

2. Related work

Bluetooth Low Energy [3] communications represent a promising solution for implementing applications that require mobility support and easy network reconfiguration [16–19] as well as for providing connectivity to industrial applications. In particular, BLE working in connection-oriented mode is suitable for real-time industrial applications, provided that an appropriate configuration of the connection parameters is applied. The work in [4] provides a configuration method for the parameters of the BLE master–slave connections that guarantees bounded message delays in BLE star networks. For this reason, LoRaBLE exploits such a method for BLE-based intra-cluster communications.

To extend the BLE network coverage, multi-hop mesh operation is needed, but the Bluetooth mesh networking specifications [5] are not able to guarantee bounded message delivery times to real-time communications over multi-hop mesh networks. To overcome this limitation, the work in [6] proposes MRT-BLE, a real-time protocol for BLE multi-hop mesh networks that provides bounded delays. However, in large networks the end-to-end delay values obtained by MRT-BLE, although still bounded, grow with the number of relay nodes between the source and the destination. To cover large areas BLE clusters could be combined with other wireless communication technologies, such as IEEE 802.11 or Sub-GHz [20,21]. However, even in this case a high number of relay nodes would be needed, at the expenses of high deployment and maintenance costs.

For this reason, to enable communications between multiple BLE clusters spread over large areas in the plant, long-range wireless technologies are interesting candidates. Cellular networks (e.g., 5G) could represent an option, as they offer high bandwidth and lower communication delay, but they entail dependence on the telecom companies, which can be an issue for economical or strategical reasons. Moreover, as discussed in [22], there are many locations in which 5G is not enabled. Another option are the emerging Low Power Wide Area Network (LPWAN) technologies, such as the ones based on LoRa, which promise a wide coverage range, thus representing an easy-to-deploy solution to provide seamless interoperability among end devices.

Among the LPWAN protocols, LoRaWAN [23] has a few advantages, i.e., it offers a higher datarate than Sigfox and, unlike NB-IoT [24–26], it is unlicensed. For this reason, LoRaWAN is proving useful and practical for several application fields, such as smart cities [27–30], smart monitoring [31,32], and vehicular communications [33]. However, the LoRaWAN MAC layer policies cannot provide real-time flows with bounded message delivery times, and therefore LoRaWAN is not suitable for meeting the typical time constraints of industrial communications.

The work in [34] realizes time-slotted communications over LoRaWAN by enabling the nodes to self-organize the schedule of the timeslots to support collision-free transmissions, but it does not address a way to guarantee bounded delays to real-time flows. Conversely, a few works proposed to support real-time flows through a LoRa-based centralized approach, in which transmission scheduling follows a superframe structure, as in [13–15]. However, such approaches are only intended for star topologies, in which the end nodes can only exchange messages with the sink, whereas message exchanges between two LoRa end nodes are not supported. Compared with the above mentioned approaches, LoRaBLE is not bound to star topologies. Moreover, in LoRaBLE the communications between two LoRa end nodes occur in dedicated timeslots of the superframe, whose allocation to the relevant nodes is defined by the inter-cluster scheduler and communicated to all the nodes within the beacon that indicates the start of the superframe.

Some works in the literature propose approaches to extend the coverage of short-range BLE networks by utilizing LoRa, in contexts such as healthcare monitoring applications [8], smart cities [11], and wildlife monitoring systems [35]. None of them deals with industrial applications, and therefore, unlike LoRaBLE, they do not aim and are not able to guarantee real-time communication constraints.

LoRaBLE is somehow inspired by the two-level network architecture presented in [36,37], where channel hopping is used and the beacon is exploited to implement TDMA-based transmissions. However, the notable difference between the LoRaBLE protocol here proposed and the ones in [36,37] is that, whereas those approaches work over IEEE 802.15.4 networks, in LoRaBLE two different technologies, i.e., LoRa and BLE, are adopted.

As far as the cluster formation process is concerned, in LoRaBLE the BLE nodes are statically clustered at the network design time. Some works in the literature, such as [38,39], address strategies that enable the nodes to self-organize into multiple clusters, for example, for load balancing among the clusters. However, the use of dynamic clustering methods is out of the scope of this paper and is left for future work.

3. LoRa/LoRaWAN recap

The Long Range (LoRa) [9] technology is the physical layer that enables long-range robust communications in the unlicensed sub-GHz ISM band exploiting the Chirp Spread Spectrum (CSS) technique. A typical LoRa radio is characterized by some customizable parameters, such as Spreading Factor (SF), Coding Rate (CR) and Bandwidth (BW). The configuration of such parameters allows to tune the bit rate, the Time on Air (ToA), the covered distance, and the energy consumption. As discussed in [40,41], transmissions using different SFs are quasi-orthogonal. LoRa supports low physical bit rates, i.e., up to 5470 bit/s, if the bandwidth is equal to 125 kHz.

The ToA is the transmission duration of a message. The work in [42] provides Eq. (1) to calculate the ToA for the transmission of messages using the LoRa modulation. The notation used in Eq. (1) is summarized in Table 1.

$$ToA = \frac{2^{SF}}{BW}\left(NP + 4.25 + SW + max\left(\left\lceil \frac{8PL - 4SF + 28 + 16CRC - 20IH}{4(SF - 2DE)} \right\rceil (Z+4), 0\right)\right) \quad (1)$$

As discussed in [43], some restrictions on the strategies that a LoRa transmitter can adopt to access the physical medium are imposed by the ETSI regulations [44,45]. Such regulations allow to choose between using a duty cycle limitation or a Listen Before Talk (LBT) transmission management.

The maximum duty cycle is defined as the maximum percentage of time per hour a transmitter node can be transmitting on a sub-band, e.g., a duty cycle of 1% allows 36 s of transmission time per hour. Note that the transmission times on all the channels of the same sub-band must be jointly considered. The devices that use an ALOHA-based medium access strategy must comply with duty-cycle limitations and are also subject to restrictions on the maximum transmission power. Table 2 shows such limitations in the EU863-870MHz ISM Band.

Table 1
Notations used for the ToA calculation in Eq. (1).

Symbol	Definition
ToA	Time on Air
SF	Spreading Factor
BW	Bandwidth
NP	Number of preamble symbols.
SW	Length of the synchronization word.
PL	PHY payload size (in bytes).
CRC	CRC presence flag (1=yes ; 0=no).
IH	PHY header presence flag (1=no ; 0=yes).
DE	Use of data rate optimization (1=enabled ; 0=disabled).
Z	Value of the Z parameter in the LoRa CR definition $CR = \frac{4}{4+Z}$.

Table 2
EU863-870MHz ISM Band duty-cycle limitations.

Sub-band	*Frequency* band (MHz)	*Available channels*	*Maximum TX power* (dBm)	*Maximum duty cycle*
h1.4	868.00 - 868.60	3	14	1%
h1.5	868.70 - 869.20	2	14	0.1%
h1.6	869.40 - 869.65	1	27	10%
h1.7	869.70 - 870.00	1	14	1%

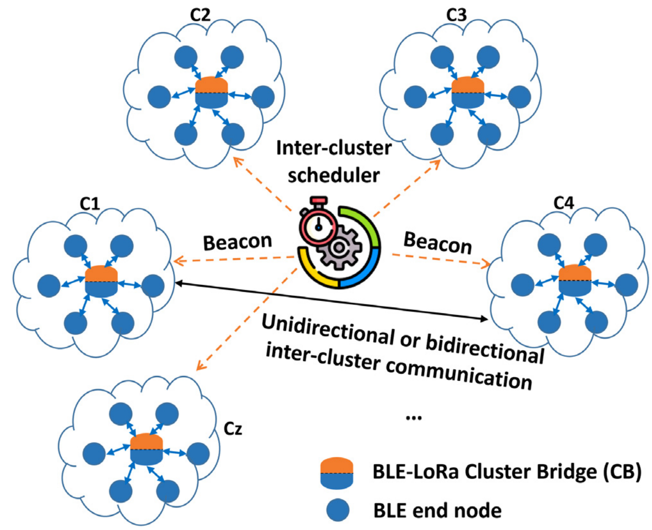

Fig. 1. The LoRaBLE topology.

The devices that use an LBT-based medium access control (MAC) protocol are also subject to duty cycle restrictions. In this case, the maximum cumulative transmission time per device must be less than 100 s per hour, i.e., a duty cycle of about 2.8%, over a 200 kHz portion of spectrum is allowed.

The standard that defines the MAC layer and the network architecture for LoRa-based networks is the LoRaWAN networking protocol. LoRaWAN [23,46] was designed for sporadic nontime-constrained communications between a relatively large number of nodes based on LoRa technology. As discussed in [43,47], at the MAC layer LoRaWAN can adopt either a pure ALOHA approach with duty-cycle limitations or a polite spectrum access technique, such as LBT. Due to this, LoRaWAN cannot provide bounded delays to the real-time flows typically found in industrial applications. For this reason, here a novel medium access strategy for LoRa-based real-time inter-cluster communications is proposed.

4. Design

LoRaBLE is a long-range communication protocol able to transmit, through BLE-LoRa bridges, messages between clusters of BLE nodes, with bounded delays. Such bridges, here called Cluster Bridges (CBs), are dual-radio nodes that forward the messages from a cluster to another one, and vice versa. We assume that each CB is located within the coverage range of all the other CBs. This way, every bridge can reach any other one via a single-hop LoRa transmission. Note that the coverage range of a LoRa device can reach several kilometers depending on the configuration parameters and the considered environment. However, the use of a high spreading factor value increases the ToA, and therefore a trade-off between bit rate and communication range is needed.

The LoRaBLE topology, shown in Fig. 1, includes a number of clusters of BLE nodes (C1, C2, …, Cz) and a LoRa inter-cluster scheduler. The BLE nodes are statically clustered at the network design time, i.e., offline. We assume that, in general, nearby nodes are organized in one cluster, unless their number is so high that multiple clusters are needed to allow the BLE star network to cope with them. However, no further assumption is made on how the offline clustering is performed and LoRaBLE works independently of the static clustering algorithm used. In LoRaBLE each cluster consists of a star network with n BLE slave nodes, e.g., sensors and actuators, and a CB, i.e., the BLE master that handles the cluster. A BLE node exchanges messages with its CB via BLE master–slave intra-cluster communications. Within a cluster, the nodes communicate with each other using the connection-oriented approach discussed in [4], which guarantees bounded delays over BLE star networks. The sensor data collected within a cluster by the BLE nodes and sent to the CB need to be processed before forwarding. In fact, the duty-cycle limitations imposed by the ETSI regulations on LoRa-based networks do not allow to forward the raw sensor data. In fact, to support the transmission of a higher number of messages without increasing the ToA, raw data forwarding would require a higher bit rate than the ones provided by LoRa or less stringent duty-cycle constraints. For this reason, the CBs calculate aggregated values (e.g., averages, etc.) and send them in messages that, according to the application requirements, may belong to one or multiple periodic or aperiodic real-time flows. LoRaBLE, by design, is able to handle mobile clusters, e.g., mobile robots equipped with BLE sensors.

The inter-cluster scheduler is a stationary node, located approximately in the center of the sensing/actuation area, which is in charge of scheduling the transmissions between the clusters. Two CBs exchange messages via single-hop inter-cluster LoRa communications. Note that the inter-cluster communications can be unidirectional or bidirectional (see Fig. 1), according to the application requirements.

LoRa-based inter-cluster communications use a Time-Division Multiple Access (TDMA) approach. In particular, the inter-cluster scheduler periodically sends a beacon that synchronizes all the CBs and indicates the start of the superframe. The latter, whose structure is shown in Fig. 2, consists of a beacon and a set of timeslots, which are used to schedule the transmission of periodic and aperiodic messages from a cluster to another one. Once a beacon is received, each CB is aware of the next superframe schedule. Consequently, each CB knows the timeslots in which it can transmit and the ones in which it has to listen to the channel, to receive the messages sent from another CB. During the remaining timeslots, the CB will stay idle.

Each superframe contains a number of timeslots (n_{ts}) equal to the number of periodic flows (n_P), plus the minimum number of timeslots reserved for aperiodic messages ($n_{AP_{res}}$), plus one (i.e., the beacon timeslot). Note that n_P and $n_{AP_{res}}$ are configuration parameters. In particular, within a superframe, zero, one, or multiple timeslots are assigned to each CB. The number of timeslots scheduled for the periodic or aperiodic transmissions of a CB is equal to zero in a given superframe if there are no transmissions planned for the CB in that superframe. We assume that all the periodic flows and their properties are known in advance, whereas the transmission requests of any aperiodic message arrive at runtime. Each request is encoded in a specific field of the periodic messages and is detected by the inter-cluster scheduler. In fact, between two consecutive beacons, the inter-cluster scheduler

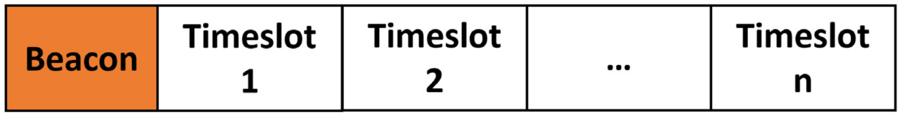

Fig. 2. The superframe structure.

keeps listening to the channel on which the communications occur and handles aperiodic transmission requests by inserting them in a deadline-based priority queue (in which the earliest deadline has the highest priority). The required aperiodic transmissions will be scheduled in one of the next superframes. In each superframe, a number of aperiodic messages up to the actual number of timeslots available for aperiodic transmissions, i.e., $n_{AP_{act}}$, is scheduled. The value of $n_{AP_{act}}$ in a superframe may be larger than $n_{AP_{res}}$. This happens if some periodic flow has a period larger than the superframe duration, and, consequently, it does not use the reserved timeslot in every superframe. As the periodic flows are known in advance and the application layers of the CBs are synchronized (i.e., they start when the first beacon is received), the inter-cluster scheduler is aware of the availability of periodic messages in each CB during the superframe as well as of the number of timeslots available for aperiodic transmissions in each superframe. The scheduling algorithm does not assign timeslots to the messages that have already expired (i.e., those that have already missed their deadline) or that would expire when their transmission is scheduled.

The timeslot duration is fixed and is set so as to ensure the transmission of a maximum-sized message according to the physical bit rate. In particular, the ToA, calculated as in [42], imposes a lower bound on the timeslot duration. Moreover, as discussed in [48], a guard band between two consecutive timeslots is highly recommended when a time-slotted approach is adopted on COTS LoRa radios, e.g., to take into account the time required to turn on the radio. For instance, at least 4 ms are required for the SX1272 LoRa transceivers [48]. Consequently, such a value has to be added to the above discussed lower bound on the timeslot duration.

The beacon communicates the allocation of the timeslots within the current superframe. Specifically, it defines the timeslots assigned to each cluster and the specific timeslots to be used to transmit aperiodic messages. In each superframe the beacon may be sent on a different channel than the one used for transmitting the previous beacon. The sequence of channels on which the beacons are sent is randomly generated. In particular, each beacon includes the channel on which the messages should be transmitted in the timeslots within the superframe, and a list of four channels on which the next four beacons will be sent. This allows the CBs to know when to switch to the right channel after the beacon. This way, the loss of three consecutive beacons can be tolerated without losing the ability to switch to the right channel and receive the next beacon. However, every time a beacon is lost by a CB, the cluster managed by that CB will not be able to send messages in the current superframe (such messages will be handled in the following superframes), but it will only act as a receiver. Note that the beacon period, i.e., the superframe duration (τ_{sfrm}), can be configured based on the application requirements by choosing a divisor of the least common multiple of the periods of the periodic flows that is also lower than the sum of the shortest relative deadline D_{min} (where the relative deadline is the maximum allowed time-span between the generation of a message and its delivery to destination) and the timeslot duration (τ_{TS}), i.e.,

$$\tau_{sfrm} \in DIV^* : \tau_{sfrm} < D_{min} + \tau_{TS} \tag{2}$$

where DIV^* is the set of the divisors of the least common multiple of the periods of the periodic flows.

The choice of the beacon period length is a trade-off between reducing the protocol overhead and offering short transmission delays to aperiodic messages. A short beacon period reduces the time available for message transmissions, due to the overhead introduced by more frequent beacon transmissions. Conversely, a long beacon period leaves more room for message transmissions, but it entails higher delays for aperiodic messages, as the scheduling algorithm runs on the scheduler at each beacon interval.

The inter-cluster scheduler periodically runs (i.e., at each beacon period) a duty cycle check function to guarantee that each LoRa node complies with the duty cycle limitations imposed by the ETSI normative. The duty cycle check function takes into account both the beacon transmissions and the other periodic/aperiodic transmissions carried out by the CBs on each allowed sub-band.

4.1. Inter-cluster scheduling algorithm

The inter-cluster scheduler is in charge of handling the timeslot assignment in each superframe. For this reason, at each beacon period, the inter-cluster scheduler runs a custom scheduling algorithm (i.e., Algorithm 1) that aims to keep the end-to-end delay as low as possible.

The inter-cluster scheduler is aware of all the periodic flows to be scheduled and maintains three arrays, i.e., *period*, *deadline*, and *src*, which contain, for each periodic flow, the period, the relative deadline, and the source node, respectively.

The Algorithm 1 works in three different steps, i.e., a preliminary phase, an ordering phase, and a scheduling phase.

Preliminary phase. During the preliminary phase, the inter-cluster scheduler initializes the *minTS* and *rT* arrays, which are very important to establish the flows' scheduling order. The *minTS* array maintains, for each flow, the index of the earliest timeslot that can be assigned to the flow during the next superframe (note that the first timeslot in a superframe has index 0). In particular, the inter-cluster scheduler, which synchronizes the application layers of the CBs and is aware of all the periodic flows to be scheduled, checks for each flow if a message is ready to be transmitted. If not, the scheduler checks when the next message of a flow will be generated. The *rT* array stores, for each flow, the residual time before the outgoing message expires. If there are no messages ready to be transmitted, the *rT* value will be equal to the remaining time until the next message generation time plus the relevant relative deadline.

Ordering phase. Next, the periodic flows are sorted by the *minTS* value in ascending order. If multiple flows have the same *minTS* value, they are sorted by the *rT* value in ascending order. In particular, the *sortFlows()* function returns an array of flow IDs (i.e., *sortedFlows*), which allows to schedule the periodic flows following a specific order. Each flow ID in the *sortedFlows* array identifies the index in the arrays *minTS*, *rT*, and *src* that corresponds to the flow to be scheduled.

Scheduling phase. Finally, during the scheduling phase, the timeslots of the next superframe, here represented by the *sfrm* array, are assigned to the CBs. In every superframe, each CB will be able to send zero, one or multiple periodic/aperiodic messages according to the superframe schedule. In particular, for each timeslot i, the scheduler tries to assign a periodic flow according to the flows' order. If no periodic flows can be scheduled in the timeslot i on the basis of the *minTS* value, the aperiodic transmission requests, which are sorted in ascending order by the remaining time before they expires (as they also have a deadline), are evaluated and scheduled (a value higher than the number of CBs, called ApMark, identifies a timeslot assigned to a CB for the transmission of an aperiodic message). If the queue of aperiodic requests is empty, the timeslot will not be used.

Algorithm 1 LoRa inter-cluster scheduler - Scheduling algorithm

```
/*Preliminary phase: superframe pre-processing*/
for (i=0; i<n_P; i++) do
  ready = checkMsgReadyToTx(period[i])
  if (ready) then
    minTS[i] = 0
    rT[i] = residualTime(period[i], deadline[i])
  else
    nextMsgTime[i] = nextGenTime(period[i])
    if nextMsgTime[i]<timeOfLastTS(currTime) then
      minTS[i] = minSchedTS(nextMsgTime[i])
      rT[i] = residualTime(period[i], deadline[i])
    else
      minTS[i] = −1
      rT[i] = −1
    end if
  end if
end for

/*Ordering phase*/
sortedFlows[] = sortFlows(minTS[], rT[])

/*Scheduling phase*/
j=0
for (i=0 ; i<n_ts; i++) do
  flowID=sortedFlows[j]
  if (minTS[flowID] ≥ i) and isNotExpired(rT[flowID], currTime) then
    sfrm[i] = src[flowID]
    j++
  else
    expired = true
    while expired and getSize(ApReqQueue)>0 do
      ApReq = QueuePop(ApReqQueue)
      expired = checkDeadline(ApReq)
    end while
    if not expired then
      sfrm[i] = ApReq.src + ApMark
    else
      sfrm[i] = −1
    end if
  end if
end for
```

As a result, for each superframe, the flows are scheduled following a specific order that allows to both reduce the end-to-end delay and improve the superframe utilization, thanks to a careful schedule of the periodic flows. The timeslots that cannot be used to schedule periodic flows, i.e., the $n_{AP_{act}}$ timeslots, are either used for the transmission of aperiodic messages or left idle (idle timeslots).

5. Proof of concept implementation

This Section presents a proof-of-concept implementation meant to show the feasibility of the proposed LoRaBLE protocol on COTS devices and to assess whether the performance obtained are in line with the expectations.

The presented implementation uses the X-NUCLEO-IDB05A1 devices produced by STMicroelectronics for the BLE nodes, and a device equipped with the SX1272 LoRa transceiver for the inter-cluster scheduler. Moreover, a low-cost BLE-LoRa bridge (i.e., a CB), shown in Fig. 3, was developed using an STM32L4 microcontroller, the X-NUCLEO-IDB05A1 expansion board, and an SX1272 LoRa transceiver connected through jumper cables.

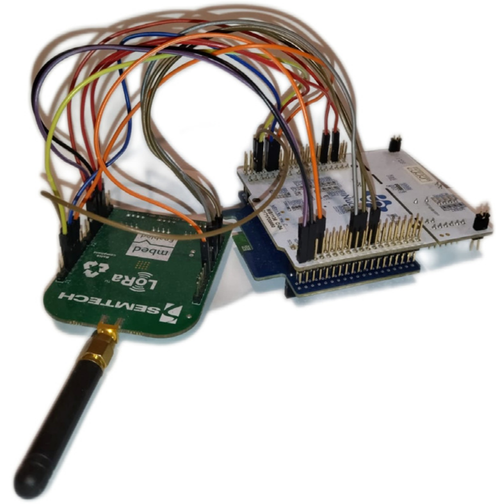

Fig. 3. The implemented low-cost BLE-LoRa bridge.

While the LoRaBLE intra-cluster communications exploit the approach presented in [4] and summarized in Section 3, inter-cluster communications are based on a novel LoRa-based medium access strategy that enables bounded delays transmissions between the dual-radio CBs. For this reason, in this Section we focus on the performance evaluation of the LoRa-based network, i.e., the one used for inter-cluster communications. This way, we consider the flows whose source and destination are the CBs, rather than the BLE end nodes. In each cluster, the sensor data collected by the BLE nodes and sent to the CB are processed before forwarding, so as to decrease the workload on the CBs.

The performance metrics used for this assessment are the Packet Loss Ratio (PLR), the Deadline Miss Ratio (DMR), and the end-to-end delay (e2eDelay).

The PLR is defined as a percentage, according to Eq. (3),

$$PLR = \left(\frac{n_{lostMsg}}{n_{txMsg}}\right) * 100 = \left(1 - \frac{n_{rxMsg}}{n_{txMsg}}\right) * 100 \quad (3)$$

where n_{txMsg}, $n_{lostMsg}$ and n_{rxMsg} are the number of messages transmitted, lost and correctly received, respectively, measured over all the CBs in the network.

The DMR is defined as a percentage, according to Eq. (4),

$$DMR = \left(\frac{n_{discMsg}}{n_{genMsg}}\right) * 100 = \left(1 - \frac{n_{txMsg}}{n_{genMsg}}\right) * 100 \quad (4)$$

where $n_{discMsg}$, n_{genMsg} and n_{txMsg} are the number of messages discarded, generated and transmitted, respectively, measured over all the CBs in the network.

The e2eDelay, as shown in Eq. (5), is defined as the time interval between the message generation at the source node (*GenTime*) and its complete delivery at the destination node (*RxTime*), measured at the application level.

$$e2eDelay = RxTime - GenTime \quad (5)$$

5.1. Evaluated scenario and configuration settings

The assessments were performed in an indoor scenario of about 150 m *x* 150 m consisting in a laboratory area with large rooms in which 7 BLE clusters and the inter-cluster scheduler located in the center of the area were deployed. Each cluster consists of three BLE nodes and a Cluster Bridge (CB). In particular, one cluster, i.e., the one handled by CB3, consists of sensors only, while the other clusters include both sensors and actuators. Each CB generates a periodic real-time flow, as shown in Table 3. Each flow has the relative deadline

Table 3
Periodic flow configuration.

Flow #	Src.	Dest.	Period (ms)
1	CB1	CB4	1500
2	CB2	CB1	1600
3	CB3	CB2	2500
4	CB4	CB2	1800
5	CB5	CB7	2000
6	CB6	CB5	2300
7	CB7	CB6	2050

Table 4
Parameters for the ToA calculation.

Parameter	Z	NP	SW	PL	CRC	IH	DE
Value	1	8 + 4	8	50	1	0	0

Table 5
CB duty cycle.

CB #	1	2	3	4	5	6	7
Periodic messages	6.8%	6.38%	4.08%	5.67%	5.1%	4.43%	4.98%

D equal to the period. As a result, the messages generated by each CB must be delivered before a new message is generated. A deadline check function was implemented in each node to prevent sending expired messages. In fact, the messages that do not meet their deadline must be discarded.

Aperiodic messages are generated by the CBs every t seconds, where t is a random variable that varies between 20 s and 30 s, and have a deadline between 6 and 8 s. If such messages cannot be scheduled within their deadline, they are discarded. Both periodic and aperiodic messages are unconfirmed. No retransmission mechanisms are implemented.

The timeslots are sized to allow a 50-byte message transmission (i.e., a typical physical layer payload for the messages exchanged in industrial applications [13]), using SF=7 and BW=125 kHz. Here we underline that the configuration here described fits the experimental scenario under consideration according to [49]. The lower bound for the duration of the timeslots was calculated using Eq. (1) with the parameter values shown in Table 4. The obtained value is 0.102s. Note that the common LoRa-modulated channels uses 8 preamble symbols (NP) [42]. Conversely, here 12 (i.e., 8+4) preamble symbols are considered, as the adopted hardware uses 4 additional symbols. Moreover, the guard band between two consecutive timeslots was set to 0.004s, i.e., the minimum value, according to [48]. The superframe duration, and therefore the beacon interval, was set to 1025 ms. The inter-cluster scheduler synchronizes the application layers of the CBs with the first beacon, which is sent over the sub-band h1.6.

All the sub-bands allowed in the EU863-870MHz ISM Band [45] were used to schedule inter-cluster transmissions in order to achieve an overall duty cycle of 12.1%, i.e., equal to the sum of the maximum allowed duty cycle values shown in Table 2. Note that, as shown in Table 5, all the CBs have a duty cycle lower than the maximum duty cycle allowed for the considered configuration (i.e., the above mentioned 12.1%). For instance, the CB1, i.e., the one with the highest value, has a duty cycle that does not exceed 7.31%. Such a value is the sum of the contribution of the periodic transmissions (i.e., 6.8% according to the flow 1 period in Table 3) and the contribution of the aperiodic transmissions, which in the worst case (i.e., when one aperiodic message is generated every 20s) is equal to 0.51%. As a result, by design, in this configuration no messages are dropped due to duty cycle constraints.

We collected data for a time length of 3600 superframes, i.e., the duration of the experimental assessment was longer than one hour.

The relevant configuration parameters are summarized in Table 6.

Table 6
Configuration settings.

Parameter	*Value*
Spreading Factor (SF)	7
Coding Rate (CR)	4/5
Bandwidth	125 kHz
Transmission Power	14 dBm
Sub-bands	EU863-870 MHz
Maximum physical payload	50 bytes
Beacon duration	67 ms
Slot duration	102 ms
Guard band	4 ms
Number of periodic timeslots (n_P)	7
Minimum number of aperiodic timeslots ($n_{AP_{res}}$)	2
Superframe duration	1025 ms

Table 7
PLR and DMR values for Periodic flows.

Flow #	1	2	3	4	5	6	7
PLR	1.02%	0.61%	0.82%	0.35%	0.55%	0.82%	0.45%
DMR	0.08%	0.18%	0.35%	0.15%	0.17%	0.32%	0.11%

Table 8
End-to-end delay - Periodic flows.

Flow #	Deadline (ms)	Max e2eDelay (ms)
1	1500	404
2	1600	388
3	2500	627
4	1800	487
5	2000	595
6	2300	646
7	2050	548

5.2. Experimental results

The results show that all the CBs received more than 99.7% of the beacons. This way, all the clusters kept synchronized, and only rarely a CB could not send messages within a superframe due to the beacon loss. For this reason, if one or more consecutive beacons are not received by a CB, some messages generated by such a CB could be discarded due to a deadline miss. In fact, if a timeslot will be assigned to a CB after a message has expired, the message will be discarded. However, only a few messages suffered from such a problem. In particular, as shown in Table 7, which gives the PLR and the DMR measured for the periodic flows, in the experimental assessments the number of missed deadline in each CB was negligible.

The results in Table 7 show that the PLR is lower than or equal to 1.02% for all the CBs. The highest PLR value was experienced by the flow 1 due to the high number of obstacles between the source and destination CBs. As far as the DMR is concerned, the percentage of generated messages that were discarded due a deadline miss does not exceed 0.35%. Here, the DMR does not depend on the scheduling algorithm adopted by LoRaBLE, but only on the cases in which, due to the beacon loss, a CB could not send messages within a superframe.

Table 8 gives both the maximum and the average end-to-end delays of the real-time periodic flows. The results show that, for every flow, such delays are always lower than the deadlines.

This result was expected, as by design the messages that would not meet the deadline are discarded by the source CB. As a result, the messages that reach the destination are upper-bounded by the respective deadline, while the discarded messages increase the deadline miss count.

As far as the aperiodic traffic is concerned, all the messages met their deadlines. Moreover, as shown in Table 9, the PLR measured by each CB for the aperiodic messages is always less than 0.88%. Here the PLR values do not depend on the LoRaBLE protocol, but only on the

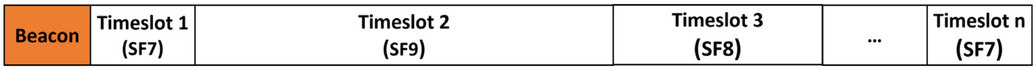

Fig. 4. A superframe structure with timeslots of different size.

Table 9
PLR values for Aperiodic messages.

CB #	1	2	3	4	5	6	7
PLR	0%	0%	0.88%	0.43%	0.43%	0.42%	0.86%

transmitted messages that were not received at the destination node due to interference or other channel effects. No aperiodic messages missed their deadline in this assessment. This was expected, as in the considered configuration two timeslots in each superframe are reserved for aperiodic transmissions and the aperiodic messages deadlines are not very tight.

6. Discussion on coverage and scalability

LoRaBLE is a long-range real-time communication protocol intended for soft real-time applications, with cycle times in the order of tens of seconds.

As far as the inter-cluster communication is concerned, the ETSI regulations [44,45] impose some limitations on the duty cycle of the LoRa nodes in LoRaBLE, i.e., the Cluster Bridges (CB) and the inter-cluster scheduler. As shown in Table 2, every LoRa node is able to achieve an overall duty cycle of 12.1% using all the sub-bands in the EU863-870MHz ISM Band. The network designer has to set the parameters (e.g., the spreading factor, coding rate, and bandwidth) of the LoRa nodes in LoRaBLE so that the application requirements in terms of bit rate, transmission range and receiver sensitivity are satisfied. Both the duty-cycle limitations and the configuration of the LoRa parameters impact on the LoRaBLE scalability and on the coverage guaranteed by a LoRaBLE network. For this reason, in the following subsections LoRaBLE coverage and scalability are discussed.

6.1. Coverage range

As stated in [50], the LoRa technology is considered an interesting solution for realizing private single-hop communications in the industrial domain. The configuration parameters depend on the application requirements and on the scenario in which a LoRaBLE network has to be deployed. According to the considered scenario, a proper value of SF has to be used for LoRa transmissions to guarantee the required coverage range. As an example, the work in [50] shows that a coverage of 100 m was easily reached with SF7 in an industrial laboratory. In [51] an indoor industrial plant with more than 100 nodes located in a circle with a radius of 500 m around the gateway was simulated. The results showed good coverage values by using SF 7.

In LoRaBLE, LoRa-based inter-cluster communications use a TDMA approach based on a superframe structure that consists of a beacon and a set of timeslots. We assume that each CB is located within the coverage range of all the other CBs. Consequently, all the transmissions can be performed using the same value of SF, and therefore all the timeslots in the superframe have the same duration. However, if needed, LoRaBLE can be easily configured to support timeslots of different duration and schedule inter-cluster communications with different SF values. In this case, the superframe would consist of a sequence of timeslots of different duration, as shown in Fig. 4. This way, the inter-cluster scheduler can provide a nonuniform coverage for the inter-cluster transmissions based on the distance between the sender and the receiver of a given flow.

Note that, on one hand, each SF increase enables a larger transmission range, on the other hand, it approximately halves the transmission rate, thus approximately doubling the ToA. Consequently, the transmissions with a higher SF value have a higher impact on the duty cycle (i.e., on the maximum number of messages that a CB is allowed to send per hour) than those with a lower SF, and this reduces the maximum supported workload. Such a reduction could be unsuitable for some industrial applications. In such cases, a message relay strategy can be adopted to avoid seeking a trade-off between bit rate and coverage range. For example, the e-Node proposed in [50] acts as a transparent range extender and can be adopted in LoRaBLE, as it can coexist with the other LoRaBLE nodes and it does not affect their operation.

6.2. Scalability

The MAC protocol on which LoRaBLE is based can be deployed using low-cost LoRa transceivers, e.g., the SX1272 [52], for both the inter-cluster scheduler and the CBs. However, the proposed medium access strategy entails a rapid growth of the superframe duration as the number of LoRa nodes in the LoRaBLE network increases. This may limit the LoRaBLE scalability in some applications, as it can cause an increase of the end-to-end delay for both the periodic and aperiodic messages.

For this reason, we plan to use a new generation of LoRa chips, such as the SX1302 [53] ones, to allow the CBs and the inter-cluster scheduler to exploit a Multi-Channel and Multi-Spreading Factor TDMA MAC protocol based on an "enhanced" superframe structure, as the one shown in Fig. 5. This way, simultaneous transmissions can be scheduled using different spreading factors and channels.

Such a solution scales well with the number of nodes and, in the case of LoRaBLE, allows to manage a high number of clusters. This way, the inter-cluster scheduler will be able to schedule inter-cluster communications with different LoRa configurations according to multiple factors, such as the distance between the source and destination nodes of a given flow, the requirements in terms of workload, reliability, etc. At the same time, several inter-cluster communications can be scheduled without significantly increasing the superframe duration. Moreover, such an approach can be used to improve the protocol reliability and flexibility. In fact, the different channels can be exploited to implement redundant transmissions, while the availability of diverse spreading factors allows the use of different LoRa configurations for inter-cluster communications.

7. Conclusions

This paper proposed LoRaBLE, a novel protocol that provides bounded delays to long-range wireless communications, both periodic and aperiodic, between clusters of BLE nodes over LoRa links.

The LoRaBLE design is kept simple enough to be implemented on embedded devices with limited resources. In fact, as it is shown in the paper, a LoRaBLE-based network that follows the superframe structure here proposed can be deployed using low-cost devices. In particular, this work adopted low-cost LoRa transceivers, such as the SX1272 [52], for both the inter-cluster scheduler and the BLE-LoRa bridges.

Future work will investigate the use of a new generation of LoRa chips, e.g., the SX1302 [53] ones, which would allow the CBs and inter-cluster scheduler to exploit a Multi-Channel and Multi-Spreading Factor TDMA MAC protocol [13,14].

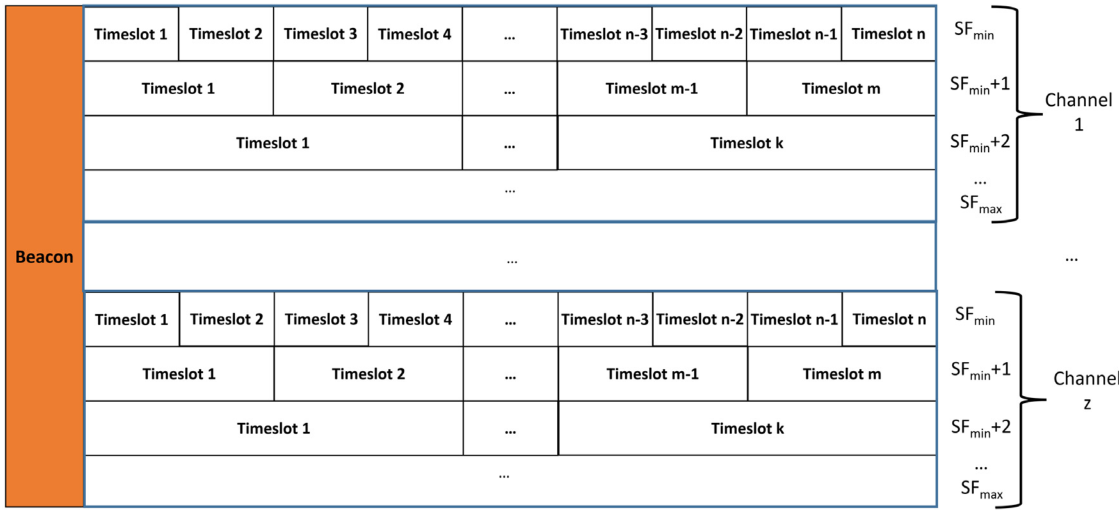

Fig. 5. An enhanced superframe structure.

CRediT authorship contribution statement

Luca Leonardi: Conceptualization, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Lucia Lo Bello:** Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Gaetano Patti:** Conceptualization, Investigation, Methodology, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was partially supported by the University of Catania through the PIA.CE.RI. 2020/2022 project, program title "Linea 2 - Progetto interdipartimentale SIS-RENEW".

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