Opportunistic Cluster Heads for Heterogeneous Networks Combining LoRa and Wake-up Radio

Nour El Hoda Djidi, Antoine Courtay,
Matthieu Gautier, Olivier Berder
Univ. Rennes, CNRS, IRISA, France
firstname.lastname@irisa.fr

Michele Magno
Dep. of Inform.Technol. Electrical Eng
ETH, Zurich, Switzerland
michele.magno@iis.ee.ethz.ch

Abstract

Connected devices using LoRaWAN standard achieve low energy consumption by leaving their sleep state only to send their data. However, this technique induces a high downlink latency that is not compatible with applications that require a low latency such as remote control or actuator-type applications. To overcome this trade-off between power consumption and latency, we propose in this paper a MAC protocol design leveraging a heterogeneous network architecture composed of both long-range and ultra low power short-range wake-up radios. The proposed protocol does not change the LoRaWAN standard but at each uplink, a node operating in LoRa class A becomes an opportunistic cluster head and thus the gateway takes the opportunity of its receive windows to send commands intended to other nodes. Thanks to this novel network architecture and appropriate MAC protocol, the latency can be reduced while maintaining or even increasing the energy efficiency. Considering clusters of ten nodes, gains of 3.33 and 2.11 can be achieved in latency and power consumption, respectively.

1 Introduction

Low-Power Wide-Area Networks (LPWANs) are capturing a huge interest for Internet of Things (IoTs) applications that require low power and long range communications such as smart cities, smart health, industry, environment monitoring, etc [5]. Long Range (LoRa) is one of LPWANs technologies initiated by Semtech to fulfill the gaps between battery life and communication range of devices. LoRa utilizes the unlicensed industrial, scientific and medical radio bands and incorporate a chirp spread spectrum technology allowing a robustness against a high degree of interference in addition to Doppler effect [4]. LoRaWAN is one of data-link layers with low bit rate in which End Devices (EDs) use LoRa to communicate with gateways in a star network topology.

There are different LoRaWAN classes (class A, B and C). In class A, the EDs can initiate an uplink transmission based on their own communication needs. Each uplink transmission is followed by two short receive windows where the gateway should wait until these receive windows to be able to do a downlink. In class B, the EDs allow for more receive slots. In addition to the class A random receive windows, class B EDs open extra receive windows. The EDs of class C open continuously receive windows, only closed when transmitting [11]. Figure 1 shows the average power consumption incurred by a downlink communication of an ED operating using different LoRaWAN classes as a function of the latency. The equations used for this evaluation are detailed in [2], and the parameters used for class A are described in Table 1 of Section 4. As it is always listening to the channel except when it is transmitting a packet, LoRaWAN class C obviously achieves the lowest latency but at the cost of a dramatically higher power consumption. The LoRaWAN class B latency strongly depends on the rate of opening the receive windows, as the more receive windows are opened, the lower latency can be achieved (but still with increased power consumption). The class A latency is the highest as it should wait for an uplink to be able to perform a downlink, but it has the advantage of the lowest power consumption. Thus, using the LoRa scheme, a trade-off between power consumption and latency for downlink communication is required.

Wake-up Radio (WuR) forms another promising solution for allowing an ultra low power consumption and a low latency for short range communications [3, 8]. WuR is continuously listening to the channel while consuming a few nanowatts [7], letting the main transceiver in deep sleep to save energy. When a specific signal called wake-up beacon is received, the WuR generates an interruption to wake-up the main micro-controller node with a low latency [1, 9, 12], and thus allowing pure asynchronous communication. Recent WuR designs perform address matching with an ultra low power micro-controller consuming a few microwatts allowing the wake-up of only the targeted node which saves more energy. The most common modulation used for the WuR is OOK [7], which allows simple circuitry in the WuR and provides power consumption reduction.

As wake-up radio and LoRa features are somehow orthogonal, one allowing short-range communications with low power and low latency while the other allows long-range communications with a trade-off between power and

International Conference on Embedded Wireless Systems and Networks (EWSN) 2020
17–19 February, Lyon, France
ISBN: 978-0-9949886-4-5

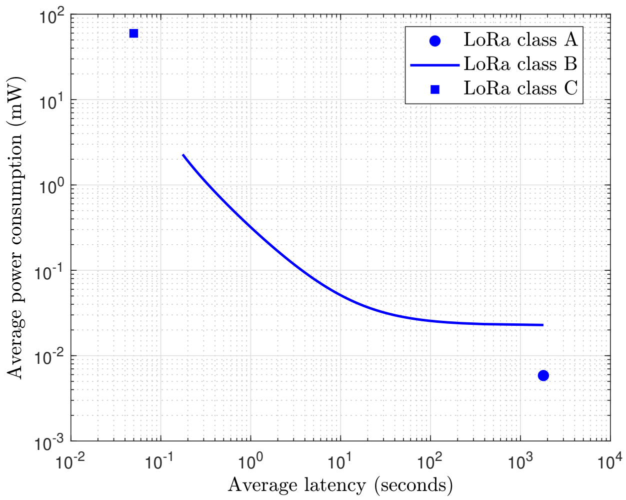

Figure 1. Average power consumption as a function of latency. For class A, parameters are given in Table 1. For class B, the ping slot rate λ_{PING} varies from $\frac{1}{3600}$ Hz to 4 Hz, the ping slot energy cost e_{PING} is 0.5645 mJ, the beacon rate λ_{BCN} is $\frac{1}{128}$ Hz and the beacon energy cost e_{BCN} is 2.178 mJ. For class C, the power consumption when receiving $P_{C,Rx}$ is 59.7 mW.

latency, network architectures combining both technologies have been proposed in [1] and [10] to achieve energy efficiency and low latency. Both of them considered a star topology with a central node called cluster head (CH) using LoRa class C which manages the received messages, from the gateway, intended for other EDs that are in the same cluster equipped with LoRa class A and a WuR. The drawback of this architecture is that CH operates in class C and therefore its energy consumption is very high. On the other hand, class A represents a promising solution for low power consumption, provided its inherent high downlink latency is counterbalanced with the help of other nodes in the cluster.

In this work a novel MAC protocol leveraging opportunistic CH mechanism is presented, where all EDs are equipped with LoRa class A and WuR. The EDs take the opportunity from each other, i.e. each ED becomes an opportunistic CH during its receive windows, giving the opportunity to receive and relay commands from the gateway intended to other nodes. Due to this architecture, low power consumption and low latency can be achieved. In particular, the energy efficiency increases with the increase of the number of opened receive windows which depends on the number of nodes present in the cluster.

The rest of this paper is structured as follows. In Section 2 the network architecture and the MAC protocol design are presented. An analytical model is detailed in Section 3. In Section 4 we present and discuss the analytical results before to conclude in Section 5.

2 Network architecture and MAC design

In the proposed hetorogeneous long-short range network each ED is equipped with two communication modules as detailed in Figure 2. The first module is a SX1267 from Semtech, which is able to handle LoRa physical layer, GFSK and OOK modulations. This transceiver allows switching between the different modulation approaches. The OOK modulation is used to forward a command (CMD) as form of a Wake-up beacon (Wub), in a Short Range (SR) communications, while LoRa class A is used for the Long Range (LR) communications. The second module is a WuR designed in [7], which receives Wub with OOK modulation. This WuR operates at a bitrate of 1 kbps, and with a sensitivity of -55 dBm. The power consumption was measured to be 1.83 uW in always listening mode and 284 uW when receiving and processing the data with the Ultra-Low Power (ULP) microcontroller embedded in the WuR.

The heterogeneous network architecture is illustrated in Figure 3. In this architecture, nodes are organized in clusters in which all the EDs can communicate with each others using SR. Located at a large distance of few kilometers from the cluster, the gateway collects the sensed data and possibly sends commands to the EDs using the LR communications. The EDs pass most of their time in sleep state as they are in class A, only wake-up to send data or when they receive an interrupt from the WuR. When an ED transmits a data using LoRa, it becomes an opportunistic CH to receive commands from the gateway intended to another node called targeted node. Then the opportunistic CH forwards this command using the SR communications.

As this scenario leads to interesting performance gains in both latency and energy compared to LoRaWAN class A standard, it can fit many applications such as smart building in which the gateway wants to request measurements from the targeted node. Moreover, it can fit applications in which the gateway needs to send commands such as synchronising or changing the data rate of the next uplink of the targeted node.

The protocol combining LoRa and WuR with all EDs in class A is presented in Figure 4. After each uplink communication (from the ED to the gateway), an ED opens two receive windows and becomes an opportunistic CH. During one of these receive windows, the gateway can take the opportunity to send a command (CMD) intended to a targeted

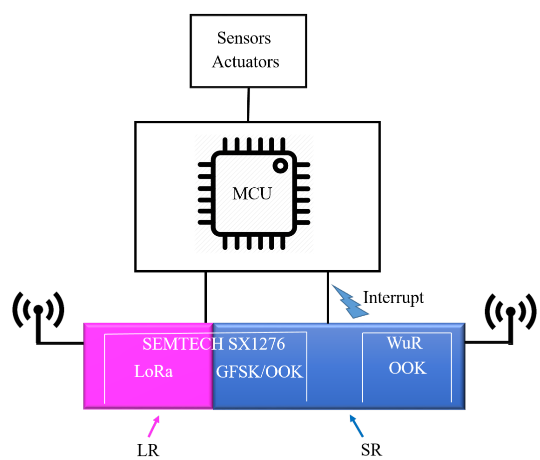

Figure 2. Node architecture.

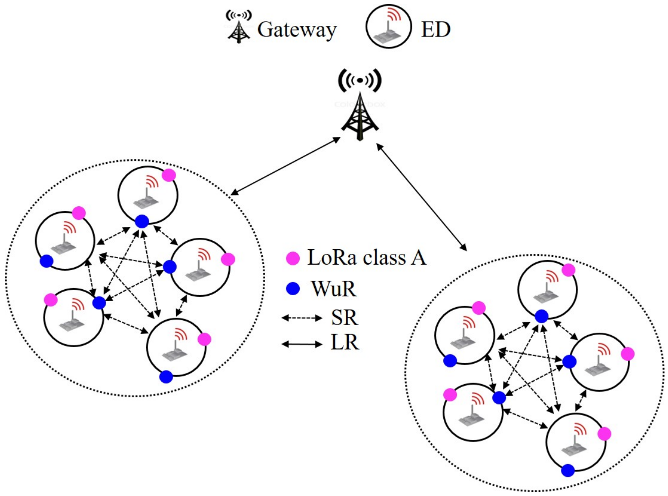

Figure 3. LoRa-WuR network architecture.

node or to send a broadcast command. The command will be received by the opportunistic CH during its receive window of the LoRa communication. Then, the CH will switch its transceiver from LoRa to OOK for a SR communication to send the command to the targeted node or to broadcast it to all nodes. The SR command is sent as a Wub composed of the preamble, the address of the targeted node or the address of the broadcast, and the command itself.

All EDs WuR will receive the Wub sent by the opportunistic CH, but as the WuR performs address matching, only the addressee ED will receive the command. In this study, no acknowledgement is considered but the addressee ED can wake-up its main transceiver to that goal. The proposed protocol does not change the LoRaWAN standard, it just takes the opportunity of the receive window of LoRaWAN class A to send commands for other nodes or broadcast the command, which will significantly reduce the latency.

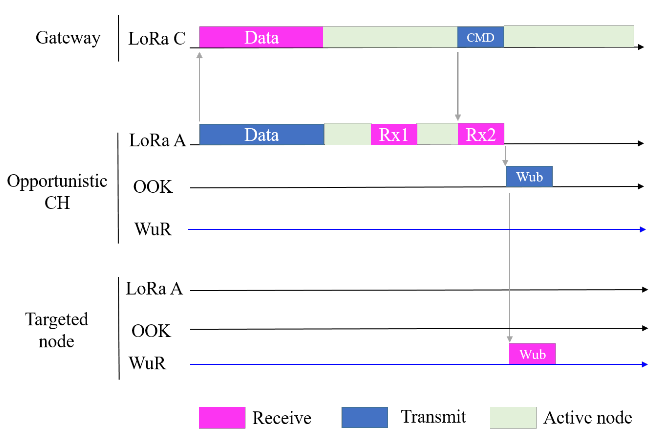

Figure 4. MAC protocol leveraging LoRa-WuR communications.

3 Analytical Models

Analytical models for both average latency and average power consumption incurred by the downlink communication are presented in this section.

3.1 Latency model

A cluster of N nodes is considered and we suppose that each node transmits at different time at a rate λ. Due to the low data rate and the short length of Wub packets, we therefore assume that no collisions occur. When using class A of LoRaWAN standard, the gateway waits for an uplink transmission of an ED before sending a command. The average waiting time to reach a target node can then be expressed as $\frac{1}{2\lambda}$ [1].

The average latency L^A_{LoRa} of the command transmission from the gateway to an ED when using only the standard LoRaWAN class A is expressed as:

$$L^A_{LoRa} = \frac{1}{2\lambda} + l_{cmd}, \tag{1}$$

with l_{cmd} the time required for the command transmission using LoRa.

The average latency of the command transmission to an ED, by using the proposed LoRa-WuR protocol, $L_{LoRa-WuR}$, depends on the number of nodes in the cluster, and is expressed as:

$$L_{LoRa-WuR} = \frac{1}{2N\lambda} + l_{cmd} + l_{wur}, \tag{2}$$

with l_{wur} the time required for the packet transmission using the SR communication (i.e. the transmission of the Wub) which is equal to $\frac{L_{wub}}{R_{wub}}$, with L_{wub} the length of the Wub (bits), and R_{wub} the bitrate of the Wub (bits/s).

3.2 Power consumption model

Using the LoRaWAN class A operating mode, commands from the gateway can only be transmitted to an ED after an uplink transmission. We assume that at each uplink, there is a downlink, and thus the average power consumption of an ED incurred by a downlink communication denoted P^A_{LoRa} is:

$$P^A_{LoRa} = e^L_{cmd}\lambda, \tag{3}$$

where e^L_{cmd} is the energy cost of receiving a command from the gateway using LoRa.

When considering the proposed LoRa-WuR protocol, we assume that at each downlink there is a command sent to a targeted node, and thus the average power consumption of the SR communications using WuR, denoted P_{WuR} is:

$$P_{WuR} = e^{wurx}_{cmd} N\lambda + (1 - N\lambda l_{wur})P^{wur}, \tag{4}$$

where e^{wurx}_{cmd} is the energy cost to receive and process the Wub by the WuR, and P^{wur} is the power consumption of the WuR when only the analog font-end is active listening to the channel, while the ULP microcontroller is in a sleep state.

One can notice that when the opportunistic CH forwards the command by sending a Wub to the targeted node, all nodes in the cluster will receive this Wub. Then, they pass to an active mode to perform the address matching by the ULP microcontroller, and as we assumed that at each uplink, there is a downlink so the average power consumption of the wake-up radio depends on the average packet transmitted rate of all nodes.

The average power consumption of an ED incurred by the downlink communication using LoRa-WuR protocol denoted $P_{LoRa-WuR}$ is expressed as:

$$P_{LoRa-WuR} = (e^{wurx}_{cmd} N\lambda + (1 - N\lambda l_{wur})P^{wur}) + (e^{L}_{cmd} + e^{wutx}_{cmd})\lambda,\ N \geq 2, \quad (5)$$

where e^{wutx}_{cmd} is the energy cost to forward the command by the opportunistic CH using the SR communication.

4 Analytical results

In this section, analytical results are presented and discussed. For the LR communications, we measured the power consumption of the platform described in [6] using a DC power analyser Keysight N6705B. For the WuR, the power consumption measured in [7] was used and are given in Table 1. Furthermore, the LoRa parameters such as SF, CR and BW are also given, with SF, CR and BW are the spreading factor, the coding rate and the bandwidth, respectively. Payload and λ_{CMD} are the length of the command/data and the command generated rate from the gateway, respectively.

Table 1. Parameter values used for analytical evaluation

Both schemes		LoRa-WuR only	
Parameters	Values	Parameters	Values
SF	9	P^{wur}	1.83 μW
BW	250 kHz	e^{wutx}_{cmd}	2.19 mJ
CR	$\frac{4}{6}$	e^{wurx}_{cmd}	4.5 μJ
Payload	5 bytes	R_{wub}	1 kbps
λ_{CMD}	$\frac{1}{3600}$ Hz	L_{wub}	2 bytes
l_{cmd}	50 ms		
e^{L}_{cmd}	21.05 mJ		
λ	$\frac{1}{3600}$ Hz		

Figure 5 shows the average latency of the downlink communication of an ED as a function of the number of nodes. Each node has a fixed packet transmitted rate $\lambda = \frac{1}{3600}$ Hz and the number of nodes is ranging from 2 to 100. It can be seen that the average latency of an ED when using the standard LoRaWAN class A scheme does not depend on the number of nodes and is equal to 1800 s. However, by using the proposed scheme LoRa-WuR, the latency is reduced as more nodes are used in the cluster. For example, when 10 nodes are used, the latency is reduced up to 10 times from 1800 s to 180.1 s.

The energy consumption of the opportunistic CH is shown in Figure 6. The energy is composed of two parts: the energy for the LR communication to receive the command from the gateway, and the one when using the SR to forward the command to the intended node. The energy cost

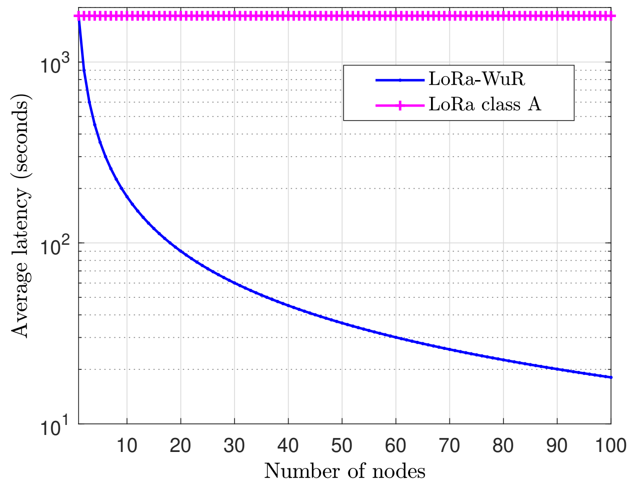

Figure 5. Average downlink latency as a function of the number of nodes.

to receive the command from the gateway using the LR is equal to 21.05 mJ. This cost includes the energy cost of the two receive delays and the two receive windows. The energy cost of the first and the second receive delays are equal to 14.6 mJ and 0.5 mJ, respectively. Moreover, the cost of the receive window is equal to 2.98 mJ. It can be seen that when the opportunistic CH forwards the command, the additional energy cost is 2.19 mJ and thus, the energy cost of receiving the command using the LR and forwarding it using the SR is 1.1 times higher than the energy consumed when only LoRa class A is used to receive the command by the LR.

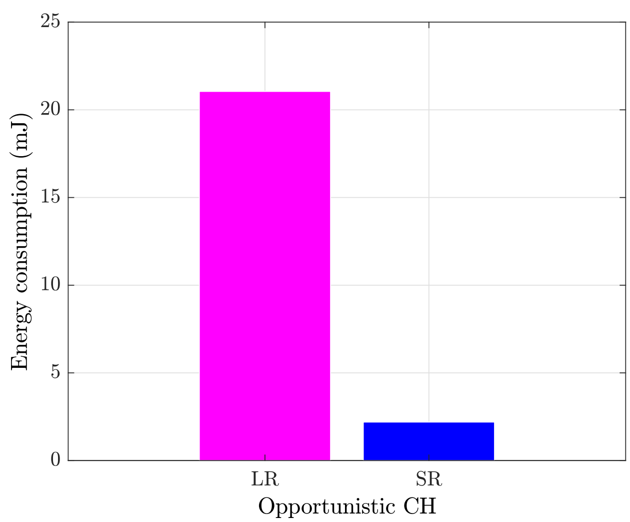

Figure 6. Energy consumption of the opportunistic CH (LR when it receives the command with the LoRa standard, and SR when forwarding it by using the WuR).

Figure 7 shows the influence of the packet transmitted rate on the latency when using the LoRa class A, and the influence of the number of nodes when using the proposed LoRa-WuR scheme. For LoRa class A, the packet transmitted rate λ was varied from $\frac{1}{3600}$ Hz to $\frac{1}{36}$ Hz, and for LoRa-

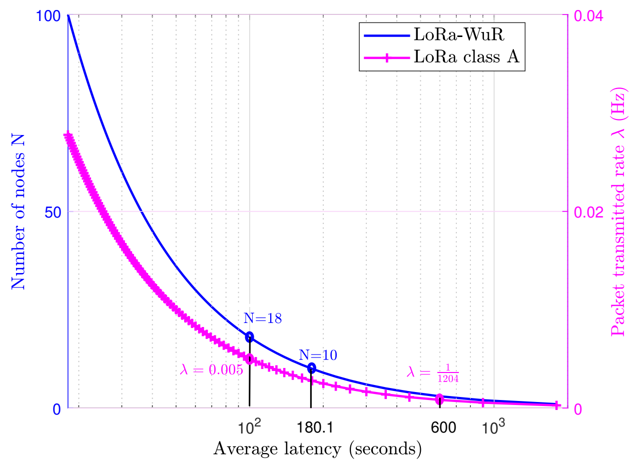

Figure 7. Influences of the number of nodes when using LoRa-WuR and the packet transmitted rate when using LoRa on the latency.

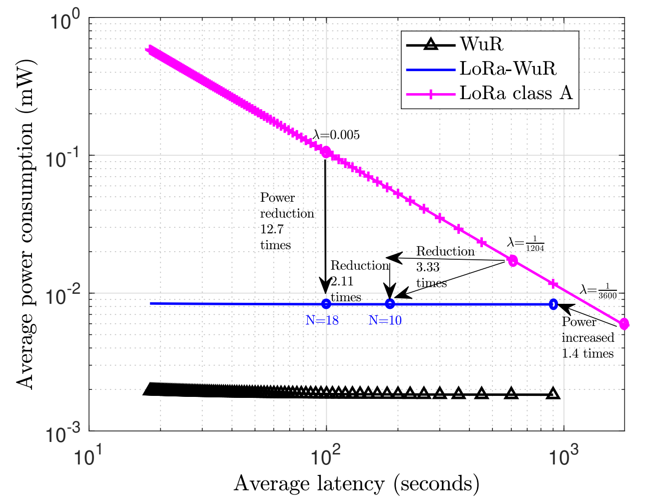

Figure 8. Average power consumption as a function of latency.

WuR scheme, λ is kept at a fixed rate of $\frac{1}{3600}$ Hz, and the number of nodes N is ranging from 1 to 100. It can be seen that to achieve the same latency, for example 100 s, 18 nodes are required in the cluster when using LoRa-WuR scheme, and a packet transmitted rate of 0.005 Hz is required when using LoRa class A.

To show the tradeoff between power consumption and latency, Figure 8 represents the average downlink power consumption of a node as a function of the latency for both LoRa class A and LoRa-WuR schemes. The average power consumption of the WuR is also given showing that it is insignificant behind the whole average power consumption of the node when using the scheme LoRa-WuR.

It can be seen, that for the same packet transmitted rate for both schemes, fixed at $\frac{1}{3600}$ Hz, the latency when using LoRa class A scheme is up to 1800 seconds while consuming in average 5.8 uW. However, this latency can be reduced when LoRa-WuR is used as more nodes are used. When 10 nodes are used for example, the latency is reduced up to 10 times but the average power consumption is increased by a factor of 1.4 times.

In order to achieve the same latency for both LoRa class A and LoRa-WuR approaches, for example 100 s, when using the standard LoRa scheme, the node consumes 12.7 times more than with the proposed LoRa-WuR scheme.

To decrease the latency and the average power consumption when using the proposed scheme LoRa-WuR, the packet transmitted rate should be reduced compared to LoRa class A. It can be seen from Figure 8 that when the packet transmitted rate is equal to $\frac{1}{3600}$ Hz when using LoRa-WuR, and $\frac{1}{1204}$ Hz when using LoRa class A, the average power consumption with LoRa-WuR is reduced by a factor of 2.11, and the latency is reduced up to 3.33 times when 10 nodes are used. The corresponding latency for these number of nodes and packet transmitted rate can be seen in Figure 7.

There is a tradeoff to make when using LoRa-WuR scheme, either dramatically reduce the latency according to the number of nodes present in the cluster but increasing the average power consumption 1.4 times, or reduce both power consumption and latency but using a reduced packet transmitted rate compared to LoRa standard.

5 Conclusion

This paper presents a novel MAC protocol that combines the long-range LoRaWAN and the short-range communication scheme leveraging wake-up radios. LoRaWAN End-devices take the opportunity from each other, and each one can become an opportunistic cluster head during its receive windows. The opportunistic cluster head can then receive from the gateway commands intended to other end-device nodes exploiting the always-on short-range communication.

The proposed architecture perfectly fits applications that require both low power consumption and low latency. We demonstrated analytically that the latency is reduced as more nodes are present in the cluster. In particular, with 10 nodes, the latency can be reduced up to 10 times while the average power consumption is increased by only 1.4 times if the same packet transmitted rate as LoRaWAN standard is used. On the other hand, with 3 times reduced packet transmitted rate, the latency and the average power consumption can be reduced up to 3.33 times and up to 2.11 times respectively with 10 nodes in the cluster.

Future works will focus on a probabilistic model that includes the probability of sending the command to the targeted node, and the protocol will be implemented and tested in-field to experimentally validate its performance .

6 References

[1] F. Ait Aoudia, M. Gautier, M. Magno, M. Le Gentil, O. Berder, and L. Benini. Long-short range communication network leveraging LoRa™ and wake-up receiver. *Microprocessors and Microsystems*, 56:184–192, 2018.

[2] F. Ait Aoudia, M. Magno, M. Gautier, O. Berder, and L. Benini. A Low Latency and Energy Efficient Communication Architecture for Heterogeneous Long-Short Range Communication. In *Euromicro DSD*, pages 200–206. IEEE, 2016.

[3] N. Djidi, A. Courtay, M. Gautier, and O. Berder. Adaptive relaying for wireless sensor networks leveraging wake-up receiver. In *IEEE*

International Conference on Electronics, Circuits and Systems, pages 797–800, 2018.

[4] O. Khutsoane, B. Isong, and A. M. Abu-Mahfouz. IoT devices and applications based on LoRa/LoRaWAN. In *Conference of the IEEE Industrial Electronics Society*, pages 6107–6112, 2017.

[5] J. C. Liando, A. Gamage, A. W. Tengourtius, and M. Li. Known and Unknown Facts of LoRa: Experiences from a large-scale measurement study. *ACM Transactions on Sensor Networks*, 15(2):1–35, 2019.

[6] M. Magno, F. Ait Aoudia, M. Gautier, O. Berder, and L. Benini. WU-LoRa: An energy efficient IoT end-node for energy harvesting and heterogeneous communication. In *DATE*, 2017.

[7] M. Magno, V. Jelicic, B. Srbinovski, V. Bilas, E. Popovici, and L. Benini. Design, Implementation, and Performance Evaluation of a Flexible Low-Latency Nanowatt Wake-Up Radio Receiver. *IEEE Transactions on Industrial Informatics*, 12(2):633–644, 2016.

[8] N. S. Mazloum and O. Edfors. Performance analysis and energy optimization of wake-up receiver schemes for wireless low-power applications. *IEEE Transactions on Wireless Communications*, 2014.

[9] J. Oller, I. Demirkol, J. Casademont, J. Paradells, G. U. Gamm, and L. Reindl. Has Time Come to Switch from Duty-Cycled MAC Protocols to Wake-Up Radio for Wireless Sensor Networks? *IEEE/ACM Transactions on Networking*, 2016.

[10] R. Piyare, A. L. Murphy, M. Magno, and L. Benini. On-Demand TDMA for Energy Efficient Data Collection with LoRa and Wake-up Receiver. In *International Conference on WiMob*, page 1–4. IEEE, 2018.

[11] A. Potsch and F. Haslhofer. Practical limitations for deployment of LoRa gateways. In *IEEE International Workshop on Measurement and Networking (M&N)*, pages 1–6. IEEE, 2017.

[12] S. L. Sampayo, J. Montavont, F. Prégaldiny, and T. Noel. Is Wake-Up Radio the Ultimate Solution to the Latency-Energy Tradeoff in Multi-hop Wireless Sensor Networks? In *International Conference on Wireless and Mobile Computing, Networking and Communications*, 2018.