A Low Latency and Energy Efficient Communication Architecture for Heterogeneous Long-Short Range Communication

***Abstract*—Low power communication has evolved towards multi-kilometer ranges and low bit-rate schemes in recent years. LoRa$^{\text{TM}}$is an example of such a long-range technology that is triggering increasing interest. Using these technologies, a trade-off must be made between power consumption and latency for message transfer from the gateway to the nodes. However, domains such as industrial applications in which sensors and actuators are part of the control loop require predictable latency, as well as low power consumption. These requirements can be fulfilled using pure-asynchronous communication and idle listening elimination, allowed by emerging ultra-low-power wake-up receivers. On the other hand, state-of-the-art wake-up receivers present low sensitivity compared to traditional wireless node receivers and LoRa$^{\text{TM}}$, which results in the fact that they can operate in short-range in the order of a few tens of meters. In this work, we propose an energy efficient architecture that combines long-range communication with ultra low-power short-range wake-up receivers to achieve both energy efficient and low latency communication in heterogeneous long-short range networks. The proposed hardware architecture uses a single radio transceiver that can communicate using both LoRa$^{\text{TM}}$and state-of-the-art wake-up receivers while the proposed MAC protocol exploits the benefits of these two communication schemes. Experimental measurements and analytical comparisons show the benefits regarding both energy efficiency and latency enabled by the proposed approach. Analytical comparisons show that the proposed scheme allows up to 3000times reduction of the power consumption compared to the standard LoRa$^{\text{TM}}$approach.**

I. Introduction

Wireless Sensors and Actuators Networks (WSANs) technologies have become a cornerstone for emerging applications targeting industrial, military, and civil domains [1]. In recent years, emerging wireless technologies enabled Long Range (LR) communication of several kilometers, at the cost of data rates typically smaller than 10 kbps, and with power consumption similar to usual WSAN nodes transceivers [2]. An example of such a technology in use is LoRa$^{\text{TM}}$ [3], by the LoRa$^{\text{TM}}$Alliance. LoRa$^{\text{TM}}$operates in the $868/915$ MHz ISM bands, allows a theorical range up to 22 km, and a bit-rate in the range between 0.37 and 46.9 kbps [4]. Using LoRa$^{\text{TM}}$, uplink communication, *i.e.* from the nodes to the gateway, is done with low latency, as the gateway is always listening to the channel. However, downlink communication, *i.e.* from the gateway to the nodes, requires a trade-off between the latency and the power consumption of the nodes [5]. However, some applications, such as industrial machine health monitoring, require both low latency and low power consumption [6], which motivates the network architecture proposed in this work.

Ultra-Low Power (ULP) Wake-up Receivers (WuRx) form an emerging technology which allows continuous channel monitoring while consuming orders of magnitude less power than traditional transceivers [7]. These devices wake up the node microcontroller (MCU) or other sleeping subsystems using interrupts only when a specific signal, called Wake-up Beacon (WuB), is detected. One of the main benefits of WuRx is to enable "pure" asynchronous communication that can significantly increase the energy efficiency of communications and reduces the latency [8]–[12]. Moreover, when WuRx provide computational capabilities directly embedded [13], [14], they are able to process the received data. For instance, this feature makes possible for a WuB to wake up only a specific node by performing address matching on the WuRx, but also it allows the WuRx to take actions without waking-up the main MCU, e.g. activating a node sub-system or changing the sensor sampling rate, with a significant amount of energy saved.

To ensure ULP consumption, WuRx are usually characterized by lower sensitivity and lower bit-rate compared with traditional WSN transceivers [7], [13], [14]. Due to this drawback, WuRx can only operate in Short Range (SR), *i.e.* tens of meters. As it can be noticed, WuRx and LoRa$^{\text{TM}}$provide orthogonal features that are often required together in WSANs applications. Therefore, in applications where nodes are deployed in a SR area, but have to communicate with a distant gateway, we propose to combine the LoRa$^{\text{TM}}$scheme and WuRx to both achieve LR communication and low downlink transmission latency. The scheme proposed in this work relies on a radio-diversity approach, in which the wide diversity of radio technologies in the power and performance is exploited to create a low latency and low power WSAN network architecture. We designed an architecture that employs a single radio module from Semtech able to handle LoRa$^{\text{TM}}$and standard Gaussian Frequency Shift Keying (GFSK) and On-Off Keying (OOK) modulations, in combination with WuRx. In our approach, uplink communication is achieved by using only the LoRa$^{\text{TM}}$scheme, while downlink communication is carried out using the LoRa$^{\text{TM}}$stack to transmit the message to one of the WSAN nodes designated as the central node, which then forwards the message to the addressee nodes by first waking them up using their WuRx, and then transmitting the message using standard GFSK modulation. WuBs are sent using OOK modulation. The LoRa$^{\text{TM}}$communication protocol has been analytically modeled as well as the proposed approach to evaluate the power consumption and latency. The designed architecture was experimentally evaluated in terms of power consumption and latency, and results show that the proposed scheme significantly reduces the latency as well as the power consumption.

The rest of this paper is organized as follows: Section II presents the related work. Section III exposes the proposed network architecture, as well as the MAC layer. In Section IV, an analytical model is derived to compare the power consumption and latency of the proposed scheme to the standard LoRa$^{\text{TM}}$approach. Section V exposes energy measurements of the LoRa$^{\text{TM}}$scheme as well as analytical evaluation of the proposed scheme. Finally, Section VI concludes this paper.

II. Related Work

As many devices embed more than one radio module, exploiting radio diversity was previously proposed to reduce energy consumption and latency for opportunistic networking [15]. The main idea is to use a low power radio combined with a high power radio. It is expected that using two radio modules instead of one account for higher energy expense, but exploiting the low power radio to save power on the high power radio can ultimately reduce power consumption of the whole system. In many devices such as smartphones, the low power radio is a Bluetooth or Zigbee module, while the high power radio is a Wi-Fi or cellular module. *Pering et al.* [16] proposed to use a low level radio to discover, configure and activate a high level radio link when a connection is needed. The authors experimented on a platform that provides Bluetooth, Zigbee and Wi-Fi, and revealed that the lower power consumption is achieved by employing Zigbee and Wi-Fi. However, using Bluetooth and Zigbee as a low power radio is still too energy costly for WSANs applications, which is the focus of this work. Moreover, neither Bluetooth, Zigbee nor Wi-Fi allow kilometers-range communication. Other proposals combining Wi-Fi and Zigbee for power saving purpose are present in literature [17], [18]. Differently from these previous works, we are using a single transceiver that is dynamically configured to work in combination with LoRa$^{\text{TM}}$for the LR, and wake up receivers for the SR.

In LoRa$^{\text{TM}}$network architecture [5], all WSAN nodes communicate directly with the gateway, which serves as a bridge between the nodes and a network server. Communication between the gateway and the server is realized using standard schemes (Wi-Fi, Ethernet...), and is not addressed in this work. The gateway is always active listening to the channel, while three types of classes are defined for end-devices: A, B and C. Class A is the lowest power consuming class, as nodes only leave the sleep state to send their data. Each uplink transmission is followed by two short downlink receive windows. Therefore, transmission slot scheduled by the device is based on its own communication needs, but downlink communication will require to wait the next scheduled uplink transmission. Class B devices open additional receive windows at scheduled time in addition to class A receive windows, and time synchronized beacons from the gateway are used to allow the gateway to know when devices are listening. Finally, class C devices are continuously listening, except when they are transmitting. Therefore, using the LoRa$^{\text{TM}}$network architecture, a trade-off must be made between latency and energy consumption for downlink communication.

To the best of our knowledge, the closest work to ours is [19]. The authors proposed the OpenMote+ platform, targeting industrial applications, which combines three communication modules: one for LR (kilometers-range) communication, one for hundreds of meters communication, and one for contact-based communication. Each module is implemented by a specific hardware chip. LR communication is implemented by the Sub-GHz EZRadioPRO radio transceiver, which provides a sensitivity of -133dBm and a transmission power up to 20dBm. In addition to this radio interface, a low-energy Atmel AT86RF233 is present. This transceiver operates in the 2.4GHz band, and supports IEEE 802.15.4 standards. Finally, contact-based communication is implemented by the NXP NT3H1201 chip, which operates in the 13.56 MHz band and supports the Near Field Communication (NFC) standard. However, contrary to our proposal, no WuRx is used to eliminate idle listening and perform purely asynchronous communication for SR communications. We propose in this work to combine LoRa$^{\text{TM}}$for LR communications and GFSK modulation for SR communications, using the Semtech SX1276 transceiver that implements both schemes, and is compatible with IEEE 802.15.4 frame structure. In addition, a WuRx is used for SR communication to reduce both latency and power consumption incurred by downlink transmission.

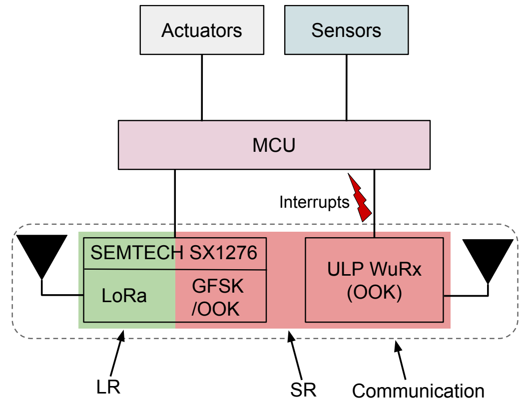
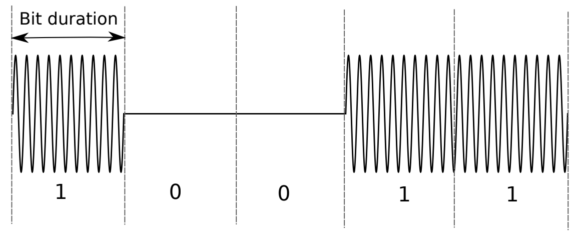


Fig. 1: Node architecture.

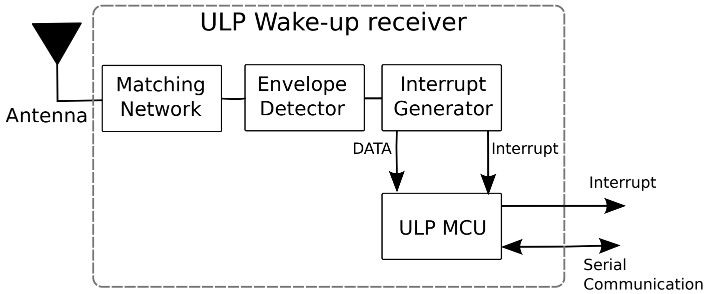
III. Node and Network Architectures

A. Communication Module Architecture

The block diagram of the designed platform is illustrated in Fig. 1. Each node comprises a microcontroller (MCU), sensors, actuators, and a communication module. However, this work focuses on the communication subsystem. The communication stack used in this work allows both SR and LR communication. The transceiver SX1276 from Semtech is used, which incorporates (G)FSK and OOK modulations, as well as LoRa$^{\text{TM}}$physical layer, permitting kilometers-range communications [4]. Moreover, the SX1276 transceiver allows switching between the different modulation schemes, enabling coexistence between different modulation approaches. LoRa$^{\text{TM}}$relies on Chirp Spread Spectrum (CSS) modulation [20], a spread spectrum technique. A chirp is a sinusoidal waveform whose frequency varies with time. Each LoRa$^{\text{TM}}$chirp codes SF bits, and SF is the spreading factor which takes value in the range between 6 and 12. LoRa$^{\text{TM}}$can recover data from weak signal, even under the noise level, and can theoretically achieve a



(a) OOK modulation.



(b) WuRx block architecture.

Fig. 2: OOK modulation and WuRx architecture.

range up to 22 km, and allows a data rate up to 46.9 kbps in the 868/915 MHz ISM bands [4], [5].

In addition to the SX1276 transceiver, each WSAN node is equipped with an instance of the WuRx designed in [13], which receives data with OOK modulation, the simplest form of amplitude shift keying modulation in which data is represented by the presence or absence of a carrier, as illustrated by Fig. 2a. The block architecture of the WuRx is shown by Fig. 2b, and it can be seen that the WuRx is made up of four main blocks: the matching network, the envelope detector, the interrupt generator and the ULP MCU that provides computational ressources to the WuRx and serial interface with the main node. The matching network guarantee maximum power transfer between the antenna and the rest of the circuit, and is optimized to work in the 868 MHz ISM band. The second stage is a passive demodulation circuit, which consists of a passive envelope detector that discards the frequency and phase content and only detects amplitude. Once the signal is rectified, the third block performs interrupt generation by first reconstructing the bits of the WuB using a nano-power comparator, and a passive adaptive threshold circuit. The interrupt generator block also provides a preamble detector to avoid unwanted awakening due to noise. Finally, the PIC12LF1552 from Microchip, provides computational capabilities. This on board processor is awaken by the interrupt generator when a WuB is detected, and was programmed to partially incorporate the MAC layer, and in particular address matching, allowing nodes to wake up only a specific node and not all neighbors. The used version of the WuRx is optimized to work at a bit-rate of 1 kbps, and the sensitivity in these conditions was measured to be -55 dBm. The power consumption of the whole WuRx was measured to be 1.83 μW in always-on listening mode and 284 μW when receiving and processing data with the processing unit of the WuRx active.

Fig. 1 summarizes the architecture of the communication module. LR communication is achieved using LoRa™modulation provided by the SX1276 transceiver. The SX1276 transceiver is also used for SR communication, as it provides (G)FSK and OOK modulation schemes, in addition to the WuRx which is only used for SR communication.

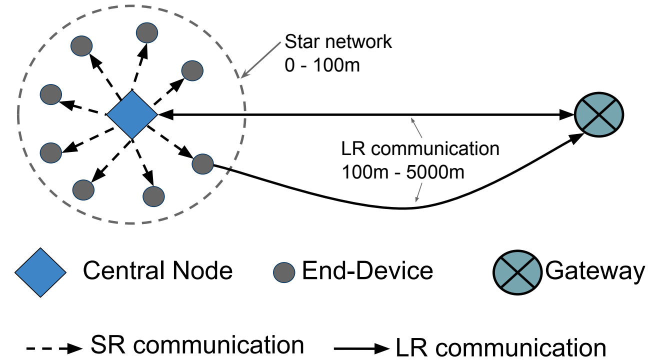


Fig. 3: Network architecture.

B. Network architecture

In the proposed network architecture, WSAN nodes are organized in a star topology around a Central Node (CN), as shown by Fig. 3. The other WSAN nodes, referred as End Devices (EDs), are distributed in a range of a few tens of meters around the CN. A gateway, located at a large distance (few kilometers) from the network, collects the sensed data, and sends commands to the nodes, e.g. to activate actuators or to set sensing parameters. As each ED is equipped with a WuRx, the CN can wake up one or more EDs by sending WuBs. EDs are assumed to be energetically constrained, and therefore spend most of their time in the sleep state. EDs only wake up when an interrupt is triggered on:

- a timer expiration, e.g. to perform periodic sensing or action,
- an event from the environment detected by a sensor,
- the reception of a WuB detected by the WuRx.

The first two events may lead to the sending of a data message intended for the gateway. In that case, the EDs send the data directly to the gateway using LR communication, as shown by Fig. 3. The last case corresponds to the sending of a command from the gateway attended to one or more EDs. The gateway first transmits the command to the CN. The CN then forwards the command to the addressee EDs, first waking up the addressee EDs by sending a WuB attended to the addressee EDs WuRx. The CN and the gateway communicate using the standard LoRa™scheme [5]. Hence, direct LR communication is unidirectional between the EDs and the gateway (ED $\rightarrow$ gateway), and bidirectional between the gateway and the CN.

C. Medium Access Control layer design

In this section, the MAC layer leveraging the proposed communication architecture, is presented. Bidirectional LR communication between the CN and the gateway is ensured using LoRa™MAC layer [5], as well as unidirectional LR

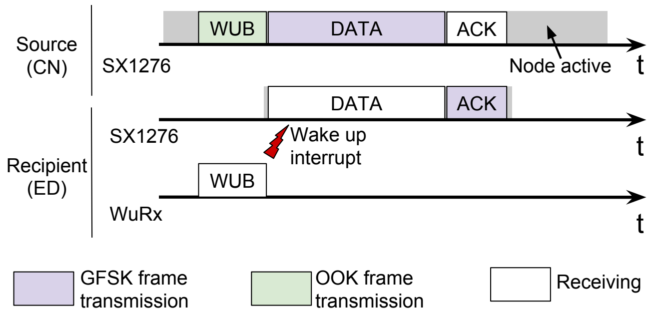


Fig. 4: SR communication using WuRx.

communication between the EDs and the gateway. The CN uses the LoRa™class C mode. The SR communication, used for unidirectional command transmission from the CN to the EDs, is done asynchronously using the scheme illustrated by Fig. 4. The CN first wakes up the ED by sending a 2 bytes long WuB, using the SX1276 transceiver and OOK modulation. The WuB consists of a 1 byte preamble, and a 1 byte address, corresponding to the address of the addressee ED. To handle the broadcasting use case, one address is reserved for broadcasting. All the EDs WuRx receive the WuB sent by the CN, but as the WuRx perform address matching, only the addressee ED is awaken. The addressee ED then switches-on its main transceiver to receive the data frame. As the data frame may be significantly larger than the WuB, GFSK modulation is used as well as the standard IEEE 802.15.4 packet frame structure which provides error detection using Cyclic Redundancy Check (CRC) code. Finally, an acknowledgment (ACK) frame is sent by the addressee ED to the CN to indicate the successful reception of the data frame. If a transmission error occurs, e.g. due to interferences, a new transmission attempt is initiated after a random backoff.

While with the standard LoRa™scheme a tradeoff must be made between latency and power consumption, the proposed architecture combined with the proposed MAC protocol allows bidirectional low latency and energy efficient communications in heterogeneous long-short range networks. This is achieved by organizing the EDs around a CN in a star network topology, and exploiting ULP WuRx to allow pure-asynchronous communications between the CN and the EDs. Using this approach, the EDs do not have to listen periodically (class B) or continuously (class C) to the channel to receive data from the gateway, and no tradeoff must be made between power consumption and latency as with the standard LoRa™scheme.

IV. Power consumption and latency analytical models

Analytical models of the power consumption incurred by the downlink transmission of the EDs are derived in this section, as well as analytical models of the packet reception latency. First, the models of the LoRa™approaches are presented. Then, the models of the WuRx-based approach proposed in this work are exposed.

A. LoRa™approaches models

The average rate at which commands are sent by the gateway to EDs is denoted λ_{CMD}. As explained previously, LoRa™proposes three operating modes for the EDs, called class A, B and C. Using the class A operating mode, commands from the gateway can only be transmitted to an ED after an uplink transmission, and the average power consumption of an ED incurred by downlink communication, denoted P_C^{LA}, is therefore:

$$P_C^{LA} = e_{CMD}^L \lambda_{CMD}, \text{ with } \lambda_{CMD} \leqslant \lambda_{SND}, \tag{1}$$

where e_{CMD}^L is the energy cost to receive a command using LoRa™and λ_{SND} is the packet transmission rate of EDs. At each command transmission, the gateway waits for the ED to perform an uplink transmission before sending a command. In average, the waiting time is $\frac{1}{2\lambda_{SND}}$ s, and the average latency of the command transmission, denoted L^{LA} is thus:

$$L^{LA} = \frac{1}{2\lambda_{SND}} + l_{CMD}^L, \tag{2}$$

where l_{CMD}^L is the time required for the command transmission using LoRa™.

Using the class B operating mode, each ED periodically opens receive windows, called ping slots, at a rate λ_{PING}. If no preamble is detected during a ping slot, the ED immediately returns to sleep. If a preamble is detected the radio transceiver stays on until the frame is demodulated. The gateway provides time reference to the EDs by periodically broadcasting beacon, at a rate λ_{BCN}. The average power consumption incurred by downlink communication of an ED using this operating scheme is thus:

$$P_C^{LB} = \lambda_{BCN} e_{BCN} + (\lambda_{PING} - \lambda_{CMD})\, e_{PING} + \lambda_{CMD} e_{CMD}^L, \tag{3}$$

where e_{BCN} is the cost of receiving a synchronization beacon and e_{PING} is the cost of opening a receiving window that leads to no preamble detection. The gateway has to wait in average $\frac{1}{2\lambda_{PING}}$ s for the ED to open a ping slot, and the average latency of command transmission is thus:

$$L^{LB} = \frac{1}{2\lambda_{PING}} + l_{CMD}^L. \tag{4}$$

The class C option is designed for EDs with sufficient power available. Using this operating mode, EDs are always listening to the channel, except when they are transmitting. Therefore, the average power consumption of an ED incurred by the downlink transmission is:

$$P_C^{LC} = (1 - \lambda_{SND} l_{SND})\, P_{C,RX}, \tag{5}$$

where $P_{C,RX}$ is the power consumption of the transceiver when receiving, and l_{SND} is the time required to send a periodic uplink packet. The latency of a downlink transmission using class C operating mode is only due to the packet transmission duration:

$$L^{LC} = l_{CMD}^L. \tag{6}$$

B. WuRx-based approach models

The power consumption EDs incurred by the WuRx-based approach proposed in this work for receiving packets from the gateway is:

$$P_C^{WuRx} = \lambda_{CMD} e_{CMD}^W + (1 - \lambda_{CMD} l_{WuB}) P_{WuRx}, \quad (7)$$

where e_{CMD}^W is the energy cost of receiving a packet using the SR MAC approach presented in the previous section, l_{WuB} is the transmission time of a WuB, and P_{WuRx} is the power consumption of the WuRx when only the analog font-end is active listening to the channel, while the ULP MCU is in the sleep state. Assuming that the CN uses the class C operating mode, the latency of a packet reception is:

$$L^W = l_{CMD}^L + l_{CMD}^W, \quad (8)$$

where the first term is the latency of the packet transmission from the gateway to the CN, while the second term is the time required for a packet transmission using SR MAC approach presented in the previous section.

V. Experimental and Analytical Results

Experimental measurements and analytical comparison results are presented in this section. The proposed architecture was evaluated using the MSP-EXP430FR5969 Launchpad Development Kit, and a testbed of the proposed hardware and network architecture has been deployed. First, measurements of LoRa™power consumption using different communication setups are exposed. Next, analytical comparisons of the scheme proposed in this work and traditional LoRa™are presented.

A. Experimental evaluation of LoRa™power consumption

This section focuses on the energy consumption incurred by the LoRa™modulation scheme regarding the spreading factor (SF), bandwidth (B), coding rate (CR) and transmission power (P_{Tx}), which are critical parameters permitting a trade-off between energy consumption, immunity to interference and nominal data rate. The CR parameter corresponds to the additional data overhead ratio incurred by the cyclic error coding used by LoRa™to perform forward error detection and correction, and takes value in the range between $\frac{4}{8} \ldots \frac{4}{5}$. Using LoRa™, the bit-rate denoted R_b can be calculated as follows [4]:

$$R_b = SF \frac{B}{2^{SF}}. \quad (9)$$

Because the parameter space defined by these four parameters is large, 3 setups corresponding respectively to the highest bit-rate setup (SH), the LoRa™default setup (SD) and the lowest bit-rate setup (SL) were considered in this work. Table I details the parameter values used for each setup. Fig. 5 exposes the energy required for sending a 14 byte payload using each setup and for different transmission power P_{Tx}. As it can be seen, the energy required to send a packet using the SL setup is two orders of magnitude higher than the energy required to send a packet using the SH setup. This is due to the much lower bit-rate incurred by the lower bandwidth and higher spreading factor, as well as the data overhead caused by a higher code rate. Therefore, the SR, B and CR parameters must be chosen very carefully to fulfill the application requirements in terms of BER, range and energy consumption. Using these measures among others, the energy costs of sending a ping, a beacon and a command (both using LoRa™and OOK) were estimated and are shown by Table II.

	SH	SD	SL
CR	$\frac{4}{5}$	$\frac{4}{5}$	$\frac{4}{8}$
B (kHz)	500	125	125
SF	6	7	12
R_b (kbps)	46.9	6.84	0.367

TABLE I: Setups use for LoRa™energy measurement.

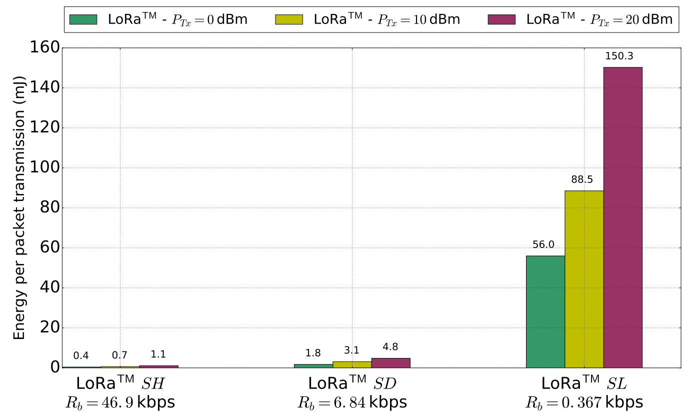


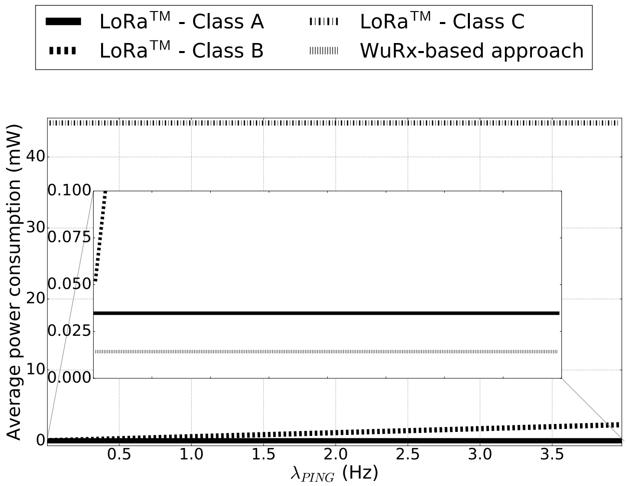
Fig. 5: Energy cost of sending a packet using LoRa™.

B. Analytical Comparison

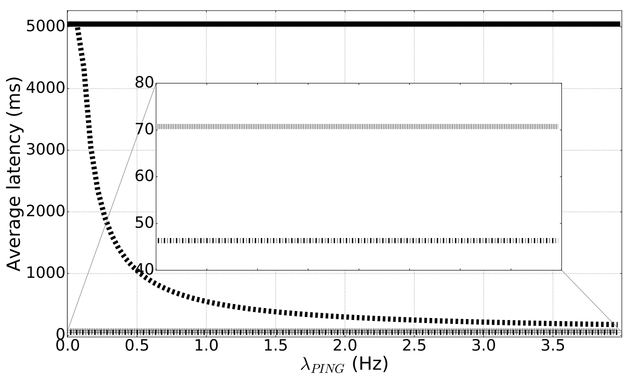
The communication scheme proposed in this work for transmitting commands from the gateway to the EDs was analytically compared to the standard LoRa™approaches using the model presented in the Section IV. The SD setup of LoRa™was considered, as it is the default setup and Table II shows the used parameter values. Energy values were calculated using power consumption measurements and by taking into account the physical layer and MAC layer overheads of LoRa™, and the default value of λ_{BCN} was used [5]. Fig. 6 shows the analytical results. Fig. 6a shows the power consumption of an ED incurred by the downlink transmission for values of λ_{PING} ranging from $\frac{1}{60}$ to 4 Hz.

λ_{CMD}	$\frac{1}{60}$ Hz
λ_{BCN}	$\frac{1}{128}$ Hz
λ_{SND}	$\frac{1}{10}$ Hz
e_{BCN}	2.178 mJ
e_{PING}	0.5645 mJ
e_{CMD}^L	2.085 mJ
e_{CMD}^W	0.7453 mJ

TABLE II: Parameter values used for analytical comparison.



(a) Power consumption of the EDs downlink transmission as a function of λ_{PING}.



(b) Latency of the EDs downlink transmission as a function of λ_{PING}.

Fig. 6: Analytical results.

It can be seen that the power consumption incurred by the WuRx scheme is the lowest one, as it is 2.5 times smaller than with the LoRa™class A approach, up to 15 times smaller than the class B approach, and 3000 times smaller than the power consumption incurred by the class C approach. Moreover, if the power consumption incurred by the WuRx-based, class A and class C LoRa™approaches do not depend on λ_{PING}, the power consumption of the class B scheme strongly depends on this parameter. Regarding the latency results exposed by Fig. 6b, for values of λ_{PING} ranging from $\frac{1}{60}$ to $4\,\text{Hz}$, we can see that the LoRa™class C scheme achieves the lowest latency, but at the cost of an enormously higher power consumption. The WuRx-based approach proposed in this scheme achieves a latency close to the one of the class C mode, while incurring the lowest power consumption. The LoRa™class B scheme latency strongly depends on λ_{PING}, as higher values of λ_{PING} allows lower latency but at the cost of a higher power consumption. Overall, using the LoRa™scheme, a trade-off is required between the latency and the power consumption for downlink communication, while the approach proposed in this scheme, which combines SR and LR communication, allows both low latency and low power consumption for downlink communication. The proposed approach requires the use of an extra hardware device, WuRx, which power consumption is negligible as it is 1.83μW in always-on listening mode.

VI. Conclusion

In this paper, a novel network architecture exploiting radio diversity by combining LoRa™and wake-up receivers was presented. Using LoRa™, a trade-off between latency and power consumption for packet transmission from the gateway to the nodes must be made. Therefore, it does not suit applications that require low latency and low power consumption in short range. We proposed in this work to combine LoRa™with ultra-low power wake-up receivers, which enables pure-asynchronous communication, and eliminates idle listening, but operates in the range of tens of meters. The novel network architecture proposed in this work combines these two schemes for applications where sensor and actuator nodes are deployed in a small range area, but need to communicate with a distant gateway, to which they send data and from which they receive commands. Analytical comparison showed the benefits of the proposed scheme, as it significantly reduces both latency and power consumption. Especially, analytical comparisons show that the proposed scheme allows up to 3000 times reduction of the power consumption compared to the standard LoRa™scheme approach.

Further work involves deploying a network to evaluate the proposed architecture in real environment, as well as performing further energy consumption and latency measurements.

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