Long-Short Range Communication Network Leveraging LoRa and Wake-up Receiver

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***Abstract*—Wireless sensor and actuator networks play a central role in the Internet of Things, and a lot of effort is devoted to enable energy efficient and low latency communications. In the recent years, low power communications has evolved towards multi-kilometer ranges and low bit-rate approaches such as LoRa™. However, the medium access layer protocols rely on the well-known duty-cycling schemes, which require a trade-off between power consumption and latency for message transfer from the gateway to the nodes. 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. Emerging ultra-low-power wake-up receivers enable pure-asynchronous communications, allowing both low latency and low power consumption, but at the cost of a lower sensitivity and lower range than traditional wireless receivers and LoRa™. 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. A hardware architecture as well as a protocol is proposed to exploit the benefits of these two communication schemes. Experimental measurements and analytical comparisons show that the proposed approach remove the need for a trade-off between power consumption and latency.**

I. Introduction

Wireless Sensor and Actuator Networks (WSANs) form a key enabler technology of the Internet of Things (IoT), by allowing novel applications in the industrial, military, and civil domains [1]. The goal of a WSAN is to perform measurements (e.g. vibration, humidity, radiation,...), process the so obtained data and send them to a remote host. Moreover, nodes can also perform some actions in their environment using actuators. The most widely-used communication scheme for WSANs is the IEEE 802.15.4 standard, which provides both physical layer and Media Access Control (MAC) layer specifications. This standard enables low-cost and low power transceivers, but suffers from a range of only a few tens of meters. In recent years, a handful of wireless technologies enabling Long Range (LR) communication of several kilometers with power consumption similar to usual WSAN nodes transceivers [2] have emerged. An example of such a technology in use is LoRa™ [3], by the LoRa™ Alliance. LoRa™ operates in the $868/915$ MHz ISM bands, allows a theoretical range up to a few tens of kilometers, and a bit-rate in the range between 0.37 and 46.9 kbps [4]. Using LoRa™, uplink communication, i.e. from the nodes to the gateway, is done with low latency, as the gateway is always listening to the channel. On the other hand, 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], [7], which motivates the network architecture proposed in this work.

An alternative and promising technology for energy efficient wireless communication targeting WSAN applications is Ultra-Low Power (ULP) Wake-up Receivers (WuRx). ULP WuRx allows continuous channel monitoring while consuming orders of magnitude less power than traditional transceivers [8] (in the order of micro-watts). These devices wake up the node micro-controller (MCU) or other sleeping subsystems using interrupts only when a specific signal, called Wake-up Beacon (WuB), is received. One of the main benefits of WuRx is to enable "pure" asynchronous communication that can significantly increase the energy efficiency of communications by reducing the activity of the main power hungry radio [8]–[14]. Typically, only the ULP WuRx is always-on listening to the channel, while the other components are in power saving states.

Recent ULP WuRx provide computational capabilities consuming few micro-watts of power [15], [16], which allows novel ULP WuRx to process data embedded in WuBs and to take decisions, without the requirement of waking up other subsystems of the node. As a result, it is possible to perform address matching directly on the ULP WuRx, but also to activate a node sub-system or to change the sensor sampling rate, according to the received WuB, and with a significant amount of energy saved [14]. ULP WuRx are typically characterized by lower sensitivities and lower bandwidth compared with traditional WSAN transceivers [8], [15], [16], which is the cost of ultra low power consumption. Therefore, they are suitable for Short Range (SR) communications, i.e. tens of meters.

As one can notice, ULP WuRx and LoRa™ provide orthogonal features that are often required together in WSANs applications. Moreover, many application scenarios are comprised by many nodes clustered in short range areas, but with the need to communicate with remote hosts which can be several kilometers apart. In this work, we propose to combine the LoRa™ communication scheme with ULP WuRx in a network architecture, which exploits radio diversity to achieve energy efficiency and low latency in both uplink and downlink communications [17]. The nodes that form the network embed

This work was already partially published in the proceedings of the Euromicro Conference on Digital System Design (DSD 16) and the IEEE/ACM Design, Automation & Test in Europe Conference & Exhibition (DATE 17).

a communication module that is able to handle LoRa™ as well as the well-known GFSK and OOK modulation schemes, in combination with ULP WuRx. The proposed network architecture achieves uplink communication by using only the LoRa™ scheme, while downlink communication is done using the LoRa™ stack to transmit the message to one of the sensors nodes designated as the Central Node gateway, which then forwards the message to the addressee nodes by first waking them up using their ULP WuRx, and then transmitting the message using standard GFSK modulation. WuBs are sent using OOK modulation. The LoRa™ 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 compared to the three LoRa™ standard schemes. If LoRa™ schemes can achieve either low power consumption or low latency, results show that the proposed scheme removes the required trade-off between power consumption and latency that is required when using LoRa™ standard schemes. The main contributions of this paper are:

- A network architecture allowing low power and low latency LR communications,
- Experimental evaluation of the proposed architecture on a new platform introduced in [18] that embeds both a LoRa™ transceiver and an ULP WuRx,
- Analytical comparisons of the power consumption and latency of the proposed architecture to LoRa™ standard schemes.

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™ approaches. Section V presents the experimental setup and the power consumption and sensitivity measurements results of the LoRa™ scheme. Section VI shows results of analytical comparisons between standard LoRa™ schemes and the proposed architecture, and finally, Section VII concludes this paper.

II. Related Work

This section starts by presenting the handful of LR communication schemes that have recently emerged in the industry [4]. Next, a description of ULP WuRx technologies is given, and finally, previous works related to heterogeneous communication network is exposed.

A. Long-range communication standards

LR communication schemes can be grouped according to the spectrum use, i.e. (Ultra) Narrow Band ((U)NB) techniques, which aim to minimize the bandwidth to reduce the probability of interference, or spread spectrum schemes, which take advantage of spectral diversity.

The physical layer developed and patent by the french company SigFox achieves UNB by broadcasting binary data using BPSK modulation at very low bitrate (100 bps), on a much larger band, typically 192 kHz in the 868 MHz or 915MHz band. Frequency hopping inside the band is supported to improve reliability, and medium access is done using a modified Aloha scheme, where node access to the channel randomly both in time and frequency domain.

Another NB physical layer is proposed by Weightless, an organization which aims to provide wireless standards for internet of things networks. Multiple standards, targeting different use cases, are proposed. The Weightless-N standard, based on DBPSK modulation, is unidirectional and allows a range of 5 km. Similarly to SigFox, frequency hopping is used to counteract interference and fading. The Weightless-P standard is based on the Weightless-N standard, but enables bidirectional communication and acknowledgement. It uses FDMA and TDMA to scale to a large number of devices, but reduces the range to 2 km in urban environment. The last proposed standard, Weightless-W is not NB, but is a spread spectrum scheme. It operates in TV white space spectrum, and uses variable modulation modes coupled with spreading codes, to enable 5 km range and bidirectional communication.

The scheme proposed by Ingenu differs from the other long-range communication methods in that it operates in the 2.4 GHz ISM band. It is a spread spectrum technique, called Random Phase Multiple Access (RPMA), that enables a range of 10 km, using a typical channel bandwidth of 1 MHz. Both uplink and downlink transmission are allowed, and performed in a half-duplex way with a downlink period of 2 s, followed by an uplink period of 2 s. The spreading factor is dynamically adapted based on the received power.

Another spread spectrum technique for long-range communication was patented by Cycléo, and is based on Chirp Spread Spectrum (CSS). Named LoRa™, this physical layer operates in the 868 MHz or 915 MHz ISM bands, and enables a range up to a few tens of kilometers. In the LoRa™ network architecture [5], all WSAN nodes communicate directly with the gateway, which serves as a bridge between the nodes and a network server. 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. 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™ network architecture, a trade-off must be made between latency and energy consumption for downlink communications.

B. Wake up receivers

ULP WuRx designs present in the literature can be classified in two categories: passive circuits, which are exclusively powered by the energy of the received signal, and drain no energy from the node power supply, and active circuits, which require a supply power to operate.

Fully passive WuRx are attractive as they do not require a power supply to operate. However, they are characterized by a very low typical sensitivity of -25 dBm, which allows a range

of a few centimeters [19]. Due to this limitation, the majority of ULP WuRx architectures used in WSANs are active, although their power consumption stays in the range of few micro-watts. With such a small power envelope, the sensitivities of these ULP WURx are typically in the range of 50-55 dBm, which allows a range of $20-30$ meters with 3 dBi gain antennas [15], [20]. In this work, the state-of-art ULP WuRx presented in [15] is used, which achieves a sensitivity of -55 dBm and embeds an ULP MCU.

The network protocols must take advantage of ULP WURx to fully exploit these emerging circuits, and therefore a handful of MAC protocols leveraging ULP WuRx were proposed in the recent years [21], [22]. The benefits of using these new devices compared to traditional approaches, in terms of energy efficiency and latency, were shown in previous works [9], [14].

C. Heterogeneous communication networks

As many devices embed more than one radio module, exploiting radio diversity was previously proposed to reduce energy consumption and latency for opportunistic networking [23]. 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. Some combinations of low power radio (typically Bluetooth or Zigbee) and high power radio (typically Wi-Fi or cellular) were previously proposed [24]–[26]. More recently, *Tuset-Peró et al.* proposed in [27] a platform which combines three communication modules: one for LR (kilometers-range) communication, one for hundreds of meters communication, and one for contact-based communication. However, the authors did not detailed the MAC protocols or network architecture, as the paper focuses on the platform design.

In this work, we propose to combine the LoRa™ communication scheme, able to achieve kilometer-range communication, with ultra low power wake-up receivers, which enable short-range distant wake up of the nodes with no significant power consumption increase, and low downlink latency. This work emphasizes on the network architecture and the MAC protocols.

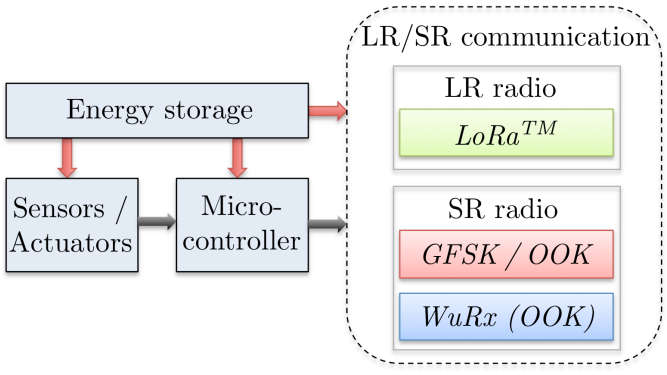


Fig. 1: Long-Short range node architecture.

III. Long-Short Range Network Architecture

A. Communication module architecture

This work addresses the use of heterogeneous radio systems to enhance energy and latency of LR communication. The block diagram of the proposed WSAN node is illustrated in Fig. 1. Each node embeds a MCU, sensors, actuators, an energy storage device and a communication module. The communication stack allows both LR and SR communications.

LR communication relies on the LoRa™ physical layer, which can recover data from weak signal, even under the noise level. SR communications relies on GFSK and OOK modulations. GFSK modulation is compatible with IEEE 802.15.4 frame allowing bit rate up to 300 kbps, while OOK modulation is used to wake-up the WuRx devices. Indeed, each WSAN node is equipped with an ULP WuRx, which receives data with OOK modulation. Typically, the WuRx is continuously listening to the wireless medium while the main transceivers (i.e. LoRa™ and GFSK) are in a power saving state. Moreover, the WuRx embeds address matching features, which allows a no to wake up only a specific subset of its neighbors.

B. Cluster-based network architecture

In the proposed network architecture, WSAN nodes are organized in clusters as shown by Fig. 2. A gateway, located at a large distance (few kilometers) from the clusters, collects the sensed data, and sends commands to the nodes, e.g. to activate actuators or to set sensing parameters. Each cluster is organized in a star topology network composed of long-short range nodes introduced in the previous section allowing both LR and SR communications. In a cluster, a Central Node (CN) is in charge of bidirectional LR communications with the gateway and of SR communications with the other nodes of the clusters, referred to as End Devices (EDs). The EDs are distributed in a range of a few tens of meters around the CN and can use either SR to communicate with the CN or LR to directly communicate with the gateway.

The gateway is assumed to have no energy constrains, and therefore operates in LoRa™ class C. The CNs operate in class B or C according to their energy constrains and the application requirements. EDs are energetically constrained, and therefore spend most of their time in the sleep state. EDs only wake up when an interrupt occurs. This interrupt can be triggered on a timer expiration, e.g. to perform periodic sensing or action, or on an event from the environment detected by an embedded sensor. These interrupts may lead to the sending of a data message intended for the gateway. To this aim, the EDs directly send the data to the gateway using LR communication, as shown by Fig. 2. For the EDs, LoRa™ class A is used to send the data.

Another kind of interrupts that can wake up the EDs is the reception of a WuB detected by the WuRx. Indeed, as each ED is equipped with a WuRx, the CN can wake up one or more EDs by sending WuBs. This interrupt occurs in the "data request" scenario when the gateway first sends a command attended to one or more EDs and the EDs transmit in a second step data to the gateway in response to the command. This scenario will be experimented in the following as it leads to interesting performance gains (both energy and latency) compared to LR-only communication schemes.

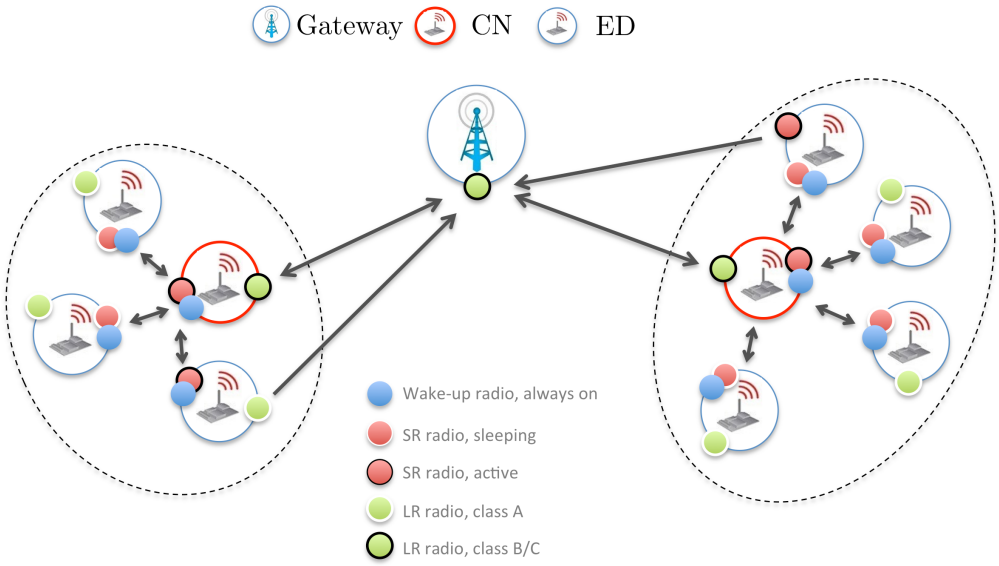


Fig. 2: Cluster-based network architecture for Long-Short range communication.

In this scenario, the gateway first transmits the command to the CNs using standards LoRa™ communication schemes. Then, the CNs forwards the command to the addressee EDs, by waking up the addressee EDs by sending a WuB to their WuRx. Finally, the EDs send the requested data to the gateway using the standard LoRa™ approach. Hence, direct LR communication is unidirectional between the EDs and the gateway (ED → gateway), and bidirectional between the gateway and the CN. The protocol dedicated to this scenario is detailed in the next section.

C. Medium Access Control layer design

The protocol that addresses the "data request" scenario is illustrated by Fig. 3. The gateway first sends the command (Cmd) to the CN of the addressee cluster. Once the command is received, the CN wakes up the ED by sending a 2 bytes long WuB, using 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 ED 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, the ED sends its requested data (Data) to the gateway using LoRa™ class A. The transmission is followed by two short receive windows (not shown on the figure).

To ensure good SR transmission, an acknowledgement (ACK) frame can be 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 back-off.

While with the standard LoRa™ scheme a trade-off 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 WuRx to allow pure-asynchronous communications between the CN and the EDs. Using this approach, the EDs do not have to periodically (class B) or continuously (class C) listen to the channel to receive data from the gateway, and no trade-off must be made between power consumption and latency as with the standard LoRa™ scheme.

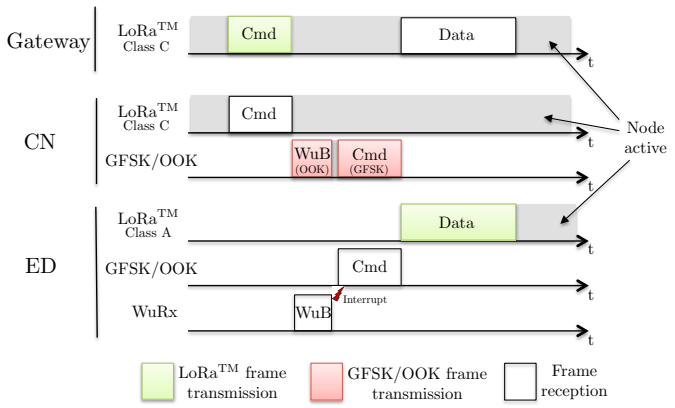


Fig. 3: Long-Short range MAC protocol using WuRx.

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. Models of LoRa™ communication schemes

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:

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

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:

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

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:

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

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:

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

The class C option is designed for EDs with sufficient available power. 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:

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

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:

$$L^{LC} = l_{CMD}^L. \quad (6)$$

B. Models of LoRa-WuRx communication scheme

The ED power consumption incurred by the L&W approach proposed in this work for receiving packets from the gateway is:

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

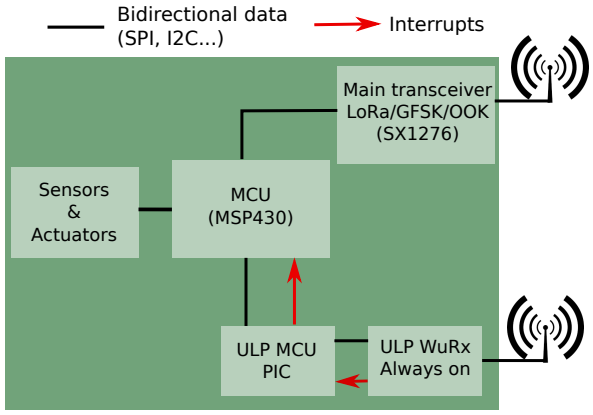
where e_{CMD}^W is the energy cost of receiving a packet using the SR MAC approach presented in the previous section, l_{WuB} is the transmission time of a WuB, and P_{WuRx} is the power consumption of the WuRx when only the analog font-end is active listening to the channel, while the ULP MCU is in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

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

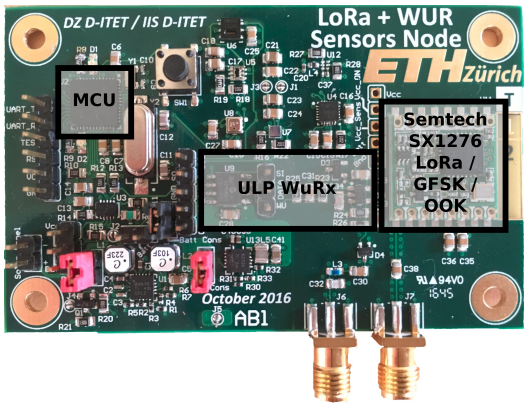
where the first term is the latency of the packet transmission from the gateway to the CN, while the second term is the time required for a packet transmission using SR MAC approach presented in the previous section.

V. Experimental Measurements

This section presents power consumption and sensitivity measurements. First, the experimental setup is exposed. Then, the measurements results are given.



(a) Block diagram of the prototype.



(b) Picture of the prototype.

Fig. 4: Prototype used for experimentations [18].

A. Experimental setup

The prototype, introduced in [18] and shown by Fig. 4, that includes a Texas Instruments MSP430FR5969 MCU, the WuRx from [15], multiple sensors and a Semtech SX1276 transceiver, was used to evaluate the proposed architecture. The transceiver SX1276 from Semtech provides (G)FSK and OOK modulations, as well as the LoRa™ physical layer. Moreover, it allows switching between the different modulation schemes, enabling coexistence between different modulation approaches. LoRa™ relies on CSS modulation [28], where a chirp is a sinusoidal waveform whose frequency varies with time. SF is the spreading factor which takes value in the range between 6 and 12.

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

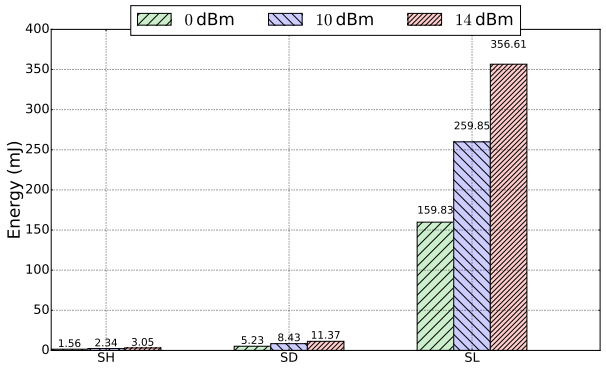
$$R_b = SF \frac{B}{2^{SF}}. \quad (9)$$

Because the 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.

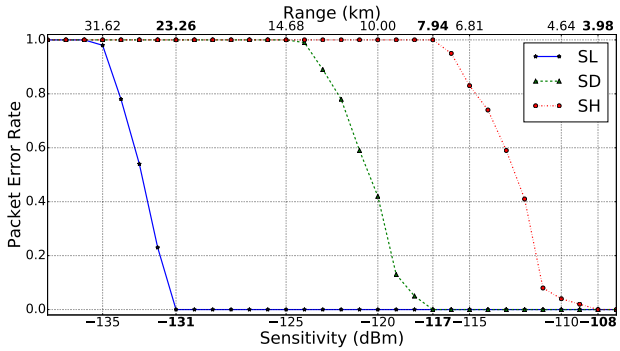
In addition to the SX1276 transceiver, each WSAN node is equipped with an instance of the WuRx designed in [15], which receives data with OOK modulation, the simplest form of amplitude shift keying modulation in which data is represented by the presence or absence of a carrier. The WuRx is made up of four main blocks: the matching network, the envelope detector, the interrupt generator and the ULP MCU that provides computational resources to the WuRx and serial interface with the main node. The matching network guarantees 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

	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.



(a) Energy cost of sending a packet using LoRa™.



(b) LoRa™ sensitivity and theoretical range for different setups.

Fig. 5: LoRa™ experimental evaluations.

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 -55dBm. 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.

Finally, the platform embeds the ultra low-power TI MSP430FR5969 micro-controller that is connected with the sensors, the actuators and the communication module. The micro-controller executes data collection from sensors and sending data or commands with the SX1276 module (using LoRa™ or OOK modulation).

B. Measurements results

Fig. 5a exposes the energy required for sending a 14 bytes payload using each setup and for different transmission powers 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 the higher spreading factor, as well as the data overhead caused by a higher code rate. However, if increasing

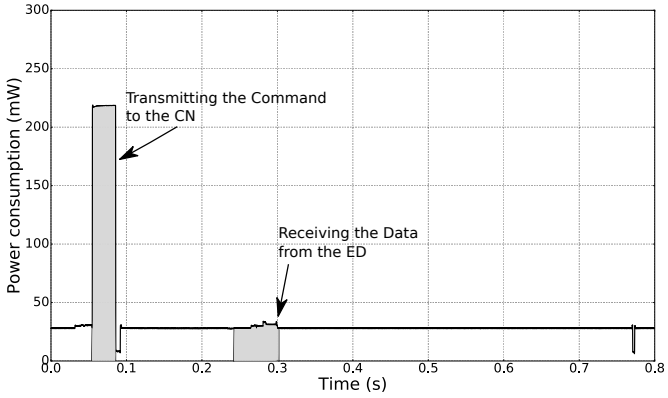
the throughput reduces both the latency and the consumed energy, it also significantly decreases the communication range as shown by Fig. 5b. This figure shows the Packet Error Rate (PER) achieved for different received powers, and the sensitivity is estimated for a PER of $0\,\%$. A theoretical range was computed using the log-normal shadowing propagation model with a path loss exponent of 3 and a power transmission of 0 dBm. These measurements were done using two nodes connected by a variable attenuator, and radio-frequency leakages were cancelled by isolating one node in an anechoic chamber. The measured sensitivities show a 13 dBm difference between the SL and SD setups and a 7 dBm difference between the SD and SH setups. As it can be seen, the range is strongly impacted by the used setup, as using the SL setup theoretically improves the range by a factor of 5.8 compared to the SH setup. Therefore, the SR, B and CR parameters must be chosen very carefully to fulfill the application requirements in terms of range and energy consumption.

Fig. 6 shows the power consumption of the gateway, CN and ED when using the proposed scheme. In this example, the CN is operating in class C. These measurements were obtained using an Agilent N6705 DC analyzer. The different stages of the proposed MAC protocol, detailed in Section III-C, can be seen here, as well as the two receiving windows required by the class A LoRa™ scheme. Moreover, the hardware and software overhead can also be seen, between two frame transmissions/receptions. These measurements were used to compute the energy costs needed by the analytical model.

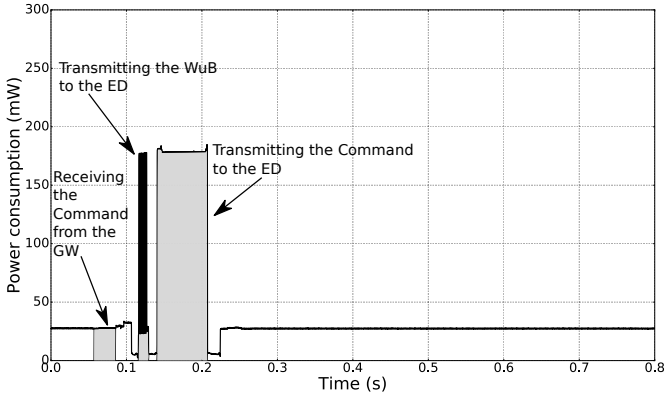
VI. Analytical Comparison

The communication scheme proposed in this work for transmitting commands from the gateway to the EDs was analytically compared to the standard LoRa™ approaches by including experimental measurements in the models presented in Section IV. This hybrid evaluation has been proposed in [29] and allows to quantify thanks to microbenchmark measurements the gain in terms of energy and/or latency provided by the proposed cluster-based architecture. The three setups introduced in the previous section (SL, SD and SH) were considered. 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].

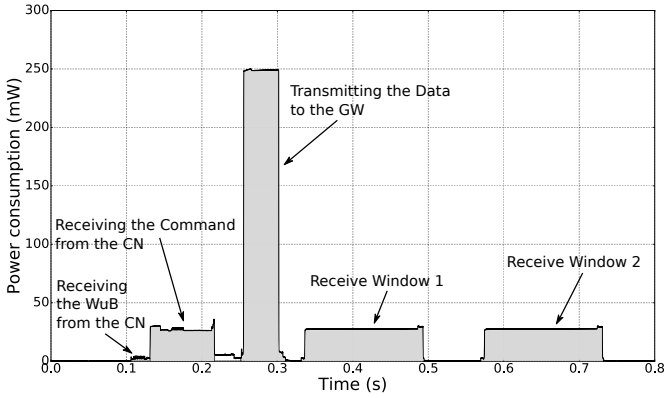
Fig. 7 shows the power consumption and the latency of an ED node operating using the different evaluated schemes. The LoRa™ class B was evaluated for values of λ_{PING} ranging from 0.1 to 33Hz, and, when evaluating the proposed approach, the CN node was assumed to operate in class C. The size of the LoRa™ frame was set to 14 bytes, λ_{CMD} to $\frac{1}{90}$ Hz, λ_{BCN} to $\frac{1}{128}$Hz, and λ_{SND} to $\frac{1}{10}$Hz. It can be seen that using LoRa™, a trade-off between power consumption and latency is required. Indeed, the class A allows very low power consumption, but at the cost of high latency as the gateway can send commands to an ED only after an uplink transmission. On the other hand, if the ED operates in class C, downlink communications are performed with low latency, as the node is always listening to the channel, but at the cost of high power consumption preventing long-term applications. The class B allows a trade-off between these two extremes, by taking advantage of the well-known duty-cycled approach. When operating in class B, the ED periodically wakes up to listen to the channel, and the trade-off between power consumption and latency is set using the λ_{PING} parameter. The WuRx-based approach proposed in this work, which combines SR and LR communications, achieves a latency close to the one of the class C mode, while incurring a low power consumption. The proposed approach requires the use of an extra hardware device, the WuRx, which power consumption is negligible as it is 1.83μW in always-on listening mode. Hence, no more trade-off is required



(a) Gateway (GW).



(b) CN.



(c) ED.

Fig. 6: Microbenchmarks showing the "data request" scenario. The SD setup is used.

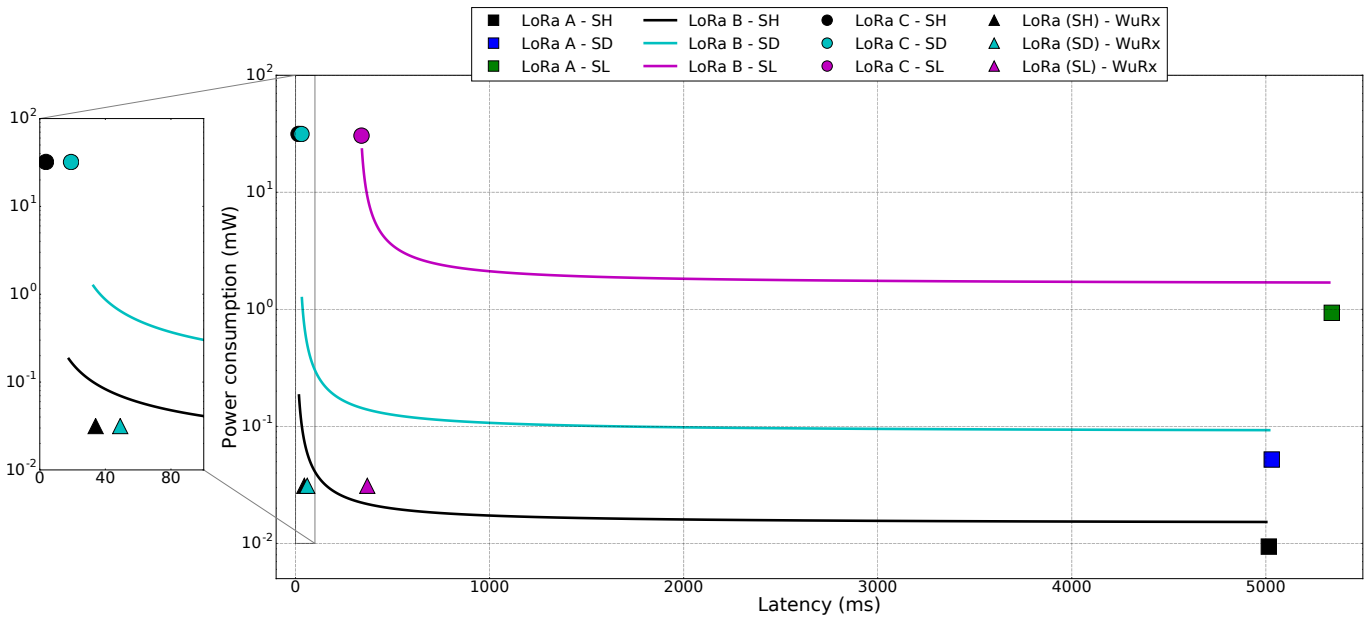


Fig. 7: Power consumption vs Latency.

for downlink communication, as it is the case with standard LoRa™ approaches.

VII. Conclusion

This paper presents a novel network architecture exploiting radio diversity by combining LoRa™ and wake-up receivers. 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 wake-up receivers, which enables pure-asynchronous communication, and eliminates idle listening, but operates in the range of tens of meters. The proposed network architecture 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. To this aim, nodes must be organized in clusters with a central node in charge of bidirectional long range communications with the gateway and short range communications with sensor and actuator nodes.

The long-short range architecture is validated with an hybrid approach that combines analytical models with experimental measurements. A dedicated platform that embeds both LoRa™ and wake-up receiver technologies has been prototyped for the experiments. Experimental and analytical comparison showed the benefits of the proposed scheme, as it removes the trade-off between power consumption and latency.

In our future works, we intend to evaluate in the field the performance of the proposed protocol and to define algorithms that dynamically select the central node among a cluster.

VIII. Acknowledgment

This work was supported by "Transient Computing Systems", a SNF project (200021_157048), by SCOPES SNF project (IZ74Z0_160481) and by "POMADE" project, funded by CG22 and the Brittany region.

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