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Article

# How Can Wake-up Radio Reduce LoRa Downlink Latency for Energy Harvesting Sensor Nodes ?

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**Abstract:** LoRa is popular for internet of things applications as this communication technology offers both a long range and a low power consumption. However, LoRaWAN, the standard MAC protocol that uses LoRa as physical layer, has the bottleneck of a high downlink latency to achieve energy efficiency. To overcome this drawback we explore the use of wake-up radio combined with LoRa, and propose an adequate MAC protocol that takes profit of both these heterogeneous and complementary technologies. This protocol allows an opportunistic selection of a cluster head that forwards commands from the gateway to the nodes in the same cluster. Furthermore, to achieve self-sustainability, sensor nodes might include an energy harvesting sub-system, for instance to scavenge energy from the light, and their quality of service can be tuned, according to their available energy. To have an effective self-sustaining LoRa system, we propose a new energy manager that allows less fluctuations of the quality of service between days and nights. Latency and energy are modelled in a hybrid manner, i.e. leveraging microbenchmarks on real hardware platforms, to explore the influence of the energy harvesting conditions on the quality of service of this heterogeneous network. It is clearly demonstrated that the cooperation of nodes within a cluster drastically reduces the latency of LoRa base station commands, e.g. by almost 90% compared to traditional LoRa scheme for a 10 nodes cluster.

**Keywords:** Internet of Things, Wake-up radio, LoRa, heterogeneous networks architecture, opportunistic cluster heads, energy harvesting

## 1. Introduction

Low-Power Wide Area Networks (LPWANs) have gained in the recent years a significant interest by both research community and industry for different Internet of Things (IoT) applications, such as smart cities, smart health and smart farms. Such technology offers a link range of several kilometers and a low power consumption, but at the cost of small data rate. Many technologies belong to LPWAN category such as SigFox, Narrowband IoT, Weightless and LoRa [1]. Among these existing LPWANs sets, LoRa is the most popular due to its open communication protocol (LoRaWAN) and its ability to achieve a long range and to recover data from weak signals even below the noise floor [2]. Therefore, many projects were conducted with LoRa technology in different applications, such as in smart farms where animal health monitoring and tracking is having a growing interest [3]. Three classes are defined in the LoRaWAN specification (A, B and C) that will be detailed in Section 2.1. A tradeoff needs to be made between power consumption and downlink latency for these three classes.

Wake-up Radio (WuR) is a consolidated technology that helps to achieve the trade-off between power consumption and latency. WuR is a secondary always-on Ultra Low Power (ULP) radio subsystem that is connected to the main node. The WuR power consumption is several orders of

34 magnitude less than that of the main node, but it has a short range communication capability [4].  
 35 The WuR is continuously listening to the channel while the main radio is in sleep mode, and when a  
 36 specific signal called Wake-Up Beacon (WUB) is received, the WuR wakes up the main radio through an  
 37 interrupt. Thus, the WuR allows an asynchronous wake-up of the main node with a low latency. Recent  
 38 circuit designs of WuR embed a decoding capability through a ULP-MCU or a correlator allowing to  
 39 wake up only a specific node, thus blackcucing considerably the waste of energy consumption of the  
 40 main radio [5].

41 As LoRa and WuRs present orthogonal features (long range with LoRa and short range with  
 42 WuRs), recent works have proposed to combine these two technologies to achieve an energy efficiency  
 43 and reduce the downlink latency [6,7]. Nevertheless, LoRa resilience is limited if the devices are battery  
 44 powered, which also limits their deployment in constrained environments as the cost of the battery  
 45 replacement is high in difficult to access environments. Therefore, improving energy efficiency is not  
 46 sufficient in itself. Energy harvesting, that converts energy from environmental sources, is a viable  
 47 alternative to ensure sustainable operation and perpetually power devices or at least extend their  
 48 lifetime [8].

49 This work investigates the use of energy harvesting, in a network architecture that combines the  
 50 two technologies LoRa and WuR, with an adequate MAC protocol LoRa-WuR to reduce the downlink  
 51 latency and to keep nodes self sustainable. Another challenge is to achieve a consistent downlink  
 52 Quality of Service (QoS) (i.e. the received command rate) with low fluctuation between periods of  
 53 plenty energy and sparse energy. To that goal, the node uplink QoS (i.e. the packet generation rate) is  
 54 tuned according to the harvested energy by a software component called energy manager. In this work,  
 55 a novel energy manager dedicated to LoRa-WuR MAC protocol is presented, allowing an improvement  
 56 of both downlink latency and downlink QoS consistency. Therefore, the main contributions of this  
 57 work are:

- 58 • A novel energy manager suitable to heterogeneous nodes with energy harvesting capabilities.
- 59 • A new MAC protocol leveraging WuR that reduces LoRaWAN downlink latency.
- 60 • Hybrid energy and latency models based on real platform microbenchmarks.
- 61 • Evaluation of the influence of energy harvesting conditions on the downlink QoS and the latency.

62 This paper is structured as follows. In Section 2 related works are given. Section 3 details the  
 63 network architecture and the MAC protocol. A latency and average power consumption models  
 64 and evaluation with experimental measurements are presented in Section 4. A use case with energy  
 65 harvesting nodes is proposed in Section 5 followed by a conclusion in Section 6.

## 66 2. Related works

67 **The related works concern both long range and WuR communication technologies and the**  
 68 **combination of these two technologies in a heterogeneous architecture. The energy harvesting**  
 69 **dedicated to LoRa sensor nodes is also investigated.**

### 70 2.1. Long Range communications

Some IoT applications require both long range connectivity and low power consumption, and recent LoRa technology allows such performance. LoRa physical layer uses the Chirp Spread Spectrum (CSS) modulation which allows a resilient communication to interference and a long coverage with low power characteristics [9,10]. Different configuration parameters can be exploited with LoRa: the carrier frequency, the spreading factor  $SF$ , the bandwidth  $BW$  and the coding rate  $CR$ . The combination of these parameters provides different tradeoffs between battery lifetime and transmission range [11]. The bitrate  $R_b$  is calculated by:

$$R_b = SF \frac{BW}{2^{SF}} CR. \quad (1)$$

71  $SF$  represents the number of chips per symbol and can take values from 6 to 12. The higher the  
 72 value is, the more time is taken to send a packet and the higher range is achieved. The coding rate

73 CR can take the following values:  $\frac{4}{5}$ ,  $\frac{2}{3}$ ,  $\frac{4}{7}$ ,  $\frac{1}{2}$ . The smaller the coding rate is, the higher the time on air  
74 is and the more reliable the data transmission is. BW can be chosen among three options: 125 kHz,  
75 250 kHz or 500 kHz. For long range, the lowest value should be configured.

76 LoRa can be associated with any MAC protocol, but LoRaWAN (developed by LoRa Alliance)  
77 is currently the only standardised MAC. LoRaWAN networks typically use a star topology in which  
78 gateways gather messages from nodes, also called End-Devices (EDs), and a central network server at  
79 the backend [12]. LoRaWAN specification defines three classes:

- 80 • Class A: in this class, EDs can initiate an uplink transmission based on their own communication  
81 needs. Each uplink transmission is followed by two short downlink receive windows [13]. This  
82 class has the lowest power consumption of the ED but the highest downlink latency from the  
83 server.
- 84 • Class B: in addition to class A receive windows, EDs in class B open extra receive windows,  
85 called ping slots [14]. If no preamble from the gateway is detected during this ping slot, the ED  
86 immediately returns back to sleep. If a preamble is detected, the radio transceiver stays on until  
87 the frame is demodulated. The gateway also provides a time reference to the EDs by periodically  
88 broadcasting beacon.
- 89 • Class C: EDs in class C continuously open receive windows, only closed for transmission. These  
90 EDs consume more power than with class A or class B but offer the lowest downlink latency.

91 A tradeoff needs to be made between downlink latency and power consumption of these three  
92 classes. Usually, in applications such as smart building or environment monitoring, the EDs use  
93 LoRaWAN class A as it offers the lowest power consumption but at the cost of a high downlink latency.  
94 On the other hand, gateways are using class C as they are not energy constrained. Some applications  
95 such as applications based on event driven, in which the gateway has a critical command to send to  
96 the EDs, require a low downlink latency. This is why we investigate the use of the WuR with LoRa.

## 97 2.2. Wake-up Radio

98 WuR is a ULP receiver that is continuously listening to the channel while consuming a few  
99 nanowatts or microwatts depending on the circuitry design. WuR is used in addition to the main  
100 transceiver and allows an asynchronous wake-up of the main node with low latency. Using the WuR  
101 allows to reduce the power consumption of the network, without suffering the bloated latency of all  
102 mechanisms of time synchronization induced by duty cycled MAC protocols [15]. When a WUB is  
103 received by the WuR, the latter wakes up the main node via an interrupt. The WUB can contain the  
104 address of the destination node to only wake-up a specific node. In such case, an address matching  
105 is performed with a ULP-MCU or a correlator. Different circuit designs of the WuR can be found in  
106 the literature, and most of them work with OOK (On-Off Keying) modulated signals [16], allowing a  
107 simplified WuR circuitry. As a consequence, WuRs have both a low sensitivity and a low bitrate. In  
108 this work, the WuR proposed in [5] is used. This WuR consumes  $1.80 \mu\text{W}$  in sleep mode when listening  
109 to the channel. It works at 868 MHz, and achieves a sensitivity of -55 dBm. Moreover, this WuR design  
110 provides address decoding capabilities with a ULP-MCU (a PIC12LF1552 from Microchip), at a cost of  
111 few additional micro-watts when a signal is received, achieving a power consumption of  $284 \mu\text{W}$ .

112 Designing dedicated MAC protocols is important to deal with WuR features and to improve  
113 the performance of the sensor nodes. Therefore, several cross layer protocols leveraging WuR were  
114 proposed in the literature. Mahlke et al. proposed in [17] WuR-MAC for multi-hop wireless  
115 sensor networks that allows a low power consumption and a low hop-to-hop delay thanks to the WuR.  
116 Sampayo et al. proposed in [18] a MAC protocol that allows a load balancing parent selection for  
117 RPL using WuR. Djidi et al. proposed in [19] WARP, a MAC protocol, that allows an adaptive power  
118 transmission and a relaying technique that improves the network lifetime. WuR was also combined  
119 with long range communications and specific MAC protocols will be presented in the next Section.

### 120 2.3. Heterogeneous architecture

121 Nodes can embed different radio technologies and can therefore exploit such radio diversity in  
122 order to reduce both energy consumption and latency. If it could be expected that using more than one  
123 radio technology increases the power consumption, exploiting low power radio to save the energy of  
124 high power radio can significantly reduce the global power consumption of the network. Ait Aoudia  
125 et al. proposed in [6] to combine LoRa communication with WuR-based short range communication  
126 to reduce both power consumption and LoRa downlink latency. Piyare et al. proposed in [20] to use  
127 the same heterogeneous architecture but with a new MAC protocol. Both of them considered a star  
128 network topology with a Cluster Head (CH) that uses LoRa in class C, which manages the received  
129 messages, from the gateway, intended to other EDs that are in the same cluster. The drawback of this  
130 architecture is the use of the CH in class C that has a high power consumption and thus inducing  
131 a short lifetime of the network. We propose in this work to extend the previous work of Djidi et  
132 al. [7] that introduced a novel MAC protocol for heterogeneous architectures combining LoRa and  
133 WuR. The novel MAC protocol allows opportunistic CH mechanism, since all EDs operate in LoRa  
134 class A, reducing significantly both downlink latency and the power consumption. In this work,  
135 we also investigate the use of energy harvesting for sensor nodes that are using this heterogeneous  
136 architecture.

### 137 2.4. Energy harvesting dedicated to LoRa sensor nodes

138 Maintaining nodes sustainably alive is important for a large deployment of IoT nodes, and  
139 improving the MAC protocol and reducing circuit power consumption are not always sufficient.  
140 Therefore, recent works are investigating the use of energy harvesting nodes in LoRa networks.  
141 Ferrero et al. investigated in [21] solar, thermal and piezo harvesting techniques for autonomous  
142 sensing applications that communicate with LoRa. Lee presented in [22] a novel floating device  
143 with multi-sources energy harvesting techniques that harvests solar and thermoelectric energy and  
144 communicates with LoRa. Sherazi et al. presented in [23] a LoRaWAN architecture in which the  
145 gateway is powered by an energy harvesting source. Soledad et al. proposed in [24] a testbed for smart  
146 farming applications that uses LoRa technology to communicate and uses a solar panel to extend the  
147 device lifetime. Benkhelifa et al. studied in [1] the resource allocation in LoRa networks supplied by  
148 ambient energy harvesting. Mabon et al. presented in [25] a prototype of an energy harvesting LoRa  
149 platform with an accurate sizing of both the solar cell and the battery.

150 In this work, we propose to exploit the use of solar energy harvesting in the heterogeneous  
151 network architecture that combines LoRa and WuR in order to make nodes sustainable and to better  
152 explore the uplink/downlink QoS of sensor nodes and highlight the advantage of the novel MAC  
153 protocol, namely LoRa-WuR.

## 154 3. Architecture and MAC protocol design

155 In this section, the heterogeneous network architecture that combines LoRa and WuR, and the  
156 MAC protocol LoRa-WuR are presented.

### 157 3.1. Network architecture

158 The heterogeneous network architecture considered in this work is shown in Figure 1. Nodes  
159 are distributed in clusters in which they can communicate with each other using Short Range (SR)  
160 communication [6,26]. At a distance of few kilometers from a cluster, a gateway can receive data from  
161 nodes or may send commands to the nodes using Long Range (LR) communication like the traditional  
162 LoRa scheme (i.e. LoRaWAN). The command can be for example a command for changing the data  
163 rate or any control command for actuators based applications. Therefore, this network architecture  
164 targets applications for which the gateway can have control of the network for data collection, nodes  
165 configurations and even actuator activation. Each node embeds two different communication modules.

166 The first one can handle LoRa and OOK modulations. This transceiver allows switching from both  
 167 modulation schemes, LoRa is used for the LR communication with the gateway, and OOK modulation  
 168 is used between nodes that are in the SR of each other. The other module is a WuR that is always  
 169 listening to the channel and receives data with OOK modulation as form of a WUB. Nodes uses LoRa  
 170 class A to communicate with the gateway and thus they are passing most of their time in sleep state,  
 171 and are only wake-up to send data to the gateway or when they receive an interrupt from the WuR.  
 172 Furthermore, all nodes are equipped with an energy harvesting device, for example a solar panel. In a  
 173 real deployment, some nodes will obviously harvest less power than others, either because a problem  
 174 occurs in their solar panel, or being hidden by an obstacle or being under the cloud. Therefore, two  
 175 types of harvesting conditions are considered in Figure 1: nodes that harvest less energy are in zone 1  
 176 and those that harvest more energy are in zone 2. Nodes that are in zone 2 will maximise their uplink  
 177 QoS that is expressed in terms of packet generation rate. In the contrary, those who are in zone 1 will  
 178 reduce the uplink QoS as they harvest less energy. The uplink QoS tuning according to the harvested  
 179 will be presented in Section 5.1.

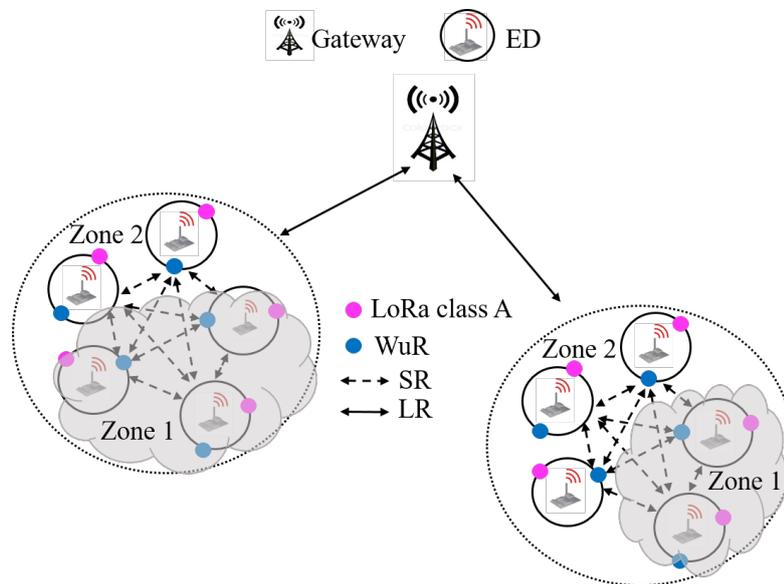


Figure 1. Heterogeneous network architecture with energy harvesting.

### 180 3.2. LoRa-WuR MAC protocol

181 The proposed MAC protocol is described in Figure 2. It concerns nodes that are in the SR of  
 182 each other and thus forming one cluster. It is assumed that the gateway already knows the location  
 183 of all nodes and all the potential clusters. Nodes communicate with the gateway using LoRa class A.  
 184 When a node sends data to the gateway, it opens two receive windows as it is in class A, and becomes  
 185 systematically an Opportunistic Cluster Head (OCH). Therefore, the gateway can take the opportunity  
 186 from one of its receive windows to send Command (CMD) intended to another node called targeted  
 187 node. If the OCH receives during one of its receive windows a CMD that it is intended to the targeted  
 188 node, it switches its LoRa module to OOK modulation and forwards the CMD in the SR to the targeted  
 189 node as form of a WUB. The WUB contains the address of the targeted node and the CMD itself. The  
 190 targeted node will receive the WUB via its WuR. Thanks to this MAC protocol, namely LoRa-WuR,  
 191 the downlink latency will considerably be reduced, as the gateway will take the opportunity from  
 192 any receive window of any node. Nodes that are in zone 1 (low energy), having a lower uplink QoS  
 193 than those in zone 2 (high energy), become less frequently OCH than those in zone 2, but all nodes  
 194 cooperate together as each node can become an OCH during one of its LoRa receive window.

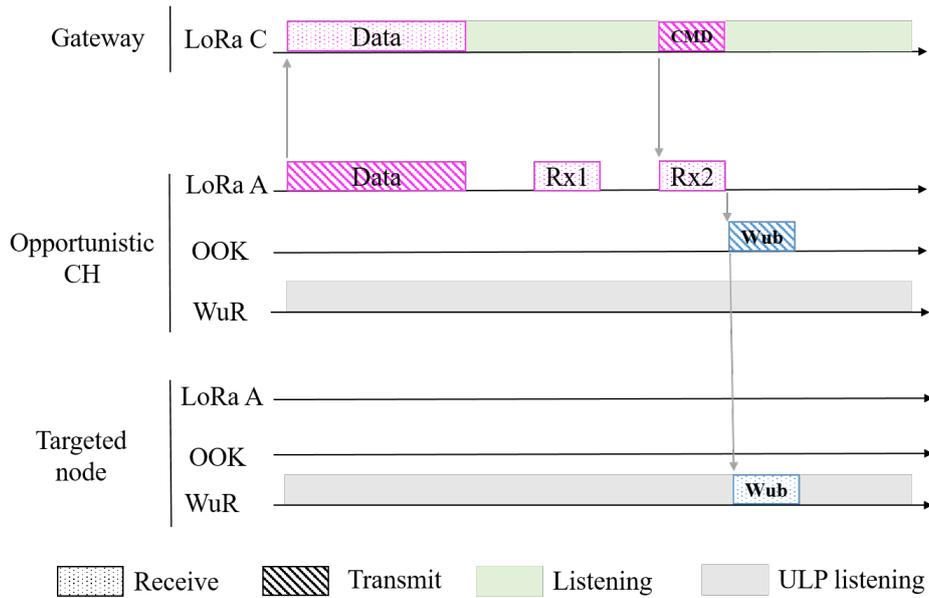


Figure 2. LoRa-WuR MAC protocol.

#### 195 4. Latency and power consumption models and evaluation

196 In this section, the models of average downlink latency and average downlink power consumption  
 197 of nodes using both the traditional LoRa scheme and LoRa-WuR are given. For an accurate evaluation  
 198 of the models, experimental measurements from microbenchmark are included in the models. The  
 199 average downlink latency is evaluated for different uplink QoSs, and the uplink QoS is tuned in  
 200 Section 5.1 according to the harvested energy.

##### 201 4.1. Latency model

202 Figure 3 illustrates the difference of latency between the traditional LoRa scheme and LoRa-WuR  
 203 one. A chronogram with only two nodes is presented for clarity purpose. For LoRa scheme, when  
 204 the gateway sends a CMD intended to node 2, it has to wait until the node 2 will be active to receive  
 205 the CMD during its receive window. However, for LoRa-WuR scheme it has to wait any node to be  
 206 active that will become an OCH, i.e. node 1 in this illustration, to transmit the CMD and then the OCH  
 207 forwards it to node 2 using the SR communication.

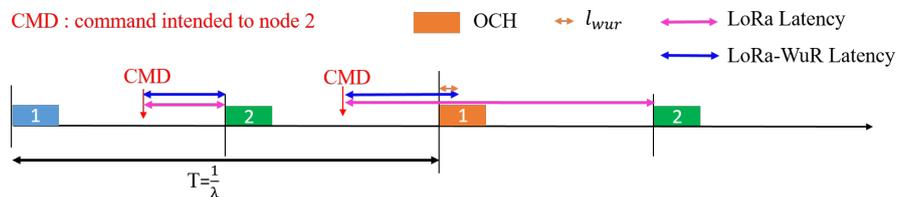


Figure 3. Chronogram illustrating the downlink latency.

208 A cluster of  $N$  nodes is considered and no collisions is assumed due to the low packet generation  
 209 rate and the short length of WUB packets. When using LoRa class A scheme, the gateway waits  
 210 for an uplink transmission of a node before sending a CMD. The average waiting time to reach a  
 211 targeted node is thus  $\frac{1}{2\lambda_i}$  [6], with  $\lambda_i$  the packet generation rate (uplink QoS) of any node  $i$ . The average  
 212 downlink latency  $L_{LoRa}$  of the CMD transmission from the gateway to a node is expressed as:

$$L_{LoRa} = \frac{1}{2\lambda_{cmd}^{LoRa}} + l_{cmd}, \quad (2)$$

213 with  $l_{cmd}$  the packet duration of sending the CMD using LoRa, and  $\lambda_{cmd}^{LoRa}$  is a novel metric that  
 214 represents the average received CMD rate by the EDs, called downlink QoS, when using the traditional  
 215 LoRa scheme. As when using the traditional LoRa scheme, an ED can receive a CMD from the gateway  
 216 only after its self uplink, so  $\lambda_{cmd}^{LoRa}$  is equal to:

$$\lambda_{cmd}^{LoRa} = \frac{\sum_{i=1}^N \lambda_i}{N}, \quad (3)$$

217 with  $N$  the number of EDs in a cluster.

218 An ED that uses LoRa-WuR can receive a CMD from the gateway after an uplink of any ED that  
 219 becomes an OCH, and thus the average downlink latency  $L_{LoRa-WuR}$  is expressed as:

$$L_{LoRa-WuR} = \frac{1}{2\lambda_{cmd}^{LoRa-WuR}} + l_{wur} + l_{cmd}, \quad (4)$$

220 with  $l_{wur}$  the packet duration using the SR communication (i.e. the transmission of the WUB) which is  
 221 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), and  
 222  $\lambda_{cmd}^{LoRa-WuR}$  the average downlink QoS when using LoRa-WuR scheme and it is expressed as:

$$\lambda_{cmd}^{LoRa-WuR} = \sum_{i=1}^N \lambda_i. \quad (5)$$

#### 223 4.2. Power consumption model

224 Using the LoRa class A scheme, CMDs from the gateway can only be transmitted to a node after  
 225 an uplink transmission. The average power consumption of a node with an average packet generation  
 226 rate  $\lambda$  incurred by a downlink communication denoted  $P_{LoRa}$  is:

$$P_{LoRa} = e_{cmd}^L \lambda, \quad (6)$$

227 where  $e_{cmd}^L$  is the energy cost of receiving a CMD from the gateway using LoRa.

The average power consumption of a node incurred by the downlink communication using  
 LoRa-WuR scheme denoted  $P_{LoRa-WuR}$  is expressed as:

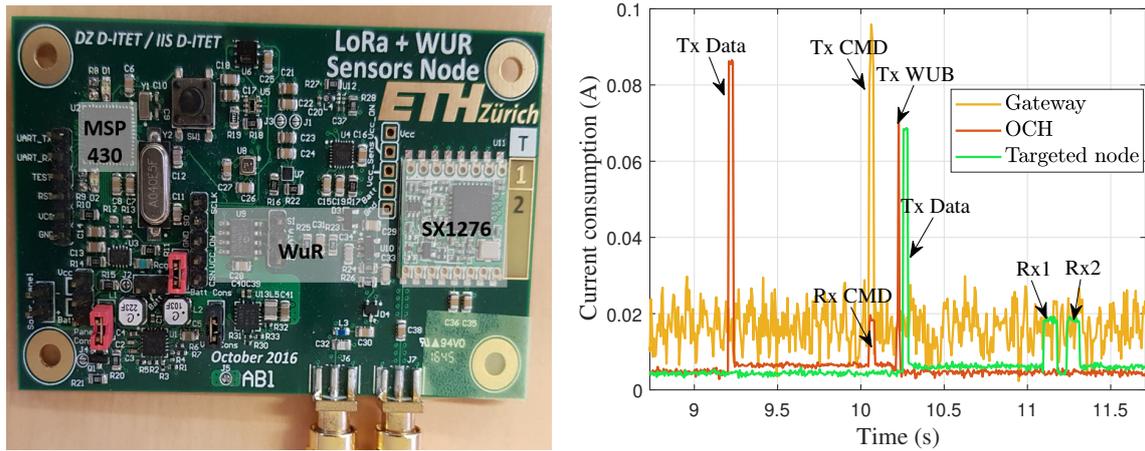
$$P_{LoRa-WuR} = (e_{cmd}^{wurx}(N-1)\lambda + (1 - (N-1)\lambda)l_{wur})P_{idle}^{wur} + (e_{cmd}^L + e_{cmd}^{wutx})\lambda, \quad N \geq 2, \quad (7)$$

228 where  $e_{cmd}^{wurx}$  is the energy cost to receive and process the WUB by the WuR,  $P_{idle}^{wur}$  is the power  
 229 consumption of the WuR when the ULP-MCU is in a sleep state and only the radio is active listening to  
 230 the channel, and  $e_{cmd}^{wutx}$  is the energy cost to forward the CMD by the OCH using the SR communication.

#### 231 4.3. Experimental platform and microbenchmark

232 The proposed LoRa-WuR MAC protocol was implemented on the platform designed in ETH  
 233 Zurich [27] and shown in Figure 4(a). It contains a SX1276 module from Semtech that allows OOK  
 234 modulation and LoRa, a WuR from [5] and a MSP430 MCU from Texas Instruments.

235 Figure 4(b) shows a microbenchmark considering three nodes, one node as a Gateway, and two  
 236 EDs. It shows the current consumption of each node during a packet forwarding with LoRa-WuR  
 237 protocol. The measurements were performed by using a DC power analyser Keysight N6705B. The  
 238 node (in red) that transmits the data becomes an OCH and when it receives the CMD from the gateway  
 239 (in yellow), that is intended to a targeted node (in green), it forwards the CMD as form of a WUB. Once  
 240 the CMD received from the OCH, the targeted node transmits data packet to the gateway using LoRa.  
 241 All these steps of the protocol are illustrated in Figure 4(b).



(a) Platform used for experimentations

(b) Microbenchmark showing the LoRa-WuR protocol

**Figure 4.** Experimental platform and microbenchmark.

242 The measured power consumption, at a voltage of 3.3 V, and all durations of different steps of the  
 243 MAC protocol are summarised in Table 1. These measurements are used to feed the analytical models  
 244 and the results are given in the next section.

**Table 1.** Measured values from microbenchmark

Parameter	Value	Parameter	Value
$e_{cmd}^{wutx}$	2.19 mJ	$p_{idle}^{wur}$	1.83 $\mu$ W
$e_{cmd}^{wurx}$	4.5 $\mu$ J	$R_{WUB}$	1 kbps
$e_{cmd}^L$	92.52 mJ	$L_{WUB}$	2 bytes

#### 245 4.4. Power consumption and latency tradeoff

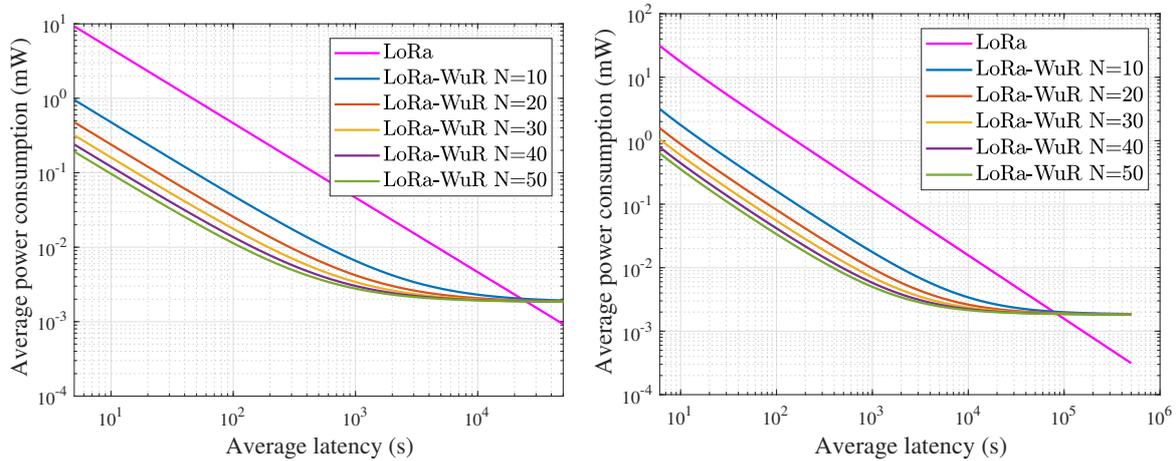
246 Figure 5 shows the average power consumption of a node as a function of the average downlink  
 247 latency for both schemes LoRa and LoRa-WuR, and with different number of nodes  $N$  ranging from 10  
 248 to 50 in case of LoRa-WuR. Moreover, two different configurations of SF, BW and CR are set and are  
 249 listed in the Table 2, and are also noted at the bottom of both Figure 5(a) and Figure 5(b). These results  
 250 are obtained from analytical models that are fed with the measured power consumption of the different  
 251 operating modes. The average downlink latency and the average power consumption only depend on  
 252 the downlink QoS for LoRa scheme whereas they depend on both the downlink QoS and the number  
 253 of nodes for LoRa-WuR. The uplink QoS is varied from  $10^{-6}$  packet/s to 0.1 packet/s. It can be seen  
 254 from Figure 5(a) that the node achieves lower power consumption and lower downlink latency than  
 255 the node in Figure 5(b), as it uses the lowest SF. The choice of the configuration has an impact on  
 256 both downlink latency and the average power consumption of the node, but the performance gain  
 257 of LoRa-WuR over LoRa scheme is about the same for both configurations. It appears from both  
 258 figures that to achieve the same downlink latency with LoRa-WuR as with LoRa scheme, the average  
 259 power consumption is reduced with LoRa-WuR when the downlink latency is less than  $2.2 \times 10^4$  s  
 260 and  $8.3 \times 10^4$  s, respectively in case of Figure 5(a) and Figure 5(b). For example to achieve 250 s, the  
 261 average power consumption is reduced down to 8.9 times (Figure 5(a)) and 9.4 times (Figure 5(b)),  
 262 respectively with 10 nodes compared to LoRa. However, when the downlink latency is very high  
 263 and greater than  $2.2 \times 10^4$  s (Figure 5(a)) and  $8.3 \times 10^4$  s (Figure 5(b)), respectively, the traditional LoRa  
 264 scheme becomes more energy efficient than LoRa-WuR because of the overhead of idle listening of  
 265 the WuR. It can also be seen that, for LoRa-WuR, the higher the number of nodes is, the lower the  
 266 average power consumption is. For example to achieve a downlink latency of 250 s, the average power

267 consumption is reduced down to 3.7 times (Figure 5(a)) and 4.3 times (Figure 5(b)), respectively with  
 268 50 nodes compared to when using 10 nodes. This is due to the fact that, to achieve the same downlink  
 269 latency, the uplink QoS needs to be higher when the number of nodes is low compared to when the  
 270 number of nodes is high, which induces an increase of the power consumption.

271 Figure 5 also shows that the downlink latency is reduced with LoRa-WuR for a given power  
 272 consumption. To achieve the same power consumption with LoRa-WuR as with LoRa scheme, the  
 273 uplink QoS is reduced to compensate the overhead of forwarding the CMD by the OCH, but as nodes  
 274 cooperate with each other, the downlink QoS is improved and the average downlink latency is reduced  
 275 with LoRa-WuR even if the uplink QoS of a node is reduced, and the more the nodes are used in  
 276 the cluster, the more reduced the downlink latency is. Therefore, the proposed LoRa-WuR protocol  
 277 achieves better performance than the traditional LoRa scheme. However, this improvement is not  
 278 sufficient to keep nodes sustainable. This is why the use of energy harvesting is investigated in the  
 279 next section. The uplink QoS can be tuned according to the harvested energy in order to take a full  
 280 advantage of the proposed MAC protocol.

**Table 2.** Setup used for LoRa

Config. 1		Config. 2	
Parameter	Value	Parameter	Value
$SF$	6	$SF$	12
$BW$	500 kHz	$BW$	125 kHz
$CR$	$\frac{4}{5}$	$CR$	$\frac{4}{8}$
$R_b$	37.5 kbps	$R_b$	0.183 kbps
Payload	5 bytes	Payload	5 bytes
$l_{cmd}$	5.6 ms	$l_{cmd}$	1.09 s



(a) Config. 1:  $SF=6$ ,  $BW=500KHz$ ,  $CR=\frac{4}{5}$

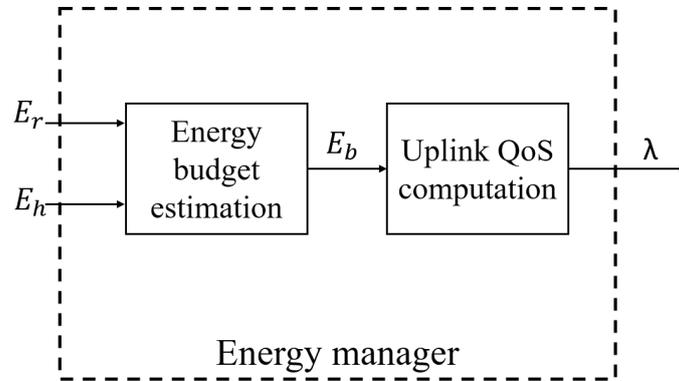
(b) Config. 2:  $SF=12$ ,  $BW=125KHz$ ,  $CR=\frac{4}{8}$

**Figure 5.** Average power consumption as a function of average downlink latency.

## 281 5. Combining LoRa-WuR architecture with energy harvesting

282 In this section a combination of the LoRa-WuR architecture with solar energy harvesting profile is  
 283 considered. Therefore, the uplink QoS is tuned for each node according to the harvested energy with  
 284 an energy manager. An energy manager is proposed and compared to two different energy managers.  
 285 The proposed energy manager is called Redistribution of the Harvested Energy (RHE) that allows a  
 286 small variation of the uplink QoS between days and nights. Figure 6 shows the procedure of the energy

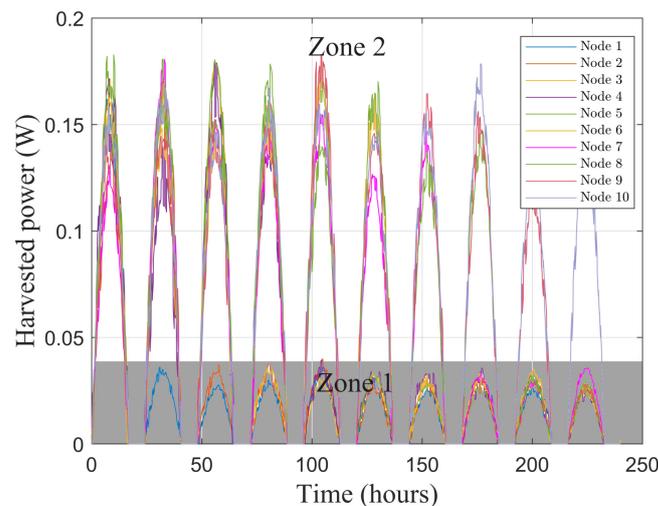
287 manager which consists in two blocks: the energy budget estimation and the uplink QoS computation.  
 288 The energy manager is periodically executed at each slot  $T_s$ , the energy budget estimation block  
 289 estimates the energy budget  $E_b$  that corresponds to the energy that a node can consume in the next slot.  
 290 Then, according to this  $E_b$  and the used MAC protocol, the uplink QoS is calculated for each node.



**Figure 6.** Energy manager: uplink QoS tuning procedure.

### 291 5.1. Energy harvesting profile

292 Outdoor solar daytime energy sources are considered in this study and power traces are generated  
 293 by considering a solar panel area set to  $30 \text{ cm}^2$  for each node. As in real deployment some nodes  
 294 will harvest less power than others, either because they are hidden from the solar source or due to a  
 295 dysfunction of their solar panel. Therefore, the average power density is equal to  $50 \text{ W/m}^2$  for nodes  
 296 that are in zone 2 whereas it is set to  $10 \text{ W/m}^2$  for nodes in zone 1 that harvest less energy. Figure 7  
 297 shows the harvested power traces generated for 10 nodes during 10 days using the algorithm proposed  
 298 in [28], with nights lasting for 8 hours. To evaluate the influence of the ratio between the number of  
 299 nodes in zone 1 and in zone 2, one node is moving each day from zone 2 to zone 1. The first day, all  
 300 nodes are assumed to have the same average harvested power and are in zone 2. The second day, one  
 301 node moves in zone 1 and has a reduced average harvested power and so on until the last day when  
 302 nine nodes have a reduced average harvested power and only one node is still in zone 2 with a high  
 303 average harvested power.



**Figure 7.** Harvested power for each of the 10 nodes during 10 days.

## 304 5.2. Energy budget estimation

305 To determine the uplink QoS of a node, an energy budget  $E_b$  should be estimated. Therefore,  
 306 three Energy Managers (EMs) are implemented to compare their performance, the first one is based  
 307 on Fuzzyman [29] that is model free, the second one is based on GRAPMAN [28] that allows a  
 308 gradual tuning of the packet generation rate, and the novel one RHE is based on a redistribution  
 309 of the harvested energy between days and nights. These three EMs are quite simple and incur few  
 310 computations, and therefore are well-adapted to wireless sensor networks.

311 The simulation was run in Matlab for 10 days (simulation time) and super-capacitors of 15 F are  
 312 used to store energy as super-capacitors are more durable and also have higher power density when  
 313 compared to rechargeable batteries [30].

314 Fuzzyman takes as inputs the residual energy denoted  $E_r$  and the harvested energy denoted  $E_h$ .  
 315 Fuzzyman is executed each slot  $T_s$  fixed at 600 s. According to the harvested energy and the residual  
 316 energy,  $E_b$  is estimated for the next slot  $T_s$  by considering five fuzzy sets with their membership  
 317 functions [29]. Two sets concern the harvested energy called weak and strong, and three sets concern  
 318 the residual energy and are called fail, empty and full. A minimum energy budget is fixed to 1 J which  
 319 is the energy required to allow a minimum uplink QoS corresponding to  $\lambda$  equal to 0.0103 packet/s,  
 320 when using LoRa scheme, and it is equal to 0.0100 packet/s when using LoRa-WuR scheme.

321 GRAPMAN [28] gradually adapts the wake up interval (that is the reverse of the packet generation  
 322 rate). At the beginning of each time slot  $T_s$ , GRAPMAN checks the wake up interval used at the  
 323 previous slot. If the wake up interval prevents nodes from power failure, then it is decreased.  
 324 Otherwise, it is increased. Thus, at each time slot, the wake up interval either stays the same, or  
 325 is incremented by  $\pm\Delta TWI$ .  $\Delta TWI$  is fixed to 1 s in our simulation, and the other parameters of the  
 326 algorithm are used from [28].

327 As Fuzzyman is a model free that allows a high uplink QoS during the day and a low uplink QoS  
 328 during the night, and GRAPMAN gradually tunes the uplink QoS without taking in consideration the  
 329 ratio between days and nights, therefore a novel energy budget estimation is proposed that allows a  
 330 small fluctuation of the uplink QoS between days and nights. To tackle this issue and limit the uplink  
 331 QoS variation, the idea of RHE is to store enough energy in the super-capacitor during periods of high  
 332 harvested energy in order to reuse it during periods of energy scarcity (being at night for example).  
 333 Unlike WVR-PM [30], RHE considers, at each slot, the harvested energy of the previous slot. whereas  
 334 WVR-PM requires the estimation of the harvested energy of the next slot. At each slot  $kT_s$ , RHE checks  
 335 the harvested energy of the previous slot  $(k-1)T_s$ , if it is greater than certain threshold  $E_h^{th}$  fixed at  
 336 10 J, the node uses  $E_b(kT_s)$  that is equal to:

$$E_b(kT_s) = \frac{TE}{TNE + TE} E_h((k-1)T_s), \quad (8)$$

337 with  $TE$  is the energy harvesting interval (when the energy harvesting is greater than  $E_h^{th}$ ), and  $TNE$  is  
 338 the non-energy harvesting interval (when the energy harvesting is lower than  $E_h^{th}$ ) and it is equal to  
 339 10 hours per day with the harvested profile described in Section 5.1. When the harvested energy is  
 340 less than  $E_h^{th}$ , the node uses the stored energy in the super-capacitance. This technique allows a small  
 341 variation of  $E_b$  between days and nights.

## 342 5.3. Uplink QoS computation

343 The uplink QoS expressed in terms of packet generation rate  $\lambda$  that will be calculated each  $T_s$   
 344 once  $E_b$  is estimated.  $E_b$  corresponds to the energy that a node will consume during a time slot  $T_s$ ,  
 345 thus to determine  $\lambda$ , the total energy consumption of a node should be derived and depends on the  
 346 MAC protocol: LoRa scheme or LoRa-WuR in this study. A node using LoRa class A passes through  
 347 different states, transmitting data ( $Tx$ ), first wait window ( $W1w$ ) before opening the first receive  
 348 window ( $Rx1w$ ), a second wait window ( $W2w$ ) before opening the second receive window ( $Rx2w$ )  
 349 and finally come back to sleep state. The description of these states and their duration and power

consumption are illustrated in Table 3. The duration  $T_{tx}$  (that is equal to the Time on Air),  $T_{Rx1w}$ ,  $T_{W2w}$ , and  $T_{Rx2w}$  depend on the used data rate [31] that is given in config. 1 of Table 2.

**Table 3.** Parameters description and their values

Parameter	Description	Value	Unit
$T_{Tx}$	Time to transmit a packet (Time on Air)	5.6	ms
$P_{Tx}$	Power consumption when transmitting with LoRa	273.9	mW
$T_{W1w}$	Duration of the first wait window	983.3	ms
$P_{W1w}$	Power consumption during the first wait window	89.1	mW
$T_{Rx1w}$	Duration of the first receive window	5.6	ms
$P_{Rx1w}$	Power consumption of the first receive window	115.5	mW
$T_{W2w}$	Duration of the second wait window	978.1	ms
$P_{W2w}$	Power consumption during the second wait window	89.1	mW
$T_{Rx2w}$	Duration of the second receive window	33	ms
$P_{Rx2w}$	Power consumption of the second receive window	115.5	mW
$P_{sleep}$	Power consumption during sleep state	$148.5 \times 10^{-3}$	mW

The average uplink QoS when using LoRa scheme denoted  $\lambda_{LoRa}$  can be expressed as:

$$\lambda_{LoRa} = \frac{E_b - P_{sleep}T_s}{(T_{Tx}P_{Tx} + T_{W1w}P_{W1w} + T_{Rx1w}P_{Rx1w} + T_{W2w}P_{W2w} + T_{Rx2w}P_{Rx2w} - P_{sleep}T_{act})T_s} \quad (9)$$

with  $T_{act}$  the duration of all states related to the node activities except sleep state, and it is expressed as:

$$T_{act} = T_{Tx} + T_{W1w} + T_{Rx1w} + T_{W2w} + T_{Rx2w}. \quad (10)$$

When using LoRa-WuR, as an OCH will forward a CMD to a targeted node, then its power consumption will be increased. To compensate this increase of power and consume the same as when using the traditional LoRa scheme, the node using LoRa-WuR will reduce its uplink QoS, and thus the uplink QoS when using LoRa-WuR denoted  $\lambda_{LoRa-WuR}$  is expressed as:

$$\lambda_{LoRa-WuR} = \frac{E_b - P_{sleep}T_s - P_{idle}^{wur}T_s}{(P_{act}T_{act} + e_{cmd}^{wutx} + (N-1)e_{cmd}^{wurx} - (N-1)P_{idle}^{wur}T_{wub} - P_{sleep}T_{act}^{LoRa-WuR})T_s} \quad (11)$$

with  $T_{act}^{LoRa-WuR}$  the duration of all states related to the node activities including the duration of forwarding the CMD as form of a WUB and it is equal to:

$$T_{act}^{LoRa-WuR} = T_{act} + l_{wur}. \quad (12)$$

#### 5.4. Downlink QoS and downlink latency evaluation

The downlink latency depends on the downlink QoS (i.e. received CMD rate), and it can be calculated for both LoRa and LoRa-WuR schemes by (2) and (4). Further, in the considered scheme, the downlink QoS directly depends on the uplink QoS, following (3) and (5). And the uplink QoS (i.e. packet generation rate) is finally calculated by (9) and (11) according to the used MAC scheme. Figure 8(a) shows the average downlink QoS during 10 days, with both the traditional LoRa (dashed line) and LoRa-WuR (continued line) schemes, and with the three different EMs. It appears that when there is light, Fuzzyman achieves a downlink QoS between GRAPMAN and RHE, and by night it

368 achieves the minimum downlink QoS. GRAPMAN can achieve the highest downlink QoS but in a  
 369 short time horizon when there is light, and in the night the downlink QoS achieves its minimum  
 370 like Fuzzyman. RHE shows a minimum fluctuation of the downlink QoS between night and day.  
 371 When comparing LoRa and LoRa-WuR schemes (the dashed line compared to the continued line), it is  
 372 shown that with LoRa-WuR the downlink QoS is 10 times higher than when using the traditional LoRa  
 373 scheme, as all nodes contribute to forward the CMD in the SR. The average downlink QoS and its  
 374 variance according to the used EM, and with both the traditional LoRa scheme  $\lambda_{cmd}^{LoRa}$  and LoRa-WuR  
 375  $\lambda_{cmd}^{LoRa-WuR}$  are summarised in Table 4.

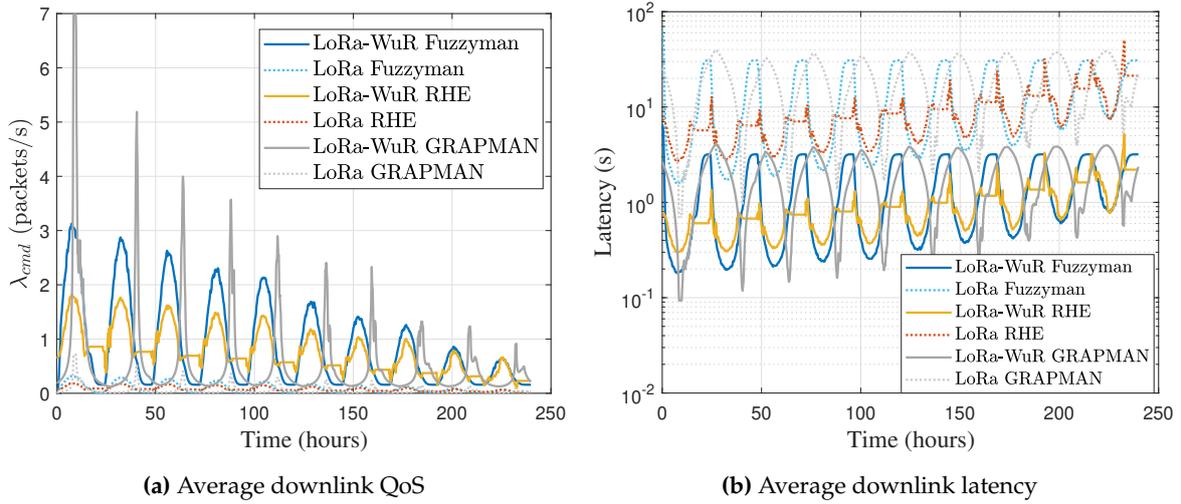


Figure 8. Average downlink QoS and average downlink latency during 10 days.

Table 4. Evaluation of both average downlink QoS and average downlink latency for Fuzzyman, RHE and GRAPMAN

Metrics \ EMs		Fuzzyman	RHE	GRAPMAN
CMD rate average (packet/s)	$\overline{\lambda}_{cmd}^{LoRa}$	0.090	0.077	0.056
	$\overline{\lambda}_{cmd}^{LoRa-WuR}$	0.883	0.750	0.548
CMD rate variance (packet/s)	$\overline{\sigma}(\lambda_{cmd}^{LoRa})$	0.007	0.002	0.008
	$\overline{\sigma}(\lambda_{cmd}^{LoRa-WuR})$	0.632	0.154	0.729
Downlink latency (s)	$L_{LoRa}$	13.32	8.78	19.56
	$L_{LoRa-WuR}$	1.39	0.92	2.03

376 The downlink latency with both schemes LoRa and LoRa-WuR are calculated by (2) and (4).  
 377 Figure 8(b) shows the average downlink latency during the 10 days with both the traditional LoRa  
 378 (dashed line) and LoRa-WuR (continued line) schemes, and with the three EMs. It can be seen that  
 379 regardless of the used EM, the downlink latency is reduced when using LoRa-WuR scheme compared  
 380 to the traditional LoRa scheme. RHE allows to have the lowest fluctuation on the downlink latency, so  
 381 at any time, the ED can receive the CMD from the gateway with roughly the same downlink latency.  
 382 Contrary to Fuzzyman and GRAPMAN where the downlink latency depends on the zone where the  
 383 ED is present (harvest less or more energy). Table 4 summarises the average downlink latency with  
 384 both schemes and with the three EMs. The downlink latency is reduced in average of a factor 9.5  
 385 (corresponding to a reduction by almost 90%) with LoRa-WuR scheme compared to the traditional  
 386 LoRa scheme.

## 6. Conclusion

This paper presents a MAC protocol for heterogeneous architecture combining LoRa for long range communication and wake-up radio (WuR) for short range communication (LoRa-WuR). Nodes are equipped with solar panel for harvesting energy, and a novel energy manager is proposed allowing an adaptive tuning of the quality of service for each node. Moreover, as in a real deployment nodes that harvest energy are subject to different perturbations, e.g. solar panels are hidden from the solar source, then two zones are considered in which nodes harvest a high or a low power. Results show that even if nodes harvest less energy, the downlink latency using LoRa-WuR can be reduced compared to the traditional LoRa scheme. It can be reduced by almost 90% for a cluster of 10 nodes. Thanks to the protocol LoRa-WuR, nodes are cooperative with each other and each node can contribute to forward commands received from the gateway to another node. This technique resolves the traditional bottleneck of LoRa protocol in which the gateway has not a full control of the network and has a long downlink latency. Furthermore, the more the nodes are present in the cluster, the more the downlink latency is reduced with LoRa-WuR (the maximum number of nodes that can be used in a cluster is however naturally limited by the short range of the WuR).

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