WaterAMI - Water Automated Metering Infrastructure Based on an Energy Aware Wireless Mesh Network Communication Protocol

Alexandra Vieira[1](✉), Carlos Patrão[2], Tiago Gonçalves[3], Paulo Monteiro[1], Sylvain Marcelino[3], Edmundo Filipe[3], João Damasceno[4], Hélio Pereira[5], Catarina Sousa[5], Paulo Oliveira[5], and João Carvalho[3]

[1] ApplianceARTS, Figueira da Foz, Portugal
{alexandravieira,pmonteiro}@appliancearts.com
[2] Institute of Systems and Robotics, University of Coimbra, Coimbra, Portugal
carlospatrao@isr.uc.pt
[3] CWJ-Power Electronics, Figueira da Foz, Portugal
{tiagogoncalves,smarcelino,efilipe,jcarvalho}@cwj.pt
[4] Águas da Figueira, Figueira da Foz, Portugal
joao.damasceno@aguasdafigueira.com
[5] Aquapor, Lisbon, Portugal
{heliopereira,catarinasousa,paulooliveira}@aquaporservicos.pt

Abstract. The WaterAMI is an Integrated Management of Efficiency System (IMES) of Water Distribution Networks (WDN) supported in an Automated Metering Infrastructure (AMI). It has a positive impact in energy consumption and in the water management, on one hand decreasing the water losses, on the other, by measuring and controlling water resources as well as water demand, supported in data science by predictive analytics.

The communications between devices of WaterAMI are realized through a Low Power Wide Area Network - All for Everyone - Energy Aware (LPWAN-AfE-EA), developed by CWJ Power Electronics. The AfE-EA protocol uses a mesh topology that grants the coverage of all the water infrastructure's devices, including devices placed in building's basements, normally not covered by other IoT communications protocols.

In order to maximize the operational performance of entire network, AfE-EA uses an efficient math algorithm that computes efficiently the Optimal Hop-Constrained Maximum Capacity Spanning Tree (OH-CMCST), which maximizes the routing path energy capacity and minimizes the number of hops of a battery-operated or energy constrained AMI's communications network, by taking in account the strengths of radio signal links and the State of Charge (SoC) of all batteries that power the smart sensors.

The WaterAMI is already installed and in full operation in several WDNs in Portugal. Where it solved constrains of previously installed similar systems.

This publication presents the main features of AfE-EA protocol, compares with other LPWANs and briefly describes AfE-EA implementation in the first application of WaterAMI in Portugal.

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1 Introduction

Over the last 20 years, the Internet of Things (IoT) technologies have evolved significantly [1]. The IoT refers to the inter connection and exchange of data among devices/sensors [2]. The combination of different devices with wireless communication forms a network named Wireless Sensor Network (WSN). The WSN provides a promising infrastructure for numerous control and monitoring applications fields [3] namely, Agriculture [4], Industrial, Utilities [5], Security, Asset Tracking, Smart Metering, Smart Cities, Smart Buildings/Facilities and Smart Homes.

The IoT technologies aim to efficiently utilize the resources, improve the quality of living, and reduce the cost of management and administration of resources [6]. Once each application field has specific requirements, to implement a WSN is necessary to select the appropriated communication protocol. Currently, specific applications such as Smart Cities require technological solutions with long range, low data rate, low energy consumption, and cost-effectiveness [2]. In response to these requests the LPWAN technology has been created [7].

LPWAN technology provides several communication protocols namely, Long Range (LoRa) [8], SigFox, and Narrow-Band Internet of Things (NB-IoT) [2]. Despite their promise, these protocols are still in their infancy with a high number of challenges in terms of spectrum limitation, coexistence, mobility, scalability, coverage, security, and application-specific requirements such as data rates and real-time communication which make their adoption challenging [6]. So the selection of the communication protocol with more advantages for one application, takes into account the present requirements of each network layer, separately [7], and also the future needs of the network that can arise with a possible growth of infrastructure [6].

To address the issues of coverage of all devices, battery lifetime of each device and cost-effectiveness, an AfE-EA protocol developed by CWJ Power Electronics is presented in this paper. In addition, the AfE-EA protocol allows the creation of a network highway for all the Smart City's devices, by integrated devices from the different infrastructures (e.g. luminaries, valves, sensors and controllers), in a concept of multi-infrastructure operation and management. Also, the AfE-EA protocol can integrate devices from different communication protocols, by the use of adequate hardware/interconnectable gateways (NB-IoT, LoRa, etc.).

The WDN study, implemented in Figueira da Foz, Portugal, uses the LPWAN-AfE-EA technology in a real deployment scenario of CELBI's neighborhood Measuring & Control Station (M&CS). The AfE-EA, embedded in a smart water telemetry solution named WaterAMI, provides successful results for the M&CS.

The paper is organized as follows: Sect. 2 presents a brief review of technological options for IoT; Sect. 3 describes AfE-EA protocol; Sect. 4 describes the WaterAMI solution, namely based in the sensor device Wireless Water Meter Transceiver (WWMT), with embedded AfE-EA protocol; Sect. 5 details a study case with WaterAMIs. Finally, Sect. 6 presents the main conclusions of this publication.

2 Technological LPWAN Options for IoT

The exponential growth of the number of companies based in IoT connectivity technologies boost the development of different wireless communication technologies [9]. These technologies characterized by specific features are selected in function of applications' requirements. The key requirements for IoT networks are coverage, battery life, costs, scalability and performance flexibility. These requirements drive up to the emerge of a new wireless communication technology, the LPWAN, which is characterized by the ability of connecting a significant number of devices, covering big areas using just one base station or gateway, and lowering power consumption [5]. SigFox, LoRa, and NB-IoT are the three leading LPWAN technologies that compete for large-scale IoT deployment.

SigFox is the most mature and widespread IoT technology, already deployed in 31 countries [2]. It is defined by a high coverage and communication range [10]: up to 10 km in urbane zone and up to 40 km in rural zone. Its bidirectional communication is limited to 140×12 bytes (uplink) and 4×8 bytes (downlink) messages/day [2]. SigFox adopters need to leverage on a communication infrastructure provided and owned by SigFox, which limits the options for coverage improvement and network optimization [10]. Between the three leading LPWAN technologies, SigFox has the lowest end-device cost [11]. Like LoRa, SigFox uses unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia) that have no additional costs. Both technologies have very high interference immunity [2].

LoRaWAN® is a bi-directionally communication protocol [12], like NB-IoT, constituted by a LoRa physical layer. It is a low-power long-range wireless protocol [13] which can reach ranges up to 5 km in urbane zone and up to 20 km in rural zone. In opposition to SigFox and NB-IoT, it has an unlimited number of messages/day. The payload length of LoRa (243 bytes) is higher than SigFox and lower than NB-IoT which has a payload length of 1600 bytes [2]. The network density of LoRa and SigFox affects its performance which drops exponentially as the number of end-devices grows. One significant advantage of the LoRaWAN® ecosystem is its flexibility [14], i.e., its adaptability to local/private network deployment. The LoRa technology is currently deployed in 42 countries.

Standardized by the 3rd Generation Partnership Project (3GPP), NB-IoT is a communication technology based on narrow band radio technology which is in development [2]. It uses licensed Long Term Evolution (LTE) frequency bands (e.g. 700 MHz, 800 MHz, and 900 MHz) [1] and is message-based, similar to SigFox and LoRa, but with a higher data rate [11] (i.e., NB-IoT up to 200 kbps, LoRa up to 50 kbps, and SigFox up to 100 bps). NB-IoT has the lowest coverage of the three LPWANs which indicates that it has a low capacity to penetrate deep indoor (e.g. basements). By contrast, NB-IoT has a high scalability [2] which allows the network growing over the time without disrupting existing services [5]. It allows connectivity of up to 100 thousand end-devices per cell compared to 50 thousand per cell for SigFox and LoRa [2]. NB-IoT has the higher Maximum Coupling Loss (MCL): NB-IoT 164 dB, LoRa 157 dB, and SigFox 153 dB [15]. Once MCL defines the range, NB-IoT has the lower range capacity, i.e., <1 km in urbane zone and <10 km in rural zones. Followed by LoRa, NB-IoT has the higher Quality of Service (QoS) [2]. However, it also has the higher end-device cost [11] which adds to the frequency spectrum use cost. Despite NB-IoT has low interference immunity, it has the higher network security [7]. From a global interoperability perspective, NB-IoT undoubtedly has the clearest advantage, being the output of extensive global standardization processes, followed by SigFox technology. The interoperability of LoRa is not guaranteed due to its highly customizable nature [5].

SigFox, LoRa, and NB-IoT, end-devices are in sleep mode most of the time when they are not in operation. The sleep mode reduces the amount of consumed energy and extends the battery lifetime of the devices. However the energy consumption of these protocols is still too high for the requirements of most of the online or quasi-online telemetry applications. The NB-IoT technology has the lower battery lifetime due to the additional energy consumption of the synchronous communication process and QoS handling [2]. In example, with a battery of 5 Wh, a MCL = 150 dB, and a medium payload of 50 bytes/2 h; the end-device lifetime of SigFox and LoRa is 13 years and of NB-IoT is 11 years [11]. Note that these values only take into account the energy consumption for communications, the other energy consumptions are neglected, namely the energy used by water transducers to perform measurements and data storage. However, NB-IoT offers the advantage of low latency. The higher values in latency performance are obtained by SigFox [2].

With the advent of IoT era, the number of connectivity links is growing exponentially causing emergence of the massive IoT networks which can connect tens of thousands of devices and covering hundreds of square kilometers. The LPWAN technologies mentioned above can be used in massive IoT applications, but their utilization would increase the cost and add some extent contradicts in their value proposition of being able to provide wider connectivity for less [5].

Based in meshed networks, a brand-new alternative is now available, the AfE-EA protocol, which is described in next chapter. The AfE-EA network connects a myriad of nodes in densely, sparse, and wider areas, with whole coverage of all the nodes, at same time. It allows the real cost-effectiveness of the IoT solutions, completely in accordance with the particular QoS requirements of the customers.

3 AfE-EA Protocol

AfE-EA is a LPWAN communication protocol developed by CWJ Power Electronics. The designation of the “All for Everyone”, or shorter AfE, means that all the IoT nodes of an infrastructure ecosystem can communicate efficiently among them, through the formation of a meshed network, by providing a communications highway, which can be used by all different IoT devices of a smart infrastructure (smart city, smart building or smart home).

The meshed technology allows the connectivity of an ultra-high number of devices significantly higher than SigFox and LoRa [5]. Wireless meshed networks can cover wide geographical areas, using IoT technologies with high coverage since the backbone that connects the gateways can be selected in function of application’s requirements. So, LPWAN-AfE-EA can simultaneously connects the devices of a massive IoT network, providing regional and national geographical reach through multi-hop between end-devices extending hundreds of kilometers from the gateway (i.e., high scalability), and overcomes the coverage constraints, e.g. related with hard geographical topology requirements, either in high urban density, or in low rural density.

The performance of AfE-EA protocol relays in Wireless M-Bus networks. However, unlike Wireless M-Bus Standard (EN 13757-5 Wireless M-Bus relaying) that only supports one hop relaying, AfE-EA supports an infinite number of hops which provides it with ultra-high coverage. In each hop, the communication can be realized bidirectional through different frequency bands, including the 169, 433, and 868 MHz and 2.4 GHz frequencies. To maximize the network coverage, according to the algorithm, every node of a LPWAN-AfE-EA network can be set as a router network role.

Other significant advantage of AfE-EA is the energy consumption which, in specific cases, is lower than in other communication protocols already described, due to the relative short transmission distances between nodes compared to star topologies [5]. Although a mesh network will require a higher number of hops, the AfE-EA algorithm minimizes the number of hops using a lower transmission power. The simple processor present in each one of the nodes, their energy efficiency and the fact that the algorithm takes into account the Sate of Charge (SoC) of each node, increases lifetime expectance of the network and justifies the nomenclature EA – Energy Aware, in the protocol designation. Depending on end-devices, its battery lifetime, when using AfE-EA protocol can be up to 15 years. The lifetime of the network is increased by: (1) the reduction of the power consumption which is obtain with the realization of coordinated short transmissions between nodes; and (2) the use of an efficient algorithm to compute an Optimal Hop-Constrained Maximum Capacity Spanning Tree (OH-CMCST) which maximizes the routing path energy capacity and minimizes the number of hops of a battery-operated or energy constrained AMI's communications networks. After each periodic computation of the OH-CMCSTs, performed by the Control Center (CC), the nodes follow the route that assures the lower possible communication latency to a gateway, maximizes the period of operation and assures the total coverage of the devices that compose the network. The need of computing a new OH-CMCST can arise when a communication link becomes less reliable; a new device is integrated on the network; a node is reaching the configured limit of available energy; or when there is the need to change data flow.

The computation of OH-CMCST from the data concentrators (DC) (or gateways) to all the others nodes, or from the nodes to the DC, is realized taking into account the State of Charge (SoC) and the average energy consumption of each node, i.e., the network role selected for each node minimizes the energy consumption to the lower possible value and maximizes the available stored energy. Note that all nodes from the extremities of the network tree, i.e., nodes without descendants, optionally, can be configured to a deep sleep mode and only wake up at defined periods. Being the hop-constrained spanning trees a NP-Hard problem, CWJ Power Electronics developed a mathematical algorithm which reduces the computational complexity, in polynomial time, of the OH-CMCST calculation. This algorithm allows the computation of thousands of nodes in a low cost/low capability processor or micro-controller (even to run dozens of thousands of nodes by a regular processor).

The QoS of AfE-EA is assured by its capacity of response to any outage, interruption, throughput and latency of network connectivity [5]. A link communication can fail unexpectedly due to multiple reasons, such as obstacles or tampering. Using alternative OH-CMCST of the multiple OH-CMCSTs calculated for each network, AfE-EA has the capability of self-optimizing and self-healing, with enhanced network security architecture (through the employment of standard approaches such as AES 128 bits encryption).

AfE-EA has a maximum payload length (i.e., 128 bytes/message) lower than LoRa, which was designed in accordance with the requirements of most of the field applications, and not by devices' constraints. However, it has a throughput than can excesses the NB-IoT results, e.g., at 2.4 GHz AfE-EA data rate is 250 kbps. At the same frequency, also has a very interesting latency result (i.e., 4 ms for each hop/2.4 GHz). Consequently, AfE-EA has an elevated QoS.

The diversity of Industry 4.0 or Digitalization project businesses require IoT technologies with flexible Level of Service Agreements (LSA), which in case of the AfE-EA, is a really big advantage due to the determinism of QoS. In opposition to SigFox and NB-IoT, or even, LoRa, AfE-EA network (as a private network meshed solution) can be well suited and adapted for specific, unique and local requirements of end-users namely, improvement of coverage in buildings' basements with hard radio coverage. The cost-effectiveness of the AfE-EA also is significantly better than NB-IoT, SigFox, or LoRa.

In addition, LPWAN-AfE-EA solution has decoupled the software layer from the hardware layer, and thus enables the protocol to benefit from the economies of large scale of any hardware platform from different manufacturers of radio modules, which solves the interoperability issues usually encounter in the rollout processes of new technologies.

Although meshed networks, like AfE-EA, are established in a quite different way of the common star configurations (P2MP) available on the market, a comparison needs to be performed. Figure 1 summarizes AfE-EA in terms of different IoT factors and compares them with SigFox, LoRa and NB-IoT. Thus, should be denoted that in the practical terms, although AfE-EA was specifically designed to overcome the LPWAN protocols, their features are not fairly comparable, due to the different nature of the communication principles, namely the restricted modes of operation based on limited/reduced up-links and down-links, the spray-and-pray transmissions, the costs of telecommunications fees, the hard paybacks of investments, etc.

The crescent demand of deployments in smart cities and smart buildings & facilities are based on monitoring and control the myriad of different services, supported by IoT devices namely, artificial lighting, urban solid waste, irrigation of green spaces, quality of air, car parking spots and traffic, people traffic, security, safety, water, electricity, and gas distribution. The high diversity of IoT devices available can be integrated into a whole AfE-EA communication network, which can consequently contributes to the creation of network communications highways for all smart city or smart building & facilities. These highways allow all different IoT devices be monitored and managed/controlled by a single Control Center (CC). They also allow the integration of new devices at any moment without adding new communication fees and, at the same time, making possible the return of investment in short-time, which depending on the use case, can be as low as one or two years.

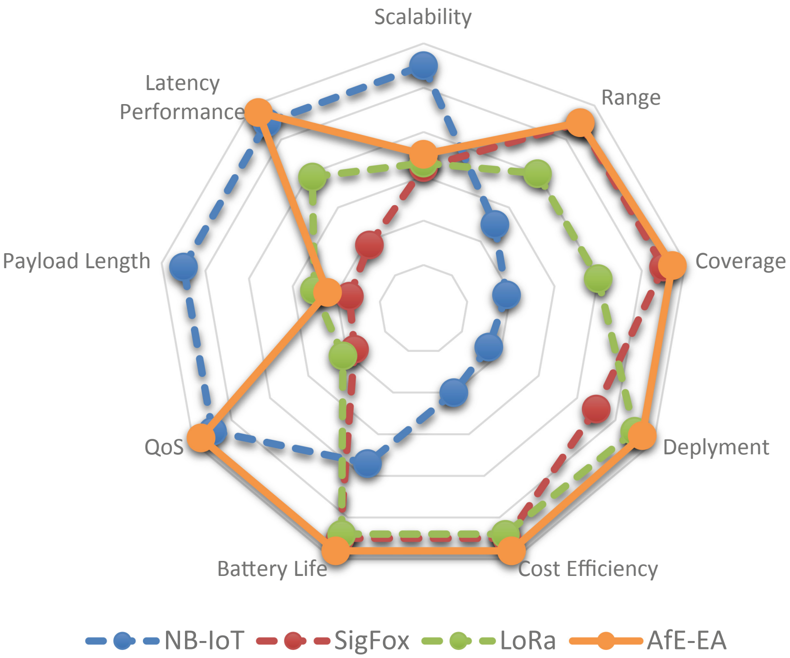

Fig. 1. Respective advantages of NB-IoT, SigFox, LoRa and AfE-EA in terms of IoT factors (adapted from [2])

4 WaterAMI

Water is vital for the existence of humans, animals and plants and consequently it is a basic requirement for numerous sectors. Although water covers over 70% of the Earth, only 1% is fresh water. The increase of the world population from 7 billion currently to over 10.5 billion by 2050, and the growing of the humans' life-styles of current and emergent societies are increasing the water demand.

The balance between water demand and availability has reached a critical level in many areas of Europe (water scarcity). In addition, more and more areas are adversely affected by changes in the hydrological cycle and precipitation patterns (droughts) [16]. The consideration of all these facts arise the importance of treat water as one of the most important resource available on Earth. So to identify and prevent the water leakages in residential and distribution networks [17], which in Europe are in average higher than 50% [18], it was introduced on the market the water telemetry solutions.

Aware of water importance, CWJ Power Electronics developed a smart metering solution: a water automated metering infrastructure, named WaterAMI (illustrated in Fig. 2) for real-time monitoring and control of WDNs, through an Integrated Management of Efficiency System (IMES).

WaterAMI allows the change of concept, from the conventionally called "telemetering", to a new concept called "tele-measuring/control", which finally allows that the "designed" Measuring & Control Stations (M&CS) can perform real-time measurement and control of all the parameters of the WDN.

By the way, WaterAMI can provide direct readings for end-consumers, who can use this information to increase consumption awareness and can adapt their consuming behaviors accordingly, i.e., avoiding waste of resources [12]. The utility metering service operator can remotely obtain the readings, stored every 15 min (or other configured value) with a precision of one liter, and consequently eliminates the incorrect human readings that can create customer complaints and/or dissatisfaction, and increase water utility companies' exploration costs [19]. At same time the utility can use the bidirectional communication functionality to control the WDN, by the integration of controlled valves or other devices. This solution also brings advantages in terms of the detection of the Non-Revenue Water (NRW), leakages and network planning in function of the real needs of the consumers.

Although, there is a high diversity of smart metering solutions available on the market (e.g. WAVIoT [20], Itron [21], and Kamstrup [22]), WaterAMI is an innovative solution because it uses the disruptive functionalities of LPWAN-AfE-EA communication protocol.

AfE-EA has several advantages, as described in previous chapter, and it highlights the WaterAMI solution with: low power consumption and energy aware algorithms which increases the networks' lifetime; high coverage by having the ability to reach devices located in places with limited communication access namely, buildings' basements with high radio signal constraints, metal boxes or similar enclosures; bidirectional communication from the Control Center (CC), through the water Measuring & Control Stations (M&CS), to the end-point water utilization.

The proof of concept of AfE-EA protocol was performed in 2017 at "Águas da Figueira (AdF)" WSN, in Figueira da Foz, Portugal. The WaterAMI solution was implemented taking into account the custom requirements in places, with known radio communications issues, designated by the water utility's management entity. In these places other smart devices were previously tested, with different communication protocols that were not able to provide reasonable coverage, in accordance with expected level of QoS. The 1st place was a neighborhood area with 7 condo buildings that had about 100 water meters, installed inside metal boxes, at the buildings basements, with identified issues in radio frequency coverage. The Data Concentrator (DC) of WaterAMI solution, operating as Control Center (CC), was installed in the headquarters' water utility, and had the ability to compute the OH-CMCST trees with the links among all the 100 nodes, in about 7 ms, using a low-cost processor (ARM Cortex-A8, 1 GHz). Even with the identified radio coverage constrains, the meshed topology of the AfE-EA protocol allowed the successful coverage of all the devices, as intended. Other places with identified radio coverage issues were identified and successfully deployed with 100% coverage.

From the general knowledge, the use of batteries is a big issue of smart sensors, once the power of batteries is limited [23] and their replacement can be a difficult and expensive task. So CWJ Power Electronics is already developing an update version of WWMT which is powered by energy collected from the water circulation [24], i.e., powered by energy harvesting technology. While the next generation of WaterAMI is not

Fig. 2. The WaterAMI is composed by a Wireless Water Metering Transceiver (WWMT), powered by standard non-rechargeable/depletion batteries, prompt to be installed in conventional water meters (e.g. JANZ JV400). After, reading the data with an incremental encoder, the WWMT sends the data collected through AfE-EA communication protocol to DC.

available, the WWMT, illustrated in Fig. 2, is already commercialized with successful results, as proved in the case study described in next chapter.

5 Case Study

Water utilities Management Entities (ME) are currently requiring smart solutions to monitoring and control their WDNs. As above mentioned, since 2017, CWJ Power Electronics has deployed the WaterAMI solution at Figueira da Foz, Portugal, according to their custom requirements and in places with known radio communications issues, designated by the water utility “Águas da Figueira (AdF)”.

At the moment of writing this article, Águas da Figueira (AdF) is in the process of smart meters’ rollout, has already deployed more than 5000 Wireless Water Meter Transducers (WWMT), that send the data collected to the Control Center (CC), installed at the water utility’s headquarters, through the AfE-EA communications network. Those first chosen places to rollout represent the different kinds of deployment densities, in urban, peri-urban, or rural areas, which are representative of the entire WDS.

However, for the purpose of this article, beyond the demonstration of efficiency of AfE-EA communication protocol, will be demonstrated the cost-effectiveness of the WaterAMI solution, by allowing the increment of water sales revenues, at same time, allowing the mitigation of the exploration costs (reducing water leakages, energy, labor, etc.).

Therefore, was chosen a representative neighborhood area of the AdF’s WDS, designed as a Measuring & Control Station (M&CS), called CELBI’s MC&S, which is an urban zone of the municipality with an area extension of 98 ha, where are in service 498 WWMT assembled over the conventional water meters. These smart devices form a meshed network of 3.68 km with 300 branches where each node communicates with other node using AfE-EA protocol. Figure 3 shows the real deployment scenario of CELBI’s M&CS with the smart devices scattered along the area. The CC, installed in the headquarters’ water utility, has the ability to compute the OH-CMCST trees with

Fig. 3. WaterAMI solution installed in CELBI's M&CS: each green point signs out one WWMT, i.e., a network node (Color figure online)

the links among all the 498 nodes, in about 19.3 ms, using a low-cost processor (ARM Cortex-A8, 1 GHz, 512 MB of RAM), which is suitable for real-time operation in terms of the QoS adopted by the agreed LSA.

The heart of the WaterAMI, the AfE-EA protocol, allows the communication of data from/to places where are deployed the smart devices. There are devices deployed inside metal boxes, at the buildings' basements, which normally causes deficient radio frequency coverage in competitors' solutions. Even with this constrains, the meshed topology of the AfE-EA protocol allows the successful coverage of all smart devices without the limitations as for example LoRa that would require need an additional gateway to insure the coverage of the end-devices implemented on basements.

With the WaterAMI solution, the utility can monitor directly all the water network of the study zone through the remote collection, in real time, of water consumption of final costumers, and calculate the Non-Revenue Water (NRW), which are the difference between the water injected in WDN and the accounted consumption. These loses are the product of leakages (in networks pipes and in house of final consumer), pipe bursts and unauthorized/unused water (i.e., water theft). When a NRW is detected the WaterAMI platform emits an alert alarm. With the identification of hits approximate location, the water utility can activate the necessary means, to for instance, send the technical team to inspect and repair the problem, or close/open existent electronic valves, or even send an alert message to the final consumer if a leakage is detected inside his house.

With this investment, at this neighborhood alone, the utility verified a reduction of water losses from 23% at the implementation moment, from the beginning of May 2019, when compared with the homolog month, in May of 2018, to 12% in June of 2019, which represents 354 m^3/month of water savings and about 9.511 €/year.

Taking into account these results, the utility will have the payback of the system (water meter + WWMT including AfE-EA protocol) in about 2.8 years, this has a lifetime of about 12 years. Or, if only in terms of the WWMT, the payback could be of 1.8 years, by having in consideration that the replacing of the water meter is enforced by legal and regulatory requirements.

6 Conclusion

This paper has described an energy-efficient communication protocol developed by CWJ Power Electronics. The wireless meshed network based in AfE-EA protocol allows the coverage of thousands, or even, dozens of thousands of devices, even the ones located in places with radio frequency coverage constrains or hidden by signal obstacles. Moreover, by using the OH-CMCST algorithm, it can maximize the network lifetime and minimize the number of hops, minimizing the latency.

Other advantage of this protocol is the possibility to be embedded in different IoT devices, using different frequency bands, that could be already deployed or have better hardware features for the specific application.

WaterAMI and his communication protocol was the one of other solutions tested at the WDN in Figueira da Foz, Portugal, but was the only that best fitted the service requirements of the water utility, providing the total coverage of the water meters. The results of this case study have demonstrated that in places where the previously used other IoT solutions based on different communication protocols have coverage and cost-effective limitations, the AfE-EA could successfully establish communications and provide data readings from all the water meters, at same time that provided short payback times.

By the way, was proved that the WaterAMI solution is a completely cost-effectiveness solution, once has very short payback periods, at same time that increment the sales revenues and reduce the exploration costs – WaterAMI is a double sense performance "driving force" for water utilities management entities.

Taking into account the positive results of the current case study, CWJ Power Electronics is now integrating the AfE-EA protocol in several public utilities, such like, outdoor lighting, water, sewage, car parking, irrigation and waste, into one whole integrated management of efficiency system, throughout Portugal country.

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