Adige: An Efficient Smart Water Network Based on Long-Range Wireless Technology

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ABSTRACT

Outworn water distribution infrastructures require real-time monitoring and management of water pressure and flow, together with accurate leak detection and localization techniques. Smart water networks based on wireless sensors offer a huge potential in this domain, but their deployment and maintenance is often costly and labor-intensive. In this paper, we present Adige: an efficient smart water network architecture based on long-range wireless technology that improves the scalability and robustness of water distribution systems. We developed a sensor node prototype using a LoRa radio transceiver and used it to carry out a set of experiments showing the benefits of Adige's approach. Our evaluation shows that, in contrast to previous approaches, the use of long-range wireless technology allows to significantly reduce energy consumption while covering large areas indoors, outdoors, and underground.

CCS CONCEPTS

•**Computer systems organization** →**Sensors and actuators;** •**Networks** →*Network experimentation;*

KEYWORDS

Cyber pysical systems, LoRa, IoT, Smart Water Networks.

ACM Reference format:
Marco Cattani, Carlo Alberto Boano, David Steffelbauer, Stefan Kaltenbacher, Markus Günther, Kay Römer, Daniela Fuchs-Hanusch, and Martin Horn. 2017. Adige: An Efficient Smart Water Network Based on Long-Range Wireless Technology. In *Proceedings of The 3rd International Workshop on Cyber-Physical Systems for Smart Water Networks, Pittsburgh, PA, USA, April 21 2017 (CySWATER '17),* 4 pages.
DOI: http://dx.doi.org/10.1145/3055366.3055367

1 INTRODUCTION

Guaranteeing an efficient operation and maintenance of water distribution systems (WDS) is a task of utmost societal importance, and its priority increases alongside population growth and urbanization. Especially in developing countries and growing economies, millions of cubic meters of water are lost daily due to leakages in deteriorating water distribution networks [9], causing many people to suffer from intermittent supply and poor water quality.

To address the problems caused by aging infrastructures, the water service providers require accurate leak detection and localization techniques to quickly repair the piping system and minimize the amount of water outflow. At the same time, solutions enabling a real-time monitoring and management of water pressure and flow are necessary to meet customer demands and expectations [17].

The enhancement of water distribution systems with networks of highly precise sensors alongside a calibrated EPANET [11] hydraulic model [15] has a huge potential in this regard, and can help solving the aforementioned problems. These model-based techniques, indeed, allow to significantly optimize water distribution and detect leaks with limited additional infrastructure [5]. However, the deployment and maintenance of these smart water networks (SWN) [18] is often costly, inflexible, and labor-intensive [8].

Costly sensors. Traditional SWNs employ precise flow and pressure sensors that can cost several hundreds of Euros each. The high cost of the sensors limits the number of devices that can be deployed on the WDS and hence the spatial resolution of data. Furthermore, it calls for an optimal sensor placement, which is often hard to attain.

Insufficient connectivity. In small-scale WDS, sensor devices are wired to the rest of the SWN using cables. Unfortunately, in large-scale systems, cables are not a viable option due to the high infrastructure costs. Information is thus often stored on a local memory and periodically collected by operators [4] or regularly uploaded to a server by means of a GSM/3G modem [1, 2, 16]. Nevertheless, because the cellular connectivity is managed by an external telecom provider, water utilities have no control over the wireless coverage of the SWN, especially in rural and remote areas.

Power-hungry devices. Precise sensors and GSM radio modules consume a significant amount of energy. For this reason, and because a connection to the power grid is seldom available, sensor devices need to be equipped with large batteries and frequently maintained.

To address these problems, we propose Adige: an efficient SWN based on long-range wireless technology. Adige prioritizes low cost and connectivity over accuracy, in order to improve the scalability and robustness of the WDS. The advantages of Adige are four-fold:

i) Adige uses inexpensive sensors to reduce the deployment cost of the SWN while increasing the number of sensing devices. Even though sensors are less accurate, they are more numerous and have a lower communication overhead, resulting in an higher spatial and temporal data resolution.

ii) The large coverage of long-range wireless technologies such as LoRa allows to form an energy-efficient network of inexpensive sensors also in remote and rural areas, as well as to use fewer

CySWATER '17, Pittsburgh, PA, USA

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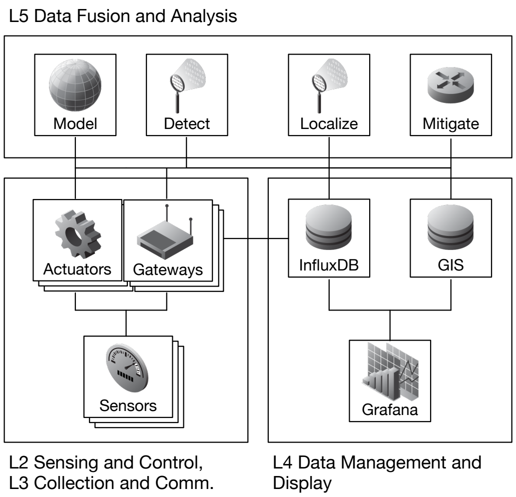

Figure 1: Adige's smart water network architecture classified according to the SWAN layers [18]. Layer 1 (L1) correspond to the water distribution system.

gateways for uploading sensor readings to the cloud. LoRa radios can indeed communicate up to several hundreds of meters with a much lower energy expenditure than the one required by sensors using GSM-based technology.

iii) The sensors employed in Adige are designed to be highly energy-efficient and hence can be powered by smaller batteries or even sustained by compact hydro-electric harvesters. This can drastically reduce the expensive and labor-intensive maintenance that is typical for off-the-shelf solutions.

iv) Adige allows to seamlessly connect the LoRa-based sensors and actuators to the rest of the SWN, i.e., to the data fusion and analysis layer, as well as to the data management and display layer. The latter is built using modular open-source components and facilitates the administration of the SWN.

We detail next Adige's architecture and present a sensor node prototype built using an RFM95 LoRa module (Sect. 2). We use this node to carry out a set of experiments that show the feasibility and the benefits of Adige's approach (Sect. 3). Our preliminary evaluation shows that LoRa-based sensors allow to reduce the energy consumption by an order of magnitude compared to other radio technologies, and to sustain reliable connectivity over large areas indoors, outdoors, and underground.

2 SYSTEM ARCHITECTURE

Adige is based on the observation that in SWNs connectivity, scalability, as well as flexible and inexpensive installation and management, are as important properties as precision and performance. For a timely leakage detection, for example, it is indeed more important to access a live flow of information from many low-accuracy sensors rather than receiving sporadic bursts of highly precise data from fewer locations. We detail next Adige's modular architecture, which is shown in Fig. 1.

2.1 Sensing, Control and Collection

At the core of Adige is a network of wireless devices having one or more of the following roles: *sensor*, *actuator*, and *gateway*. Sensors have the task to collect information about water pressure and flow at different points of the WDS. The sensed information is then collected by the closest gateway, which forwards this information to the *data management and display* layer. Finally, actuators allow to reconfigure the SWN in case of leakage (e.g., by closing valves) and to guarantee a minimum water pressure to the consumers.

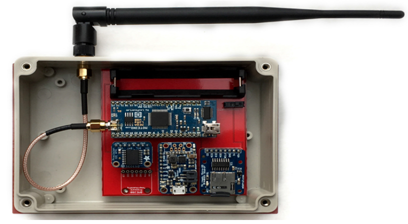

Figure 2: An Adige Sensor is equipped with a Moteino MEGA, a real-time clock, a generic sensor interface, a power management circuit, and an SD card interface.

Sensors. Adige's sensors are based on a Moteino MEGA equipped with an ATMega1284P microcontroller and a HopeRF RFM95 LoRa transceiver operating at 868 MHz. Sensors are powered by a 3.7V Li-Ion battery with a capacity of 3.4 Ah that can be charged via a dedicated circuit. Furthermore, they are connected to a low-cost Honeywell PX3AG1BH010BSAAX pressure sensor and a micro hydro generator that acts both as a flow meter and power harvester. For persistent storage, an SD card logs the collected data together with a time-stamp provided by a real-time clock module.

Actuators. Adige actuators are wireless devices with the capability of controlling a proportional valve. In the event of a pipe burst, Adige is able to adjust pressure and flow levels by controlling each valve position, with the aim of minimizing the leakage outflow while maintaining consumer demands.

Gateways. Adige gateways are networking devices equipped with a LoRa transceiver and one or more additional interfaces (e.g., Wi-Fi or 4G) to forward the sensor data towards the *data management and display* layer. Because LoRa allows to form a multi-hop network covering large distances, only few gateways are required to cover a large deployment area. While our design utilizes LoRa radios, it does not follow the LoRaWAN specification [13]. Thus, gateways do neither need to form a star-topology nor to be equipped with more powerful hardware. This allows to reconfigure the network depending on different needs and situations, improving flexibility.

2.2 Data Fusion and Analysis

In Adige, the data fusion and analysis layer is composed of the four different modules that we describe next.

Hydraulic model. For model-based leakage detection and localization, a calibrated EPANET model is used. This steady-state model is able to predict the pressure and flow at any point and at any time.

Leakage detection. The leakage detection mechanism constantly compares the pressure and flow values predicted by the hydraulic model against the data reported by the *sensing* layer by using time series analysis techniques [10]. If a mismatch between the model and observation occurs, a leak is detected. Compared to techniques based on acoustic/vibration sensors, this model has a far lower bandwidth requirements that nicely fits with LoRa's characteristics.

Table 1: Energy consumption of SWN radios. The models of 3G, GSM, and Wi-Fi are derived from [3], LoRa values are derived from our measurements.

	3G	GSM	Wi-Fi	LoRa
Transmission energy [J/KB]	0.025	0.036	0.007	2.5
Ramp energy [J]	3.5	1.7	5.9	-
Tail energy [J]	7.75	1.5	-	-
Maintenance energy [J/s]	0.95	1.62	3.0	0.54
Total energy for 100 B/60 s [J]	**12.2**	**4.8**	**8.9**	**0.79**

Leakage localization. After a leak is detected, the aim of the model-based localization algorithm is to find the position of the leak in the WDS. Leakage localization is formulated as an inverse problem where the discrepancy between the measurements and the simulated values from the hydraulic model is minimized to get the approximate leak location [14].

Leakage mitigation. This mechanism allows to reconfigure the valves in the WDS in order to minimize the system pressure (especially in the damaged areas), while maintaining a minimal required pressure for the consumers [19]. This reduces the damage caused by leakages and minimizes the water loss before a manual intervention is possible. Additionally, this module can completely isolate the damaged water pipes during maintenance to facilitate repair [6].

2.3 Data Management and Display

The data produced by Adige's sensors is persistently stored on a time series database, which is able to efficiently handle arrays of numbers indexed by time. In our prototype implementation we employ *InfluxDB*, an open-source database that is optimized for fast, high-availability storage and retrieval of time series data. At the same time, a GIS database is used to store the location and characteristics of each sensor, pipe, valve, and pump in the system. The combined data is used by the *data fusion and analysis layer* to build the hydraulic model and run the detection and localization mechanisms. To visualize the sensor readings and leakages we use Grafana, an open-source, general purpose dashboard and graph composer that runs as a Web application.

3 FEASIBILITY STUDY

In order to show the benefits of Adige, we carry out two different testbeds. First, we augment an existing WDS installation with Adige's data fusion and analysis layer, as well as data management and display layer. Equipped with wired and highly-precise sensors, the experimental WDS installation covers an area of 21 m^2 and consists of 9 valves, 14 pressure sensors, 19 flow sensors, and 14 solenoid valves able to accurately emulate the user demand of customers. Second, in a separate testbed, we evaluate the reliability and energy-efficiency of the LoRa-based sensors presented in Sect. 2.1, as well as verify whether they can communicate over large distances indoor, outdoor and underground. We report next the insights obtained from this preliminary evaluation.

3.1 Data Fusion, Analysis, Management, and Display

Grafana allows us to explore Adige sensor data with powerful functions such as zooming, aggregation, and range selection. Because

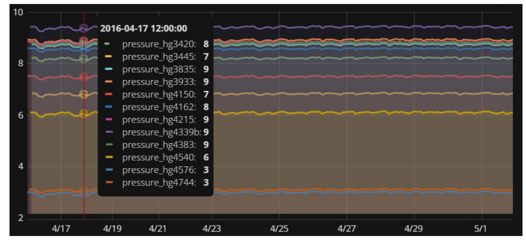

Figure 3: Grafana visualizing 12 sensor in our testbed.

InfluxDB is optimized for time series, queries are much more responsive than in SQL-based solutions, which greatly improves the interface usability. A screen-shot of the implemented system is visible in Fig. 3. In the future, we plan to extend Grafana's interface with a plugin that is able to visualize also geo-referenced data.

3.2 Sensing, Control, and Collection with LoRa

In a separate installation, we evaluate the reliability, coverage, and energy efficiency of LoRa-based sensor nodes. In particular, we carry out measurements in three scenarios that are representative of real-world SWN: indoor, outdoor, and underground. LoRa wireless technology exposes four parameters: bandwidth (BW), spread factor (SF), code rate (CR), and transmission power (PWR). These parameters allow to trade range for energy-efficiency and reliability [7]. Reducing LoRa bandwidth, for example, allows to improve the radio sensitivity at the cost of a lower data rate [12]. Our experiments aim to study the effect of these parameters on radio performance and to propose an optimal configuration for each of the considered scenarios (indoor, outdoor, underground).

Coverage and reliability. We fix the transmitter at a given location and place the receiver at three different distances for each scenario: *indoor* with obstacles, *outdoor* with no obstacles and *underground*, covered by a metal manhole. The two nodes exchange packets of 100 bytes payload every 60 seconds at transmission power 20 dBm, emulating a timely report of water pressure and flow readings. Fig. 4 shows the packet reception rate (i.e., the number of packets sent that were correctly received) indoor, outdoor and underground for a number of different radio settings (see Table 2). The best performing setting, i.e., BW=125, SF=9, CR=4/5, and PWR=20 dBm (setting number 7 in Table 2), achieves a packet reception rate above 95% for all scenarios and distances. Due to the lower multi-path and fading effects, in the outdoor and underground scenarios LoRa performs significantly better, with packet reception rates above 97% for almost all radio settings. This is not surprising, as LoRa is a technology specifically designed to cover large distances outdoors.

Energy-efficiency. Using the settings that maximize the reliability in our experimental setup (i.e., setting number 7 in Table 2), we now compute the energy-efficiency of LoRa and compare it to other solutions. We measure the consumption of LoRa using a Keysight MSO-S 254A mixed signal oscilloscope and compare it to the energy model of other technologies presented in [3]. Table 1 shows that for a periodic transmission of 100 B every 60 seconds, a sensor employing LoRa consumes 0.79 J – significantly less than 3G, GSM, and Wi-Fi radios performing the same action. This is because in 3G and GSM a large fraction of energy is spent in high-power states before and after the actual data transfer (*ramp* and *tail* energy), whilst in Wi-Fi the energy is wasted in the association

Table 2: Settings of the LoRa transceiver used in our experiments.

Setting ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Bandwidth	125	250	500	125	250	500	125	250	500	125	250	500	125	250	500	125	250	500
Spreading Factor	7	7	7	7	7	7	9	9	9	9	9	9	12	12	12	12	12	12
Code Rate	4/5	4/5	4/5	4/8	4/8	4/8	4/5	4/5	4/5	4/8	4/8	4/8	4/5	4/5	4/5	4/8	4/8	4/8
TX Energy (J/KB)	0.80	0.40	0.20	1.29	0.64	0.32	2.50	1.25	0.63	4.00	2.00	1.00	15.02	7.51	3.75	24.03	12.01	6.01

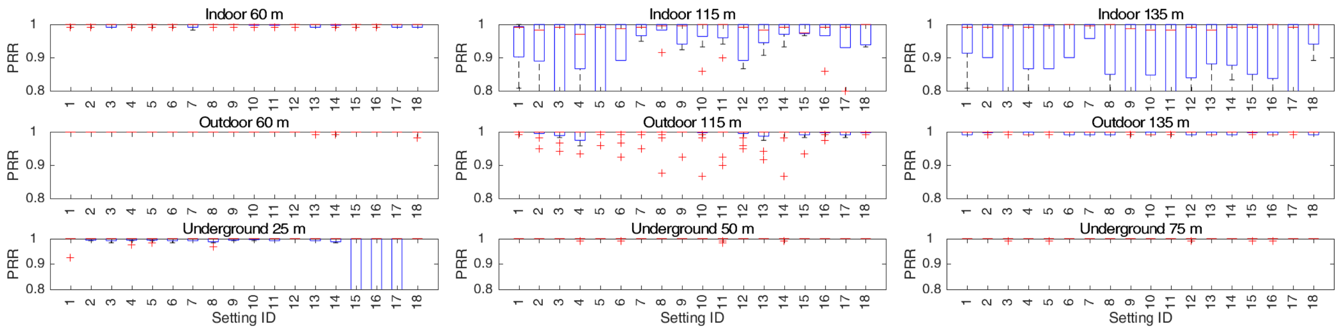

Figure 4: Packet Reception Rate (PRR) of LoRa for different distances, scenarios and settings.

and scanning procedures (reported in Table 1 as ramp energy) [3]. For LoRa, instead, the overhead is minimal, with no ramp and tail energy and no association and scanning procedures. Even though the energy spent by LoRa for the actual transmission is far higher than its competitors (due to the extremely low data rate of the radio), the resulting energy consumption in practical SWN applications is significantly lower. Note also that small-scale SWN allow to use high-bandwidth settings, that support only short distances but require far less energy (Table 2). Surprisingly, the most reliable setting in our experiments is also one of the most energy-efficient. This implies that in our experiment scenarios not all LoRa mechanisms were equally effective. We plan to carry out further experiment to understand the best configuration settings for each deployment.

4 CONCLUSIONS

In this paper we presented Adige, an efficient SWN architecture based on long-range wireless technology, and showed the results of preliminary experiments demonstrating the feasibility of its approach. The high reliability, energy efficiency, and coverage shown by our prototype of LoRa-based sensors is a desirable feature for water utilities that aim to reduce deployment and maintenance costs, while still being able to monitor the user demand in real-time.

We plan next to carry out a large-scale deployment of Adige in the city of Jaxing, China. This deployment will allow us to accurately profile the energy consumption of our system, and stress-test its reliability. Furthermore, we aim to better understand how different spatial and temporal resolution of data affect the tasks of leakage detection and localization.

ACKNOWLEDGMENTS

This work has been supported by the Sino Austrian Electronic Technology Innovation Center.

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