ICUD-0588 IoT driven low-power radio technology for highly distributed in-sewer monitoring – a data collection technique that shifts paradigms?

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Summary

Urban drainage systems traditionally lack adequate monitoring and evaluation technologies. Although weather radar and high-resolution remote sensing technologies promise vast advances for rainfall and land-use data collection, it is still challenging to deploy dense hydrological monitoring networks for sewers. Low-power data transmission technology, which is the communication backbone in the Internet-Of-Things (IoT), has the potential to contribute to a game change towards an evidence-based management of urban drainage systems. In this paper, we share our experiences with establishing and operating a wireless sensor network (WSN) at full-scale with approximately a 1 sensor per hectare connected catchment area and a monitoring frequency of 5 minutes or less. Specifically, we discuss i) the monitoring and deployment approach and ii) the adequacy of sensor- and LoRaWANTM wireless data transmission technology for monitoring applications in sewer networks. A thorough evaluation of the telemetry performance provides evidence that the proposed technique allows a highly distributed monitoring of drainage capacity, sewer infiltration, performance of retention basins and overflows, with a far less effort compared to conventional methods. Remaining challenges concern the radio network architecture to allow better access to deep underground structures and efficient methods for automated data quality control to handle this type of data in the future.

Keywords

distributed monitoring, wireless sensor networks, spatio-temporal in-sewer dynamics, LoRaWAN, internet of things, cyber-physical systems

Introduction

Monitoring in-sewer processes in adequate temporal and spatial differentiation has been a great challenge with regard to both sensor and communication technologies. The spatially-distributed character of drainage networks, the restricted access to underground infrastructure, the hazardous and unfavorable environment, and the rapidly and randomly-changing loading situations during dry and wet weather make it challenging to monitor volume and substance flows in urban drainage systems. Regarding rainfall and land-use, recent technological advances in weather radar and high-resolution remote sensing are very promising. Now, current developments associated with the Fourth Industrial Revolution (i.e. IoT, cloud computing, machine learning) promise to provide the communication layer for wireless sensor networks by compiling the data from thousands of sensors. While early examples have been reported with specifically-tailored communication systems (Montestruque and Lemmon 2015; Ruggaber et al. 2007), it is currently unclear which low-power (LP) wireless communication technology will outlive rapid advances in the field, which quality of service (QoS) is required for which type of application (i.e. uni- or bidirectional communication), as well as how to optimize the data rate, radio range and power costs while ensuring sufficient data transfer quality for in-sewer applications. The objective of this paper is twofold: i) to illustrate the successful implementation of an autarkic wireless sensor network (WSN) in urban hydrology as a proof of concept without covering up the challenges related to such a full-scale deployment, and ii) to discuss our experiences regarding sensor network performance and the corresponding implications for future sewer monitoring applications. Despite the fact that adequate techniques for the processing and handling of increased data volumes are an indispensable part in the process data acquisition (see Fig. 1) the steps 3a and 3b are not discussed in detail here.

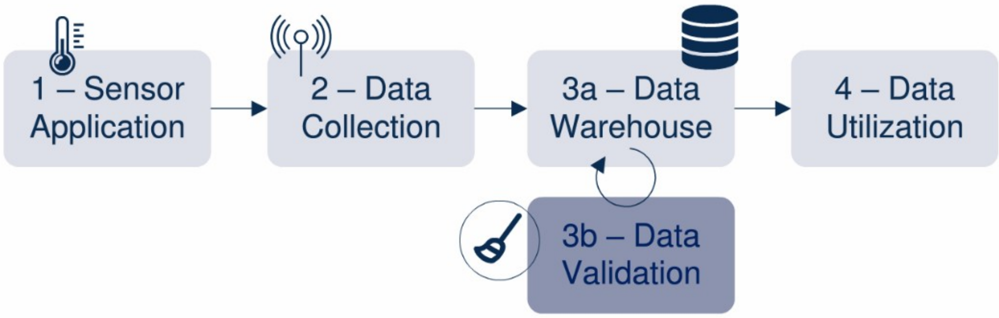

Fig. 1. *"From sensor signal to a consistent data set" - conceptual understanding of the evolution of information for monitoring as understood in this study.*

Approach and Methods

The implementation of the WSN in full-scale was motivated by the research initiative "The Urban Water Observatory" (UWO[1]), which has been jointly funded and supported by ETH Zurich and Eawag since November of 2015. With this unique initiative, we want to monitor the dynamics of the urban water balance across multiple compartments, including catchment areas, sewer networks, groundwater, and receiving waters, in a typical, medium-sized Swiss community over a period of five years to provide the basis for data-driven water research.

Monitoring requirements

Given the aforementioned difficulties in sewer monitoring, we can summarize the following challenges: i) substantial effort is required to install and operate monitoring equipment in difficult to access environments, underground and with potential risk of explosion, and ii) there is – so far – a clearly limited scalability and flexibility in terms of the number of installed sensors, the location of installation and the period of autarkic operation. For our full-scale deployment, we therefore formulated the following requirements. The monitoring system must contain:

- widely energy-autarkic operation of sensors and transmission technology with a minimum battery lifetime of two years,
- easy and fast installation of equipment without changing structures, such as implementing wired antennas through the ground or the use of specific, radio-enabled manhole lids,
- a direct connection between sensor nodes and the internet without additional installations above ground,
- a non-proprietary, license-free radio standard without manufacture-specific requirements for peripheral equipment,

[1] Further information is available at: www.eawag.ch/uwo (last access: 26/06/2017).

- an option to operate the sensor network via an autarkic, private radio network or via existing, publicly available network infrastructure,
- a high standard regarding cyber security and data decoding,
- hardware and technology that enables implementation in ATEX-environments,
- an straightforward linkage to in-house data servers.

Sensor network

We focus on data transmission technology that is based upon the non-customized standard LoRaWAN™ (LoRa®Alliance 2015) allowing for a bidirectional radio communication link between battery-driven sensor nodes over a long range (~10km, above ground). This format was chosen for two main reasons: i) low-power data transmission on a license-free bandwidth (868 MHz) and ii) a network standard with an open-source-like character with a growing community of developers and users. The standard LoRaWANTM network architecture is laid out in a star-type topology, i.e. sensor nodes communicate with the best available coordinator or gateway. In our case, thus far, two gateways (Kerlink Wirnet Station 868), one solar-powered and one AC-powered, collect information from 35 sensor nodes (see Fig. 2). Communication between sensor nodes and gateways is spread out on different frequency channels around the frequency band of 868 MHz. Throughput is managed individually for each sensor node through the Adaptive Data Rate (ADR) method in order to minimize energy costs (increase battery lifetime) and used radio network capacity. Battery-powered sensor nodes are partly in-house prototypes and partly tailor-made by an external supplier. Currently, 35 low-power sensors are connected to the WSN: 24 ultrasonic water level sensors (MaxBotix MB7389, MB7369, MB7386), 6 dielectric conductivity sensors (Decagon 5TM), 2 pressure gauges (Keller 36 XKY), 2 multi-parameter probes for groundwater quantity and quality monitoring (STS DL/N 70), and 1 Davis-Pluviometer in addition to 4 standard rain gauges (OTT Pluvio² L) equipped with off-the-shelf GSM transmission modules.

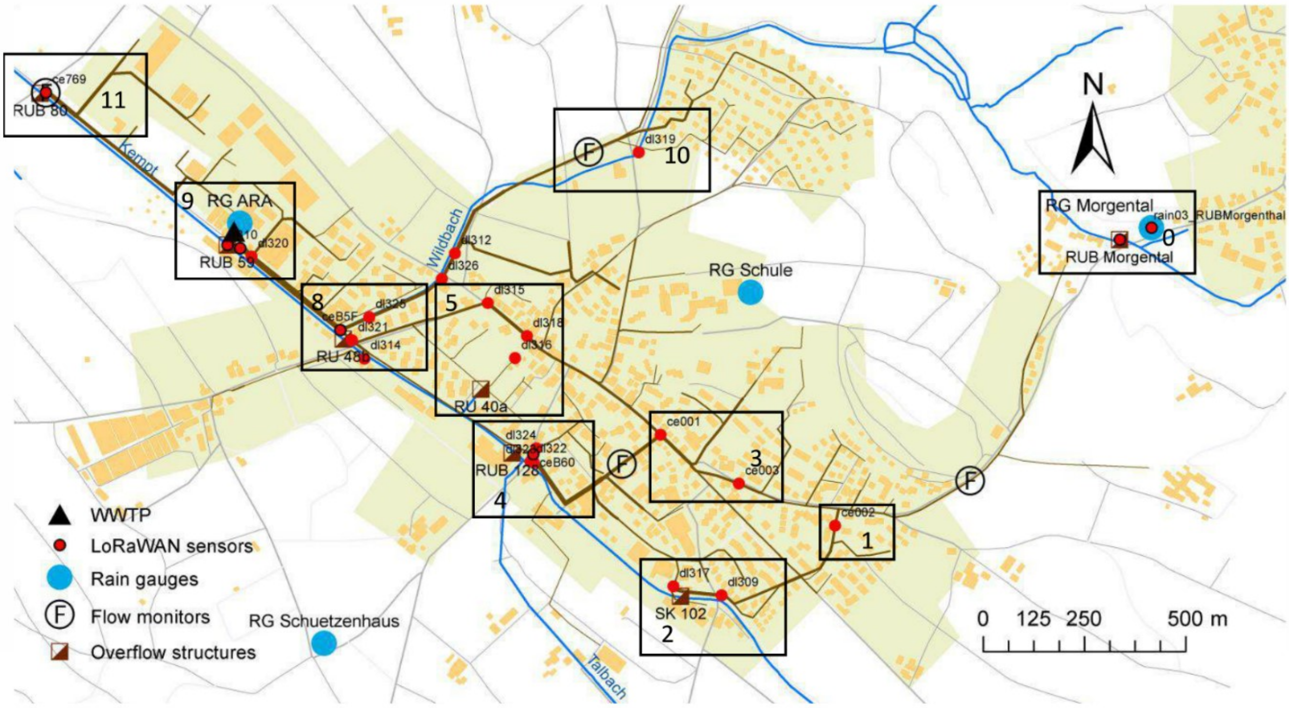

Fig. 2. *Overview of sensor node locations (●) linked to the LoRaWAN WSN. Seven off-the-shelf flow sensors are installed and used as a flow reference (F). In total, five rain gauges have been operating*

in the catchment since March of 2016; only four of which are shown. Rectangles indicate clusters of sensors associated with specific network structures (throttle, overflow, pump, flow split).

Case study area

The investigated urban catchment (Fig. 2) is drained through a combined gravity-driven sewer network, where 13 km are combined sewers, 4.6 km are foul sewers and 10.9 km are storm sewers directly discharging into receiving creeks and rivers. The total settlement area adds up to 127.3 ha; however, 40 ha can be accounted for as connected areas. A significant share of the sewer pipes lay below the groundwater table. Thus, sewer infiltration contributing to WWTP inflow is with an estimated varying rate of 35% up to 55% considerable. Four retention basins (specific storage volume of 36.1 m3 hared-1) are implemented to mitigate impacts on the receiving waters. Excess flows are discharged via five combined sewer overflow (CSO) structures into a sensitive receiving river. The average dilution ratio between base flow at the catchment outlet and WWTP effluent discharge is 3:1. Sensors are, according the monitoring objectives, positioned at overflow structures and in the central part of the drainage network, primarily along the main collectors. Many locations are equipped with two or more sensors of the same type or of different type to pursue the concept of signal redundancy and signal diversity. The sensor positioning is clearly motivated by aspects related to urban drainage and flow topology, but not related to network coverage.

Data handling

The increased amount of collected observations requires rigorous data validation and systematic, automated data housekeeping. Previous studies provide a variety of useful concepts (Alferes and Vanrolleghem 2016; Branisavljevic et al. 2010); however, only few of them address spatially-distributed observations in a network. We apply a four-step procedure to handle data obtained through distributed monitoring: i) scheduled, script-based data transfer from dashboard servers via an Application Programming Interface (API), ii) instantaneous preprocessing and filtering of individual signals including validity range check, outlier detection, and noise reduction, iii) anomaly detection through a collective analysis of various signals (e.g. through a correlation analysis), and iv) systematic and consistent archiving in a data warehouse application (PostgreSQL database). With this, we pursue two main objectives: i) to achieve a quasi-real-time maintenance of sensor hardware through automated anomaly detection, and ii) to provide pre-validated data sets with a high degree of consistency. Since the focus of this paper is clearly on the implementation and the performance of the data transmission concept, aspects of data handling are not discussed in depth.

Results and Discussion

The presented study shows i) a to-date one-year, stable operation of low-power wide area network (LPWAN) connecting low-tech sensor technology in sewers, ii) an added value by combining signal redundancy and signal diversity in a highly-distributed monitoring approach. Here, we evaluate the telemetry performance of the sensor network focusing on aspects, such as coverage, quality of service, signal strength, gateway performance, data throughput, and energy costs. The performance evaluation is based on ten-months of data, from May of 2016 to March of 2017, totaling to 102,240 hours of operation (9 sensor nodes for 10 months, 26 sensor nodes for 2 to 3 months in operation).

Coverage, signal strength (RSSI), Signal-to-Noise ratio (SNR)

In general, the network coverage is dependent on the following factors: i) geographical positioning (sightline between node and gateway), ii) housing density and tall building density (deflection of the radio signal through tall buildings), and iii) weather. Regarding the latter issue, our analysis of signal strength (RSSI) and signal noise (SNR) clearly indicates that rainfall influences the signal noise while RSSI remains stable (Fig. 3). In this case, transmission performance is conserved by auto-adjustment of the Spreading Factor (SF), i.e. the degree of which the signal is spread over the available bandwidth (see Fig. 4). Data package transfer is so ensured despite of an increased noise level. Fig. 3 further indicates that noise increases with decreasing signal strength.

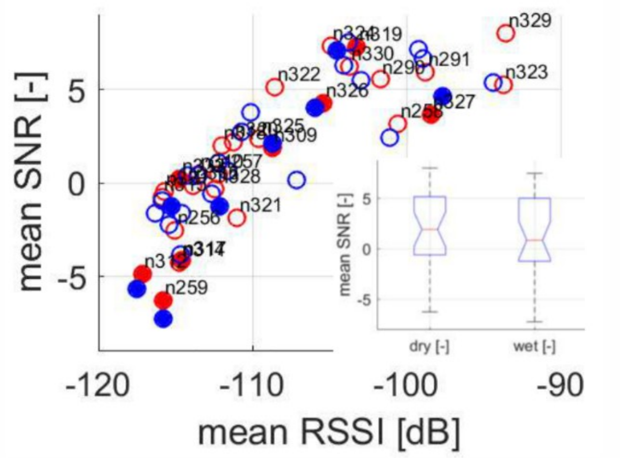

__Fig. 3__. mean RSSI vs. mean SNR for individual radio nodes and further differentiated after dry (red) and wet (blue) weather days (right). Filled scatters indicate nodes positioned above ground. Node labels correspond to Fig. 2.

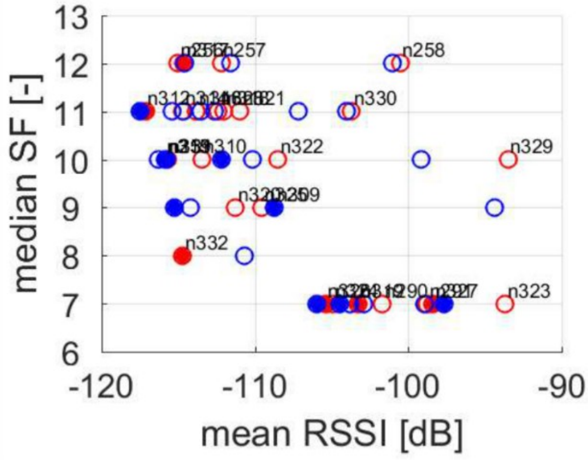

***Fig. 4.** mean RSSI vs. median Spreading Factor (SF), whereas SF varies between 7 and 12. Data transmission at a SF level of 7 is very efficient (short radioing, large packages), whereas transmission at a SF level takes longer and goes at the expense of the global transmission capacity.*

While coverage shortages above ground may be compensated through a higher gateway density, a limited reception below ground represents a particular challenge. In our study however, the observed signal quality for nodes below ground is not particularly less poor than for nodes above ground (filled scatters in Fig. 3). However, it must be taken into account that sensor nodes above ground are located further way from the gateway (see Fig. 4). This underlines the complex dependence of the telemetry performance on the abovementioned factors.

Quality of service (QoS)

Before deploying the sensor nodes, we carried out site-specific tests to verify radio coverage and signal strength below and above ground. As a result of these tests, we found that two outdoor gateways located on the roof of two elevated buildings were enough to provide sufficient signal strength in the entire urban catchment with an expansion of approximately 3 by 3 kilometres. On the other hand, signal strength decreases at underground locations, eventually affecting QoS rates. In this work, the reliability that a data package is transmitted in the worst case decreases to 63 %. On average, 83 % of the data packages were transmitted, whereas 71 % of all installed sensor nodes radioed directly from underground. Furthermore, we observed that the QoS increases over time (current status: 88 %) - individual adaptation, e.g. optimized radio node positioning, leads to an increased performance.

Recent research envisions further technological improvements aiming at more stable telemetry: the implementation of repeater nodes, which are positioned above ground and receiving signals from several nodes positioned underground, improves the QoS. An additional, hardware-specific backup solution is the integration of a circular buffer in the sensor node such that sensor recordings can temporarily be stored in case there is a lack of network coverage.

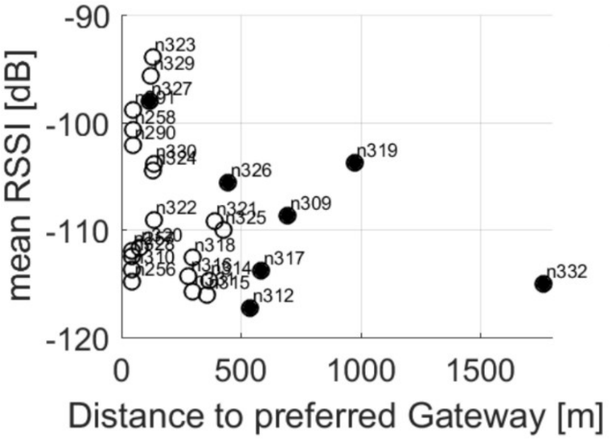

Fig. 4. mean RSSI vs. distance to the best available, i.e. preferred gateway. Node n259 is not shown since it connects to a public network gateway (Swisscom) which is over 15 km away.

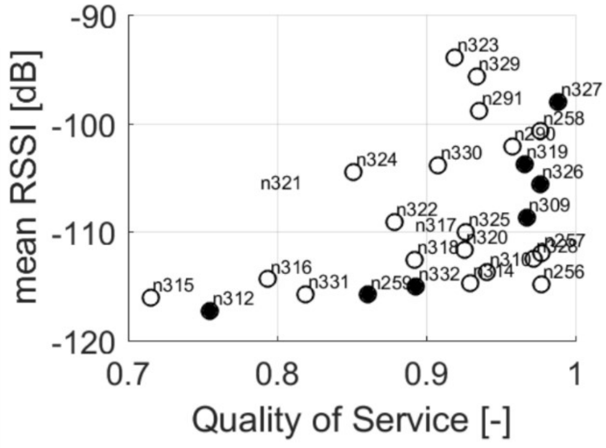

Fig. 5. mean RSSI vs. Quality-of-Service (QoS). Node n317 and n321 are not shown since the QoS rates are below 0.7.

Gateway performance

The gateway operation has been stable thus far with one exception: a single multi-hour blackout (included in the QoS estimation) occurred due to a firmware update via the network management. However, these outage times can be minimized by implementing a watchdog script, i.e. an SMS remote control. The stability of the gateway powered through a solar panel was increased by a larger panel (approximately 1 m², 160 Wp), which is particularly relevant in winter periods.

Transmission capacity

The duty cycle restriction of 1%, imposed by the regulating authority, enabled a license-free transmission; however, it also may quickly constrain the application, for example, in the case of many different sensor nodes sending large amounts of data at a high frequency. Particularly in the case of rain, a transmission frequency of 1 minute would be desirable. In our study with 35 sensor nodes, 2 active gateways, and a transmission of small data packages (few bytes) at a frequency of 5 minutes, we do not reach capacity limits. If, and to what extent, the maximum capacity would be reached when increasing the transmission frequency depends on the signal strength, the number of gateways deployed, as well as the amount of data to be transferred, and hence would need to be verified individually. Smart methods, such as data compression directly at the sensor node, adaptive transmission regimes and varied measuring and transmission intervals can help to optimally utilize the technology despite the potential capacity limitation.

Battery lifetime

The lifetime of the battery-driven sensor nodes is estimated, depending on the connected sensor and the type of radio node. Given a monitoring frequency of 5 minutes and a low-power ultrasonic water level sensor connected, the radio node prototypes (powered by a standard Lithium-Polymer battery - 3.7V, 6700 mAh) run an estimated time of approximately two years without a battery change, whereas the externally manufactured radio nodes (powered by two standard LR20 Alkali-Mangan mono cells - 1.5V, 18000 mAh) last approximately six years. So far, after one year of operation (May 2016 – May 2017), we did not observe any blackouts due to unexpected voltage drops. The online operation control provided by the network management to date shows a remaining capacity of more than 60% for all installed nodes.

Conclusions and Outlook

What is possible?

The primary advantage of this wireless sensor network is its nearly unlimited scalability, the ultra-low power consumption of the entire system, as well as the comparably low costs for investment and operation per recorded value. This approach enables application of signal redundancy and signal diversity concepts, ultimately increasing the quality of the observed information. An additional benefit is the option to migrate the concept to either a stand-alone, private, autarkic network (as discussed here) or a network integrated in a publicly-available radio network infrastructure, e.g. established by professional telecommunication operators.

Where are the main challenges?

Despite the fact that the benefits clearly outweigh the deficiencies, a few challenges remain. These include: i) improvement of the transmission reliability (QoS) particularly for underground applications, ii) self-organized or meshed routing towards a wider coverage and an increased network resilience, iii) improvement of the bidirectional functionality to enable Over-The-Air (OTA) updates or other controls, and iv) self-contained operation of sensor nodes through exploitation of on-site energy sources (energy harvesting). The success of the described transmission approach is undoubtedly dependent on the availability of compatible low-power sensor technology as well as adequate methods to support data handling. With this background, further research should focus on robust solutions for data warehousing and automated data validation, in parallel to the rapidly advancing hardware development.

What remains unclear?

The rapid pace of technological change leads to some side-effects. Prognostication of the future development of individual LPWAN standards is vague. Issues like demand management and tariffs the operators will charge make the future of the technology unclear. Since 2014, new LPWAN standards have been arriving on the market on an annual basis with no end in sight. However, recent developments in Europe to establish LoRaWAN on a nation-wide basis, are confronting trends that favor Narrow-Band-IoT (NB-IoT). In this light, we understand the experiences shared and the conclusions drawn in this report.

Synopsis

With a stable, to-date one-year operation of a full-scale LPWAN sensor network, we show a new possibility to efficiently and adaptively monitor process dynamics in urban drainage systems and beyond. With the experience gathered and the prototyping carried out in this study, we hope to contribute to a next-generation approach of monitoring in-sewer dynamics, thereby lowering the hurdle for operators to monitor their systems and ultimately leading to a better system understanding. The fact that the leading European telecommunication providers (KPN, Swisscom) have recently started establishing LoRaWAN communication infrastructure on a nation-wide basis underlines the potential for using this infrastructure in water utilities in the near future. Follow-up work will address deficiencies in the radio network architecture, which is currently limited to star-type, as well as a more in-depth analysis of the bidirectional functionality of the LoRaWAN standard for control purposes.

Notwithstanding the actual LPWAN standard, the aspects discussed here remain relevant. The outlined field experiment enables us to collect experience in full-scale with distributed sensor networks in urban drainage systems. Based on this experience, we can further evaluate the undoubtedly large potential towards an evidence-based management of urban drainage systems.

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