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Conference Paper · March 2018

DOI: 10.1109/EE1.2018.8385262

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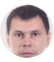

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Evaluation of Low Power Wide Area Network Technologies for Smart Urban Drainage Systems

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***Abstract*—Smart urban drainage systems (SUDS) with real-time control are considered to be one of the prominent approaches to tackle the impact of climate change which results in heavy rainfall and floods in urban areas. However, the lack of reliable and efficient communication with sensors buried underground is considered as one of the main deficiencies preventing ubiquitous application of SUDS. With the recent developments of new noise insensitive technologies for ultra-narrow band (UNB) and chirp spread spectrum (CSS) communication, introducing new low-power long-range communication technologies (e.g. NB-IoT, LoRa), implementation of such drainage systems is becoming feasible. This paper presents a comparative study of NB-IoT and LoRa and evaluate the potential of these technologies to be used for SUDS. The study is conducted in different underground scenarios such as dry and damp conditions to highlight the potential benefits offered by LoRa and NB-IoT in terms of coverage, information rate, and energy consumption. It has been shown through the simulation results that NB-IoT offers capillary coverage with a high level of scalability as compared to LoRa. Furthermore, NB-IoT also provide high information rate and low energy consumption and is best suited for underground scenarios.**

***Index Terms*—Narrowband Internet of Things (NB-IoT), LoRa, smart drainage system, information rate, coverage, energy consumption.**

I. INTRODUCTION

Climate change will have considerable impact on urban areas. One of the effects of this process, especially in Northern Europe, is the increase of storm water peak intensities and extreme rainfall events and it is expected that the frequency of rainfall events will increase more than 3 times by the year 2030 [1]. Currently, urban drainage systems (UDS) are typically designed to operate on ca. 2/3 water elevation rate in the conduits as this is hydraulically the most efficient stage. In addition to that, free space between the pipe obvert and the water level allows ventilation of the UDS and avoids thus trapping the air in the conduits. Trapped air may lead to disturbances and impair the operation of pumping stations and treatment plants. If the design threshold for the water height is exceeded, the system becomes surcharged, i.e. losing the free capacity, which will eventually lead to the situation where water is flowing backwards from the manholes to the ground. This is the common reason of urban floods caused by the extreme rainfall events, posing risk on buildings, structures and disturbing life in cities. In case of combined sewer systems where stormwater and wastewater is conveyed through the same system, this type of flood brings a threat on the surface water quality and human health as untreated wastewater may reach to surrounding water bodies.

There are several options available to tackle the surcharge problem of UDS. As the UDS infrastructure is deep underground, situated in dense urban environment, rebuilding the system is the most expensive and effort demanding approach. Replacing drainage collectors with new and larger pipelines in such environments may cost thousands of euros per meter and will have substantial indirect costs related to the closure of the streets and ensuring constant operation of other communication lines. In addition, over-dimensioning the pipes will decrease the critical flow velocities needed to self-clean the system. Therefore, other less interruptive methods to reduce the risk of UDS surcharge and consequent flood have been largely investigated during the past decades [2]. These options comprise structural approaches, were the system is supplied with additional storage tanks capable to temporarily accumulate the excess water and non-structural solutions focusing on operational possibilities, i.e. better management of pumping stations in the system [3]. The efficiency of these solutions is relatively moderate (10-25% cut from of the peak flow) [4]. The reason for that is the lack of free space in urban environments to construct massive storage tanks and scarcity of network actuators, i.e. pumps to lead possibilities to adjust the operation of UDS.

Smart urban drainage systems (SUDS) with real-time control has been seen as a most efficient way to reduce the water level overload and thus tackle the impacts of climate change and surface sealing [5]. For that, different actuators, i.e. gates, weirwalls, closable inlets and curbs are installed into the system to control the flow at the upstream. These are usually easy to install and need therefore no extensive construction projects. In addition to that, the control system will be fed with data from weather radar to turn real-time control (RTC) proactive. This means that water levels are decreased in the system prior the rainfall event and thus lowering the risk of flood. It has been found that these type of RTC systems are able to cut the peak flow in the system by up to 50% [6]. This is significantly higher result than in the case of conventional options. Therefore, smart urban drainage systems are seen as economically feasible. Until today the development of SUDS has been impeded inter alia by limitations of the communication options between the sensors in the network and the control unit. This paper contributes filling this gap and thus accelerating the development of efficient and affordable SUDS.

As mentioned, the lack of reliable and efficient communication with sensors buried underground is considered as one of the main deficiencies preventing ubiquitous application of SUDS. The attenuation of electromagnetic (EM) waves in (wet) soil is so significant that communication through soil has been considered not feasible for decades, especially for low transmission power battery-powered devices and decent communication ranges of at least hundreds to tens of meters. Furthermore, another major challenge is the connectivity issue, due to the difficult location, particularly non-line of sight (NLOS) in which underground sensors are deployed. Legacy (2G, 3G) mobile M2M networks would enable establishing wireless link at short distances but as far as such wireless devices consume significant amount of energy, the battery-powered operation time would be limited [7]. Better energy efficiency would be achievable with sub-gigahertz short range wireless communication technologies like IEEE802.15.4g based WiSUN and WMBus operating at 433 MHz or 169 MHz ranges [8]. Still, the maximum achievable radio link budget would be around 135-140 dB with short distances. That may be still insufficient for decent communication ranges between underground sensors and wireless access points above the ground.

However, due to recent developments of new noise insensitive technologies for ultra-narrow band (UNB) and chirp spread spectrum (CSS) communication, introducing new low power long range communication technologies (e.g. NB-IoT, LoRa), implementation of energy efficient wireless sensor networks for drainage systems is becoming feasible. NB-IoT is a cellular technology based on licensed spectrum, whereas LoRa is a CSS modulation based radio technology that is usually deployed at 868 MHz in Europe and 902-927 MHZ in North-America, respectively. NB-IoT provides better coverage with a high level of scalability due to high maximum coupling loss (MCL) as compared to LoRa. LoRa is prominent because of it possibility to operate in sub-GHz ISM bands and transfer short messages efficiently, as required by SUDS systems.

However, to deploy these technologies for practical applications, achievable information rate, coverage and energy consumption are the key performance measures that need to be evaluated. In the literature, few efforts has been made to investigate the coverage and device capacity of both NB-IoT [9] and LoRa [10]. In [11], the author presents the general overview of LoRa and investigated the scalability and capacity of LoRa in an outdoor environment in terms of throughput and number of devices that can be served by cell. Similarly, in [12], the coverage measurement has been presented for outdoor scenario along with the channel characterization aspect of LoRa. The effect of mobility and doppler effect on LoRa have been presented in [13]. In addition, the evaluation of NB-IoT in smart-grid application has been presented in [14]. Furthermore, capacity evaluation of NB-IoT has been presented [15] and it is shown that NB-IoT is able to achieve the expected capacity of 52K devices per cell. To the best of the authors knowledge, there are no studies investigating the impact of environment on the performance of these technologies, particularly in underground scenarios. It is, therefore, necessary to answer the following:

- Whether it is sufficiently reliable to use these technologies for SUDS systems?
- Which technology is able to provide high spectrum and energy efficiency while maintaining quality of service (QoS)?

To address these question, this paper presents an extensive study on the feasibility of LoRa and NB-IoT in a star-like network used for SUDS systems. The focus of evaluation is on the impact of underground environment on the radio transmission characteristics of LoRa and NB-IoT. The performance of LoRa and NB-IoT is presented in terms of coverage, effective information rate and energy efficiency.

The remainder of paper is organized as follows. In Section II, the system model under consideration is presented along with the underground drainage system architecture and factors influencing the signal strengths. Furthermore, the simulation parameters and traffic model considered as per the 3GPP and LoRa standards are also presented. In Section III, the detailed evaluation on the performance of NB-IoT and loRa systems in term of effective cell coverage, information rate and energy consumption is provided, followed by a conclusion in Section IV.

II. SYSTEM MODEL

For this study, we have considered the most common UDS structure as presented in Figure 1. UDS are mostly underground and are therefore accessible through the manholes usually covered with an iron lid. It is not possible for EM waves to pass through the lid. Therefore, the signals has to travel through the combination of materials i.e. concrete, compacted sand, gravel or soil. However, EM waves has to suffer much more attenuation in such underground environment as compared to air which significantly degrade the communication quality. Furthermore, multi-path fading due to

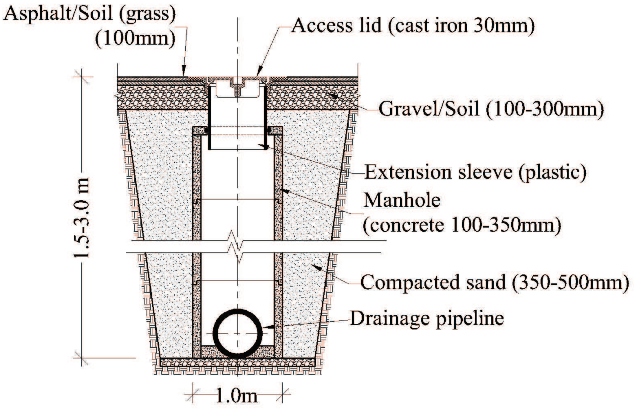

Fig. 1: Urban drainage system architecture

the small particle such as rock or tree roots in soil results in refraction and scattering of EM waves. This further degrades the performance of communication link.

As presented in Figure 1, we have taken into account the loss in signal strength due to **concrete, sand and soil or gravels**. Furthermore, as the UDSs are deployed either under roads, pathways or greenery, with different groundwater level. We have evaluated the performance of NB-IoT and LoRa in both dry and damp environments to observe the impact of water content on the signal in these surfaces as well. As, each of these surfaces will impact the propagation of signals differently, therefore, we have considered soil (greenery) with a thickness of 100 mm for this analysis. The sensor communication process in remote sensing of SUDs is governed by the target geometry and dielectric properties relative to the sensor parameters. At microwave frequencies, i.e. 800 MHz, the dielectric properties of sand and soils are particularly important as they are very susceptible to moisture content and at incidence angles. The signal attenuation that can be caused from the above-mentioned materials are presented in Table I. The values in Table I have been taken from the already existing work on the effect of dielectric properties of soil, sand and concrete on EM waves [16], [17].

TABLE I: Different medium and signal losses in 800 MHz band

Concrete	16 dB/ 35 cm
Dry Soil	21 dB/m
Damp Soil	44 dB/m
Dry Sand	6 dB/m
Damp Sand	15 dB/m

A. Simulation Setup

In this study, the performance analysis has been conducted in a single-cell scenario with an inter-site distance of 500 m. All the sensors are uniformly random distributed. For NB-IoT, the deployment is in standalone mode with a bandwidth of 180 kHz consisting of 12 subcarriers (multi-tone) at 15 kHz subcarrier spacing. The performance of multi-tone is considered to be worse than single-tone e.g. 3.75 kHz or 15 kHz. The performance achieved in this study can be regarded as lower bound as compared to single-tone NB-IoT system. Thus, for NB-IoT investigation, it is a more realistic assumption to consider. For LoRa, the bandwidth is assumed to be 125 kHz with 8 symbols of preambles and header enabled. The other simulation assumptions that closely follows NB-IoT and LoRa standards are presented in Table II.

TABLE II: Simulation Assumption

Parameters	Assumptions
Cell layout	Hexagonal grid
Frequency band	800 MHz
Cell Radius	1 km
User distribution	Users dropped uniformly in entire cell
Sensor Transmit power	23 dBm (NB-IoT), 14 dBm (LoRa)
Pathloss Model	L=120.9 + 37.6 log10(R), R in km
Shadowing standard deviation	8 dB
SC between cell sectors	1.0
Noise figure at base station	5 dB
Noise figure at UE	3 dB
Noise power spectral density	-174 dBm/Hz

Furthermore, the maximum achievable information rate can be calculated using the Shannons formula for Gaussian channel, if signal-to-interference-plus-noise (SINR) is known. Thus, the information rate R_i for a node i is given by:

$$R_i = B \log_2(1 + SINR_i) \tag{1}$$

where B is the bandwidth assigned for transmission and $SINR_i$ for node i and is given as:

$$SINR_i = \frac{P_i h_i}{N_o} \tag{2}$$

where P_i is the transmit power of the node and h_i is the channel gain between node i and the base station. N_o is the noise power spectral density. Based on the SINR, the corresponding MCL is computed. The relationship between SINR and MCL is given as [14]:

$$\begin{aligned} \text{Target SINR} &= \text{Tx power} + 174 - \text{Noise figure} \\ &\quad - 10\log_{10}(\text{Bandwidth}) - \text{MCL} \end{aligned} \tag{3}$$

For this study, chase combining is used based on MCL, such that the same information is repeated N times in case of NB-IoT or different spreading factors are used for LoRa. The number of repetitions and spreading factors assumed with different MCL values are presented in Table III.

B. Traffic Model

For this study, we have considered the Mobile Autonomous Reporting (MAR) periodic traffic model as presented in annex E of 3GPP standard [18]. Based on the model, the application payload size is Pareto distributed with alpha = 2.5, minimum (beta) = 20 bytes, cutoff = 200 bytes. However, for simplicity, we have assumed an average 25 bytes of uplink packet size. On top of that, a header of 32 bytes including CRC field is applied to NB-IoT and 13 bytes with CRC to LoRa as specified in the standards. Furthermore, all sensors apply the QPSK and 4/5 coding scheme.

III. PERFORMANCE EVALUATION

In this section, the system-level performance of the NB-IoT and LoRa is evaluated through Monte Carlo simulations in terms of coverage, effective information rate and energy consumption. With the settings presented in Table II and subsection II-B, the simulation is run for over 5000 random samples.

TABLE III: Coverage classes with repetition factor (RF) for NB-IoT and spread factors (SF) for LoRa

MCL-dB	RF (NB-IoT)
Below 145	1
145 to 147	2
147 to 150	4
150 to 153	8
153 to 156	16
156 to 159	32
159 to 162	64
162 to 164	128

MCL-dB	SF (LoRa)
Below 138	6
139 to 142	7
142 to 146	8
146 to 149	9
149 to 152	10
152 to 155	11
155 to 157	12

First, we evaluate the minimum link loss that can be achieved by the sensors deployed in SUDS with both NB-IoT and LoRa. It will help to evaluate how many sensors can be in outage due to poor signal strength. The minimum link loss between the base station and sensor in terms of cumulative distribution function (CDF) is presented in Figure 2. The sensors are uniformly distributed in a cell with radius of 1 km. The MCL of LoRa (157 dB) and NB-IoT (164 dB) is presented by doted and dash vertical lines, respectively as defined in the technical specifications. The part of the CDF to the left of a dashed line indicate the sensors which are in outage. This means that these device cannot be served by these technologies as the link loss exceeding the MCL. The results show that with an MCL of 164 dB, NB-IoT provides the best coverage. The NB-IoT has an outage of 5.4% sensors for locations with damp environment experiencing high penetration loss in addition to the outdoor path loss. LoRa cannot provide coverage for 11.2% of those sensors. The results also show that the performance slightly degrade further when multi-path fading effect will be considered.

Figure 3 shows the CDF of the average information rate in both dry and damp scenarios with an information packet size of 25 bytes in uplink. The information rate is defined as the number of information bits transmitted per second. This includes the overhead information such as control information of NB-IoT and header and preamble required for LoRa transmission. The result reveals that the maximum information rate that can be achieved with NB-IoT and LoRa are 65 Kbps and 5 Kbps, respectively. It can be noted that LoRa throughput is significantly lower than that of NB-IoT. In addition, in case of damp environment, the information rate reduces significantly by up to 49.5% in NB-IoT (i.e. 30 Kbps) and 60.1% in LoRa (i.e. 1 Kbps). The impact of damp environment on LoRa is much more than NB-IoT, this is due to the use of higher spreading factor in LoRa. As the signal quality decrease due to damp environment, higher spreading factors in case of LoRa and more repetition in NB-IoT are required to overcome the MCL, resulting in performance degradation.

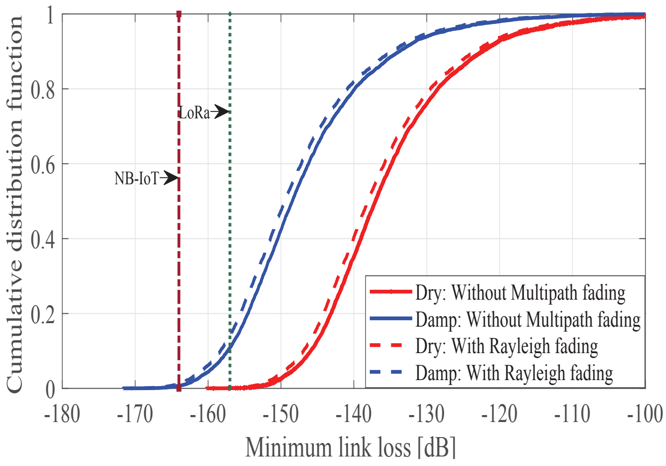

Fig. 2: MCL CDF for sensor deployed underground with 35 cm thick concrete and 50 cm compact sand and 30 cm soil layer in an urban area

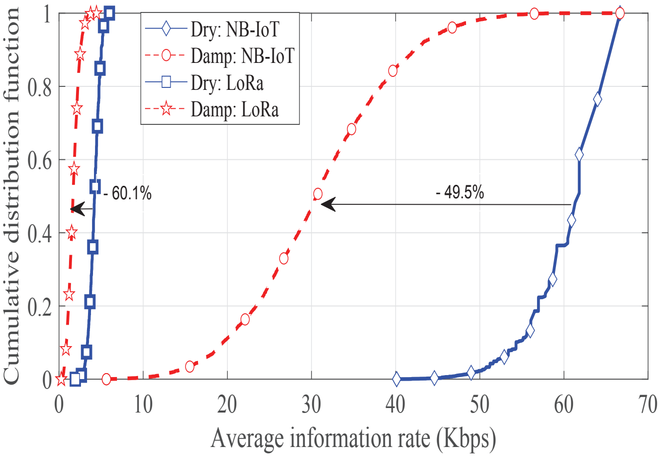

Fig. 3: Effective information rate (Kbps) per sector for sensor deployed underground in an urban area with rayleigh fading for both dry and damp scenario

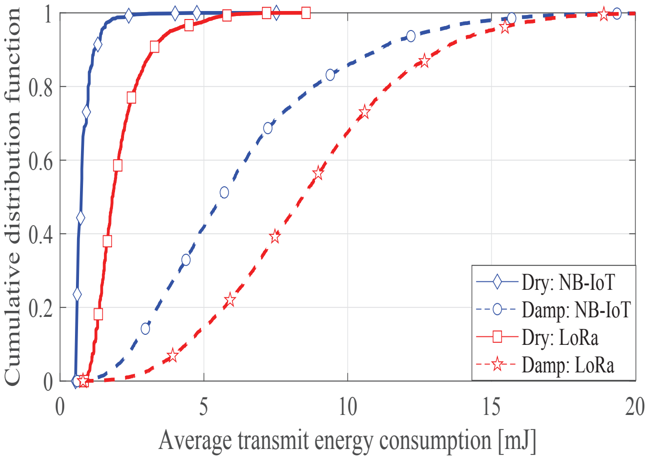

Fig. 4: Average transmit energy consumption (mJ) per sector for sensor deployed underground in an urban area with rayleigh fading for both dry and damp scenario

Figure 4 shows the CDF of the average transmit energy consumption per sector in both dry and damp scenarios with an information packet size of 25 bytes in uplink. It can be observed that the energy consumption of NB-IoT is much less than that of LoRa. This is because the time required to transmit the packet over-the-air in LoRa is significantly higher than in NB-IoT. Furthermore, the energy consumption is significantly higher in damp environment due to increased number of repetitions and spreading factor in NB-IoT and LoRa, respectively.

IV. CONCLUSION

In this paper, we have presented a detailed performance analysis of NB-IoT and LoRa for underground drainage systems in an urban area. From the conducted analysis, it is observed that the performance of these technologies highly depend on the moisture content in the underground environment. However, these technologies are still able to provide the required reliability of communication for SUDS at the feasible density of gateway network. Furthermore, it is also observed that NB-IoT outperforms LoRa in all aspects i.e., coverage, information rate and energy consumption. Therefore, to provide a suitable solution for SUDS, NB-IoT can be regarded as a prominent technology.

As future work, based on the results presented in this study, we will be able to evaluate different strategies for resource management in NB-IoT and LoRa systems for specific SUDS use-cases in urban areas.

ACKNOWLEDGEMENT

"This research was supported by the Estonian Research Council through the Institutional Research Funding IUT19-17, and by the Horizon 2020 ERA-chair Grant Cognitive Electronics COEL H2020-WIDESPREAD-2014-2 (Agreement number: 668995; project TTU code VFP15051). This material reflects only the authors view and the EC Research Executive Agency is not responsible for any use that may be made of the information it contains".

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