Demystifying Low-Power Wide-Area Communications for City IoT Applications

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ABSTRACT

Low Power Wide Area (LPWA) communication technologies have the potential to provide a step change in the enablement of cost-effective and energy efficient Internet of Things (IoT) applications. With an increase in the number of offerings available the real performance of these emerging technologies remain unclear. That is, each technology comes with its own advantages and limitations; yet there is a lack of comparative studies that examine their trade-offs based on empirical evidence. This poses a major challenge to IoT solution architects and developers in selecting an appropriate technology for an envisioned IoT application in a given deployment context.

In this paper, we look beyond data sheets and white papers of LPWA communication technologies and provide insights into the performance of three emerging LPWA solutions based on real world experiments with different traffic loads and in different urban deployment contexts. Under the context of this study, specialized hardware was created to incorporate the different technologies and provide scientific quantitative and qualitative information related to data rates, success rates, transmission mode energy and power consumption, and communication ranges. The results of experimentation highlight the practicalities of placing LPWA technologies in real spaces and provide guidelines to IoT solution developers in terms of LPWA technology selection. Overall aim is to facilitate the design of new LPWA technologies and adaptive communication strategies that inform future IoT platforms.

1. INTRODUCTION

Low power wide area (LPWA) communication technologies have recently emerged as a viable alternative to cellular and mesh networks for providing cost effective IoT connectivity in cities. With several manufacturers and consortia now announcing national rollouts using different LPWA technologies, IoT solution and connectivity providers are now faced with the dilemma of what technology may be applicable in different enviroments or scenarios. Unfortunately, there is little empirical evidence that provides a good understanding of the performance tradeoffs of these solutions applied to different application requirements and deployment contexts [9].

IoT deployments in urban environments for smart city applications provide one of the most appropriate scenarios for LPWA technologies (see Figure 1). However, they also impose diverse requirements on LPWA technologies in terms of application demands and deployment contexts. To illustrate the case let us briefly look at two simple smart city application examples.

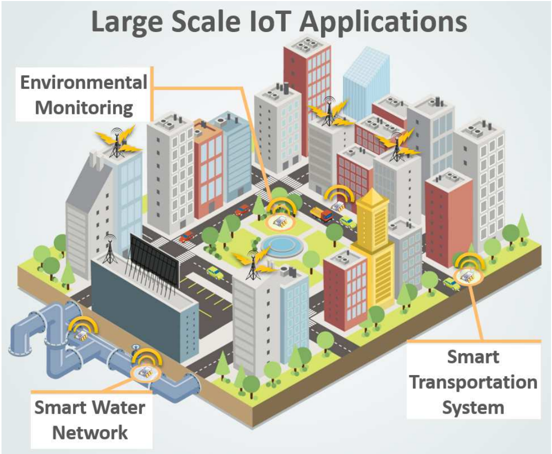

Figure 1: IoT Applications and LPWA Communication Scenarios.

Typical urban environmental monitoring, such as in a park, requires a small number of samples (e.g. water quality or soil conditions) to be taken at regular intervals sparsely distributed throughout the day. This is situated in an environment that is characterized in terms of communications either as line of sight or non-line of sight (LoS or NLoS respectively) - vegetation or people here tend to be the main obstructions. The delivery of data is delay-tolerant, that is the exploitation of the data is typically non-time critical. On the other hand, the built environment brings additional challenges, it remains a delay-tolerant class of application but the penetration of radio through built spaces can greatly impact the design choice for IoT. In contrast, monitoring of critical infrastructures (e.g. leak detection in a water network) has quite different requirements. Data transmission is event-based in nature, and only occurs if critical events or warning signs are detected. The penetration challenge here is exacerbated due to underground deployments of nodes, which places them in a very harsh radio environment. As the effects of leaks or contamination can be severe, the delivery time of such events is critical and communication delays are not tolerated.

The study presented in this paper has been motivated by initial experiments performed when designing a real-world sensing solution using different LPWA modules. These preliminary studies began to observe that the theoretical capabilities of the modules differ drastically from real capabilities observed in our tests. Therefore, we could see the benefit of a more in depth evaluation of LPWA technologies, thus the methodology taken in this study is to mimic realistic conditions aiming to cover the majority of city IoT applications and to place the technologies in real environments, for reasonable durations.

The increasing importance of the experimental evaluation of IoT solutions is also evident by the recent emergence of diverse IoT testbeds [5]. However, to our knowledge, no such publically accessible testbed exists that permits comparative experiments with LPWA technologies to be performed in real deployment contexts. To this end, we designed BentoBox, a testbed node that allows in-the-wild multi-radio experiments with different LPWA communication modules (i.e. LoRa, XBee868, and nWave) to be performed in a collocated fashion, to enable conclusive comparisons across various LPWA technologies. For our experiments, a number of BentoBoxes were installed in and around the Imperial College area in different buildings and roof tops, in Hyde Park, and in manholes by reporting the following metrics: data rates, success rates, transmission energy and power, and communication ranges.

The multidimensional approach of our study, results in an empirical characterization of the performance limitations and trade-offs of the different LPWA technologies, and allows readers to define the appropriate communication set-up for their particular IoT applications and deployment contexts.

The rest of the article is organized as follows. Section 2 summarizes prior related wireless communication technology comparisons. Section 3 introduces LPWA technologies in general and the systems used in this article in particular. Section 4 presents the evaluation results of the LPWA experiments. Section 5 discusses these results in terms of IoT application contexts and 6 concludes the article.

2. PRIOR RELATED WORK

Many City Internet of Things (IoT) applications require large scale wireless communication among devices, which can be located underground, within crowded streets, or in more sparse urban parks. Initially, evaluations of suitable technologies focused primarily on short-range communications such as WiFi [7], [2], [10], Bluetooth, and Zigbee [7, 1, 2, 3, 4, 10, 12] due to their low power features, therefore making them appropriate for battery powered IoT applications. To extend range such systems required mesh/multi-hop protocols, which were difficult to realize and increased deployment costs and communication delays. While a number of real deployments exist there are very few that report comprehensive evaluations of the technologies used. In fact, many recent comparative studies make use of simulations, are based on datasheets [7, 1, 2, 10, 14], or focus on practical evaluations over a single technological dimension e.g. power consumption [3, 4, 12].

Recently, low power wide area (LPWA) technologies have become available that allow kilometer wide communication. There is a lack of understanding of how such technologies behave under real conditions [9], their limitations are unclear, and for most studies, online product datasheets constitute the only information source to evaluate their capabilities. Examples, [11] presents an evaluation of the LPWA Zigbee family but in a deserted area, while [6] evaluates the LoRa LPWA solution in a small-scale multiple building roof deployment. Likewise, [11] provides a comparison between CC1200-DK and LoRa iM880A but is based on line of sight (LoS) and semi-line of sight (in moderately/heavily wooden areas) experiments only. The narrow selection of the environments and conditions of these experiments are unable to define the real limitations of LPWA technologies under the context of IoT applications.

In this paper, we evaluate three state-of-the-art LWPA technologies under the same spatiotemporal conditions: LoRa (no-standard), Xbee868 (Zigbee), and nWave (Weightless protocol). Our findings are based on real experiments, which were conducted in multiple distinct environments: a park with semi-LoS, a built up area, underground-to-over-ground, and underground-to-underground. The nature of the experiments were inspired by the many deployments of sensors in Cities we have carried out in the past.

3. LPWA TECHNOLOGIES

LPWA technologies are emerging with new physical layer communications capable of leveraging the trade-off between range and data-rates, and which are suitable for non-data-intensive IoT applications. Communication theory suggests that data rates, link distances and power consumption can be mutually traded in the physical layer design depending on the application scenario yet existing wireless devices typically leverage the trade-off between range and power consumption as data rate is often non-negotiable for many application scenarios.

In order to increase the communications range, a wireless device essentially needs to increase the link budget, which technically implies enhancing the signal-to-noise ratio (SNR) at the receiver. Spread-Spectrum and Ultra-Narrow-Band (UNB) are two candidate technologies offering low-power long-range communication, and based on these technologies there are some specially tailored products being offered by various vendors. For example, LoRa by Semtech uses Chirp Spread-Spectrum modulation, and NWave, Sigfox, Texas Instruments etc. are offering modules based on Ultra-Narrow-Band technology.

Spread-Spectrum Technology based devices spread the energy of the signal over a wide band which effectively reduces the spectral power density of the signal. This is accomplished by convoluting the band-limited information signal with a much higher bandwidth pseudo-random chirp sequence, this is popularly known as Direct Sequence Spread Spectrum (DSSS). Another variant of spread spectrum technology is based on frequency-hopping, which generates a wide band by transmitting at different frequencies, jumping from one frequency to another according to a pseudo-random code sequence. The ratio of the RF bandwidth (signal to be transmitted) to the bandwidth of the information signal is termed as processing gain which proportionately enhances the SNR, which implies that increasing the processing gain results in underutilization of the spectrum (and a decrease in data rate) but in turn improves the range.

Ultra-Narrow-Band (UNB) Technology attempts to enhance the SNR by reducing the noise-floor of the receiver by narrowing down the receive bandwidth (BW_{Rx}) which in turn reduces the modulation bandwidth resulting in a lower data rate. BW_{Rx} is related to the noise floor of the system as per equation: $PdBm = 174 + 10log10(BW_{Rx})$ i.e., the noise floor scales with the receive bandwidth (174 dBm is the thermal noise floor at room temperature in a 1-Hz bandwidth) [13].

Conventional Narrow-Band Systems such as XBee868 uses modulation schemes (e.g. MSK, GMSK etc.) which changes frequency and phase gradually during the whole bit-interval, which result in upper and lower sidebands around the carrier frequency. Ultra-Narrow-Band devices are attempting to remove the side-lobes in order to narrow-down the channel-width, and they achieve this using modulation schemes which result in an abrupt change in frequency and phase while transmitting – examples of such schemes are DBPSK (differential binary phase shift keying), VMSK (very minimum sideband keying), minimum sideband (MSB) modulation etc. Although, this technology has been conceived in 1985, only now has it been practical as it requires RF filters with zero group delay; the implementation of which needs agile and sophisticated RF components [8].

Technology Comparison: For a given output power (often defined by governmental regulations), the range of the RF link is determined by the data rate, i.e., lower rates provide longer ranges due to increased sensitivity for the receiver. There is, of course, also a trade-off, since very low rates mean a considerable long time of transmission, which in turn reduces battery lifetimes. Theoretically, given the same net data rate/throughput, systems based on both Ultra-Narrow-Band and Spread-Spectrum technologies will have achieve ranges [13]. The drawback of ultra-narrowband technology has been the higher requirements on the RF crystal, whereby a frequency error on the RF crystal leads to an offset on the programmed RF frequency. Therefore, large offsets may lead the signal to fall outside the channel and be filtered out by the receive filters [13].

UNB technology promises better utilization of the spectrum in cases where implementation hurdles can be addressed. This utilization feature requires a relatively complex media access layer for handling the inter-channel interference and the coexistence with other RF devices in the same band. Additionally, the system needs to opportunistically manage a large number of channels in the same band due to narrow channel-width in a volatile RF environment such as a city.

On the other hand, spread-spectrum based devices are likely to under-utilize the spectrum relatively to what could be achieved with an ideal implementation of the Ultra-Narrow-Band technology. However, this simplifies other key issues such as interference and coexistence with other wireless devices as its signal appears as background noise to other systems. Other narrow-band devices, conversely, cause from low level to no interference with the spread spectrum systems because the correlation receiver effectively integrates over a wide bandwidth to recover a spread spectrum signal. This simplifies the implementation of the media-access layer as it involves only dealing with code-sequences from users point of view. In an urban space, this is expected to perform better as the spread spectrum signal is less susceptible to multipath fading. One added inherent advantage comes along with this technology, because of the available wide bandwidth, is the increased difficulty to jam, detect, intercept or demodulate the signals. Due to the pseudo-random nature of the code sequence, the signal in the air has been ”randomized”. Only the receiver having the exact same pseudo-random sequence can de-spread and retrieve the original signal. Consequently, a spread spectrum system provides signal reliability inherently.

Overall, from a long-term scalability perspective, Ultra-Narrow-Band seems to be more promising, however for early stage IoT applications, a more resilient technology will be crucial, which is likely to give advantage to spread spectrum based devices until Ultra-Narrow-Band devices mature to an acceptable level. In the subsequent sections we explore these hypothesis with regard to the technologies available now and with regard to the urban space.

4. EVALUATION

This section presents the hardware infrastructure and evaluation environmental scenarios and setup, while provides quantitative and qualitative performance comparison among three LPWA communication technologies. Additionally, it reveals critical insights for these contemporary technologies.

4.1 Hardware Infrastructure

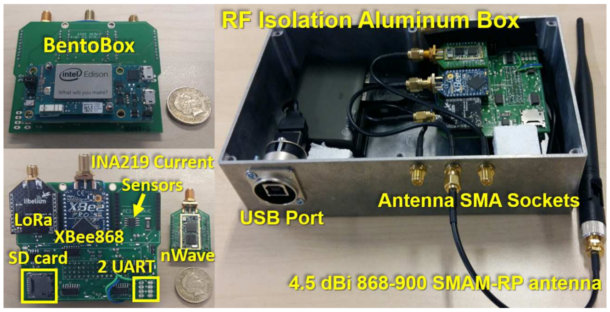

Figure 2: BentoBox: Hybrid LPWA Communication Box.

To conduct the field experiments we developed BentoBox; a custom hardware platform based on the Intel Edison board. BentoBox incorporates multiple LPWA communication modules, software to facilitate easy programming of the modules for different experiments, and experimental data collection mechanisms (see Figure 2).

While communication modules for various LPWA technologies exist, in this evaluation campaign, we focused on the well-established XBee868 chip and two more recent technologies specifically developed for long range coverage: nWave and LoRa. The reasons for this selection were both technical (range and power consumption) and logistical (access to hardware to create a collocated node).

To provide optimal power management and enable energy performance characterizations, the board has the ability to power off and to measure the power consumption of each communication module separately. Additionally, a micro SD card extends the Edison storage capacity to log experimental data (Figure 2).

To ensure stable environmental and RF conditions, critical aspect in our experimental design was the hosting hardware infrastructure of BentoBox. Each nodes were installed inside aluminum boxes, which shield the communication modules from the external RF environment by blocking other interfered signals and allowing the optimal communication performance. Separate coaxial RF connectors (SMA) connect to the three communication modules. A shielded aluminum USB port connects the power supply and communication to an Intel Edison. In our experiments we placed a single 4.5 dBi 868-900 SMAM-RP antenna in a static position by connecting it to a SMA connector with coaxial cable, in order to maintain the same conditions for all modules.

4.2 Communication Modules

In our experiments, all the modules were set at maximum transmission power so that their coverage limitations were identified. LoRa determines its transmission mode based on three configurable parameters: bandwidth (BW), coding rate (CR) and spreading factor (SF). We use 10 different modes as provided by the Libelium API [6] where mode-1 corresponds to the largest distance with lowest data rate (0.2 kbps), and mode-10 corresponds to a higher data rate (6.45 kbps) and shortest distance; the remaining 8 intermediary modes represent a tradeoff between link distance and data rate. Gradual variation of LoRa from mode-10 to mode-1 effectively results in enhancement in sensitivity from -114 dBm to -134 dBm (see Table 1), which increases the link budget for the same transmission power. On the other hand, the other modules, XBee868 and nWave, provide less configuration freedom by allowing only the selection of radio frequency and power level.

4.3 Experimental Methodology and Environments

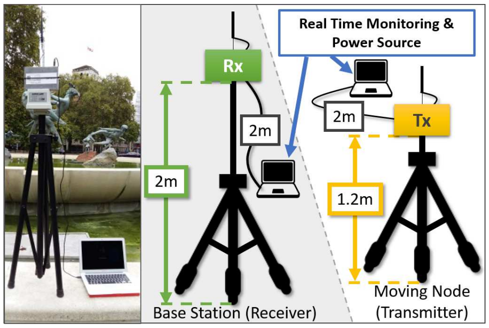

Figure 3: Base station (Receiver - Rx) and moving node (Transmitter - Tx) installation.

Four main experiments were performed at the university and its surroundings. During each of these experiments we varied the transmission payload sizes (Table 1: Payload in our Evaluation) and distances between the transmitter and receivers (Figure 4a and Figure

Table 1: Technical parameters LPWA modules

Frequency: 868 MHz **Power Supply: 3.3V**		**LoRa** **(Spread Spectrum)**	**Xbee Pro** **(Narrow Band)**	**nWave** **(Ultra-Narrow Band)**
Data Rate (kbps) per datasheet		0.3-50 flexible	24	0.1
Power Consumption	**Transmit**	Range: 7 to 20 dBm 18 mA - 125 mA	Range: 0 to 25 dBm 85 mA - 500 mA	Range: -10 to 16 dBm 22 mA @10 dBm 54 mA @15 dBm
	Receive	11 mA	65 mA	N/A
	Sleep	1 A	55 uA	1.5
Rx Sensitivity		-137 dBm	-112 dBm	N/A
Max Link Budget		157 dBm	137 dBm	N/A
Payload in our Evaluation		10, 100, 180, 250 bytes	10, 50, 100 bytes	10, 20 bytes

Semi-Line of Sight					Modules/Modes	Urban	
10	92	95	98	100	LM1	98	65
20	85	90	98	100	LM2	92	65
40	80	85	97	100	LM3	90	10
19	70	78	65	100	LM4	86	0
0	20	35	52	100	LM5	85	0
0	0	10	68	100	LM6	90	0
0	0	0	65	100	LM7	85	0
0	0	0	5	100	LM8	80	0
0	0	0	0	100	LM9	28	0
0	0	0	0	100	LM10	18	0
0	0	100	87	100	Xbee868	92	0

(a) Ground to Ground Evaluations in Semi Line of Sight and Urban scenario.

Modules/Modes	Underground		Overground		
	Overground	Underground			
LM1	95	99	100	86	72
LM2	93	98	95	88	0
LM3	95	97	94	85	85
LM4	97	98	99	78	0
LM5	96	95	98	50	0
LM6	94	96	98	49	0
LM7	95	95	98	10	0
LM8	7	95	99	0	0
LM9	0	96	98	0	0
LM10	0	95	97	0	0
Xbee868	0	99	94	18	0
NWave	0	N/A	82	17	0

(b) Building-Top to Underground and Overground Evaluations in Urban scenario.

Figure 4: Experimental Environments

4b), transmitting 100 packets for each XBee868 and LoRa experiment and 20 packets for nWave. nWave was ran fewer times due to significant delays in getting experimental results from the cloud server. LoRa has 10 modes as described earlier, each of which was tested per experiment. All experiments for each technology ran over 868MHz, and were interleaved automatically using the BentoBox software in a round-robin fashion to minimize the difference in medium properties for each technology at a given moment.

Experiment set 1 (G2G) considered the case where both receiver and transmitter are located close to ground level and deployed in a semi-LoS configuration (see Figure 4a). The receiver was located at the highest elevation point of Hyde Park [1] and 2m above ground (Figure 3 - left). The transmitter was placed on a pole at 1.20m height (Figure 3 - right). As the receiver was positioned at the edge of the park, it allowed us to explore two different environments: open green space and built environment. For each experiment set, we increased the distance of the transmitter from the receiver. In the case of the open green space area, we increased the distance in steps of 400m until none of the LPWA technologies were able to communicate successfully. In the case of the built environment, the increase was in 100m steps. The experiments were performed for both LoRa and XBee868. Unfortunately, the nWave base station required an Internet connection to a cloud based backend and constant 220V power source. Thus, we could not consider it for this deployment, as such facilities were unavailable at the experimentation site.

Experiment set 2 (G2RT) considered a ground to roof-top communication scenario, where the receiver was placed on top of an eleven floor building on the university campus. The transmitter node was placed on the ground at a height of 1.20m. As depicted in Figure 4b, we varied the distance between the transmitter and

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[1] The altitude was measured accurately by using high resolution survey class GPS (`http://www.geosurvey.co.uk/geomax-gps-gnss-glonass/geomax-zenith-gps-gnss`).

receiver in 100m steps until no reception was possible. As the roof top location provided us with an Internet connection, we could include nWave.

Experiment set 3 (U2RT) considered the communication case where a transmitter is placed underground and the receiver node remains at the roof top. Figure 4b shows underground (manhole) deployment. The transmitter was placed in a manhole and the Bentobox was placed just under 1m deep with the antenna pointing down into the manhole [2] The manhole was covered with cast iron. All three LPWA technologies were evaluated.

Experiment set 4 (U2U) considered the underground to underground communication case where both sender and transmitter were placed in two manholes 80 m apart (see Figure 4b). The manholes were located in a mixed built, tree lined area with a mix of sand/brick clay. Similar to Experiment set 1, the utilization of nWave base station was impossible in such harsh underground environment. The placement of both nodes and antenna direction were as described in the experiment set 3.

4.4 Experimental Results

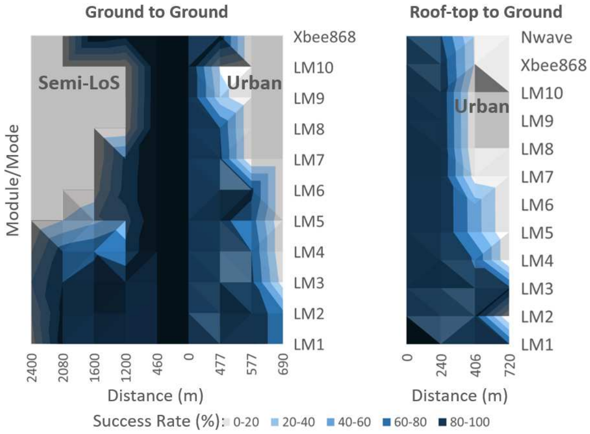

Figure 5: Success Rate chart for different modules/modes and range.

It should be noted that the results presented here are specific to our particular experimental set up; other environments and hardware support for these communications technologies may produce different figures. However, the aforementioned well-studied hardware and software infrastructure aims to carry out the experimentation as scientifically as possible to produce guidelines to IoT solution developers. The results are in line with communication theory, intuition and initial controlled lab tests.

Figure 4a presents the results from the G2G experiment carried out mostly in a semi-line of sight green area (Hyde Park, London) and partially in the built-up area; both nodes were placed at person level. We can observe the maximum ranges achievable for our experimental set up and associated success rates at each point. Taking the urban figures first (right two columns), we see reasonable reliability until about 500m from the base station for low data rate LoRa and Xbee868. Then beyond that distance the reliability drops significantly for all mid to high data rate LoRa (LM4 and above) and Xbee868. Much greater distances are achieved in the green area as expected; up to 2.4Km with lower data rate LoRa (LM1 - 0.07kbps). However, for higher data rate modes this range drops off after 500m (LM8 and LM9 - 0.69kbps and 0.94 respectively). Xbee868 can maintain reliability for greater distances compared with higher data rate LoRa by achieving just over 1.6Km. Note, Xbee868 drops its reliability at 1.2Km where the receiver was on the bridge (see figure 2) which was dense with people who, curious about the experiment, grouped around the equipment. Received signal strength indicator (RSSI) readings on the bridge dropped correspondingly. Interestingly, XBee868 is more affected by this phenomenon than the LoRa technology. This can be explained by our RSSI observations which sat at -118dBm then dropped to -127dBm, which is within the tolerable range for LoRa (LoRa is a reliable down to -135dBm). Conversely, LoRa recovers to receive data reliability beyond 1.6Km (it achieves 92% at ∽2Km before becoming unreliable).

Figure 4b presents the comparative results among LoRa, XBee868, and nWave where the base station was on the roof-top and the nodes were either at ground level or in a manhole, in an environment dense with buildings all of six floors or larger. As one would expect even with the elevation of the base station we achieve less distance with all technologies due to the built-up environment. Comparing the figures for overground to the urban results of Figure 4a we can see this difference clearly with a loss of about 20% reliability for about 450m for the LoRa results. XBee868 drops off much more significantly in the built-up area after 100m, even though it uses more power. nWave performs in a similar way to XBee868, though at significantly lower data rates (see figure 5). The results for underground to roof-top were surprisingly good for LoRa modes LM 7 and below; the success rates were similar to the above ground readings. However for LM8 and above, very few packets were received from under the cast iron cover. Likewise, no data was received from nWave and XBee868.

The U2U experiment was limited to two manholes 80m apart in a semi-built space (small park surrounded by buildings - see Figure 4b). Here all technologies, except for nWave which was not included in this experiment set, achieved very reasonable reliability of greater

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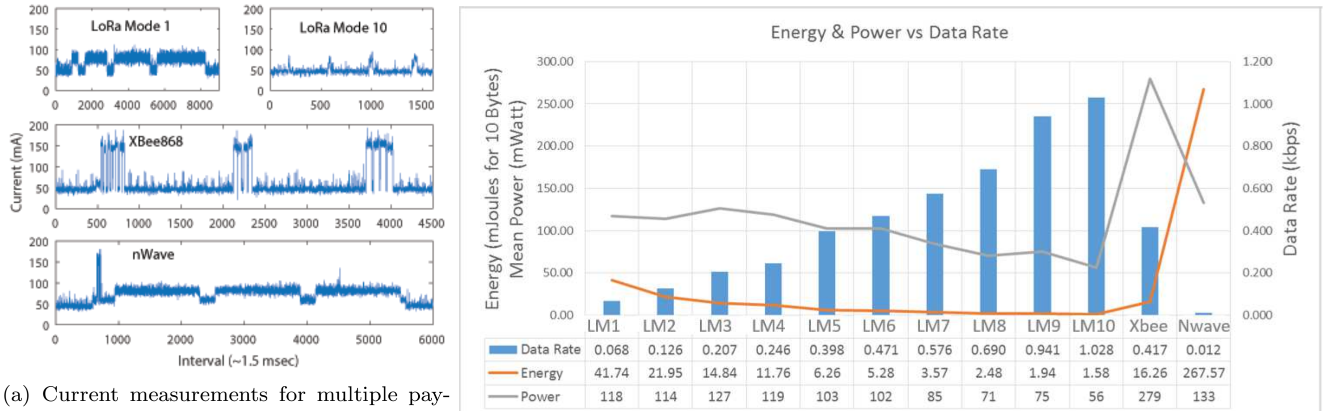
[2] The antenna direction was decided after optimal performance exhausted experimentation.



	LM1	LM2	LM3	LM4	LM5	LM6	LM7	LM8	LM9	LM10	Xbee	Nwave
Data Rate	0.068	0.126	0.207	0.246	0.398	0.471	0.576	0.690	0.941	1.028	0.417	0.012
Energy	41.74	21.95	14.84	11.76	6.26	5.28	3.57	2.48	1.94	1.58	16.26	267.57
Power	118	114	127	119	103	102	85	71	75	56	279	133

(a) Current measurements for multiple payloads as described in Table 1 for LoRa and XBee868, and 10byte payload for nWave.

(b) Experimentally measured data rate, power and energy consumption.

Figure 6: Data rate, power and energy consumption comparison.

than 95%; fact that opens a number of application opportunities for both LoRa and XBee868.

To provide an easier interpretation of the experimental results, Figure 5 and Figure 6b aggregate key information for the different communication modules under various environments in terms of range, success rates (reliability), power and energy consumption, and data rates. To ensure the comparison validity, the presented results refers to the experiment with 10 byte payload; a size which all module can support. Based on these figures three main lessons can be inferred:

Insight 1: In Figure 6, we observe that the data rate achieved by the XBee868 module is equivalent to that of LoRa LM5. Figure 5 indicates that for semi-LoS communication, XBee868 has a much longer range (around 2km) than LoRa LM5 (around 1.3km). This implies that narrowband modules such as XBee868 can provide higher data rates for the same link distances. However, at those points XBee868 uses 300mW while LoRa utilizes only 20-40mW power. Figure 6a illustrates precise current measurements during communication process with difference payloads as logged from BentoBoxes.

Insight 2: Figure 6 shows that XBee868 consumes significantly higher power (279mW) compared to the other modules. However, because of the fast transmission period the total energy consumption is similar to LoRa LM3. Because energy consumption is the main indicator of battery life, the above implies that battery-operated nodes equipped with XBee or LoRa LM3 will function for the same duration.

Insight 3: Based on Figure 6, the nWave module consumes similar average power in transmission mode as the LoRa module. However, the nWave transmission process lasts 34 times longer than XBee868 and similarly, 5 times and 85 times than LoRa mode 1 and mode 10 respectively for the same payload (Figure 6b). As such, nWave module consumes 94% more energy in transmission modes compared to the power hungry XBee868 and between 84% and 99.5% against LoRa.

5. DISCUSSION

The above presented findings provide useful insights for smart city solution developers that aim to deploy an enabling IoT infrastructure in a real world urban setting. Lets illustrate the usefulness of our findings using a real world problem.

Problem: Lets consider an example of a sustainable smart water network which engineers require 900 reliable pressure measurements every 15 minutes (∽1800 Bytes). Here, each sensor node is equipped with a 400mAh (∽5330 Joules) battery and an energy harvester, i.e. water pressure difference recharges the battery by 9 joules per 15 minutes). Furthermore, the node consumes approximately 5 Joules for sensing and data processing etc.

Solution: Figure 5 and Figure 6 can guide the selection of the most appropriate LPWA communication technology. Lets assume the water network nodes are situated in a semi-LoS with a long distance apart. Figure 5 shows the longest range, reliable communication (over 85%) can be achieved using LoRa in LM1-LM3. When evaluating data rate and power consumption needs see Figure 6, here transmission of 1800 bytes requires 3.51, 1.902, and 1.161 minutes in LoRa LM1-LM3 respectively; all represent acceptable values given the time constraint of 15 mins. We can infer that the data transmission energy needs are 7513, 3951, 2672 mJoules every 15 minutes for LoRa LM1-LM3 correspondingly. As the smart water network must be sustainable and due to the energy harvesting system performance (9 joules per 15min) and the energy requirement for sensing, and data processing (∽5 Joules), only LoRa LM2 and LM3 are acceptable. Additionally, the highest reliability (85% success rate) can be achieved using LoRa LM2 (Figure 5) over longer distances (2km). Thus, the best solution for this IoT application is the use of LoRa LM2 and creating clusters every 4km.

Lastly, during the design of IoT application, the hardware installation setup and network topology are important factors. For example, the native support for mesh routing of Xbee868 allows easy extension of network coverage. Additionally, the current nWave receiver requires a mini-PC base station connected to the Internet, which orchestrates the communication parameters. The reliance on an internet connection makes nWave inappropriate for localized deployment cases such as remote smart irrigation systems. Furthermore, the current implementation of nWave only supports uplink data collection to the base station. However, this limitation will be rectified by the addition of a downlink in an upcoming version next year.

6. CONCLUSIONS

City sensing applications require communications solutions that are low-cost and match the low-powered nature of sensing nodes allowing them to be placed or retro-fitted and maintained in a cost-effective way. We have seen a recent influx of new low-powered wide area communications offerings which leads the developer with much choice and very little objective real-world information to aid design decisions. The experiments carried out in this paper highlight the practicalities of placing LPWA technologies in real spaces and provide *guidelines* for the urban IoT developer. However different environments provide different results and ultimately one's choice of technology is down to the application (e.g. many edge devices sending unidirectional data verses a bi-directional mesh) and is also influenced by vendor business models, technology maturity, costs (number of base stations) etc. In he study conducted for this paper the LoRa approach would win, but the real question is: in a city of a billion devices would this approach still hold up? In this future scenario utilization of bandwidth may come to dominate which means the conclusions herein may no longer be relevant. To this end future work, will study the scalability and coexistence properties of these technologies.

Acknowledgment

This work forms part of the Smart Water Networks project funded by NEC Corporation, Japan, Water Analytics and Intelligent Sensing for Demand Optimised Management, FP7 619795 and the Intel Collaborative Research Institute on Sustainable Connected Cities.

7. REFERENCES

[1] B. E. Bilgin and V. Gungor. Performance evaluations of zigbee in different smart grid environments. *In Proc. Computer Networks*, 56:2196–2205, 2012.

[2] D. Camps-Mur, A. Garcia-Saavedra, and P. Serrano. Device-to-device communications with wi-fi direct: overview and experimentation. *In Proc. IEEE WC*, 20(3):96–104, 2013.

[3] E. Casilari, J. M. Cano-García, and G. Campos-Garrido. Modeling of current consumption in 802.15. 4/zigbee sensor motes. *In Proc. Sensors*, 10(6):5443–5468, 2010.

[4] A. El Kouche, A. M. Rashwan, and H. Hassanein. Energy consumption measurements and reduction of zigbee based wireless sensor networks. In *In Proc. IEEE Globecom*, pages 557–562, 2013.

[5] A. Gluhak, S. Krco, M. Nati, D. Pfisterer, N. Mitton, and T. Razafindralambo. A survey on facilities for experimental IoT research. *In Proc. IEEE Comm. Mag.*, 49:58–67, 2011.

[6] C. Hacks. Lora experiments, 2016. `www.cooking-hacks.com/documentation/tutorials/extreme-range-lora-sx1272-/module-shield-arduino-raspberry-pi-intel-galileo`.

[7] J.-S. Lee, Y.-W. Su, and C.-C. Shen. A comparative study of wireless protocols: Bluetooth, uwb, zigbee, and wi-fi. In *Proc. IEEE IECON*, pages 46–51, 2007.

[8] Microwaves&rf. Understanding UNB modulation. `mwrf.com/markets/understanding-ultra/-narrowband-modulation`, 2016.

[9] B. Moyer. Low power, wide area: A survey of longer-range IoT wireless protocols. *Electronic Engineering Journal*, September 2015.

[10] M. Onsy, R. Salah, M. Makar, G. Badawi, A. Kenawy, H. H. Halawa, T. K. Refaat, R. M. Daoud, H. H. Amer, H. M. ElSayed, et al. Performance of wsns under the effect of collisions and interference. *Wireless Sensor Network*, 2014.

[11] N. Rathod, P. Jain, R. Subramanian, S. Yawalkar, M. Sunkenapally, B. Amrutur, and R. Sundaresan. Performance analysis of wireless devices for a campus-wide iot network. In *In Proc. IEEE WiOpt*, pages 84–89, 2015.

[12] C.-S. Sum, F. Kojima, and H. Harada. Energy consumption evaluation for power saving mechanisms in recent ieee 802.15. 4 low-rate wireless personal area networks. In *In Proc. IEEE ICC*, pages 4449–4454, 2013.

[13] TI. Long-range RF communication. `www.ti.com/lit/wp/swry006/swry006.pdf`, 2016.

[14] M. Zennaro, A. Bagula, D. Gascon, and A. B. Noveleta. Planning and deploying long distance wireless sensor networks: The integration of simulation and experimentation. In *Ad-Hoc, Mobile and Wireless Networks*. 2010.