Ultra Narrow Band Radio Technology in High-Density Built-Up Areas

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Abstract. The Internet of Things (IoT) is an ever mentioned phenomena which is closely linked to a rapidly growing Low-Power Wide-Area Networks (LPWAN). Although LPWANs are already widely deployed the performance under real-life conditions of the communication system such as Ultra Narrow Band (UNB) radio technology has not been deeply studied yet. Smart City applications of IoT imply low energy consumption, high spectrum efficiency, and comprehensive security hence the range limits are very constrained and must be verified before deployment is started. In this work, authors verify UNB technology called SIGFOX and identify technological constraints. These constraints allow us to formulate a measurement methodology combining range measurements in an urban area to show transmission characteristics of SIGFOX technology. The subsequent evaluation of the technology using reference/commercially available SIGFOX hardware in real urban areas shows the impacts to possible applications of this novel UNB technology.

Keywords: Internet of things · SIGFOX · Ultra narrow band · Methodology

1 Introduction

In 1999, British visionary Kevin Ashton established the term "The Internet of things" as a futuristic world of seamlessly connected devices [5]. In less than twenty years after, the Internet of Things (IoT) is experiencing rapid growth with estimations between 25 and 50 billion connected devices by 2020, with up to 40 Machine-Type Communications (MTC) devices per household [1,11,20]. Although multiple solutions are emerging, the focus on specific services and applications let to the heterogeneity in communication protocols, network technologies and standards [2,17]. Despite the fact that network technologies are different, they all share common objectives: low power consumption, low device cost and a long extended range [11].

Predictions say that smart commercial buildings will have the highest usage of IoT by 2017, with smart homes taking the lead in 2018 [13]. Supported by the Smart Grids Task Force that advises the European Commission on the development and deployment of smart grids, the EU aims to replace at least 80 % of

© Springer International Publishing Switzerland 2016
G. Dregvaite and R. Damasevicius (Eds.): ICIST 2016, CCIS 639, pp. 663–676, 2016.
DOI: 10.1007/978-3-319-46254-7_54

the electricity meters with smart meters by 2020 [8]. Smart Metering, such as smart meters and remote sensors, is currently seen as the first application [12]. Contemporary solutions on the market are mainly represented by traditional cellular technologies that have a higher power consumption, entry cost and low transmission efficiency due to the different nature of Machine to Machine (M2M) communication. M2M sensor applications generally produce a small payload size with bursty nature of the traffic and require wide coverage [15,21]. As ETSI depicts, IoT applications where long-range with low bandwidth and power consumption are not supported by existing technologies, Low Power Wide Area Network (LPWAN) technologies gain their momentum as an alternative to cellular M2M connections [17].

Authors of this paper focus on one of the significant players in LPWANs called SIGFOX marked as the first operator of a dedicated M2M cellular network [1,5,14]. As one of the emerging proprietary technologies, SIGFOX is frequently mentioned as the reference player in IoT but almost no works about real life experiences have been published. As the authors had the privilege to be a part of SIGFOX technology testing in an urban area in the Czech Republic, the paper presents real-life measured data showing variety of impacts to this novel LPWAN technology. By analysing more than 3,700 samples captured over a period of 8 months, during the network roll out, authors try to verify a real-life performance and its constraints.

The paper is structured as follows. In Sect. 2, we present related works and standards. Section 3 details the SIGFOX technology and Sect. 4.1 closes up our experimental setup for stationary and nomadic measurements. In Sects. 4.2 and 4.3, achieved results are presented and we conclude our paper by summary in Sect. 5.

2 Related Works

Most of the related work focuses on IoT competitor LoRa technology. As for example [27], where authors outline the resistance to intentional interference and echo. Experimental studies on coverage limits and attenuation models for LoRa technology [3] concluded measurements to find out a formula for a channel attenuation model. This model was also taken as a ground for stationary measurements in this article. On the other hand, SIGFOX technology is generally described and compared with main competitors in article on lessons learnt from industrial implementations [12], where authors describe an up-link channel structure and access mechanisms.

Standardization work in LPWANs is ingoing, for example within the 3GPP on usage of IoT in licensed spectra LTE-M and EC-GSM [1,21]. Moreover, one of the main initiators in this area is ETSI on open specification of a new standard for Low Throughput Networks (LTN), where one of the main contributors is SIGFOX company [11].

3 SIGFOX at a Glance

3.1 Architecture

SIGFOX, a French technology start-up, was established in 2009. Although the SIGFOX solution is proprietary, the company is also closely cooperating with ETSI on definition of an open LTN standard; thus, we can expect significant intersections [12]. What makes SIGFOX different from other competitors and why it gained momentum on the IoT market is likely a comprehensive business model offered to its customers [9].

The network is based on one-hop star topology and consists of transmitting devices, gateways/base stations and SIGFOX back-end. The network coverage is deployed per each country by chosen partner called SIGFOX Network Operator (SNO). Receiving base stations/gateways operated by SNO are typically placed on Mobile Network Operator's radio towers [16]. These gateways communicate with SIGFOX Cloud platform back-end operated by the SIGFOX company itself. To reach full operational capability, the whole ecosystem has to fulfil only three requirements - coverage from SNO, device/sensor, and a valid device subscription. Subscribers with a yearly subscription fee for each device will be then able to receive messages via web interface, REST API or by a callback mechanism. A general network architecture is depicted in Fig. 1.

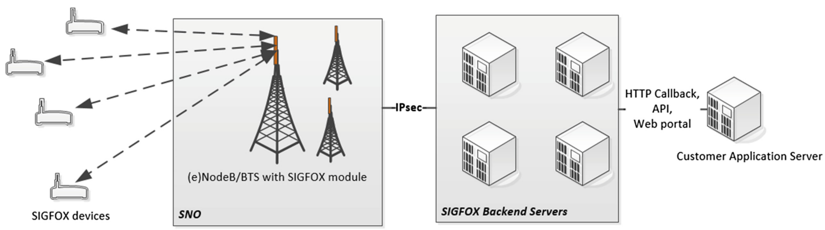


Fig. 1. General network architecture.

3.2 Technology

SIGFOX allows bidirectional communication using Industrial, Scientific and Medical (ISM) radio band, namely frequencies 868 MHz for Europe and 902 MHz for USA. Due to the physical nature of the UNB transmission with random channel frequency hopping, the noise contribution is very low, approx. −150 dBm at 290 K, and the link budget can reach up to 159 dB [19, 24].

The protocol exists currently in two versions. The original one where the up-link is using 48 kHz macro channel centered at 868.2 MHz, and the second version using a 192 kHz macro channel centered at 868.13 MHz, that is being deployed since the end of 2014 [25]. The up-link channel bandwidth is 100 Hz with theoretically 480 slots for a 48 kHz macro channel and 1920 slots for a 192 kHz macro channel. Although the authors [12] point that channels 181–219 are reserved and not used in the 48 kHz macro channel. In the Czech Republic, a member country of European Conference of Postal & Telecommunications Administrations (CEPT), used frequencies are a part of spectrum allocations for Short Range Devices (SRDs). Namely for up-link band h1 and for down-link channel band h3 [7].

Since SIGFOX does not employ Listen Before Talk (LBT) nor any sense mechanism to prevent interference among devices operating in the same band (Adaptive Frequency Agility (AFA) technique), duty cycle limitations do not allow to transmit more than 1 % of the time with the maximum of 500 mW (27 dBm) effective radiated power (ERP) for the down-link and maximum power of 25 mW (14 dBm) ERP for the up-link [7,23].

A message emission can take several seconds depending on a required number of repetitions in different subchannels. Typically, the 3-repetition scheme takes approximately 6 s (3×1s emission + 3×1s gap). Based on expression 1, this leads to a fixed maximum of 140 messages per device per day.

$$n_{max} = \frac{t_d}{t_e} \tag{1}$$

where n_{max} is the maximum number of messages [messages/day], t_d [s] stands for number of seconds per day and t_e is emission time of one message [s].

An important aspect for device manufactures is that each device has to undergo a certification process. Based on the regulations, SIGFOX defined a scale of values to classify a device according to its radio performance as in Table 1.

Table 1. SIGFOX certification up-link classes

	Class 0u	Class 1u	Class 2u	Class 3u
ERP [dBm]	$14 > P > 12$	$12 > P > 7$	$7 > P > 0$	$P < 0$

One of the main characteristics of UNB is a reduced band occupation; therefore, the noise contribution; is lessened and for a given targeted error probability we can reach much longer distances [19]. SIGFOX technology allows to demodulate an extremely weak received signal −142 dBm [12]. On the other hand, with extended coverage increases the number of devices sharing the same access medium and the medium access control (MAC) protocol gains higher importance. For up-link used modulation technique is Differential Binary Phase-Shift Kying (DBPSK) and for down-link Gaussian Frequency-Shift Keying (GFSK) [4].

A minimization of fading is achieved by the implementation of the Random Frequency Division Multiple Access (R-FDMA) schema. Random frequency hopping in predefined channels that applied on transmitting side devices may use any channel at any time and a receiver must listen on all channels in parallel with the use of signal processing algorithms to retrieve the message [12]. Primarily, due to the contradictory requirements of power limitations while keeping the extended range the technology modulation (G)FSK supports only data rate of 100 bps in up-link and 600 bps in down-link [4].

4 Technology Evaluation

4.1 Experimental Setup

Most of the measurements were done in Prague district in the Czech Republic. Prague with population of approx. 1.2 million inhabitants was a part of the pilot phase which was comprised of three base stations plus one base station in a neighboring region. SNO for the Czech Republic is deploying approximately 350 SIGFOX base stations by the end of 2016 [26]. Thanks to the pilot phase, we could verify the technology in limited roll-out for stationary measurements. Nomadic measurements, i.e. measurements, where the end-device has moved with determined velocity, were carried out in pre-production setup as described later in this paper. The setup for our measurements, which is in principle the same for both nomadic and stationary measurements, is depicted in Fig. 2.

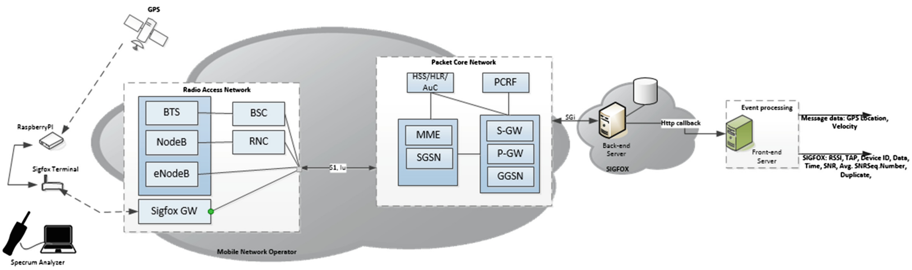


Fig. 2. Diagram of the measurement setup.

Our testing environment consisted of three reference transmitters used during the network roll-out. Devices were equipped with Telecom Design (TD) module that is based on a EFM32/ARM Cortex-M3 micro-controller with a 868 MHz-Band swivel $\frac{1}{2}$ wave antenna. For our measurements, we used TD1208 having a radio chip Si4461 with a receiver sensitivity of −126 dBm with active radio power consumption of 19 mA (for 14 dBm) [10]. All experiments were realized with a device set to ERP = 14 dBm (class 0u) and only in up-link direction. The module is capable of standard communication through AT commands allowing to send custom messages regardless the built-in reference measurement test function. We use this approach later for nomadic measurements, because the TD1208 is not equipped with any GPS module.

A single up-link message is by default sent three times at three distinct channels to increase the probability of reaching at least one base station. The number of repetitions can be even increased or the message can be acknowledged by in down-link channel in case of crucial applications [12].

Since an important factor contributing to the degradation and variability of the link quality is a radio interference, as a mitigation of major external radio interferences, we investigated level of noise in the 868 MHz ISM spectrum before each stationary measurement and during the process as well. We used portable RF Spectrum Analyzer SPECTRAN HF-6060 V4 connected to the computer, with cut-off level set to −100 dBm which is the lowest value possible [6].

4.2 Stationary Measurements

Since the roll-out strategy and radio configuration is largely dependent on the maximum range between transmitter and receiver, in the first set of measurements, we were analysing a relation between distance and reception probability based on messages received by three base stations. Three independent devices were set to send ten messages at each position. This helped to avoid an accidental interference. Measured distances were grouped to show a variation of number of received messages in distance ranges. Additionally, we focused to find the maximum range of the technology.

Figure 4 shows a probability of delivery as a function of distance. From the graph we can deduce two main observations. For shorter distances we see a bigger dispersion than for longer distances and there is also significantly lower probability of delivery for the range between 35–45 km and 90–110 km. Better understanding comes with the representation of data in the map (Fig. 3), where we can clearly see that the higher probability of delivery goes in-line with measurements taken from highlands with better line of sight (LOS).

With the goal of finding the maximal distance authors focused out of the three main propagatiom modes (ground waves, sky waves and LOS waves) on LOS propagation, that is the most relevant for used spectrum. Many authors as well as SIGFOX official specification indicate, that, in open rural areas with LOS, the typical coverage should be approximately 40 km [4,12,23,24]. Theoretical maximal LOS distance LOS_{MAX} is dependent on the earth's curvature E_R, height of the transmitter H_1 and height of the receiver H_2 as defined in expression 2 [28].

In line with the theoretical expectations, the maximal measured distance of 119.9 km (with success rate 100 % with detection of signal on all four TAPs and with average RSSI −96, 6 dBm) was truly achieved from the highest peak of Czech Republic called Sněžka, where the difference between height of transmitter and receiver was the greatest (1258 m).

$$LOS_{MAX} = \frac{\sqrt{2 * H_1 * E_R} + \sqrt{2 * H_2 * E_R}}{1000} \quad (2)$$

Since the static parameters: Gain of receiving antennas (G_{Rx}) and transmitting power (P_{Tx}) of devices are known, dynamic parameters: Received Signal Strength Indicator (RSSI) and Signal-to-noise-ratio are obtained from SIGFOX back-end, we could apply following formula to calculate Path Loss (PL) [18]:

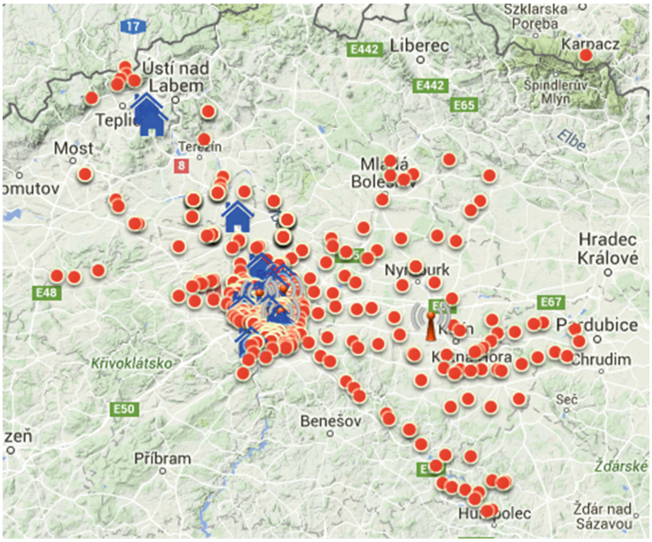


Fig. 3. Stationary measurements carried out in central Bohemia.

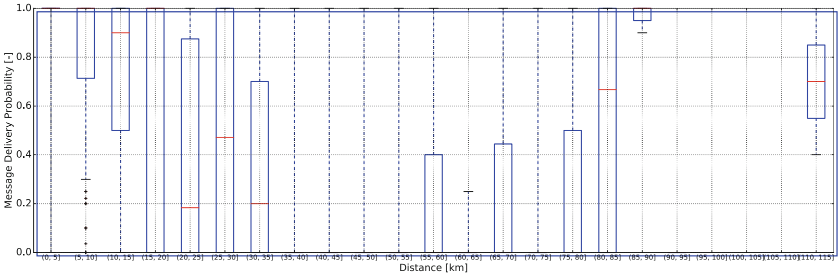


Fig. 4. Probability of delivery as a function of distance

$$PL = |RSSI| + SNR + P_{Tx} + G_{Rx} \tag{3}$$

Keeping in mind that this formula is defined only for far field distances (d) farther than Fraunhofer distance d_F:

$$d > d_f = \frac{2D^2}{\lambda} \tag{4}$$

where D is the largest physical linear dimension of the antenna, λ wavelength of the signal, and it must be satisfied $d_f >>$ D and $d_f >> \lambda$

Expected path loss (EPL) was derived using the linear polynomial fit of the logarithmic link distance where B is path loss; n is the path loss exponent; d is the distance; and d_0 is the reference distance, in our case 1 km

$$EPL = B + 10nlog_{10}(\frac{d}{d_0}) \quad (5)$$

As reference free space loss (FSL) values were used obtained from following formula [14]

$$FSL = 20log(\frac{R}{1000}) + 20log(f) + 32,4 \quad (6)$$

The Measured path loss (PL), EPL and FSL as a function of logarithmic distance are depicted in Fig. 5.

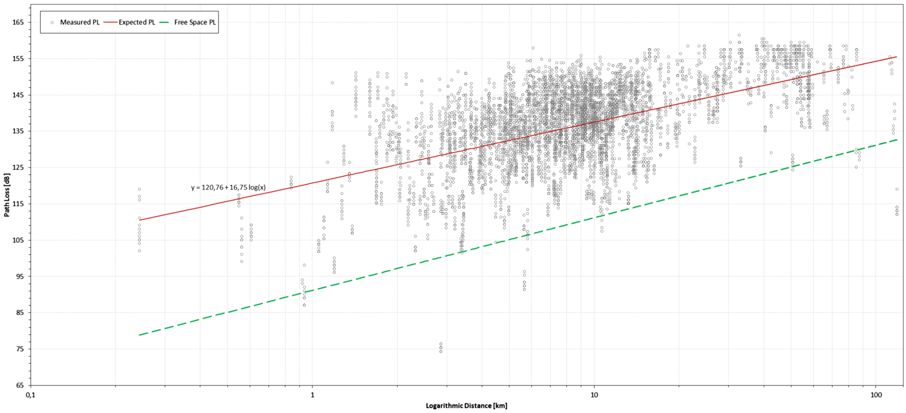


Fig. 5. Path loss as a function of logarithmic distance

From the expected path loss parameters we have concluded the path loss exponent that equals to 1.68. Such value is typically inside a building with a line of sight and it is even lower than the free space value that equals to 2 [22] (Table 2).

Table 2. Results of stationary measurements

Variable	Value
d_{max} [km]	119,9
LOS_{MAX} (for d_{max}) [km]	209.3
d_F [m]	0,984
B [dB]	120,76
n [-]	1,68

4.3 Nomadic Measurements

The term Nomadic measurements stands for measurements carried out during a monitored movement of the terminal. The setup was expanded for a second modem to decrease possible device-selective faults. Both modems were fixed to opposite sides of car roof railings. Modems were set to emit messages alternately to not influence each other during the broadcasting.

The measurements were realized in March, 2016 when the SIGFOX network in Prague (Czech Republic) city was shortly before the production roll out. The network consisted of 21 base stations plus 13 base stations nearby the city border. This is probably not the final state of the construction, and the network will be extended in the region around Prague. Measurements were split in several runs reflecting distinctive urban areas as depicted in Fig. 6.

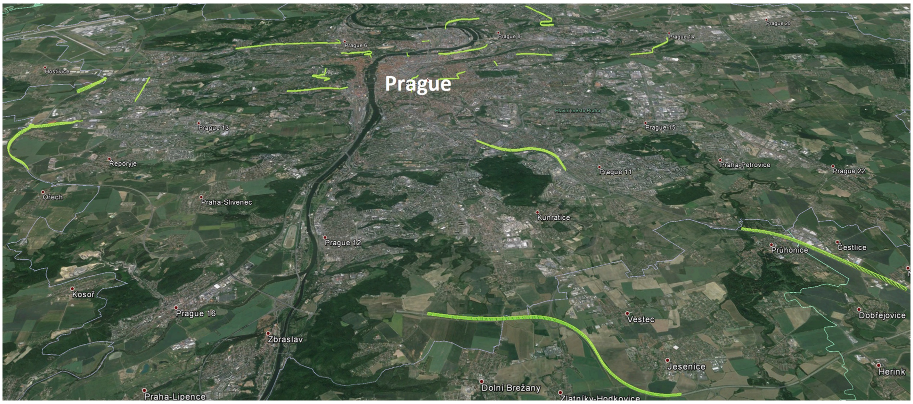


Fig. 6. Urban area where nomadic measurement runs, indicated by green lines, were carried out. (Color figure online)

The main goal was to verify the expected impact of Doppler effect on the transmission loss rate. The Doppler frequency shift f_D is proportional to the frequency of the electromagnetic wave f [29], and even a relatively low velocity can affect the loss rate at UNB. The Doppler shift is defined as in expression 7.

$$f_D = \frac{v_r f}{c} cos(\alpha) \tag{7}$$

where c is the speed of light [m/s], v_r [m/s] stands for the relative velocity between the terminal and base station, $\alpha \in [0, \pi]$ determines the velocity vector.

The velocity vector angle has a maximum effect on the frequency shift when $\alpha = 0$. In the Table 3 are some examples of real-life speeds expected at regular end-user applications and related frequency shifts. It is obvious that the frequency shift for such UNB technology as SIGFOX could be a real weakness especially if we consider transmission length of a single message.

Table 3. Example Doppler frequency shifts for 868 Mhz

Activity/Limit	Velocity [km/h]	$f_D(\alpha = 0)$ [Hz]	$f_D(\alpha = 45)$ [Hz]	$f_D(\alpha = 90)$ [Hz]
Jogging	10	8,04	4,22	-3,60
Residential zone	30	24,11	12, 67	-10, 80
In town	50	40,19	21,11	-18, 01
In tunnels	70	56,26	29,55	-25, 21
Outside town	90	72,33	38,00	-32, 41
On highway	130	104,48	54,89	-46, 82

Since the area is covered by many base stations, the α between the moving terminal and a particular base station is presumably dissimilar for each case. Moreover, the α can change during the message transmission. Those facts imply that the message is successfully received only in case the Doppler frequency shift aligns with one of the valid channels at least at one of the receiving base stations for the whole time of the transmission. This criterion is most likely more relaxed and the receiver handles also cases when the transmission is not perfectly aligned to the channel center frequency.

As the number of factors affecting the potential loss of message is high and the overall model is complex, we decided in the first attempt for a simple measurement model. The measurement application was basically set to emit a message in regular intervals containing position, velocity and a unique (in the context of this measurement) identification. Simultaneously, the measurement device stored all tracking data and sent messages locally for further analysis. Although velocity and position in messages was not necessary, we followed the idea of an end-user tracking device as one of the potential applications.

The data captured during measurements was compared with the data received via the SIGFOX backend system that forwarded every single received message from the network including all duplicates. In the analysis, we compared data sets and computed message loss-rate for particular travel velocities. Since every broadcasting took several seconds, and it was not possible to keep the velocity constant during all measurements (regular city traffic), we split the data to ranges from 0 to 110 km/h.

The first result describing loss-rate is depicted in Fig. 7. This perspective shows how much the captured samples differ over measurement runs which were carried out in different part of the measurement areas meaning various building density. As one can see, the mean value of the loss-rate is fluctuating around 20 % but it does not evince any trend. However, it is worth to focus on a few particular areas. Slightly higher loss rate for velocities lower than 50 km/h is most probably caused by the fact that those samples were captured in the urban areas with high building density. On the other hand, the loss-rate at higher velocities is in some cases interestingly low, except the ranges (60, 70] and (80, 90] km/h where there was insufficient number of samples. This is most probably caused by several factors. At first, measurements were taken mostly in suburban areas with an improved LOS to base stations. At second, the traffic outside the

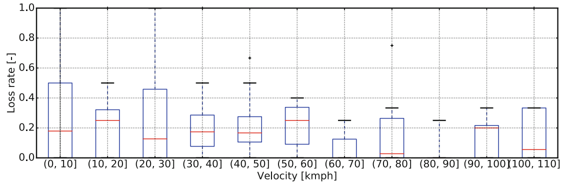


Fig. 7. Message loss-rate for various travel velocities aggregated over measurement runs.

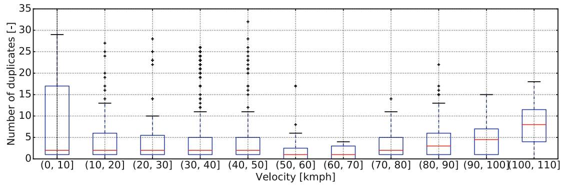
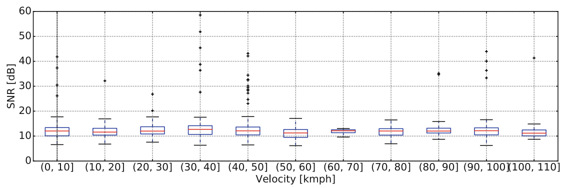


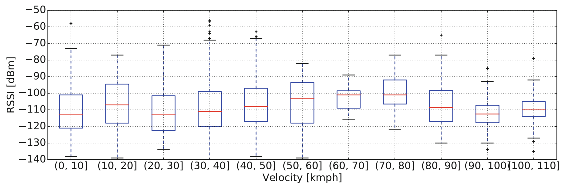
Fig. 8. Number of received duplicate messages aggregated over velocity ranges.

city is more fluent without the need for frequent acceleration. The acceleration is from the perspective of Doppler effect even more problematic, since it causes a continuous frequency shift. The receiving base station may be in such case unable to fix on the particular channel when the frequency changes during the transmission.

The presumption that open space is the originator of the lower loss-rate is supported by the subsequent analysis showing number of received duplicates per single message as is depicted in Fig. 8. As one can see, in extreme cases



(a) SNR aggregated over velocity ranges.



(b) RSSI aggregated over velocity ranges.

Fig. 9. Radio-related parameters and its dependency on travel velocity.

outliers reach almost 30 receiving base-stations, 32 at maximum. Those cases are mostly caused by the terrain relief where the measurements were taken on elevated places with better LOS to some base-stations. However, the trend of increasing number of duplicated packets with higher velocities, i.e. measurements in open-space areas, is apparent.

While the number of duplicated messages shows a specific behavior with increasing velocity, the radio-related parameters as RSSI and SNR are not as obvious. The results of SNR and RSSI dependencies are shown in Fig. 9. A mean value of both parameters is fluctuating in a relatively narrow zone for most samples. Outliers are in lower velocities most likely caused by the short distance between the measurement place and the local base station. In higher velocities, those are related, as in case above, to the open-space area.

5 Conclusion

The paper presented new UNB technology called SIGFOX and investigations based on 3,700 samples measured before the network commercial launch. Stationary measurements indicate that within limitations of ISM band regulations, the SIGFOX technology can reach an exceptional maximum range. Measurements prove the range limit is strongly dependent on the geographical profile of area. And based on the expectations, the maximal measured distance value of 119.9 Km was achieved from the location with the biggest difference in height of transmitter and receiver antenna and with the potential to reach an even longer distance somewhere where terrain profile would allow us a direct line of sight. Although this is a truly great result in other measurements the loss-rate was strongly dependent on the type of area. In case of high-density built-up areas, the loss increased rapidly above distance of 10 km. This issue will be most likely solved by thickening the network with more base stations, at least in bigger metropolitan areas.

Based on the extensive channel attenuation measurements, authors derived value of path loss and path loss exponent that. Such parameters can be used in the distance estimations of location algorithms and prior to SIGFOX network deployment to properly dimension the network.

The nomadic measurements carried out in pre-production network show that the reached mean loss rate of about 20 % can be acceptable for applications as for example asset tracking. As in the stationary measurements, the nomadic measurements showed a high dependency of the loss rate on the type of area where the terminal is moving.

In the future, authors plan to compare SIGFOX performance with other M2M technologies, namely with LoRa competitor. As many contemporary applications use an accelerometer to determine when is the right time to emit a message, we plan to focus more on the effect of acceleration on the transmission and estimate loss-related limits.

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