Empirical indoor propagation models for LoRa radio link in an office environment

Silvano Bertoldo[1,*], Miryam Paredes[1], Lorenzo Carosso[1], Marco Allegretti[1], Patrizia Savi[1]
[1] Politecnico di Torino, Department of Electronics and Telecommunications (DET),
Corso Duca degli Abruzzi, 24, 10129, Torino (Italy)
[*] email: silvano.bertoldo@polito.it

Abstract—**LoRa (Long Range) is one of the most promising candidate technology for Internet of Things (IoT). It supports a high number of communication devices spread across large areas. In this paper, we present some indoor measurements performed in a standard office environment using LoRa links. The aims of the work is to assess the indoor propagation performance of LoRa technology and to indicate the best model to be used for a preliminary design of a LoRa based radio link in an office environment. The measured data highlights that LoRa technology can be used in office environment to realize a wireless sensor network. Five commonly used propagation models were also analyzed and their results compared with the measurements. This analysis highlighted that the Motley-Keenan's is the best model to describe indoor propagation.**

Index Terms— **Empirical models, indoor propagation, LoRa, measurement, radio link.**

I. INTRODUCTION

One of the main challenges in the realization of wireless sensor network (WSN) systems is to minimize the node deployment and maintenance cost. To this end, the knowledge of the propagation characteristics is a key point for designing an efficient, reliable and cost-effective network.

There are different communication technologies available nowadays for WSN. The choice depends on the amount of exchanged traffic that is needed, on the power consumption constraints, and on the propagation condition in different environments.

LoRa is only one of many Low Power Wide Area Network (LPWAN) technologies available nowadays [1]. Some of the most used are Sigfox, (it offers longer-range communication with respect to LoRa but has service subscription costs), NarrowBand IoT (focused on indoor coverage), and other multi-purpose IoT technologies as Weightless, 5by5 Wireless, HaLow and Zigbee. To realize a WSN operative in an indoor office environment, LoRa technology can be a good and versatile solution.

Great attention has been paid to the applications of LoRa technique in outdoor environments, but only few applications are related to LoRa propagation in urban environment. For example in [2], the coverage range of LoRa in the city of Oulu, Finland for two scenarios (in the city, on the sea) is investigated and the propagation performance of LoRa in both scenarios is evaluated. The packet loss ratio and signal strength against the coverage range by logging the signal strength indicator (RSSI) from the LoRa, in line of sight (LOS) condition is also investigated. In this experiment, the transmitter is in a fix position and the receiver is moving at a speed ranging from 40 to 100 km/h. The measurements are compared with the log-distance model to derive the path loss exponent. In [3] we presented some propagation measurements in the complex urban environment of the city of Turin. The measurements are compared with the Okumura-Hata Model [4] showing that LoRa can be used for a multipurpose network in urban environment.

Some studies on indoor LoRa propagation applications are presented in [5] and [6]. Authors tried not only to access the indoor propagation performance of LoRa technology, but also to identify the model that best describes the indoor propagation of LoRa. They concluded that COST 231 Multi-Wall [7] model has the best performance amongst the models. Recent results about indoor LoRa propagation for smart building applications are presented in [8], while a good case study for indoor industrial environment is described in [9] in which large industrial space is taken into considerations for studying LoRaWAN network coverages and performance.

This work focuses on LoRa propagation aspects in an office environment. Some measurements were performed inside a multi-floor building in order to study the LoRa propagation in such conditions. The measurements are compared with results obtained using different empirical models in order to find the best model to describe the behavior of LoRa link in office environment.

II. LoRa TECHNOLOGY

The LoRa technology modulation scheme derives from the Chirp Spread Spectrum (CSS) modulation technique, which encodes the information in chirps [10]. As the expression spread spectrum implies, this technique uses the entire allocated bandwidth to transmit the signal. For this reason, it exhibits robustness to noise and other channel degradation mechanisms such as multi-path fading existing in urban environments. It also mitigates the Doppler in mobile applications.

LoRa is a physical (PHY) layer implementation (the lowest layer in OSI communication stack) and it works regardless of the technology operating on upper layers. In this respect, the LoRa Alliance™ has developed the open-source LoRaWAN specification [11]: an infrastructure consisting of media access control (MAC), network and application layers built on top of LoRa. LoRaWAN is organized in a star-of-stars topology in which gateways relay messages between end-devices and a central network server; gateways are connected to the network server via standard IP connections, while end-nodes use single-hop LoRa communication to reach gateways.

It is possible to use different configuration of LoRa in order to adapt the technology to the working scenario and the needs of the network. The main parameters are:

- the bandwidth, defining how wide the transmitted signal is (to be chosen among 125, 250 and 500 kHz);
- the spreading factor (a number in the range 6-12); it expresses the ratio between the period of the symbol and the period of the chip, being chip the bit used for spreading the signal;
- the code rate specifying the proportion of useful transmitted bits (non-redundant) (from 4/5 to 4/8).

III. EMPIRICAL MODELS FOR INDOOR PROPAGATIONS

Indicating with P_T the power radiated by the transmitter, G_T and G_R the antenna gains of both the transmitter and receiver, respectively, L_P the path loss attenuation, the received power, P_R, can be calculated as:

$$\mathrm{P_R}|_{\mathrm{dBm}} = \mathrm{P_T}|_{\mathrm{dBm}} + \mathrm{G_T}|_{\mathrm{dB}} + \mathrm{G_R}|_{\mathrm{dB}} - \mathrm{L_P}|_{\mathrm{dB}} \tag{1}$$

There are no path loss models specifically introduced for LoRa technology in indoor environments in order to estimate $L_P|_{dB}$. However, there is a large number of empirical propagation models derived from measurements using different standards, different frequency and in various propagation conditions. Some of them (the one used for comparisons of experimental measurements in office environment) are reported in the following paragraphs. We do not take into account deterministic models (e.g. ray-tracing) and modified parametrized empirical models (e.g. [12, 13]).

A. Free space model

The free space attenuation model is the base for all empirical models with narrow band information:

$$\mathrm{L_{P\_FS}}|_{\mathrm{dB}} = 20\log_{10}\left(\frac{4\pi df}{c}\right) \tag{2}$$

where d is the distance between transmitter and receiver and c is the speed of light.

B. Motley-Keenan's model

Using the Motley-Keenan model [14], $L_P|_{dB}$ is computed as:

$$\mathrm{L_{P\_K}}|_{\mathrm{dB}} = \mathrm{L_1}|_{\mathrm{dB}} + 20\log_{10}(\mathrm{d}) + \mathrm{n_f a_f}|_{\mathrm{dB}} + \mathrm{n_w a_w}|_{\mathrm{dB}} \tag{3}$$

where, L1 is the loss at 1 m distance computed with (2), d is the distance in meter, af is floor attenuation, aw is the wall attenuation, nf and nw are respectively is the number of floors and walls between transmitter and receiver.

C. ITU-R P.1238 model

The indoor model proposed by ITU in 1999 depends on the indoor environment scenario [15]. It accounts for attenuation caused by floors but not by walls:

$$\mathrm{L_{P\_ITU}}|_{\mathrm{dB}} = 20\log_{10}(\mathrm{f}) + \mathrm{N}\log_{10}(\mathrm{d}) + \mathrm{L_f(n_f)} - 28 \tag{4}$$

where L_f stands for a floor penetration factor provided by ITU-R recommendation and it depends on n_f. N is the losses coefficient factor regarding distance and is it also provided by the same recommendation. The frequency f must be expressed in MHz.

D. One Slope Model

The One Slope Model adapts itself to the environment characteristics through its N parameter. It does not account explicitly for the existence of either floors or walls. Both occurrences are expressed through N, which is equal to 33 for indoor office environment at the operative frequency of a LoRa system. The frequency f must be expressed in MHz.

$$\mathrm{L_{P\_OSM}}|_{\mathrm{dB}} = 20\log_{10}(\mathrm{f}) + \mathrm{N}\log_{10}(\mathrm{d}) - 28 \tag{5}$$

E. COST-231 multi wall propagation model

The COST 231 multi-wall model [7] for the indoor scenario considers the presence of multiple walls between transmitter and receiver:

$$\mathrm{L_{P\_MW}}|_{\mathrm{dB}} = \mathrm{L_1}|_{\mathrm{dB}} + \mathrm{N}\log_{10}(\mathrm{d}) + \textstyle\sum_{i=1}^{M} \mathrm{L_i} \tag{6}$$

where M is the number of walls and L_i the attenuation of each one, L_1 is the loss at 1 m distance computed with (2) and d is the distance in meter.

F. COST-231 indoor office propagation model

The COST 231 presented also a specific model for indoor office propagation [7]:

$$\begin{aligned}\mathrm{L_{P\_OFFICE}}|_{\mathrm{dB}} = \mathrm{L_1}|_{\mathrm{dB}} + 3.4\mathrm{K_{w1}} + 6.9\mathrm{K_{w2}} &+ \\ + 18.3\mathrm{n}^{\left(\frac{n+1}{n+1}-0.46\right)}&\end{aligned} \tag{7}$$

where n is the number of traversed floors (reinforced concrete, but not thicker than 30 cm), K_{w1} is the number of light internal walls (e.g. plasterboard), windows and K_{w2} is the number of concrete or brick internal walls.

IV. MEASURMENT SETUP DESCRIPTION

The measurement setup is shown in Fig. 1. The number of transmitters is n=1 for point-to-point measurements and n=5 for star-topology networks. Both transmitters and receiver are equipped with the same electronic components, microcontroller µC (Arduino© Nano), communication module and quarter-wave monopole antenna with a gain G=3.16 dB (Linx Technologies, model ANT-868-CW-RCS), operating in the band 860-868 MHz. A specific controlling software was developed for each test using the Arduino© Integrated Development Environment (IDE).

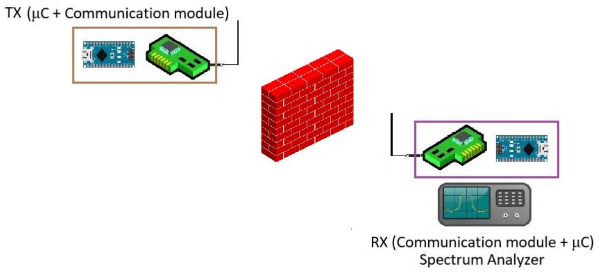

Fig. 1. Block scheme of the measurement setup. The number of transmitters is n=1 for point-to-point measurements and n=5 for star-topology network measurements

A. *Communication module*

The communication module installed in both the receiver and transmitter is the Adafruit® Feather 32u4 LoRa Radio RFM95. It is an embedded module, which contains a LoRa® transceiver RFM95 and an ATmega32u4 microcontroller (Fig. 2). The chip has 32 kB of flash memory and 2 kB of RAM memory. The radio module can be powered using 3.3 volts either by using a micro USB or an external battery. The operative frequency range is 868-915 MHz, including the band around 868 MHz allowed by the European laws, and the transmitted power ranges between 5 dBm to 20 dBm.

The module is controlled by an Arduino© microcontroller, since the microcontroller of the Adafruit® Feather 32u4 LoRa Radio RFM9 can be programmed with the same libraries of Arduino©.

Fig. 2. Adafruit® Feather 32u4 LoRa Radio RFM9 on the left and LoRa Radio RFM9 transceiver module on the right.

A set of standard LoRa parameters (FSK modulation, bandwidth B_W=125 kHz, Spreading Factor SF=10, equivalent bit rate B_R=0.976 Kb/s, Receiver sensitivity R_{Xsens}= -132 dBm [7]) were selected to configure the prototypal transmitters and perform the measurements.

B. *Spectrum Analyzer characteristics*

The received power was measured using a Spectrum Analyzer (SA) model R&S ZVL connected to the receiver module. The setting parameters are listed in Table I. Since the sensitivity of the used LoRa receiver module is below the noise floor of the SA with the used settings, for some measurements it was not possible to measure the received power

TABLE I. SPECTRUM ANALYZER PARAMETERS

Center frequency (CF)	865 MHz
Resolution bandwidth (RBW)	10 kHz
Video bandwidth (VBW)	30 kHz
Sweep time	5 ms
Span	500 kHz
Measurement mode	Max hold

C. *Measurement plan*

The measurements were made during the months of August-September 2018 in the Department of Electronics and Telecommunications (DET) of Politecnico di Torino, Turin, Italy (Fig. 3).

Fig. 3. Politecnico di Torino, Torino, Italy (DET).

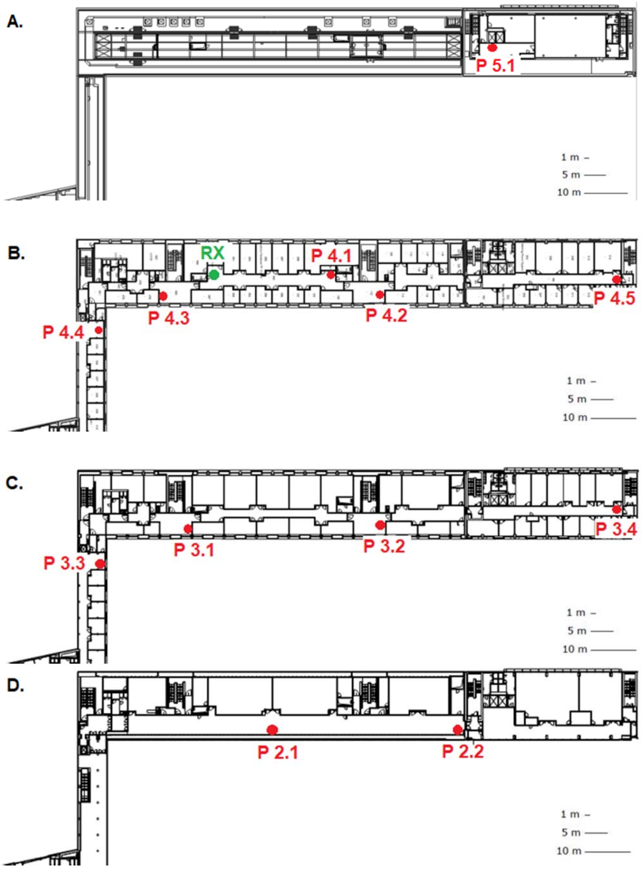

Fig. 4. Politecnico di Torino, Torino, Italy (DET). Plant of 5th floor (A), 4th floor (B), 3rd floor (C and 2nd floor (D) with indication of the position of the receiver (green) and the various positions of the transmitter (red).

The receiver was at a fixed position on the fourth floor and the transmitter was placed in 12 different positions spread on the four floor of the DET. One position was on the fifth floor, five were on the fourth floor, four were on the third floor and two on the second floor (Fig. 4).

The office environment at DET are with plasterboard and thin brick walls. These characteristics are similar for a large number of office environments recently built.

The distance between the receiver and each transmitter position was measured as straight line considering also the height of each floor. The number of crossed floor and wall was counted considering the same straight line. All the other parameters necessary for the model are derived from the tables reported in [15, 16].

V. RESULTS

A. *LoRa indoor propagations performance*

The first group of measurements was dedicated to evaluate the performance of the LoRa technology in the indoor office environment described in Section IV.

The receiver module was programmed in order to provide useful information about the signal quality: Received Signal Strength Indicator (RSSI) of the packets, Signal to Noise Ratio (SNR) and percentage of LoRa packets received correctly. The set of analysed data consists of blocks of 1000 packets for each transmitter position. Results are reported in Table II.

TABLE II. RESULT FOR INDOOR OFFICE MEASUREMENTS – INDICATORS MEASURED BY LORA RECEIVER

	SNR (dB)			**RSSI (dB)**			
Point	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**% Pkt. Losses**
P 2.1	6,9	8	5	-95,2	-91	-100	0,5 %
P 2.2	4,9	7	0	-109,2	-105	-114	0,5 %
P 3.1	7,5	8	3	-81,7	-79	-90	0 %
P 3.2	6,8	8	5	-95,2	-91	-101	0,5 %
P 3.3	7,3	8	5	-96,8	-94	-100	0,5 %
P 3.4	-0,2	2	-6	-112,4	-108	-115	0,5 %
P 4.1	6,6	8	5	-59	-54	-69	0 %
P 4.2	7,8	8	5	-65,2	-64	-70	0,5 %
P 4.3	7,2	8	5	-70,7	-65	-83	0,5 %
P 4.4	6,4	8	4	-94,4	-91	-105	0 %
P 4.5	6,1	8	1	-100	-97	-112	0 %
P 5.1	-1,3	5	-11	-113,5	-110	-122	5 %

The RSSI of the packets, as expected, decreased for larger distance. However, the majority of the packets was received correctly. In fact, only for Point 5.1 the number of packet loss is 5%, while for all the other point it reaches a maximum of 0.5%. These measurements highlights that LoRa technology can be properly used with good performance not only outdoor and in large environment, but also in indoor office environment where the propagation conditions are more difficult.

B. *Comparisons with empirical models*

The theoretical received power was computed using the empirical models presented in Section 3. Result are reported in Table III including the comparison of the received power measured with the SA (examples are reported in Fig. 5). From the measured data, it is possible to detect a noise floor of SA of about -80 dBm, due to the settings (see Table I). By reducing the frequency for RBW and VBW, the noise floor can be decreased and it would be possible get the measured spectra for more points. The disadvantage is that each measurement would take more time. Settings in Table I were a good compromise for this experiment, but in the future, new SA configuration will be considered.

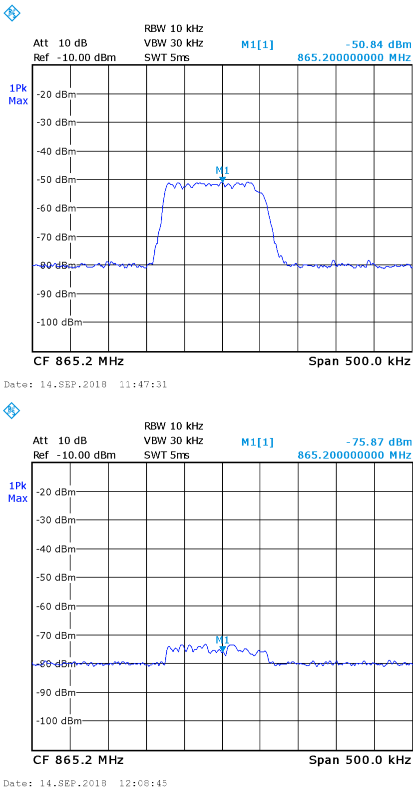

Fig. 5. Examples of measured power spectrum for point P 4.1 (above) and point P 3.1 (below).

It is evident that, despite both ITU-R P.1238 and COST231 multi-wall models are useful to have a good estimation of the received power in an indoor office environment using a LoRa communication system, Keenan's model is the best. Very good performance are also achieved using the COST 231 model for indoor environment when the LoRa transmitter and receiver are on the same floor.

The relative error and the standard deviation were computed in order to give a further evidence that the Keenan's model is the best empirical model to be used to design a LoRa communication link in an office environment. The power measured with SA and the maximum RSSI value measured with LoRa receiver were considered as reference. Results are reported in Table IV. The table highlights the best performance of Keenan's model and the possibility to use both COST 231 multi-wall and ITU-R P.1238 models with reasonable power budget estimation. Note that the good performance of the COST 231 office model are related to the five measurements point with transmitter on the same floor of the receiver.

It is important to point out that two out of three models achieving the best performance takes into account the number of floors and the number of walls crossed by the LoRa signal. In particular, Keenan's model and COST 231 multi wall model consider also the different type of walls.

TABLE III. COMPARISON OF RECEIVED POWER MEASURED WITH SA WITH THEORETICAL VALUES COMPUTED WITH EMPIRICAL MODELS

Received power (dBm)							
Point	**Free Space**	**One Slope**	**ITU-R P.1238**	**COST 231 Multi Wall**	**COST 231 Indoor Office**	**Keenan**	**MEAS.**
P 2.1	-44,48	-60,08	-79,08	-62,58	-97,18	-76,98	
P 2.2	-54,98	-77,28	-96,28	-86,78	-110,88	-99,48	
P 3.1	-41,18	-54,58	-63,58	-67,08	-95,78	-72,88	-75,87
P 3.2	-51,48	-71,58	-80,58	-73,08	-78,58	-77,38	
P 3.3	-49,38	-68,18	-77,18	-84,68	-99,28	-89,18	
P 3.4	-59,38	-84,58	-93,58	-99,06	-102,58	-102,18	
P 4.1	-48,88	-67,28	-67,28	-69,78	-63,58	-65,38	-50,84
P 4.2	-51,88	-72,28	-72,28	-73,78	-60,18	-68,88	-68,71
P 4.3	-42,58	-56,78	-56,78	-63,28	-67,18	-59,88	-61,84
P 4.4	-49,38	-68,18	-68,18	-84,58	-80,88	-80,18	-80,4
P 4.5	-59,28	-84,58	-84,58	-98,98	-84,28	-101,08	
P 5.1	-56,78	-80,28	-89,28	-96,78	-98,78	-100,18	

TABLE IV. AVERAGE RELATIVE ERROR AND STANDARD DEVIATION FOR EMPIRICAL MODELS COMPARED WITH RSSI AND MEASURED POWER

	Model - RSSI max		**Model - Measured**	
Model	**Avg. Error**	**Dev. Std.**	**Avg. Error**	**Dev. Std.**
Keenan	11,21	1,76	1,99	2,69
ITU-R P.1238	7,14	2,26	4,96	2,42
COST 231 multi-wall	9,7	7,18	7,68	6,1
COST 231 Office	8,56	2,02	4,7	3,3
One Slope	14,25	3,88	5,86	3,35
Free Space	17,14	7,35	10,38	5,79

VI. CONCLUSIONS

This work was focused on the study of the propagation aspect of a wireless network based on LoRa technology in an office environment. A set of measurements was conducted inside the Department of Electronics and Telecommunications (DET) of Politecnico di Torino, using a point-to-point communication link based on LoRa technology. The receiver was placed in a fixed place and the transmitter was moved in different positions in the four floors of the DET.

Results highlight that LoRa technology can be used with very good performance in an office indoor environment recently built, with thin walls. The comparisons between the measured power and the theoretical values computed with the most common empirical models for indoor propagations show that Keenan's model is the best one to be used for a preliminary design of a LoRa based communication link. ITU-R P-1238 and COST models can also be used with good performance. These results can be a starting point for the design of a LoRa wireless sensor network and to predict its propagation performances.

Future work will be focused on experiments and studies about indoor propagations in building with different and more complex characteristics, considering also fading and multipath both on theoretical analysis and experimental measurements.

REFERENCES

[1] M. Rizzi, P. Ferrari, A. Flammini and E. Sisinni., "Evaluation of the IoT LoRaWAN Solutions for Distributed Measurement Applications". IEEE Trans Instr. and Meas., vol. 66. no .12, pp. 3340-3349, 2017.

[2] J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hanninen and M. Pettissalo, "On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology," 14th International Conference on ITS Telecommunications (ITST), Copenhagen (Denmark), pp. 55-59, 2-4 December 2015.

[3] S. Bertoldo, M. Paredes, L. Carosso, C. Lucianaz, M. Allegretti, P. Savi, "Feasibility analysis of LoRa ad-hoc network in a urban noisy environment", Mediterranean Microwave Symposium 2018 (MMS2018), Istanbul (Turkey), pp. 357-360, 31 October – 2 November 2018.

[4] M. Hata, "Empirical formula for propagation loss in land mobile radio services," in IEEE Transactions on Vehicular Technology, vol. 29, no. 3, pp. 317-325, August 1980.

[5] L. Gregora, L. Vojtech and M. Neruda, "Indoor signal propagation of LoRa technology," 17th International Conference on Mechatronics - Mechatronika (ME), Prague, pp. 1-4, 2016.

[6] S. Hosseinzadeh, H. Larijani, K. Curtis, A. Wixted and A. Amini, "Empirical propagation performance evaluation of LoRa for indoor environment," IEEE 15th International Conference on Industrial Informatics (INDIN), Emden, pp. 26-31, 2017.

[7] COST Action 231: Digital Mobile Radio Towards Future Generation Systems: Final Report, 1999.

[8] L. H. Trinh, V. X. Bui, F. Ferrero, T. Q. K. Nguyen and M. H. Le, "Signal propagation of LoRa technology using for smart building applications," IEEE Conference on Antenna Measurements & Applications (CAMA), Tsukuba, pp. 381-384, 2017.

[9] J. Haxhibeqiri, A. Karaagac, F. Van den Abeele, W. Joseph, I. Moerman and J. Hoebeke, "LoRa indoor coverage and performance in an industrial environment: Case study" 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, pp. 1-8, 2017.

[10] A. Springer, W. Gugler, M. Huemer, L. Reind, C. Ruppel and R. Weigel. "Spread spectrum communications using chirp signals". IEEE/AFCEA Information Systems for Enhanced Public Safety and Security (EUROCOMM 2000), Munich (Germany) pp. 166–170, 19 May 2000.

[11] LoRaWAN 1.1 Specification. Available online: https://lora-alliance.org/sites/default/files/2018-04/lorawantm_specification_-v1.1.pdf (accessed on July 2018).

[12] K. Kar, S. Datta, M. Pal and R. Ghatak, "Motley Keenan model of in-building coverage analysis of IEEE 802.11n WLAN signal in electronics and communication engineering department of National Institute of Technology Durgapur," International Conference on Microelectronics, Computing and Communications (MicroCom), Durgapur, pp. 1-6, 2016.

[13] A. Zyoud, M. H. Habaebi, and R. Islam, "Parameterized indoor propagation model for mobile communication links", Microw. Opt. Technol. Lett., vol. 58, pp. 823-826, 2016.

[14] J. Keenan and A. Motley, "Radio coverage in Buildings", Br. Telecom Technol. Jorunal. vol.8, no.1, 1990.

[15] Recommendation ITU-R P.1238-9, "Propagation data andprediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz", 2017.

[16] Indoor path loss. Application note XST-AN005a-Indoor, DiGi, 2012.