A Comparative Study of Performance Analysis of Empirical Propagation Models for NB-IoT Protocol in Suburban Scenarios

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Abstract— **Among the protocols available for Internet of Things (IoT) applications, the Narrow Band-Internet of Things (NB-IoT) is one of the most relevant for presenting advantages, such as long range, low latency and low energy consumption. One of the points questioned for every protocol is the ability to serve applications that are in a mobile environment. To validate the possibility of the protocol working in this scenario, it is necessary to evaluate its performance in different propagation environments. This article presents field measurements that were made on an NB-IoT operational network in a suburban environment. The measurement results were compared with the results calculated on three propagation models used to predict loss of propagation in a mobile environment: Cost-231 Hata, ITU-1225 and Erceg Greenstein. Comparisons show that the Cost-231 Hata model offers the best performance in predicting propagation loss in the considered scenarios. These results provide relevant information about the performance of the propagation models used, applied to the NB-IoT protocol in a suburban environment.**

Keywords-IoT; NB-IoT; Performance Analysis; Propagation Models.

I. INTRODUCTION

A. Background

The heterogeneous characteristics of communications between things introduce considerable challenges to the networks that are part of these new scenarios, including scalability, different traffic volumes, and Quality of Service (QoS) requirements. The requirements of the applications used by these devices can also vary from the sending of information with extremely low latency to the establishment of highly reliable and prioritized communication. The IoT networks should allow the communication of specific data rate and low complexity to meet all these critical requirements of the devices. There are also variations in coverage, where there is a possibility of areas with a radius from one meter to more than one kilometer [1].

Low Power Wide Area Network (LPWAN) networks were designed to meet long-range coverage applications. There are solutions proposed to work in unlicensed bands, like LoRA and SigFox [2][3], and others to operate in mobile communications bands, such as NB-IoT, which was designed to work with Long Term Evolution (LTE) [4].

NB-IoT is a promising technology developed to support massive implementations with low data rates and narrow bandwidth [5]. It also offers low-cost devices, battery life of more than ten years, and great capacity [6]. It can be deployed in three different modes: (i) stand-alone, as a dedicated carrier (200KHz channel), (ii) in-band, within the occupied bandwidth of a Physical Resource Block (PRB) carrier - 180KHz, and (iii) within a guarding period in the LTE carrier (PRB - 180KHz) [7]. It is interesting to note that the third mode presented allows NB-IoT support with minimal impact on LTE [8]. Figure 1 presents the joint NB-IoT operation with the LTE structure.

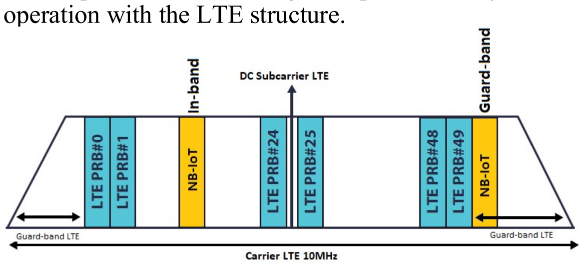

Figure 1. Operation Mode in-band and out-band.

The highest modulation scheme considered in NB-IoT is the Quadrature Phase Shift Keying (QPSK) [5], and only Frequency Duplexing Division mode (FDD) is supported. The multiple access scheme is identical to the LTE, i.e., Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier - Frequency Division Multiple Access (SC-FDMA) for downlink and uplink, respectively. In downlink transmission, only one PRB is used, whereas, in the uplink, there are two options: single-tone transmission and multi-tone transmission. In single-tone, the spacing between subcarriers can be 3.75KHz or 15KHz [9]. Multi-tone enables sets of 3, 6, or 12 subcarriers. LTE's protocols are used in totality by NB-IoT users, and five new physical channels should be introduced. A new category of user equipment, called Cat-N, came with NB-IoT [10]. In addition to operating in LTE bands, NB-IoT can also work on the Global System for Mobile Communications (GSM), which is seen as a significant advantage since GSM already has global coverage. In this case, the signal is transmitted in standalone mode [4] and operates with 200kHz bandwidth, the same as in GSM [11].

The range of NB-IoT technology is around 15 km, and the loss of extended coupling is approximately 20dB [7]. The operating frequencies available for NB-IoT are the same for LTE.

B. Motivation

Comparative analyses between real environments and empirical propagation models prove to be quite relevant for different protocols and technologies. They have a significant contribution to network planning and performance analysis of the adopted parameters [14].

Unlike protocols that operate in unlicensed frequency bands, protocols based on mobile communications networks, such as NB-IoT, are promising technologies developed to support massive deployments, with reduced data rates and narrow bandwidth [6]. However, their performance in mobile environments is not widely explored.

The main objective of this study is to analyze the performance of the NB-IoT protocol. The chosen scenario was the suburban mobile environment in the city of Santa Rita do Sapucaí, Minas Gerais - Brazil, using the network installed by the operator TIM (Telecom Italia Mobile). The main goal is, based on field measuremts (using a Quectel test device BG96), to find the best propagation model to characterize the network's performance.

C. Paper Organization

The remainder of this paper is organized as follows. Section II summarizes the related work. Section III presents the propagation models considered in our analysis. Section IV presents the conditions of field measurements. Section V focuses on the performance analysis of the results. Section VI concludes the paper and suggests future works.

II. Related Work

Several studies involving the performance of the NB-IoT protocol have been carried out to trace its performance in different scenarios. Also, comparative analyses between real environments and empirical propagation models prove to be quite relevant for different protocols and technologies as they have a significant contribution to network planning and performance analysis of the adopted parameters [14]. Ravi et al. [15] present the results obtained through experimental measurements to analyze the attenuation suffered in NB-IoT in indoor environments. According to Shin et al. [16], there are still many open problems concerning the link adaptation, performance analysis, and project optimization of the NB-IoT. A study of the NB-IoT performance is presented by Adhikary et al. [17] with an analysis of the different NB-IoT channels in various scenarios, considering the Typical Urban (TU) channel model, however, in a static environment, without mobility. Finally, Ingabire et al. [18] present a comparative study between the LoRaWAN coverage and the Okumura-Hata, Cost 231-Hata, Extended-Hata, and ITU-R 1225 propagation models in a static urban environment.

The related work present analyzes the NB-IoT protocol, as well as its advantages and behavior analysis in certain scenarios. And there is a similar analysis that relates the LoRaWAN protocol to propagation models.

III. Propagation Models

This section summarizes three propagation models used for this study: Cost-231 Hata, ITU-R 1225, and Erceg Greenstein models.

A. Cost-231 Hata Model

This model is an extension of the Okumura Hata model [19]. It is valid for frequencies between 500 MHz and 2000 MHz and can be applied in urban, suburban, and rural settings. The path loss is computed using the expressions below [20]:

$$PL\ (dB) = A + B\log(d) + C \quad (1)$$

where:

$$A = 46.3 + 33.9\log10(fc) - 13.28\log(hb) - a(hm) \quad (2)$$

fc is the frequency (MHz)
hb is the base station antenna height (m)
$a(hm)$ for urban scenarios is defined as:

$$a(hm) = 3.2(\log(11.75hr))^2 - 4.97 \quad (3)$$

hr is the device height (m)
$a(hm)$ for suburban scenarios is defined as:

$$a(hm) = (1.1\log(fc) - 0.7)hr - (1.56\log(fc)*0.8) \quad (4)$$

$$B = 44.9 - 6.55\log10(hb) \quad (5)$$

C = 0 for medium city and suburban areas and
C = 3 for metropolitan areas

B. ITU-R 1225 Model

Defined by the International Telecommunication Union - Radiocommunication Sector (ITU-R) [21], this empirical and semi-deterministic model can be used in urban and suburban scenarios and was designed for frequencies around 2000 MHz. In this model, the path loss is computed by (6).

$$PL\ (dB) = 40\log(d) + 30\log(f) + 49 \quad (6)$$

where d is the distance in kilometer and f is the frequency in MHz.

C. Erceg Greenstein

Erceg Greenstein is a statistical model derived from experimental data collected in the United States in 95 macrocells. This model is applicable in suburban scenarios

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and has different categories for different terrain types [22]. The path loss in this model is computed by (7).

$$PL\ (dB) = A + 10\gamma \log(d/d0) + Xf + Xh \quad (7)$$

where;

$$A = 20\log(4\pi d0/\lambda) \quad (8)$$

$$\gamma = a - b^{*}(hb) + c/hb \quad (9)$$

d = distance between the device and base station (m)
d0 = 100m
hb is the base station antenna height (m)

$$Xf = 6\log(fMhz/2000) \quad (10)$$

The parameter Xh is related to the type of terrain (A, B or C). Terrain A refers to hilly/moderate-to-heavy tree density. Terrain B refers to hilly/light tree density or flat/moderate-to-heavy tree density. Terrain C refers to flat/light tree density.

For terrain types A and B:

$$Xh = -10.8\log(hm/2) \quad (11)$$

For terrain type C:

$$Xh = -20\log(hm/2) \quad (12)$$

where;

h is the device antenna height (m)

Also, parameters a, b and c are related to the type of terrain and are described in Table 1.

TABLE I. PARAMETERS TO DIFFERENT TYPES OF TERRAIN

Parameter	Terrain A	Terrain B	Terrain C
a	4.6	4	3.6
b, m^{-1}	0.0075	0.0065	0.005
c, m	12.6	17.1	20

The choice for these models was based on the possibility of use in environments with mobility and on the similarity in the construction characteristics of each one, which include frequency, distance between the mobile device and the tower, height of the device, height of the tower, among others.

IV. FIELD TEST MEASUREMENTS

The scenario used in carrying out the measurements has a suburban profile with small obstructions caused by some low-rise buildings and constructions. The relief variation is approximately 50 meters. Routes that could totally obstruct the signal were avoided to prevent incorrect interpretations of the results, and the route layout also considered the need to repeat the experiment several times. It is important to note that an experiment refers to the round trip of the specified route. Twenty experiments were carried out on three routes within the city of Santa Rita do Sapucaí, and one route on the BR-459 highway in order to validate the behavior of the protocol at higher speeds, totaling the collection of 3000 samples.

All routes started at the same location, a few meters from the tower where the transmitting antenna was installed.

For route 1, the path was basically made in a straight line with some variations in altitude along the route.

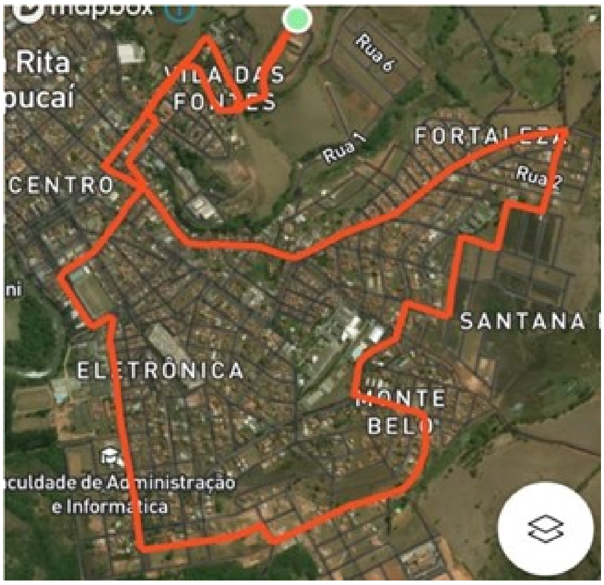
For route 2, the path traveled was crossing the city through the flattest part. The analyzed site presented residential buildings with no vegetation.

Route 3 was made in the part of the city where there were hills. The place had a certain density of vegetation, and residential buildings.

Finally, route 4 was carried out on the highway, having its format similar to route 1.

(a). Route 1.

(b). Route 2.



(c). Route 3.

Figure 2(d). Route 4.

As all routes presented similar characteristics with a certain density of vegetation and residential buildings, the environment was considered suburban.

The routes carried out within the city covered 11 km, 6.5 km and 8.7 km for routes 1, 2 and 3, respectively. For these, the average travel speed was 30 km/h. The route carried out on the highway covered 15 km, at speeds of 40km/h, 60 km/h and 80 km/h. Figures 2a, 2b, 2c, and 2d illustrate the routes used in the experiments.

A gateway Quectel model BG96 was used in the experiments. It is a wireless IoT communication module with LTE Cat M1, LTE Cat NB1, and General Packet Radio Services (EGPRS) functions. For the NB-IoT solution, the transmission power of the device is 23dBm. Also, it provides a Global Navigation Satellite System (GNSS).

The transmitting antenna information is in Table 2.

TABLE II. ANTENNA TRANSMITTING PARAMETERS

Parameter	Values
Frequency of operation (MHz)	1800
Polarization (º)	+/-45
Gain (dBi)	16.7
Horizontal Beamwidth (º)	68
Vertical Beamwidth (º)	7.0

We used a Universal Subscriber Identification Module (USIMCard) from the operator TIM. The base station is located on the top of the Cruzeiro hill in Santa Rita do Sapucaí.

V. PERFORMANCE ANALYSIS

In this section, the NB-IoT coverage will be analyzed along the four traced routes, and a comparison will be made with the three propagation models presented.

The conditions inserted in each propagation model for each route are presented in Table 3:

TABLE III. PROPAGATION MODELS PARAMETERS

Parameter	Values
Frequency of operation (MHz)	1800
Device antenna height (m)	1
Maximum distance between Tx and Rx (m)	4000
Basestation Antenna Height (m)	40

For each route, the measured values were compared with the values presented by the considered propagation models. The parameter used to represent the signal strength was the Received Signal Strength Indication (RSSI) [22] measured in dBm. The analytical expression for the theoretical RSSI values is presented below:

$$\text{RSSI (dBm)} = Pt + Gt + Gr - PL - A \qquad (13)$$

where;

Pt is the transmission power (dBm)
Gt is the transmission gain (dBi)
Gr is the reception gain (dBi)
PL is the Path Loss (dB)
A is the attenuation (dB)

Figure 3 compares the measured values of RRSI (samples) for one route and the values predicted by the propagation models.

To better interpret the measurements results, the measurement samples were grouped into clusters, with each cluster containing samples in a range between d - a and d + a, where d represents a given distance from the radio base.

After that, we computed the mean value of the RSSI, taking all samples belonging to the same cluster. Figures 4, 5 and 6 show the average RSSI measured and the RSSI computed using the propagation models for urban routes 1, 2, and 4. For route 3, the graph was not represented in this paper, because the results are similar to the of route 2.

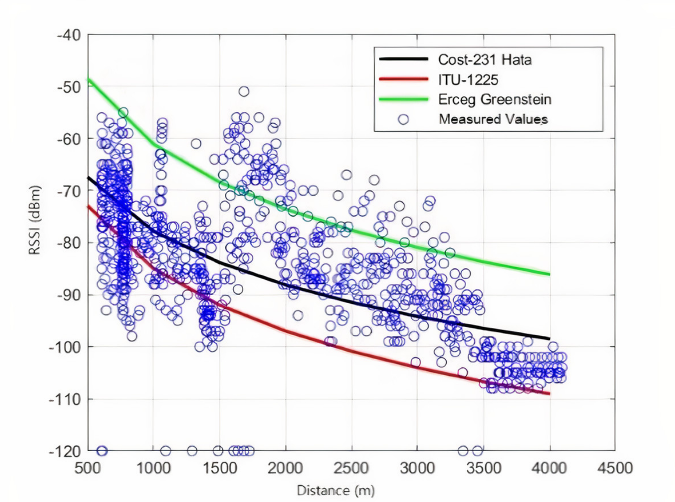


Figure 3. Measurements (samples) obtained in one route in comparison with the propagation models.

The behavior of the RSSI measurements are relatively similar in all these routes as the device moves away from the transmitting antenna.

Finally, Figure 7 shows the result of the average RSSI considering the samples of all routes.

Based on Figures 4, 5, 6, and 7, we can conclude that the Erceg Greenstein model is not accurate in predicting the propagation loss in the scenario considered in this paper.

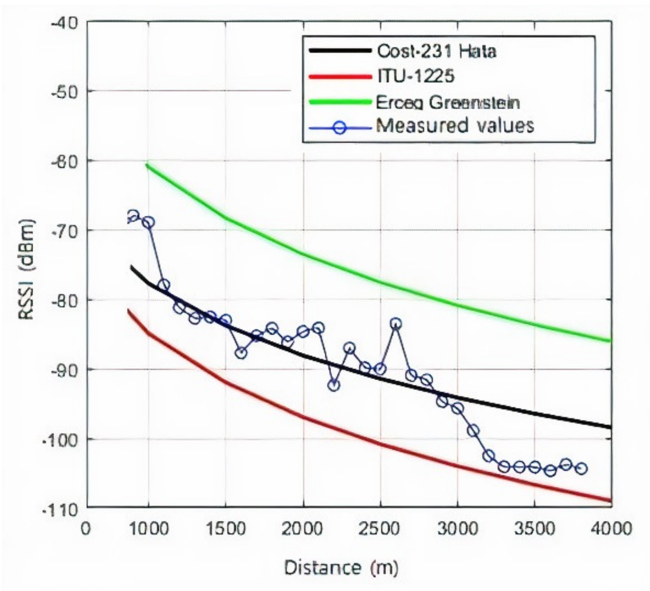


Figure 4. RSSI on the urban route 1.

The ITU-1225 model is adequate to predict the propagation loss for long distances on some routes. For short distances, the most accurate model is Cost-231 Hata. Also, when we grouped all measurements of all routes (Figure 7), the Cost-231 Hata model has the best performance.

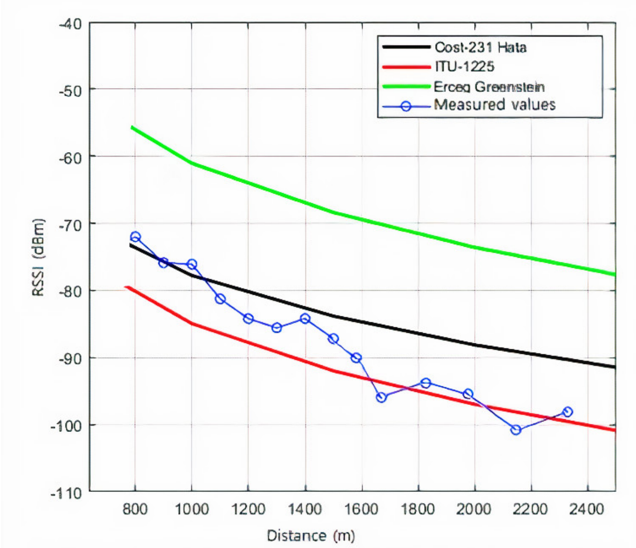


Figure 5. RSSI on the urban route 2.

In the route taken on the highway, the protocols behavior is different, and there is a sharp drop in the collection of samples after the distance of 2000m. As the average speed of travel of the device on this route is from 60 to 80 km/h, it is proved that the performance of NB-IoT in scenarios with mobility for medium to high speed is not efficient, which can impact the use of this protocol in mobile applications.

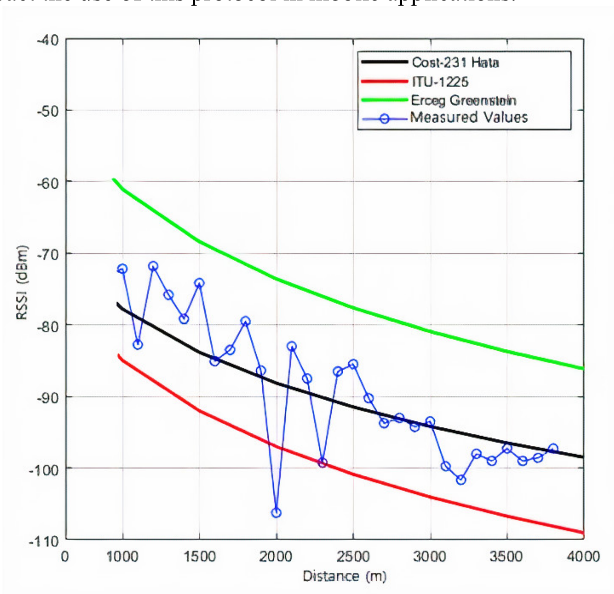


Figure 6. RSSI on the urban route 4.

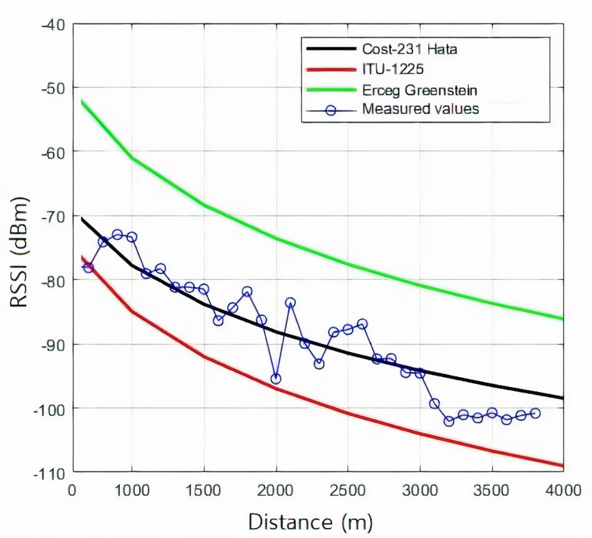


Figure 7. RSSI grouping all samples of all urban routes.

One key performance metrics used in evaluations is The Mean Absolute Error (MAE), which measures the average of all absolute errors between the measured values and the calculated results from the propagation models.

The performance of each propagation model is presented in Table 4.

TABLE IV. ERROR PERFORMANCE METRIC

Error Parameter	MAEs
Cost-231 Hata	3,588488
ITU-1225	8,568521
ERCEG GREENSTEIN	14,74494

According to the results, the Cost-231 Hata model has the lowest absolute mean error, confirming that this is the model that most closely matches the actual measured values.

VI. CONCLUSION AND FUTURE WORKS

In this paper, the NB-IoT protocol coverage was analyzed through real field measurements on four different routes in the city of Santa Rita do Sapucaí-MG, Brazil.

The measured results were compared with three propagation models used in mobile communication scenarios: Cost-231 Hata, ITU-R 1225, and Erceg-Greenstein.

The results presented by the Erceg-Greenstein model are not accurate for all considered routes. The ITU-R 1225 model has good performance for long distances on some routes. The best results are presented by the Cost-231 Hata model, which is confirmed using the MAE metric.

The protocol behaves differently on the route taken on the highway, and a stable communication link could not be established. Thus, the performance of NB-IoT for environments with medium to high speeds is not efficient.

The future works include analyses made with other protocols with characteristics similar to NB-IoT, such as LoRa, in the same scenarios and conditions, to compare the performance between both technologies.

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