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Abstract

This paper presents a performance analysis of the Narrowband Internet of Things (NB-IoT) network coverage in urban outdoor environments, focusing on experimental measurements toward path loss modeling. Conducted in a major Latin American city, the study explores the deployment of NB-IoT in LTE guardband 28 (700 MHz), offering valuable information on the network characteristics and coverage performance within this narrow spectrum. Four path loss models are considered, including comparisons between alpha-beta-gamma (ABG) and close-in (CI) empirical models. The end goal is to provide practical tools to optimize the deployment of the NB-IoT network in various urban environments. The results obtained offer a fresh perspective on the importance of experimental validation to accurately predict NB-IoT network coverage and signal quality in a real-world setting. Notably, the work has been carried out in collaboration with a Chilean telecom operator.

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***Abstract*—This paper presents a performance analysis of the Narrowband Internet of Things (NB-IoT) network coverage in urban outdoor environments, focusing on experimental measurements toward path loss modeling. Conducted in a major Latin American city, the study explores the deployment of NB-IoT in LTE guardband 28 (700 MHz), offering valuable information on the network characteristics and coverage performance within this narrow spectrum. Four path loss models are considered, including comparisons between alpha-beta-gamma (ABG) and close-in (CI) empirical models. The end goal is to provide practical tools to optimize the deployment of the NB-IoT network in various urban environments. The results obtained offer a fresh perspective on the importance of experimental validation to accurately predict NB-IoT network coverage and signal quality in a real-world setting. Notably, the work has been carried out in collaboration with a Chilean telecom operator.**

***Index Terms*—Internet of Things, Low Power Wide Area Networks, Measurements, Narrowband Systems, Path-loss Models.**

I. Introduction

The advent of Narrowband Internet of Things (NB-IoT) technologies has revolutionized the wireless communications landscape, particularly in the context of low-power and low-cost connectivity for a wide range of IoT applications. As the demand for IoT services continues to increase, the deployment of NB-IoT networks is steadily gaining the attention of both industry and academia [1]. This increased interest can be attributed to the key features of NB-IoT, such as its ultra-low power consumption, wide coverage, and the reuse of existing LTE infrastructure, which favors ecological and sustainable wireless communications, reducing environmental impact. These benefits make NB-IoT an ideal choice for various emerging domains, including smart grids, smart ports, smart cities, and precision agriculture, among others [2].

Specifically, NB-IoT technology is a Third Generation Partnership Project (3GPP) standardized in Release 13, with subsequent updates in Releases 14 and 15. These updates have been made to further enhance the NB-IoT technology, improving its capabilities and compatibility with existing LTE networks. Furthermore, NB-IoT is expected to be implemented as a key 5G technology, particularly to support massive Machine Type Communication (mMTC), expanding its reach and potential in emerging wireless communication domains [3], [4].

Although NB-IoT promises to revolutionize the entire IoT ecosystem, several key challenges arise when optimizing its deployment and performance in different surroundings. A critical aspect revolves around understanding the intricate dynamics among different parameters, including the NB-IoT network topology, deployment modes, coverage enhancement strategies, and hardware configurations. More specifically, accurate modeling of the propagation behavior in urban environments is essential for designing efficient NB-IoT networks and accurately predicting their performance in cities [5]; a challenge we try to address here.

In this paper, we present experimental measurements of key NB-IoT performance indicators with a focus on the received power of the reference downlink signal. For this purpose, we consider one stationary base station and a variable measurement radius to characterize network coverage and path loss.

To our knowledge, this research effort contributes to the state-of-the-art (SoA) of the NB-IoT performance understanding with the following:

- We present the results of the first NB-IoT experimental campaign conducted in a Latin American urban area in collaboration with a major Chilean telecom operator.
- We discuss measurements on the NB-IoT LTE Band 28 (700 MHz) guard band offering valuable insights into the effective NB-IoT coverage in a real-world-like setting.
- We compare different theoretical models of propagation with the experimental results of the Reference Power Received Signal (RSRP) and provide hints toward a future path loss modeling.

The rest of this paper is organized as follows. Section II presents the main NB-IoT network definitions including the receiver hardware equipment used to perform the experiments. Section III presents the theoretical background of existing path loss models for urban areas. Section IV describes in detail the measurement campaign carried out, including the procedure used for each measurement and the parameters of interest. Finally, Sections V and VI offer a discussion of the results and the main conclusions, respectively.

II. NB-IoT Network Setup

In this section, we provide some important preliminaries on the NB-IoT practical foundations and basic network definitions that are essential to understanding our experimental campaign. We then describe the testbed setup and specific hardware in detail.

A. Preliminaries

NB-IoT can be deployed in three basic modes of operation: stand-alone mode, guard-band mode, and in-band mode. As stated before, these modes were first standardized in 3GPP Rel. 13, with the main specific updates in Rel. 14 and Rel. 15. The main difference of each of these modes conforms to the portion of the spectrum where the NB-IoT carrier is deployed. Essentially, since this protocol is based on the well-known Orthogonal Frequency Division Multiple Access (OFDMA), it allows operating in various LTE bands. Particularly, the stand-alone mode uses a dedicated spectrum of a 200 kHz idle channel, while the in-band mode operates within the existing LTE spectrum. The deployment of the guard band involves the use of the guard bands, which are unused frequency bands that separate adjacent LTE carriers. Note that in the LTE standard, the guardband was set to represent 10% of the total bandwidth (5% for each side). Then, although the stand-alone mode is retained as the most efficient deployment mode, the guard-band mode has better coverage than the in-band mode [3].

Additionally, NB-IoT incorporates a Coverage Enhancement (CE) mode with three levels to indicate the number of downlink and uplink retransmission messages to use; each of them using the same transmission power at each retransmission. The three levels are referred to as level 0, level 1, and level 2. The assignment of these levels is determined by variables that reflect the quality of the communication channel. At level 0, characterized by a considerably robust channel, up to 8 repetitions are allowed, and 12 subcarriers with a bandwidth of 15 kHz each. Then, at level 1, where the quality of the channel decreases, the number of repetitions allowed in the messages is increased to a maximum of 64, keeping the number of subcarriers constant. Finally, at level 2, which represents poor conditions for the transmission channel, the CE mode sets a maximum number of repetitions between 128 and 512 while increasing the number of subcarriers to 48 and reducing their bandwidth to 3.75 kHz. The objective is to achieve a flat-fading channel behavior. Note also that the modulation order varies too depending on the CE level, supporting QPSK, 16QAM, and 64QAM modulation schemes. This feature provides adaptability to changing channel conditions and improves transmission efficiency in challenging environments [6], [7].

B. Network setup

All the experiments were carried out in collaboration with our telecom operator partner ENTEL using the **guard-band mode**. This deployment mode and the type of downlink measurements were defined by the operator, enabling active measurements from a real-world base station. The LTE base station facilitated by the operator communicated within the 28-band (700 MHz), with a bandwidth of 15 MHz for both downlink and uplink. Note that this portion of the spectrum

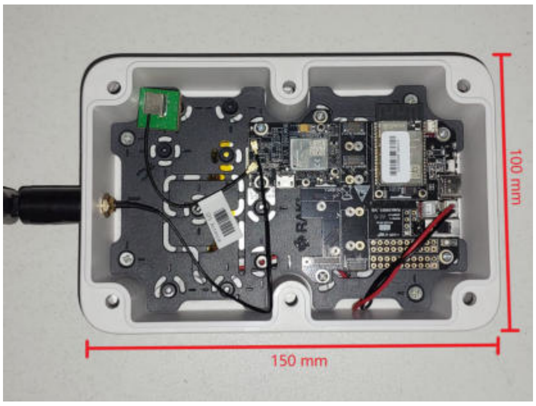

Fig. 1. Assembled NB-Kit, including ESP32, BG77, antennas, battery connection, USB-C connection, and additional modules.

was chosen since it has many well-known benefits, including the typically wide coverage provided by the low frequencies due to reduced path loss.

As stated above, in LTE, 10% of the total bandwidth is set to guardbands, which here corresponds to 1.5 MHz (750 kHz for each side). Moreover, it is worth noting that of these nominal 750 kHz, 100 kHz are allocated for out-of-band spectrum interference protection, which is not deemed a problem since 180 kHz are used for data transmission, i.e., one LTE Resource Block (RB). To perform the experiments, the Effective Isotropic Radiated Power (EIRP) on the base station was set to 23 dB, while a piece of ad-hoc user equipment with an antenna gain of 5 dBi was used on the terminal side. In all cases, the user equipment was 1.5 m above the floor, while the base station was set to 30 m.

C. User Equipment

We built a commercial IoT solution kit as user equipment using modular components provided by RAK. This includes a main backplane, a microcontroller module, and an NB-IoT shield. We selected this testbed approach because it will allow us to easily mount additional components in future campaigns, such as specialized sensors or shields, by using RAK's module slots or I/O connections. Specifically, the microcontroller used was an ESP32-WROVER 2.4 Ghz Wi-Fi & Bluetooth dual radio module [8], integrated into a RAK11200 platform. The ESP32 microcontroller was chosen because of its good communication capabilities with connectivity modules and sensors.

We used the RAK19001 as the baseboard. This board offers a core slot (here, used for the ESP32 MCU), two IO slots (here, used for two IoT modules), and six slots for sensor modules. In addition, the baseboard offers a LiPo battery connection, programmable LEDs, and a power switch, as well as several pins for additional external module connections. The board includes a USB Type-C connector that is used for functions such as programming the device, interacting with its components via a USB port, charging the battery, etc. As IoT modules, we used the Quectel NB-IoT interface [9] and the RAK15002 SD card module to save the measured data. For reference, we illustrate the user equipment in Figure 1.

III. Background on Path Loss Models

During the propagation of radio waves, various physical phenomena, including reflection, scattering, and diffraction, can influence the performance of signal transmission along a given path [10]. In particular, in wireless communication systems, energy dissipation occurs primarily due to the effect of the separation distance between the transmitter and the receiver, resulting in a concept known as path loss. Generally speaking, to effectively optimize network coverage and service in wireless communication systems, it becomes imperative to establish realistic path loss models. These models are conceived to accurately reflect real-world conditions, which requires the collection of large sets of empirical data through measurements. These measurements typically enable the construction of mathematical models that aim to identify key parameters that align well with parameterized equations that minimize path loss estimation errors [11]. These models are known as empirical path loss models and can be employed for outdoor environments. A general expression to statistically represent this phenomenon is the following:

$$PL = \overline{PL} + \chi.$$

with $\overline{PL}$ denoting the average path loss, and χ representing a stochastic fluctuation around the average value.

To the scope of this paper, four path loss propagation models are evaluated in terms of their suitability to predict service performance in urban areas. The main challenge in finding the most adequate model in this kind of surrounding comes from its heterogeneity, as each place presents different characteristics in terms of building density, green areas, and street type, for example. This impacts the different kinds of attenuation or fading effects that the signal experiences, which depend on the scale of objects the signal encounters along its path. On the large scale, for instance, fading is mainly due to distance effects, while on the medium scale, it can be due to shadowing or diffraction, for example. Similarly, on a small scale, fading can be due to scattering and/or multipath.

Free Space Path Loss (FSPL) Model. The large-scale case effect due to distance is often well described by the most general propagation model known as the FSPL, which characterizes ideal line-of-sight (LOS) conditions in the free space. Formally, the average path loss attenuation using the FSPL model is given by Equation 1 [11]:

$$\overline{PL}_{FS} = 20\log(d_{km}) + 20\log(f_{c,Hz}) + 20\log(\frac{4\pi}{c}), \quad (1)$$

where d_{km} is the horizontal separation distance from the transmitter to the receiver, $f_{c,Hz}$ is the carrier frequency in Hz, and c is the speed of light.

Okumura-Hata (OH) Model. Another popular propagation model, which is among the most widely used for urban areas, is the Okumura-Hata (OH) model. Although originally used to predict path loss in the range of 150 MHz to 1500 MHz range only, further works have shown its ability to predict other frequencies and urban conditions. Despite its multiple variants, we used here the expression in [12] for large cities, which is described by the Equation 2 as follows:

$$\begin{aligned}\overline{PL}_{OH} = 69.55 + 26.16\log(f_{c,MHz}) - 13.82\log(h_{b,m}) \\ -3.2(\log(11.75h_{m,m}))^2 + 4.97 \\ +(44.9 - 6.55\log(h_{b,m}))\log(d_{km}),\end{aligned} \quad (2)$$

where $h_{m,m}$ indicates the height of the user terminal, $h_{b,m}$ is the height of the base station, and $f_{c,MHz}$ is the carrier frequency in MHz.

Alpha-Beta-Gamma (ABG) Path Loss Model. It corresponds to a specific path loss model used to characterize NB-IoT path loss, whose fitting parameters have been rigorously characterized for urban scenarios [11]. Formally, the ABG model is defined as follows [11]:

$$\overline{PL}_{ABG} = 10\gamma\log(d_{km}) + 10\beta\log(f_{c,MHz}) + l_0, \quad (3)$$

where γ and β are the distance and frequency coefficients, which have specific values for the case studied in this paper, particularly 2.56 and 2.97, respectively, and l_0 is a constant loss which has a value of 35.27 [dB].

Close-In (CI) Path Loss Model. Like the ABG model, the CI has also been adopted as a specific NB-IoT for urban areas. Formally, the so-called single-frequency CI model is given by the expression taken from [11] as follows:

$$\overline{PL}_{CI} = 10\gamma\log(\frac{d_{km}}{d_0}) + A, \quad (4)$$

where A can be chosen between the loss at d_0, or given by estimation from the FSPL model; which for the case studied in this paper is given by 88.30.

Note that for the effects of comparison with experimental measurements, we will compute equivalent RSRP data values from the theoretical empirical models using the following expression: $RSRP_{model} = EIRP - \overline{PL}_{model} + G_{rx}$, where G_{rx} is the gain of the UE antenna.

IV. Measurement Methodology

In this section, we introduce details on the measurement site, the parameters being measured, and the data collection process.

Measurement Site. We conducted experiments with NB-IoT technology in Santiago, Chile, in an urban area that covers historic buildings, on average, seven floors high. The base station was in the center of this area, whose maximum radius of reach was 1244 meters. The evaluated area will allow us to make preliminary assessments of where it is more relevant to conduct future experiments. At this point, we are concerned about how far the coverage of the network can be achieved with good channel quality. Moreover, we note that given the seismic nature of Santiago, these kinds of buildings are often characterized by solid and thick walls, which may include metallic parts inside, thus influencing path loss.

Key Performance Indicators (KPIs) The KPIs taken into account for these measurements were the following: i) the RSRP, defined as the power level of the received signal; ii) the Received Signal Strength Indicator (RSSI), defined as the

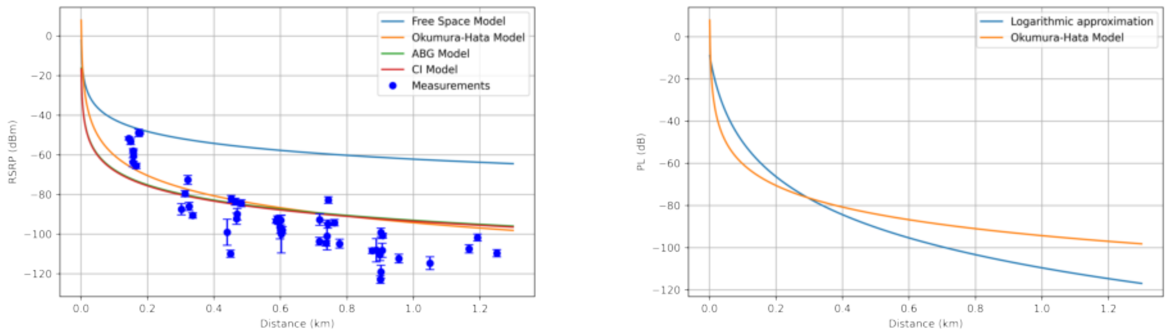

Fig. 2. (Left) RSRP versus distance and comparison with theoretical models; (Right) Okumura-Hata model and the preliminary logarithmic approximation.

power level of all the incoming signals at a given instant; iii) the Signal to Interference & Noise Ratio (SINR), which indicates the relationship between the signal used and the interference signals plus the environmental noise[1]; and iv) finally, the Reference Signal Received Quality (RSRQ), also be considered as a good indicator of the signal quality in the channel, which can be formally defined as follows [13]:

$$RSRQ = N_{prb}\frac{RSRP}{RSSI}, \tag{5}$$

where N_{prb} is the number of resource blocks.

Data Collection. We first used the BG77 module to extract GPS traces and collect precise latitude and longitude coordinates for each measurement point. However, since the built UE was not able to connect simultaneously to the NB-IoT network and the Global Navigation Satellite System (GNSS) network, both measurements were taken separately. First, GPS traces were taken, and then by connecting the UE to the NB-IoT network, the KPIs were measured. Along with the latter, the Cell ID was also recorded, resulting in three different cell IDs at each time instant, one for each antenna of the base station (recalling that theoretically each of these antennas has a radiation pattern covering 120°). Furthermore, the CE level was also measured while using a TCP-based connection, which led to a Bit Error Rate (BER) equal to zero at all points.

In all cases, 101 samples were collected at each location point on the map to ensure representativeness, resulting in 48 points sampled on the map. All these measurements were programmed using AT commands in an Arduino environment.

Note that the duration of the measurements varied significantly at each point, ranging between 6 and 22 minutes, depending on the proximity to the base station. This variation in measurement duration was mainly attributed to intermittent disconnections of the NB-IoT network, especially in areas where the SINR fell below 0 dB. As an initial observation, this shows the impact of signal quality on the stability and reliability of NB-IoT connectivity, particularly in environments with challenging propagation conditions.

[1]Despite SINR is a standard KPI used by telcos to characterize signal quality in urban areas, it is not formally defined by the 3GPP, instead available at the UE and computed through the Channel Quality Indicator (CQI).

V. Results and Discussion

Evaluating the performance of the NB-IoT link based on the active measurements performed reveals several important insights and challenges that are crucial to optimizing its deployment and operation. In this section, we analyze the main findings and observations derived from the measurement campaign.

Figure 2 (Left) shows the results of the RSRP versus distance, and it compares with the four path loss models described in previous Sections. The plot shows that among all the values recorded, the lowest value observed was -129 dBm. This value differs in considerable measure from the theoretical predictions. In fact, for all distances, the measured data differ significantly from the evaluated propagation models.

Despite this clear visual contrast, at the beginning of the distance evaluated, there is an apparent approximation to the FSPL model trend because both nodes are in LOS, since the base station is in the tallest building nearby and within a close radius. This results in a low standard deviation for the closer measured points. However, as the distance increases, the measurements show a more abrupt decrease than this model, reaching about 15 dB lower than the Okumura-Hata model when it passed a distance of 0.8 kilometers from the base station. Here, in contrast to the previous case, there is a higher dispersion, possibly attributed to more scattering and multipath.

Although the initial intention of this paper was to compare these results with the existing propagation model used for NB-IoT, it is inevitable to observe the trend of the measurements, suggesting the possibility of a logarithmic approximation modeling for the data collected. We have tried to graphically illustrate this preliminary intuition in Figure 2 (Right).

Another practical result to discuss is the maximum coupling loss (MCL), which was calculated equal to 152 dB, yet falling short of the literature claim of 164 dB [14]. This deviation can be attributed to factors such as the device's sensitivity or the optimization of the network applied according to the corresponding CE level. For example, when the RSRP reached -129 dBm, the CE was not at level 2 to guarantee sending the message. If modified, it will show an improvement in coverage. This means that it will reach a larger radius because it will be more likely to receive a signal at a lower power.

Fig. 3. RSRP measurement campaign conducted in a central neighborhood in Santiago, Chile. Latitude and longitude of the NB-IoT base station: -33.451392, -70.657928.

Furthermore, it is essential to recognize that this study focuses mainly on the downlink since the evaluated KPIs are defined for this link. However, for the uplink, the measurement values and trends are expected to differ by a constant offset since the only significant difference lies in the device's lower transmit power and the base station's higher sensitivity to the transmitted signal.

The clear discrepancy between well-established models and the empirical data emphasizes the need and importance of additional experimental campaigns to further validate this preliminary intuition and to further validate, refute, or refine existing propagation models with more detail. The end goal is to provide methods and tools that will allow us to accurately predict the performance of the NB-IoT network in various real-world scenarios, with an emphasis on urban areas.

Note that, for the sake of simplicity, this paper analyzes only the RSRP measurements. Based on the models considered, additional KPIs will be taken into account in future.

VI. Conclusion

This work presents the first research effort to characterize NB-IoT performance through real-world measurements in a large Latin American city. Provides valuable information for predicting the coverage of NB-IoT in urban areas with active measurements. It sheds light on the actual performance of the LTE Band 28 (700 MHz) guardband, contributing to better network planning and optimization. In addition, it presents four path loss models tailored to urban environments and compares their effectiveness, focusing specifically on the parameters of the NB-IoT network. The results obtained show a tendency to logarithmic behavior, with an apparent fit to the FSPL model at closer distances. Furthermore, while the theoretical MCL provided by the NB-IoT kit is 164 dB, in these measurements the highest value reached was 152 dB.

In future work, our aim is to further evaluate the path loss models introduced here, validate them in different urban and rural environments, and explore the uplink performance characteristics for the NB-IoT link.

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