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NB-IOT Density Estimation to Minimize Transmission Latency for High-Performance Data Transfer from Sensors

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One of the biggest challenges smart city sensor networks are currently facing is how to develop economic and efficient communication technologies that can avoid high transmission latency especially when deployed with a considerable range of devices. That is where Narrowband Internet of Things (NB-IoT) comes in, especially for the use case above because NB-IoT offers Low-Power Wide-Area connectivity providing the ability to support a massive number of devices as well as long battery life. Nevertheless, one of the key challenges in NB-IoT networks is to reduce transmission delays even more for time-critical applications alike traffic management or road safety monitoring. To reduce the transmission latency from sensors, this paper proposes a new method to optimize the base station (BS) density of NB-IoT based on the Characteristics of IoT data and an evaluation mechanism. For obtaining the results related to BS density, signal strength, interference and sensor density with other network parameters a mathematical model is developed. With this model, the number of base stations required for meeting low-latency communication is determined with respect to network coverage and efficiency. A simulation tool, on the other hand, is developed to emulate realistic network setups and test the latency performance under different network settings. According to the results, deploying additional base stations can drastically improve latency.

Keywords: NB-Iot (Narrowband Internet Of Things), Base Station Density, Data Transmission Delay, Sensors.

1. Introduction

The acceleration of smart cities has created an opportunity for new communication systems to be both more efficient and capable of accommodating a wide range of sensor-based applications (e.g., traffic management, environmental monitoring, security control etc) [1]. The up-and-coming technologies in IoT, Narrowband Internet of Things (NB-IoT) has exciting potential as a low-power wide-area connectivity solution for massive quantities of simple, intermittently sensed devices sending low volumes of data. This makes it an ideal candidate for applications with many sensors in large urban areas that require the sending of small data packets [2].

One of the main challenges in NB-IoT networks is to minimize delay in data transmission so that data (road conditions, emergency alerts etc) sensitive to timing get delivered on time. The network density and BS configuration determine to a large extent the performance of these networks in terms of coverage and communication efficiency [3]. More number of base stations lead to more relay-points, that increases the signal strength and reduces latency by lowering the distance between sensor and base station. But the key is to balance network performance with resource utilization and so optimizing this density is essential [4-5].

The main objective of this paper is the latency between base station density and transmission in NB-IoT networks. We will also study how to minimize the latency in the data transmission step from sensors by using mathematical modeling and software implementation so as be able to define an optimal number of base stations. The work considers multiple aspects including signal-to-interference-plus-noise ratio (SINR), bandwidth, the number of sensors, interference and higher efficacy to maximize the performance of NB-IoT networks in smart cities. In this study, a mathematical model was created that optimizes the density of the BS installation to minimize delays on the LTE-M/NB-IoT interface. The purpose of the experiment is to assess the density of base stations of the LTE-M/NB-IoT network to minimize the delay in transmission from sensors.

The achievement of the goal is facilitated by the solution of a number of scientific problems:

-To study the features of NB-IoT technology in the context of latency generation;

-To create a mathematical model describing the calculation of the optimal number of NB-IoT base stations to minimize the delay in transmission from sensors;

-NB-IoT is designed to transmit small amounts of data at low speed. The bandwidth varies from 180 kHz to 200 kHz), which is several times less than in traditional mobile networks (LTE, 5G).

-The narrow bandwidth allows NB-IoT to efficiently use the frequency spectrum and provide coverage of a large number of devices from a single station.

2. Literature Review

The theoretical basis of the experiment was the works studying the technology of mass machine-to-machine communication and the physical structure of the NB-IoT channel. Methods of random multiple access to a common channel for scenarios of mass machine-to-machine communication are investigated [7]. In the work of [9] describes the innovative characteristics of the NB-IoT network. The author notes that in particular, the innovations concerned the core of the network, implemented on the basis of EPS. The structure of the uplink is determined by the direction of the data (Figure 1).

Data from the CIoT RAN (Cellular Internet of Things Radio Access Network) or through a gateway that manages connections between mobile devices (UEs) and the core network (SGW), providing device authentication, traffic routing and mobility support (cell hopping) and a packet gateway that is responsible for routing packet data traffic from the UE to external networks. It also manages Internet access policies (e.g., speed limiting, content blocking) [8]. When a mobile device (UE) connects to a network, it first registers with the SGW, which authenticates the device and assigns it an IP address. All data traffic from the UE is routed through the SGW. If the traffic is destined for the Internet, the SGW redirects it to the PGW, which routes the traffic to the external network and manages access to the network [6].

Data from the CIoT RAN to the Mobility Management Entity (MME), which provides subscriber mobility management, authentication, authorization, and session management. For example, when a UE wants to establish a data session, the MME forwards the request to SCEF, which manages data sessions and policies: SCEF establishes a data session, assigns routes, and enforces security and billing policies [10].

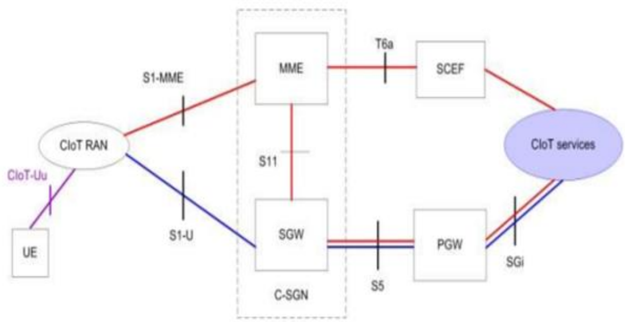

Figure 1 – Structural Diagram of EPC

The physical link structure for NB-IoT differs from traditional LTE because it is optimized for the transmission of small amounts of data at low speed and with low power consumption in mind.

Transmission from the base station to the mobile device is validated using three physical channels: NPBCH, NPDCCH, NPDSCH, and two Narrowband Reference Signal (NRS): NPSS and NSSS. Ascending channel. It consists of a Narrowband Demodulation Reference Signal (DM-RS), a Narrowband Physical Shared Uplink (NPUSCH), and a Narrowband Physical Random-Access Channel (NPRACH), which is necessary for devices to access the network and communicate with the base station (eNodeB).

When initialized, the NB-IoT device begins to transmit the preamble to a special NPRACH channel. If the preamble is decoded successfully, the eNodeB understands that the device is trying to connect.

The eNodeB sends a response to the device, informing it that its request has been received. The eNodeB response specifies information about the long-distance communication channel that will be used for further communication. The device goes to the specified data channel and can start communicating with the eNodeB.

Latency is affected in the context of three parameters:

- Access time;

- Peamble processing time;

- Response time of the base station.

The transmission of NPRACH is defined as the NREP of the repetition of the NPRACH preambles, in which the NPRACH preamble is defined as a set of P groups of characters, which is defined as a sequence of N identical characters preceded by a cyclic prefix. For this reason, a group of characters, rather than an OFDM character, can be considered as an atomic unit of NPRACH. The duration of a group of NPRACH characters depends on the format of the preamble characters for the three NPRACH preamble formats.

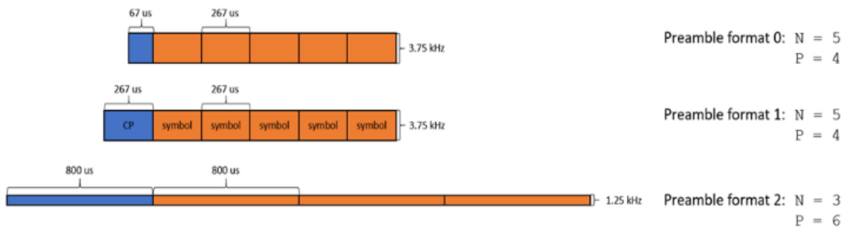

Figure 2 – Character Group Scheme for the Three NPRACH Preamble Formats

The signal to NPRACH is transmitted using single-tone modulation, i.e. at the same frequency. The frequency of NPRACH signal transmission varies with Frequency Hopping. This means that each group of symbols is transmitted at a different frequency. SubcarrierOffset defines the initial frequency for transmitting the first group of characters. NumSubcarriers: Defines the total number of subcarriers used in NPRACH. NInit determines the frequency of the first group of characters in the first preamble. NNCellID andwill be used to initialize a pseudo-random sequence that determines the frequency of the first groups of characters in subsequent preambles.

Figure 3 shows the pattern of changing the frequency for the two repetitions of preamble 0. It can be seen that the first groups of symbols for each preamble are transmitted on different subcarriers.

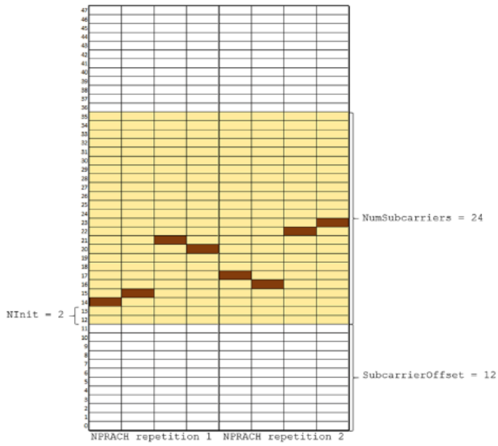

Figure 3 – Frequency Change Diagram for the First Two Repetitions of the Preamble Format 0 Taking Into Account the NPRACH Configuration

The key advantages of frequency hopping are:

-Reduced interference as the frequency change makes the signal less susceptible to interference from other devices at the same frequency;

-Increase in the reliability of communication, since frequency switching allows you to use a more reliable communication channel.

-Increased privacy, as frequency switching makes the signal more difficult to intercept and analyse.

3. Methodology

The main characteristics of NB-IoT are:

3.1 Frequency range (Bandwidth)

NB-IoT uses a narrow frequency range in an LTE network (180 kHz or 200 kHz). This is significantly less than conventional LTE channels (1.4 MHz to 20 MHz). Narrow bandwidth allows NB-IoT to efficiently use the frequency spectrum and provide coverage of a large number of devices.

3.2 Frame Structure

which is formed from a cycle of 1024hyperframes of 1024 frames each [11].

A single frame consists of 10 subframes, and each subframe is divided into two 0.5 ms slots. (Figure 4)

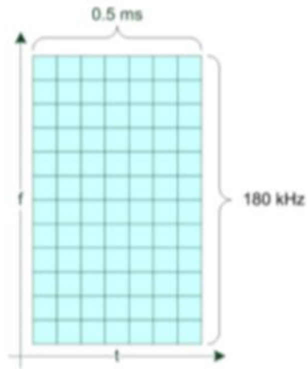

Figure 4 – Slot Structure in NB-IoT

On downlink (DL) and uplink (UL), NB-IoT supports 15 kHz subcarrier spacing, for which each frame contains 20 slots (Figure 3).

In the uplink (UL), an additional 3.75 KHz of subcarrier spacing is supported (Figure 4). In this case, each frame is divided into five 2 ms slots, with no concept of a subframe [11].

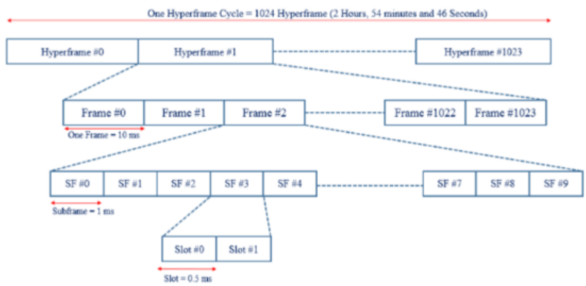

Figure 5 – Basic Frame Structure with 15 Khz Downlink and Uplink Subcarrier Spacing

To identify a hyper frame, use the hyper system number (H-SFN) in the range 0-1023, for a frame - the frame system number (SFN) in the range 0-1023, for a subframe - the subframe number (SN) in the range 0-9 [12].

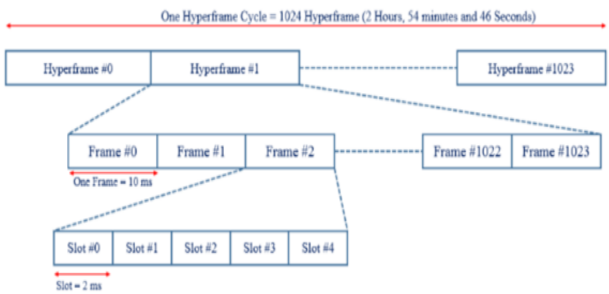

Figure 6 – Additional Frame Structure with 3.75 Khz Uplink Distance

3.3 Modulation Scheme

NB-IoT uses QPSK (Quadrature Phase Shift Keying), which refers to phase modulation, i.e. information is encoded by changing the phase of the carrier signal (Figure 7)

Figure 7 – Quadrature Modulation Diagram

First, the data bits are grouped into two (for example, "00", "01", "10", "11"). Each pair of bits corresponds to one of the four possible characters. Each symbol is represented by a unique phase of the carrier signal. QPSK uses four phases:

0°: Corresponds to the symbol "00".

90°: Corresponds to the symbol "01".

180°: Corresponds to the symbol "10".

270°: Corresponds to the symbol "11".

The modulated signal is transmitted via a radio channel to the receiver.

3.4 Coding Scheme

NB-IoT uses LDPC (Low-Density Parity-Check) and Turbo codes schemes with a lower encoding rate, which improves the reliability of data transmission in conditions of poor channel quality. The data is encoded using LDPC code by multiplying the vector of the source data by the code validation matrix. The code validation matrix contains ones and zeros that define the relationship between the source bits and the test bits.

3.5 Range of resources

Unlike LTE, NB-IoT one RB, which is divided into 12 subcarriers in the frequency domain and 1 slot (0.5 ms) in the time domain [13].

Total bandwidth occupied: 12×15 kHz = 180 kHz. In addition, each resource block has 7 time slots of 0.5 ms each, for a total of 84 Resource Elements (RE) [14].

Also, for NB-IoT, the division of RB into 48 subcarriers of 3.75 kHz in the Uplink direction is standardized, which expands the timeslot to 2 ms.

Let's build a simplified mathematical model for estimating the density of the NB-IoT BS to minimize the delay in transmission from sensors, taking into account the above features of the technology. Take into account that the frequency value is directly proportional to the susceptibility to dispersion in the medium, which leads to an increase in latency. In addition, higher frequencies have higher attenuation, hence higher transmission power may be required to ensure satisfactory communication quality, which can increase transmission time and latency. A wider frequency range allows more data to be transmitted per unit of time, which can reduce latency. However, NB-IoT operates in a narrow bandwidth, which limits the data transfer rate.

A shorter frame reduces the time it takes to transfer data. NB-IoT uses a shorter frame than LTE, which reduces latency.

The number of subframes per frame affects the amount of data that can be transferred in a single frame. Increasing the number of subframes allows more data to be transferred, but can increase latency.

NB-IoT uses a simple QPSK scheme, which reduces processing latency.

A higher encoding rate (fewer test bits) increases the data transfer rate, but can reduce the reliability of transmission and increase the likelihood of retransmissions, resulting in increased latency. NB-IoT uses LDPC schemes with low encoding rate, which provides higher reliability and reduces latency due to replays. NB-IoT uses a single RB, which limits bandwidth and can increase data transfer time and latency.

Taking into account these factors, let's choose the variables of the model.

- N : Number of Base Stations in the Area
- A (in square meters): Area of the Serviced Region
- L_i (in Watts): Transmission Power of Base Station
- G_t (unitless or in dBi): Base Station Antenna Gain
- G_r (unitless or in dBi): Sensor Antenna Gain
- f (in Hertz): Signal Frequency
- d (in meters): Distance from Sensor to Nearest Base Station:
- $\lambda = \frac{c}{f}$ (in meters, where $c = 3 \times 10^8 m/s$): Wavelength of Signal:
- $L = 20 \log_{10}\left(\frac{4\pi df}{c}\right)$: Free Space Path Loss (in dB)
- I (in Watts): Interference Power from Other Base Stations
- N_o (in Watts per Hertz): Spectral Noise Density
- BW (in Hertz): Bandwidth
- SNR_{min} (in dB): Minimum Signal-to-Noise Ratio
- $T_{procmin}$ (in seconds): Network Signal Processing Time:
- ρ (in number of sensors per square meter): Sensor Density
- T_{tx} (in seconds): Sensor Data Transfer Time
- T_{wait} (in seconds): Data Queue Wait Time

Let's Determine the Dependencies of the Model

Signal Attenuation

Signal attenuation refers to the decrease in signal strength as it travels through space. This loss is determined using the free-space path loss formula:

$$L = \left(\frac{4\pi d}{\lambda}\right)^2 \quad (1)$$

Signal loss increases as the distance (d) grows and diminishes with longer wavelengths (λ). Elevated frequencies produce shorter wavelengths, resulting in increased loss, which can impair communication quality and heighten latency.

Signal Strength at the Receiver

The received power (P_r) at the sensor of base station is expressed as:

$$P_r = \frac{P_t \,.G_t \,.G_r.\left(\frac{\lambda}{4\pi d}\right)^2}{l} \quad (2)$$

The power received is influenced by the transmitted power (P_t), the gains of the antennas (G_t and G_r), and the separation distance (d) between the transmitting and receiving units. Increased gains and shorter distances improve the signal, whereas free-space loss (L) diminishes it.

Interference

Interference (I) from base stations modelled as:

$$I = P_t \,.\, G_t \,.\sum \frac{\left(\frac{\lambda}{4\pi d_i}\right)^2}{L_i} \quad (3)$$

Interference occurs when signals from several base stations overlap. It is influenced by factors such as transmission power (P_t), antenna gain (G_t), and the distances (d_i), of nearby base stations in relation to the sensor. Reduced interference leads to improved communication quality.

Where:

d_i is the distance from the i-th base station (BS) to the sensor.

L_i is the free space loss for the i-th BS.

Signal-to-Noise Ratio (SNR):
The SNR measures the strength of the signal relative to noise and interference:

$$SNR = \frac{P_r}{I + N_o \,.BW} \quad (4)$$

The theory suggests that a greater signal-to-noise ratio SNR reflects a more distinct and trustworthy signal. This ratio relies on the received power (P_t), the level of interference (I), the spectral noise density (N_o), and the bandwidth (BW).

Minimum Distance to BS (d_{min})

The minimum distance (d_{min}) required to achieve the desired SNR is

$$d_{min} = \sqrt{\frac{P_t . G_t . G_r . \left(\frac{\lambda}{4\pi}\right)^2}{L . (SNR_{min} . (I + N_o . BW))}} \quad (5)$$

The power output, antenna gains, wavelength, and necessary SNR all affect the minimum distance. In noisy and interfered environments, a higher SNR is usually maintained at shorter distances.

Optimal BS Density (N/A)

To ensure coverage of all sensors within the minimum distance, the optimal density of base stations (N/A) in the serviced area (A) is:

$$\frac{N}{A} = \frac{1}{\pi . d_{min}^2} \quad (6)$$

For sensors inside their coverage area to continue receiving an acceptable signal strength, base station density needs to be high enough. A higher base station density results from a smallerd_{min}.

Delay

Delay consists of propagation delay ($\frac{d_{min}}{c}$), network signal processing duration (T_{proc}), data transmission period (T_{tx}), and queue delay duration (T_{wait}). Decreasing any of these elements lessens total latency.

$$Delay = \frac{d_{min}}{c} + T_{proc} + T_{tx} + T_{wait} \quad (7)$$

Queue Time (T_{wait})

The waiting time in the queue depends on the density of sensors (ρ), the coverage area (A), the data transfer time (T_{tx}), the number of base stations (N) and the flow rate (BW). A low sensor density and a high base station density can minimize the waiting time.

$$T_{wait} = \frac{\rho . A . T_{tx}}{N . BW} \quad (8)$$

The model determines the minimum BS distance required to achieve the required SNR, taking into account interference and noise. The optimal BS density is calculated to provide coverage of all sensors within d_{min}

Latency depends on the distance to the base station, network processing time, data transfer time, and queue wait time.

4 Result Analysis

The delayed function follows the index collapse scheme. This means that if you first add a base station, the delay will decrease significantly, so if the number of stations increases, the plateau decreases significantly. This reflects a decrease in profitability from additional infrastructure other than specific points.

The analysis of the relationship between the number of basic stations (BS) and the latency was carried out, and the results are presented in Table 1.

Table 1 – Dependence of Latency on the Number of Base Stations

Number of BS	Sensor density	Delay, s
1	0.0014	0.0540
2	0.0014	0.0340
3	0.0014	0.0240
4	0.0014	0.0200
5	0.0014	0.0180
6	0.0014	0.0170
7	0.0014	0.0160
8	0.0014	0.0150
9	0.0014	0.0140
10	0.0014	0.0140

By presenting the table values graphically, you can conclude that the Depending on the change in the number of stations, it is not linear.

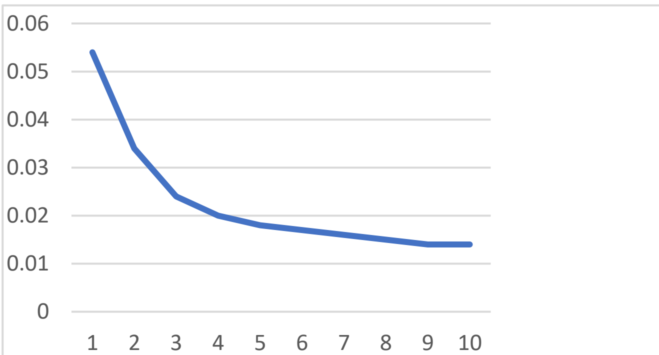

Figure 8 – Dependence of Latency on the Number of Base Stations (Delay, C)

Visualization of the data in Table 1 (Figure 8) shows that it is not advisable to distribute more than 9 BS in the study area, since the delay function ceases to decrease significantly at N>9.

Using the experimental curve, we will restore the delay function depending on the number of BS:

$$y \approx 0{,}06 \,.\, \exp^{(-0{,}15x)} \qquad (9)$$

The study of the derivative function showed that the sensitivity of the delay function to changes in the number of stations was most pronounced when moving from 1 station in the studied area to two (Figure 9).

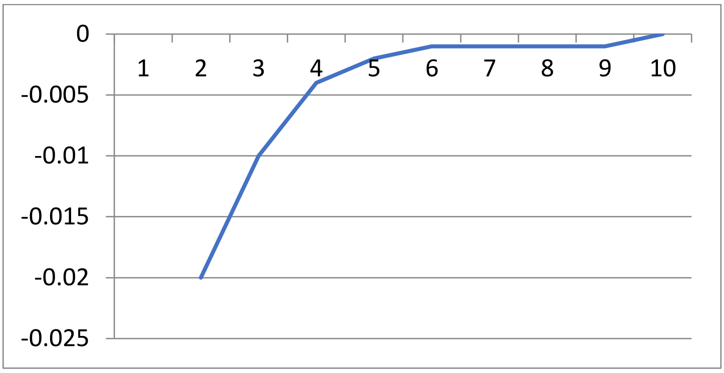

Figure 9 – Derivative of the Delay Function

Thus, we can conclude that the delay in the presence of two stations is 0.0340s, which is permissible for the operation of sensors.

The analysis shows that deploying two base stations provides an acceptable latency of 0.0340 seconds. However, to further improve performance, it is recommended to increase the number of base stations to 9. Above this threshold, the latency improvement becomes negligible and there is no need to add additional base stations in the study area. This result highlights the importance of balancing infrastructure cost and performance improvement in NB-IoT network design.

5 Conclusions

A scientific effort was made in this article to examine and analyze the ways in which different factors affect the packet loss factor. The analysis demonstrated how the packet loss rate was influenced by multiple factors, including packet size, node speed, and signal strength. An information set with a low packet loss factor was acquired. By increasing the number of variables, the analysis possibilities on this subject can be improved. Interpolation effects, multipath fading, and other elements can be included. Consequently, the initial hypothesis of the research has been validated. LTE over IPv4 can, in theory, satisfy the requirements of the IoT radar concept, but as an IoT communication standard, it is not the best option because of its high-power consumption, high cost, and limited coverage range. Furthermore, an increase in load will not attain the required quality of data transmission due to the licensed wireless spectrum's already inadequate resources. In order to create online communication systems, future research could look into new protocols and standards, security and privacy, interdisciplinary approaches, and the integration of AI and machine learning. Using direct connections between user devices (device to device, or D2D) in an unlicensed frequency band to unload mobile traffic is one of the study's potential applications.

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