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NarrowBand-IoT Performance Analysis for Healthcare Applications

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Abstract

In future remote healthcare monitoring system, it is necessary to constantly monitor the patients physiological parameters. For example, a pregnant woman parameters such as blood pressure and heart rate of the woman and heart rate and movements of fetal to control their health condition. To support the high-intensity and short-lived demands of these emerging applications, Narrowband Internet of Things (NB-IoT) is a promising technology that provides long-range communications at a low data rate for sensors with reduced device processing complexity and long battery lifetime. This paper aims to investigate the realistic performance of NB-IoT in terms of effective throughput, patient served per cell and latency in healthcare monitoring system with both in-band and stand-alone deployment.

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Keywords: Narrowband Internet of Things (NB-IoT)'; Healthcare monitoring; Throughput; Latency; Device capacity; System-level analysis.

1. Introduction

In recent years, wearable technology has contributed to reviving the consumer electronics industry. With continuous exponential rise, it is anticipated that by 2019 there will be more than 150 million wearable devices worldwide. This will enable application services like fitness and healthcare monitoring, rescue and emergency management. To meet the requirements set forth by such applications, the Third Generation Partnership Project (3GPP) has introduced a new radio access technology called Narrowband Internet of Things (NB-IoT). NB-IoT enables low data rate communication, long battery life, low device cost and signal coverage extension in delay-tolerant applications.

NB-IoT is based on existing long-term evolution (LTE) functionalities with a minimum bandwidth of 180 kHz, which corresponds to one physical resource block (PRB) in LTE transmission. With 180 kHz of minimum spectrum requirement, NB-IoT can be deployed in three possible operational modes: (1) stand-alone as a dedicated carrier, (2) in-band within the PRB of an existing LTE carrier, and (3) within the guard band of an existing LTE carrier. Since NB-

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IoT is expected to adopt a design based on existing LTE functionalities, it is possible to reuse the same hardware and to share spectrum without coexistence issues. A detailed description of the NB-IoT system can be found in standard TR45.820[1].

However, to deploy NB-IoT for practical applications, cell throughput, device capacity and latency are the key performance measures in which operators are interested. Some preliminary studies investigate the device capacity of NB-IoT as number of supported devices[2,3,4]. The technical report by Ericsson[2] presents system-level evaluation of NB-IoT in stand-alone deployment and shows that single-carrier frequency-division multiple access (FDMA) has 3 times higher maximum spectral efficiency compared to FDMA with Gaussian Minimum Shift Keying (GMSK) in uplink, which translates into a device capacity advantage. Furthermore, it is also shown that the downlink with 15 kHz carrier spacing is able to provide the desired capacity of 52K devices per cell. Capacity evaluation of NB-IoT in an inband deployment is presented in technical report by Nokia Networks[3] with 12 subcarriers at 15kHz subcarrier spacing in both downlink and uplink. It is shown that the capacity of in-band deployed NB-IoT system is 71K devices/cell with an information packet size of 32 bytes. Furthermore, application specific capacity analysis of NB-IoT for smart grid applications is presented by Persia et al.[4]. It is shown that NB-IoT satisfy the requirement of low data rate applications. However, the NB-IoT capacity of both downlink and uplink are expected to be lower, when the control channel and signaling overheads are taken into account, which has not been considered in these studies. Furthermore, the capacity evaluation has been performed on a fixed information packet sizes. In IoT application scenario, it is expected that different devices will be communicating with each other or with the base station, each device having its own information packet size. Therefore, limiting the evaluation to a certain packet size is not a realistic assumption. The suitable solution cannot be evaluated regardless of use case scenario in which NB-IoT will operate.

This paper focuses mainly on application-specific analysis of cell throughput, device capacity and latency of NB-IoT in remote healthcare monitoring system with both in-band and standalone deployment. The main contributions of this paper are as follow: **First**, an application specific system-level analysis based on healthcare monitoring application is performed through Monte-Carlo simulations. **Second**, a comprehensive comparison of NB-IoT performance for single-sensor and multi-sensor node design is also presented. The results of key performance metrics including cell throughput, number of supported device and latency under realistic environment are presented.

The remainder of the paper is organized as follows. In Section 2, we provide a general overview of the NB-IoT. Section 3 presents the application specific throughput analysis of NB-IoT based on the healthcare monitoring system along with the system and traffic model under consideration. In Section 4, we provide detailed evaluation of the performance of NB-IoT system in term of effective cell throughput, number of patients served per cell and latency, followed by a conclusion in Section 5.

2. NB-IoT Overview

NB-IoT design exploits the basic functionalities of LTE. However, the signaling and control channels for NB-IoT are new. Furthermore, in NB-IoT, frequency division duplexing (FDD) half duplex type-B is chosen as the duplex mode whereas legacy LTE also supports full duplex mode[5]. FDD Half duplex means that uplink and downlink are separated in frequency and the user either receives or transmits, i.e, does not perform both operations simultaneously. The brief frame structure of both downlink and uplink along with the control channels, extracted from 3GPP standard[1], are as follows:

2.1. Downlink Transmission Scheme

The frame structure of NB-IoT downlink is similar to LTE in the time domain with 10 ms length. Each frame consists of 10 subframes of 1 ms length and each subframe consists of two slots with a length of seven OFDM symbols. In frequency domain, it consists of one physical resource block (PRB) with 12 subcarriers having 15 Khz of spacing and normal cyclic prefix (CP). one sub-carrier × one symbol constitute one resource element (RE), the smallest transmission unit. Furthermore, unlike LTE, NB-IoT has two physical signals and three physical channels which are as follows:

- Narrowband reference signal (NRS)
- Narrowband primary and secondary synchronization signals (NPSS and NSSS)
- Narrowband physical broadcast channel (NPBCH)
- Narrowband physical downlink control channel (NPDCCH)
- Narrowband physical downlink shared channel (NPDSCH)

2.2. Uplink Transmission Scheme

In the uplink, NB-IoT support both single-tone and multi-tone transmissions. Multi-tone transmission uses the same SC-FDMA scheme with a 15 kHz subcarrier spacing. However, single-tone transmission support both 15kHz and 3.75 kHz subcarrier spacing. The 15 kHz has similar numerology as in LTE. Whereas, the symbol duration of 3.5 kHz subcarrier spacing has four times more duration compared to 15 kHz, which result in a slot length of 2ms. Furthermore, in NB-IoT uplink, a new resource mapping unit is defined as resource unit (RU). RU is a combination of a number of subcarrier (frequency domain) and number of slots (time domain). For the uplink, NB-IoT has one physical signal and two physical channels which are as follows:

- Demodulation reference signal (DMRS)
- Narrowband physical random access channel (NPRACH)
- Narrowband Uplink Shared Channel (NPUSCH)

3. Application Use-case: Healthcare monitoring system

NB-IoT can be employed in a wide range of applications. The major target applications include but are not limited to the smart city, personal IoT applications, smart grid, smart metering, logistics, industrial monitoring, agriculture, etc. In this work, we have taken the application of NB-IoT in wireless body area networks (WBAN) for providing smart health and remote wellness monitoring system. These systems constitute of wireless sensors that communicate over long-range wireless link to send or receive information. NB-IoT enables to use already deployed cellular base station and cover the whole facility (e.g., a hospital, a factory, a university campus, a parking area or a shopping mall) and all the people in the area. NB-IoT guarantees that the end user terminals (e.g., sensor nodes) will have long lifetime even if powered by batteries. However, each application is characterized by different coverage needs and performance requirements such as data rate or latency threshold limit. For example, healthcare typically requires monitoring of sweating, respiratory rate, body temperature, pulse rate and blood pressure; data rates up to 2 Kbps per sensor could be required. On the other hand, for rescue and critical application, along with vital signs monitoring, GPS positions, motions sensors could be required with data rates up to 200 Kbps[6]. Further details on the requirement of remote healthcare monitoring system are presented in Table 1.

In current healthcare monitoring system, two types of system design have been proposed in the literature which are as follows:

- **Single-sensor node design (SND)**: In this design, each sensor node such as temperature sensor, a respiratory rate sensor and etc., is considered as an individual node and each node has it own transmission module. Therefore, each node transmits data directly to the base station with the latency and data rate requirements[7]. In this design, for each patient, multiple transmission links are required with the base station.
- **Multi-sensor node design (MND)**: Unlike SND, all the sensors are connected to the central processing unit, which is responsible for the processing of data and transmission to the base station[8]. This design requires only one transmission link for each patient with the base station.

3.1. System Model

To conduct the performance analysis, we have considered both in-band and standalone deployments of NB-IoT with a bandwidth of 180 kHz in a typical LTE cell. The scenario is a regular grid of tri-sector sites with an inter-site

Table 1. Typical sensor type with data range, information size and periodicity of transmission [6]

Sensor	Data Range	Information Size	Periodicity
Heart Rate	0-150 BPM	1 byte	5 min
Respiratory Rate	2-50 breaths/min	1 byte	5 min
Blood pressure	10-400 mm Hg	2 bytes	30 min
Blood pH	6.8-7.8 pH units	1 byte	30 min
Body Temperature	24-44 °C	1 byte	5 min
GPS position	0-180 degree	4 bytes	2 hours
Motion sensor	-	2 byte	2 hours

distance of 1732 m. For in-band, NB-IoT is deployed in a single PRB in an LTE system. The network is assumed to be synchronized, and NB-IoT is deployed with the same PRB in all cells. The other simulation assumptions that closely follows [1] are presented in Table 2. The full 180 kHz bandwidth, i.e. 12 subcarriers at 15 kHz subcarrier spacing in both downlink and uplink, is used for the analysis. For uplink, this is known to perform worse than single tone e.g. 3.75 kHz or 15 kHz, so the achieved performance in this study yields lower bounds as compared to what can be achieved with single tone NB-IoT systems and it is more realistic assumption to investigate NB-IoT uplink performance [3].

The data rate $R_{i,n}$ for a node i when the nth PRB is assigned is given by:

$$R_{i,n} = B \log_2(1 + SINR_{i,n}) \tag{1}$$

where B is the assigned transmission bandwidth and $SINR_{i,n}$ is the signal-to-interference-plus-noise (SINR) for node i on nth PRB and is given as:

$$SINR_{i,n} = \frac{P_n h_{i,n}}{I_{i,n} + N_o} \tag{2}$$

where P_n is the transmit power and $h_{i,n}$ is the channel gain between node i and the base station on the nth PRB. $I_{i,n}$ is the interference experienced by node i and is assumed to be negligible in our analysis. N_o is the noise power spectral density. Based on the SINR, the corresponding maximum coupling loss (MCL) is computed. The relationship between SINR and MCL is given as [4]:

$$\text{Target SINR} = \text{Tx power} + 174 - \text{Noise figure} - 10\log_{10}(\text{Bandwidth}) - \text{MCL} \tag{3}$$

For the simulation, chase combining is used based on MCL, such that the same information is repeated N times, N being the number of repetitions. The number of repetitions assumed with different MCL values are presented in Table 3.

3.2. Traffic Model

The traffic in healthcare monitoring system is based on multiple sensors with different information packet size and time interval. In our analysis, we assume the case of a critical patient that requires constant monitoring. The corresponding sensors along with the information size and time for transmission are presented in Table 1. For SND, all the sensors communicate with an NB-IoT base station directly for each patient. As in [3], we assume that 42.8%, 28.6%, and 28.6% of report sizes are 1, 2, and 4 bytes respectively. The mean size is 2.14 ≈ 2 bytes. Whereas for MND, sensors transmit information to a gateway which communicates to the base station. we assume that 40%, 40% and 20% of the report size are 3 bytes, 3 bytes, and 6 bytes respectively. The mean size is 3.6 ≈ 4 bytes.

The inter-arrival time is distributed over three categories of periodic transmissions with constant inter-arrival times of 5 minutes, 30 minutes and two hours. The respective proportions of devices are 42.8%, 28.6%, and 28.6%. The average arrival rate of reports per device as calculated in [3] is given by

$$\frac{0.428}{300s} + \frac{0.286}{1800s} + \frac{0.286}{3600s} = 1.6610^{-3} \frac{pkt}{s} / device \tag{4}$$

The calculation from network packet rate, R [reports/s/cell], to number of devices is, as follows:

$$\frac{R \frac{pkt}{s} / cell}{1.6610^{-3} \frac{pkt}{s} / device} = 602 \times R \, device/cell \tag{5}$$

Table 2. Simulation Assumption

Parameters	Assumptions
Cell layout	Hexagonal grid, 3 sectors per site
Frequency band	900 MHz
Inter-site Distance	1732 m
User distribution	Users dropped uniformly in entire cell
BS transmit power per 200 KHz	32 dBm (3 dB boosting applied)
User Tx power	23 dBm
Pathloss Model	L=I + 37.6 log10(R), R in kilometers I=120.9 for the 900 MHz band
Shadowing standard deviation	8 dB
Shadowing Correlation distance	110 m
Shadowing Correlation between cell-sites	0.5
Shadowing Correlation between cell sectors	1.0
Base station antenna gain	18 dBi
User equipment antenna gain	-4 dBi
Base station cable loss	3 dB
Building penetration loss	40 dB
Noise figure at base station	5 dB
Noise figure at user equipment	3 dB
Noise power spectral density	-174 dBm/Hz

Table 3. Coverage classes with repetition factor

MCL	Repetition
Below 145 dB	1
146 to 148 dB	2
149 to 151 dB	4
152 to 154 dB	8
155 to 157 dB	16
158 to 160 dB	32
161 to 163 dB	64
Above 164 dB	128

According to [1], a header of 65 bytes and 24 bit CRC field are applied. Furthermore, all users apply the QPSK and 1/3 coding scheme.

4. Performance Evaluation

In this section, the system-level performance of the NB-IoT is evaluated through Monte Carlo simulations in terms of effective throughput, number of supported devices and latency. With the settings presented in Table 2 and subsection 3.2, the simulation is run for both in-band and standalone deployments for over 500 random samples.

Figure 1 shows the cumulative distribution function (CDF) of the average effective throughput in different deployment scenarios with both SND and MND. Effective throughput is defined as the number of information bits transmitted per second with all the overhead of control information. The figure reveals that the maximum effective throughputs that can be achieved are significantly lower than the peak data rate of 226.7 kbps and 250 kbps in downlink and uplink respectively for NB-IoT proposed in literature [9]. This is due to the small information packet size compared to the overhead of the control channels, particularly NPDCCH in downlink, which requires an extensive number of repetitions for successful transmission. Furthermore, in uplink, 30% of the resources are reserved for NPRACH and some for NPUSCH Format 2 packets [10]. This results in performance degradation. On the other hand, in MND, as the packet size improves, a significant gain in throughput is observed. Moreover, the in-band deployment performance is significantly degraded as compared to standalone due to the presence of LTE control information.

Figure 2 presents the average number of patients that can be served by both SND and MND in different deployment scenarios. It can be seen that MND significantly improve the supported number of patient. This is due to the increase

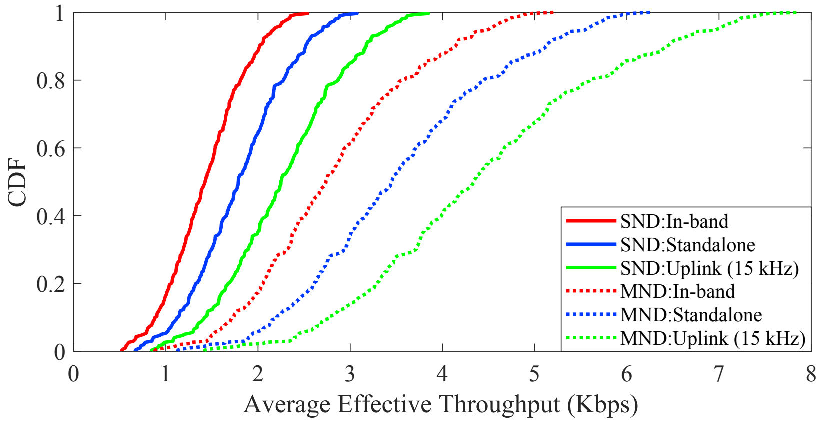

Fig. 1. Average effective throughput in different deployment scenarios with both SND and MND

in packet size which reduces the number of transmission per patient. Thus, resulting in less overhead cost and more patients can be supported. Furthermore, by jointly observing Figure 1 and 2, one can argue that with the increase in packet size, the effective throughput increases. However, the increase in throughput is achieved with the more delay, which can be observed from Figure 3.

Figure 3 presents the latency of NB-IoT in different scenarios. Latency is defined as the average time required to complete the transmission along with the required overhead control information. It can be seen that with the increase in packet size, the transmission time required for the packet also increases, resulting in an increased delay for all the devices in a network. However, increased packet size also improves throughput and number of patients served per cell. From the above discussion, it is evident that the packet size, number of supported devices, latency and throughput significantly depend on each other.

5. Conclusion

In this paper, we have presented a detailed application-specific performance analysis of NB-IoT for healthcare monitoring system with both SND and MND. From the conducted analysis, it can be seen that with MND design significant gain in throughput and number of patients per cell is observed at the cost of increased delay. This is due to the reduction in overhead of control information transmission. From the results, it is also concluded that to provide

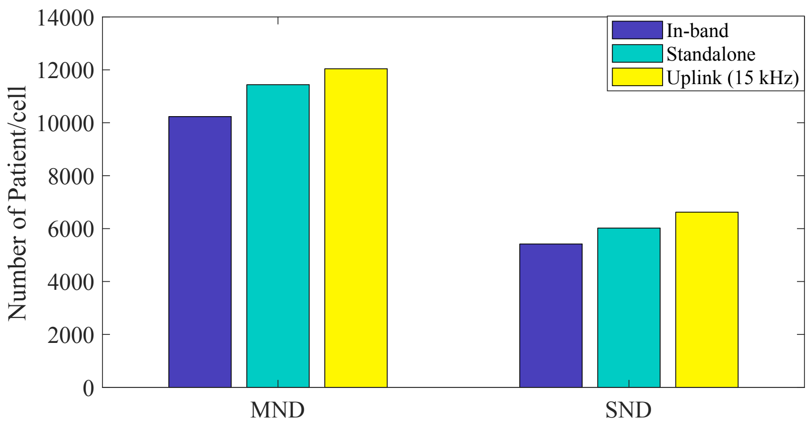

Fig. 2. Number of patients served per cell in different deployment scenarios with both SND and MND

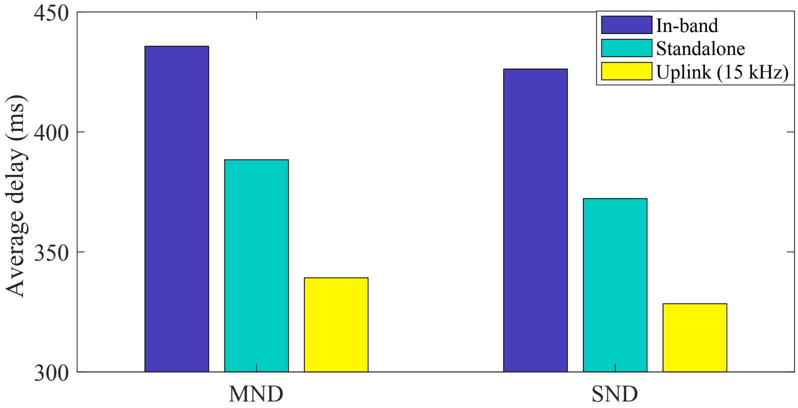

Fig. 3. Average Latency in different deployment scenarios with SND and MND

a suitable solution for the different use case scenarios, one has to jointly optimize the required throughput, delay and device density.

As future work, based on the results of this work, we will be able to evaluate different strategies for resource management in NB-IoT systems for specific use case scenarios.

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