Coverage Analysis of NB-IoT in the Presence of Radar Interference

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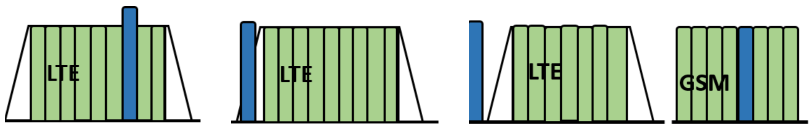
Abstract

The 3GPP Release-13 has introduced a narrowband system, namely Narrowband Internet of Things (NB-IoT), to provide low-power, wide-area cellular connectivity for the Internet of Things. NB-IoT uses a design similar to Long Term Evolution (LTE), but it makes essential modifications for reducing the device complexity. NB-IoT is optimized for machine type communications, and it aims to increase coverage, reduce overhead and reduce power consumption while increasing capacity. In this paper, we present our testbed-based experimental study on the operation of NB-IoT systems in the presence of pulsed radar signals. We leverage results from our experiments in providing a comprehensive analysis on the impact of coverage and capacity of a NB-IoT base-station when it shares an uplink channel with S-band pulsed radars. Our results indicate that the NB-IoT cell coverage is affected in the presence of radar interference.

Chapter 1

Introduction

The phenomenal growth in smarter end-user devices and machine-to-machine (M2M) connections is a clear indicator of the growth of *Internet of Things* (IoT), which is bringing together people, processes, data, and things to make networked connections more relevant and valuable. For example, according to Cisco, the number of M2M connections will grow from 780 million in 2016 to 3.3 billion by 2021, a 34 percent compound annual growth rate—a four-fold growth [1]. Keeping this in mind, radio-access technologies for mobile broadband have evolved effectively to provide connectivity to billions of subscribers and things [2]. Recently, as a part of Release 13, the 3rd Generation Partnership Project (3GPP) has specified a new radio interface to provide wide-area cellular connectivity for IoT. This system, named Narrowband Internet of Things (NB-IoT), uses a design similar to Long Term Evolution (LTE), and is a step towards the 5th generation (5G) evolution for providing



(a) In-band (b) Guard-band (c) Stand-alone

Figure 1.1: Three modes of operation of NB-IoT

low-power wide-area networking for IoT.

The main design objectives of NB-IoT are increased coverage and capacity, long battery life and low User Equipment (UE) device complexity. Techniques that help achieve these objectives include repetitions, power spectral density boosting, single-tone transmission, power saving mode, phase rotated modulations to reduce peak-to-average power ratio in the uplink, etc. NB-IoT supports three deployment modes as illustrated in Figure 1.1—(i) in-band, (ii) guard-band, and (iii) stand-alone. In in-band mode, NB-IoT works within the occupied bandwidth of a wideband LTE carrier, where one or more LTE Physical Resource Blocks (PRBs) are reserved for NB-IoT. In guard-band operation, NB-IoT is deployed within the guard-band of an LTE carrier. In standalone operation, NB-IoT can either be used as a replacement of one or more GSM carriers (200 kHz), or it can be operated in bands adjacent to LTE. In any case, NB-IoT has several similar functionalities as LTE, therefore, it can be supported using the same eNodeB hardware, particularly when operated in in-band mode.

Recently, several spectrum-sharing initiatives have been put in motion, and in some cases, regulations have been established with the aim of improving spectrum utilization efficiency through shared spectrum access [3]. Examples include spectrum sharing between multi-tiered secondary users (WiFi or LTE) and federal incumbents (ship-borne radars) in the 3.5 GHz band [4], unlicensed LTE and WiFi in the 5 GHz band [5], etc. Regarding the possible bands for NB-IoT deployment, the GSM Association—a trade body that represents the interests of mobile operators worldwide—predicts that NB-IoT will be deployed in any of the 2G/3G/4G spectrum (450 MHz to 3.5 GHz) because NB-IoT achieves excellent co-existence performance with legacy 2G/3G/4G systems [6]. Moreover, Qualcomm and others recently conducted a feasibility study for establishing a private LTE-based industrial IoT network in the 3.5 GHz band [7]. Based on these initiatives, it is not difficult to envision a future scenario where NB-IoT systems might co-exist with other technologies (e.g., with pulsed radars in the 3.5 GHz band).

NB-IoT co-existence might specially be a concern in the U.S. if they are to operate in Band 42 (3400 to 3600 MHz and Band 43 (3600 to 3800 MHz). If NB-IoT systems are deployed in these bands, they have to share the spectrum with incumbent radars. The Spectrum Access System (SAS) and Environmental Sensing Capacity (ESC)—which are the core enabling technologies for dynamic spectrum access in the 3.5 GHz band—specify that entrant technologies must tolerate a peak radar interference power upto -62 dBm (radar's peak EIRP = 122 dBm and the maximum path loss between ESC and the radar for which the ESC must detect the presence of radar = 184 dB) [8]. Therefore, all secondary users (including NB-IoT) of this band are subject to a peak radar interference of -62 dBm. This might deteriorate the performance of NB-IoT resulting in an increased block error rate (BLER), and hence, reduced coverage.

In this paper, we present an experiment-based feasibility study on the coexistence of NB-IoT with pulsed radars when NB-IoT uses the shared channel in the uplink. The study of NB-IoT uplink channel is important mainly because NB-IoT UEs are power constrained, and the coverage is determined based on the uplink performance. We use Virginia Tech's LTE-Cognitive Radio Network Testbed (CORNET) testbed and perform extensive experiments for investigating the effect of pulsed interference on the NB-IoT performance. Given a minimum required BLER threshold that is defined based on the battery-life requirement of NB-IoT UE, we show that the coverage of a NB-IoT cell is affected by the presence of radar interference.

The main contributions of this paper are outlined below:

- We perform an extensive experiment-based feasibility study on the coexistence of NB-IoT system with pulsed radars. To the best of our knowledge, this is the first coexistence study between NB-IoT and pulsed radars.

- Our results indicate that, in the presence of radar interference, NB-IoT devices that are located at the cell-edge will experience a shorter battery life because of increased retransmissions. Stated differently, in order to satisfy a predefined battery-life requirement, the NB-IoT cell coverage region should be reduced in the presence of radar interference.

The rest of the paper is organized as follows. In Section 2, we provide a brief overview of NB-IoT and pulsed radars. In Section 3, we describe our experimental setup followed by results in Section 4. In Section 5, we leverage our experimental results to demonstrate the effect of radar interference on the coverage and capacity of NB-IoT cells. Finally, we conclude our paper in Section 6.

Chapter 2

Preliminaries

2.1 NB-IoT

NB-IoT is a Low Power Wide Area Networking (LPWAN) technology standard defined in Release 13 of 3GPP [9]. As discussed in the previous section, IoT networks have the common design objectives of achieving extended coverage, low UE device complexity, long battery life, and support large capacity. To meet these objectives, NB-IoT has been highly optimized for machine type communications, providing features such as 20 dB additional maximum coupling loss (MCL) compared to LTE, more than 10 years device battery life and support for $>$ 50K devices in a cell [10]. Table 2.1 provides an overview of underlying PHY/MAC layer parameters which enable NB-IoT to achieve the following two main objectives.

Table 2.1: NB-IoT System Information

Parameter	Uplink	Downlink
Subcarrier Spacing	Single tone : 15KHz and 3.75KHz SC-FDMA : 15 KHz tone spacing	15KHz
Maximum transmit power	UE power class : 23dBm or 20 dBm	43dBm
Modulation Scheme	$\frac{\pi}{2}$-BPSK, $\frac{\pi}{4}$-QPSK	QPSK
Max. Transmit block size (TBS)	1000 bits	680 bits
Number of Repetitions	1 - 128	1- 2048
Maximum Coupling Loss	165.8dB (NPUSCH)	165.1dB (NPDSCH)

2.1.1 Coverage

To cater devices in deep indoor coverage (such as basements), NB-IoT requires a maximum coupling loss 20 dB (MCL of 164 dB) higher than LTE. This coverage enhancement is achieved using various PHY/MAC and higher layer modifications. One major, yet simple modification, is to increase the number of repetitions for transmissions on both downlink and uplink channels. For example, the narrowband physical downlink shared channel (NPDSCH) allows upto maximum of 2048 repetitions, and the narrowband physical uplink shared channel (NPUSCH) allows maximum 128 repetitions. These repeated transmissions are then soft-combined at the receiving terminals to achieve better Signal to Noise Ratio (SNR). Moreover, single-tone transmission in the uplink and $\frac{\pi}{2}$-BPSK modulation are used to maintain close to 0 dB peak to average power ratio (PAPR), thereby reducing the unrealized coverage potential due to power amplifier (PA) backoff [10]. Also, NB-IoT allows upto three coverage levels to be defined by a serving cell. Each coverage level is associated with a configuration that defines the number of repetitions to be used on each physical uplink/downlink channel. UEs choose one among the three coverage levels based on the received downlink signal power. Note that, for UEs in deep-coverage, higher bandwidth allocation is not spectrally efficient, as UEs cannot benefit from it to transmit at higher data rates.

2.1.2 Device Battery Life

One of the important design objectives for NB-IoT is to minimize device power consumption. NB-IoT uses efficient techniques such as power saving mode (PSM), Idle Mode extended discontinuous reception (I-eDRX) and Connected Mode eDRX (C-eDRX). These techniques allow the UE to be in lower power consumption states for longer duration of time. For example, PSM allows a device to be in unconnected state for 13 days and I-eDRX allows idle mode discontinuous reception for maximum of 3 hrs. The power consumption of PSM and eDRX modes is significantly lower than the power consumed during transmission. Using reasonable values of power consumption, it has been shown that NB-IoT achieves a device battery life of > 10 years when operated at a coupling loss of 154 dB with a two hour reporting interval for 50 bytes and 200 bytes application loads [11]. However, note that similar levels of battery life (> 10 years) cannot be achieved when the number of uplink repetitions is large or when the uplink BLER is high.

NB-IoT requires a minimum system bandwidth of 180 kHz (one Physical Resource Block) for both uplink and downlink, and supports three different deployment scenarios—stand-alone mode, in-band mode and guard-band mode (see Figure 1.1). In this paper, we analyze the co-existence of NB-IoT deployed in stand-alone mode with pulsed radar systems. Note that the NB-IoT system bandwidth (180 kHz) is very small compared to the nominal radar bandwidth (approx. 1.3 MHz) and the deployment mode of NB-IoT does not influence the coexistence analysis presented in this paper.

2.1.3 Pulsed Radars

The primary incumbent users of the U.S. 3.5 GHz band are the military ship-borne air traffic control radars. This type of radar is also known as AN/SPN-43C radar, and it provides real time aircraft surveillance, identification, and landing assistance data. SPN-43 is a pulsed radar which is used on medium and large aircraft carriers. It has a nominal peak pulsed power of 1 MW (90 dBm) and an antenna gain of 32 dBi [12]. SPN-43 has a range of 300 yards to 50 nautical miles and an altitude span of $30,000$ ft. Other characteristics of the SPN-43 radar are outlined in Table 2.2.

Table 2.2: Radar characteristics

Parameter	Value
Frequency range	$3500 - 3650$ MHz
Bandwidth	1.3 MHz
Pulse width	$900(\pm 150)$ ns
Pulse repetition rate	1 kHz
Radar rotation rate	4 sec (15 rpm)
Peak EIRP	122 dBm (1.6 GigaWatts)
Horizontal beamwidth	1.75 deg (19 pulses)

Chapter 3

Experimental Setup

In this section, we describe our experimental setup. Firstly, we provide a brief overview of the testbed that was used for our experiments. Secondly, we provide the block diagram of our system setup and outline the system parameters.

3.1 LTE-CORNET testbed

To perform the co-existence study between NB-IoT and radar, we leveraged the LTE-CORNET testbed at Virginia Tech [13]. The testbed's main components are several LTE base stations (eNodeBs) with their evolved packet cores (EPCs), and several LTE UEs. Multiple eNodeBs can be emulated using Amarisoft software-based LTE100 system which is installed on two PCs and a mobile workstation [14]. Another PC can be used to implement interference waveforms, among others. The testbed includes a high-fidelity spectrum analyzer, the Tektronix SA2500, for indoor and outdoor measurement studies over a frequency range of 10 kHz - 6.2 GHz. It is a mobile unit that can be connected to the testbed as needed.

The Amarisoft LTE100 software supports NB-IoT standard based on 3GPP Release 13. It allows us to configure various PHY and MAC layer parameters in the NB-IoT protocol stack. Some of the important parameters which can be configured based on the coverage level of operation are number of NPUSCH subcarriers (*npusch_n_sc*), number of NPUSCH repetitions (*npusch_n_rep*), uplink sub-carrier spacing (*ul_sc_spacing*), NPUSCH transmit block size (*npusch_i_tbs*), number of msg3 repetitions (*msg3_n_rep*), and number of msg3 sub-carriers (*msg3_n_sc*). Amarisoft also provides crucial PHY/MAC layer metrics which we use to analyze the impact of radar interference on the NB-IoT system. Specifically, we utilize the number of UL ACK/ NACK reported in the log files to compute the BLER. The uplink Signal to Interference and Noise Ratio (SINR) values are also collected from the logs. Uplink SINR is computed using the demodulation reference signals (DMRS) which are transmitted along with data symbols on the NPUSCH subframe.

3.1.1 Block Diagram and System Setup

Two high performance PCs running Amarisoft LTE100 eNodeB and LTE UE are connected to USRP N210s equipped with SBX daughter-boards,

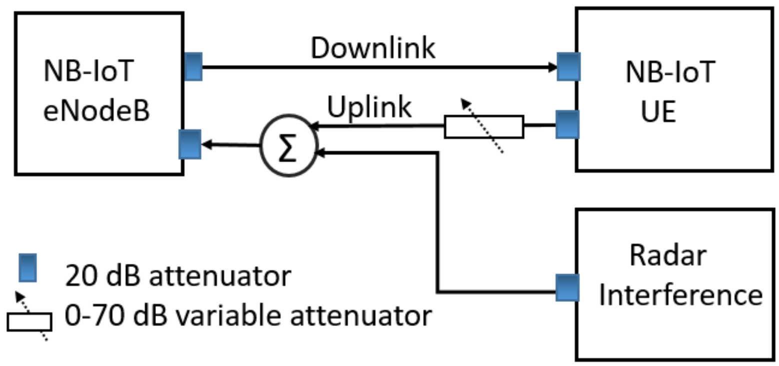
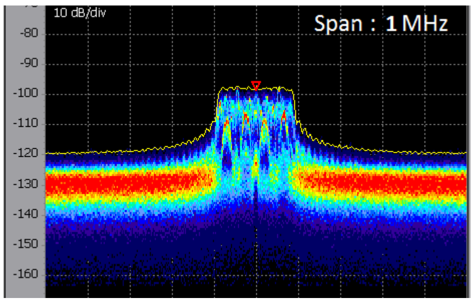
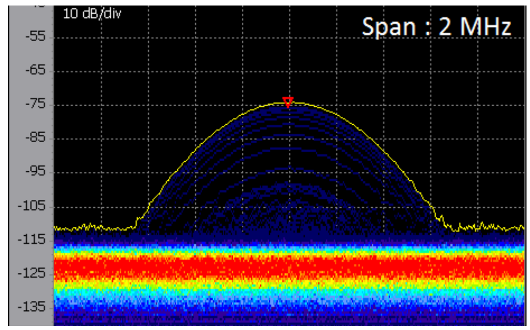


Figure 3.1: Block diagram of the experimental setup

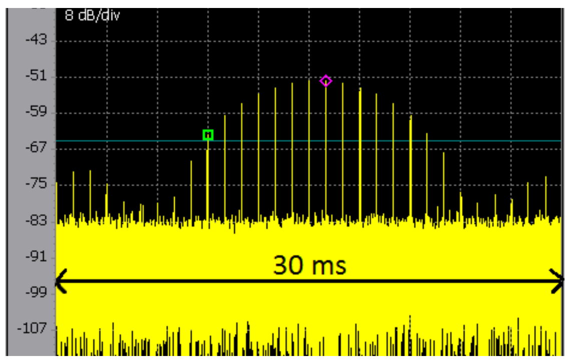
emulating a NB-IoT eNodeB and UE respectively. Amarisoft software allows NB-IoT cells to be operated in one of the possible three deployment modes. We configure the NB-IoT cell to operate in stand-alone mode (Figure 3.2(a) shows the spectrum of the uplink NB-IoT signal). Suitable values of *npusch_n_sc*, *npusch_n_rep* *npusch_i_tbs*, and *ul_sc_spacing* are used as outlined in Table 3.1. We used GNU Radio as the platform for transmitting the synthesized SPN-43 radar waveform via another USRP N210. The frequency and time domain characteristics of our synthesized radar waveform are shown in Figures 3.2(b) and 3.2(c) respectively. As we are primarily interested in the UL channels (note that as NB-IoT UEs are power limited, the NB-IoT coverage is mainly determined from the uplink performance), the radar interference is injected on the uplink channel only. Moreover, for analyzing the BLER of NB-IoT under different SINR (or SNR in case of no radar interference) conditions, we vary the value of the variable attenuator that is connected on the uplink path and note the uplink BLER at the eNodeB. Our system block diagram is shown in Figure 3.1.



(a) NB-IoT uplink spectrum



(b) Radar spectrum.



(c) Time domain plot of the radar.

Figure 3.2: Plots from the Tektronix spectrum analyzer used as a measurement device in our experiments.

Table 3.1: NB-IoT UL parameters

Operation Mode	Standalone
UL subcarrier spacing (*ul_sc_spacing*)	15 kHz
# of NPUSCH subcarrier (*npusch_n_sc*)	1
NPUSCH TBS (*npusch_i_tbs = 0*)	208 bits
# of NPUSCH repetitions (*npusch_n_rep*)	1

Chapter 4

Experimental Results

In this section, we summarize the results of our experiments. In particular, the plots of measured BLER versus measured uplink SINR and the distribution of measured uplink SINR are discussed.

4.1 Uplink BLER Performance

To study the uplink BLER performance of NB-IoT system, we maintained a fixed transmit power for the radar and varied the uplink SINR by varying the path loss (by using a variable attenuator) in the link connecting the NB-IoT UE and the eNodeB. Figure 4.1 shows the uplink BLER for different SINR received at the eNodeB. As expected, for high SINR values (SINR ≥ -1 dB), the BLER is almost zero, whereas when SINR is low (SINR < -5 dB), the BLER increases and reaches 100% for SINR less than -9 dB. In some cases, the NB-IoT system failed to establish a link at all because of the severity of the interference presented by the radar.

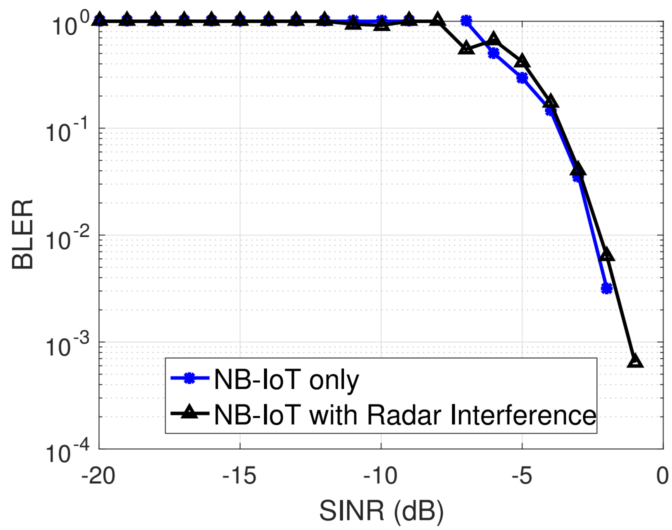


Figure 4.1: BLER versus SINR (Uplink).

Note that although the 3GPP Rel-13 specifications require a NB-IoT link to be alive for worst-case SINR values as low as -12 dB (corresponding to the required maximum coupling loss of 164 dB), we were not able to achieve this in our experiments mainly because the eNodeB hardware (USRP N210 with SBX daughterboard) used in our experiments has much lower output power and more limited receiver sensitivity than a typical eNodeB that is designed for over-the-air experiments. Also, in our experiments, we used nominal values for NB-IoT parameters (see Table 3.1) as opposed to the ones that are specified for the worst-case scenario (e.g., maximum number of repetitions, lowest TBS index, etc.). Nevertheless, our experimental results show a general trend that low SINR causes high BLER and vice-versa.

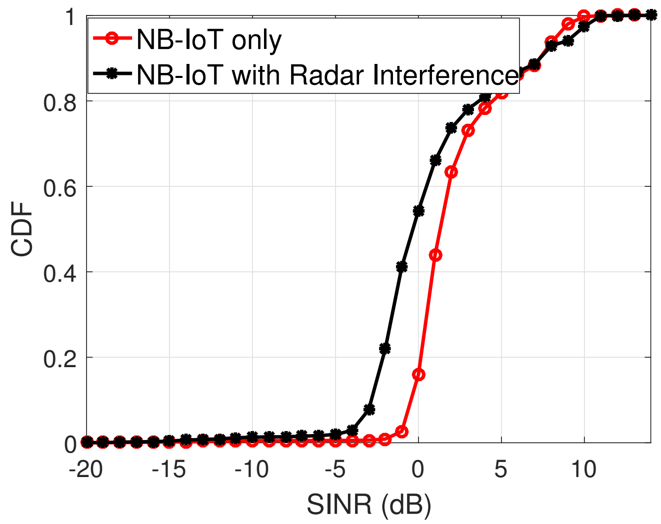


Figure 4.2: CDF of SINR.

4.2 Uplink SINR Distribution

The radar interference to NB-IoT eNodeB is non-stationary because: (i) due to radar rotation, the interference power varies periodically as a characteristic for search radars and it depends on the rotation speed of the radar, and (ii) the transmitted signals by radar consists of short pulses (see Figure 3.2 (c)) of very short duration (e.g., 1 microsec for SPN-43 radar). Therefore, even when the radar beam is directly aligned with NB-IoT eNodeB, there are inter-pulse durations with zero interference [15]. Any NB-IoT packet that gets transmitted in the time between radar pulses suffers no interference. Therefore, the SINR for each received packet depends on whether a radar pulse is present during the time in which the packet is transmitted.

Figure 4.2 shows the distribution of uplink SINR for the two cases: (i) without radar interference, and (ii) with radar interference. To generate these plots, we fixed the peak radar interference at -90dBm, and varied the uplink path loss by using a variable attenuator in the uplink path. The SINR at the eNodeB as reported by Amarisoft was logged continuously. In our experiments, the change in path loss emulates transmissions from UEs located at far-away distances (cell-edge) from the eNodeB. We changed the attenuation values such that the eNodeB receives uplink signal at an SINR level ranging from -20 dB to 15 dB.

For both cases, with and without radar interference, we changed the value of the attenuator in steps of 1 dB and logged the instantaneous SINR values at the eNodeB for over 2000 data packets. From the plots, we can observe that the radar interference causes the uplink SINR to drop when compared against the case without interference. However, because of the non-stationary nature of radar interference, the probability of low SINR values is not very large. This is intuitive because, as explained earlier, the pulsed and rotational nature of the radar leaves lots of interference-free (and hence, high SINR) time slots. In the next section, we analyze how the change in the distribution of NB-IoT uplink SINR due to radar interference, as shown in Figure 4.2, affects the NB-IoT coverage.

Chapter 5

Coverage and Capacity Analysis

Here, we provide a brief overview of the Irregular Terrain Model (ITM) and use it, along with results from our experiments, to study the coverage and capacity of NB-IoT in the absence/presence of radar interference.

5.1 Irregular Terrain Model (ITM)

The ITM is a radio propagation model which predicts tropospheric radio transmission loss over irregular terrain for a radio link [16]. It is designed for use at frequencies between 20 MHz and 20 GHz. The ITM model is based on electromagnetic theory and on statistical analyses of both terrain features and radio measurements, and it predicts the median attenuation of a radio signal as a function of distance and the variability of the signal in time and in space.

The ITM works in two modes: 1) area prediction mode—used when an exact terrain description is not available, and 2) point-to-point (PTP) prediction mode—used when terrain profile between the terminals is available. The ITM-PTP mode relates the statistical variance of terrain elevations to classical diffraction theory, and predictions made by the model agree closely with the measured data. Therefore, cellular operators often use ITM to predict their cell coverage. Using ITM, a coverage region of a base station can be defined as the zone where the path loss is less than a threshold, say P_{th}, with $x\%$ reliability. In other words, ITM defines the coverage region as the area around the base station where the probability of path loss from the base station being less than a threshold, P_{th}, is at least $x\%$. The parameter x can be specified in the ITM model according to the design requirement.

5.2 Coverage and Capacity Analysis

Let us assume that the battery-life requirement of NB-IoT UEs is such that the uplink BLER should not exceed a threshold, say B_{th}. This is because high BLER results in a large number of re-transmissions which, in turn, deteriorates the battery life performance of NB-IoT UEs. The one-to-one relation between uplink BLER and uplink SINR implies that the following requirement must be met: the uplink SINR should be greater than a threshold, say

S_{th}. Note that S_{th} can be obtained from Figure 4.1 for any given B_{th}.

Now, from the distribution of SINR obtained from our experiments (Figure 4.2), we can find the probability that SINR is greater than S_{th}. For the case with no interference, this probability is,

$$P(\text{SINR} > S_{\text{th}}) = 1 - p_n \tag{5.1}$$

where, p_n denotes the probability that SINR $\leq S_{th}$ when NB-IoT operates in the absence of radar interference.

Similarly, for the case with radar interference, the probability that SINR is greater than S_{th} is,

$$P(\text{SINR} > S_{\text{th}}) = 1 - p_r \tag{5.2}$$

where, p_r denotes the probability that SINR $\leq S_{th}$ when NB-IoT operates in the presence of radar interference.

From Figure 4.2, it is clear that $p_n \leq p_r$ in low SINR region.

The uplink SINR can be expressed in terms of UE transmit power P_{tx}; path loss between the UE and the eNodeB P_L; and interference and noise power P_{I+N} in the channel.

$$\text{SINR} = P_{tx} - P_L - P_{I+N} \tag{5.3}$$

When NB-IoT operates in an interference-free channel (e.g., when NB-

IoT operates in the licensed spectrum where interference from neighboring cells can be neglected), Equation 5.3 can be simplified as,

$$\text{SINR} = P_{tx} - P_L - P_N \tag{5.4}$$

where, P_N denotes the thermal noise in the channel.

Using Equations (5.3) and (5.4), we can rewrite Equations (5.1) and (5.2) in terms of path loss, respectively, as follows,

$$P(P_L \leq P_{th}^{(n)}) = 1 - p_n \tag{5.5}$$

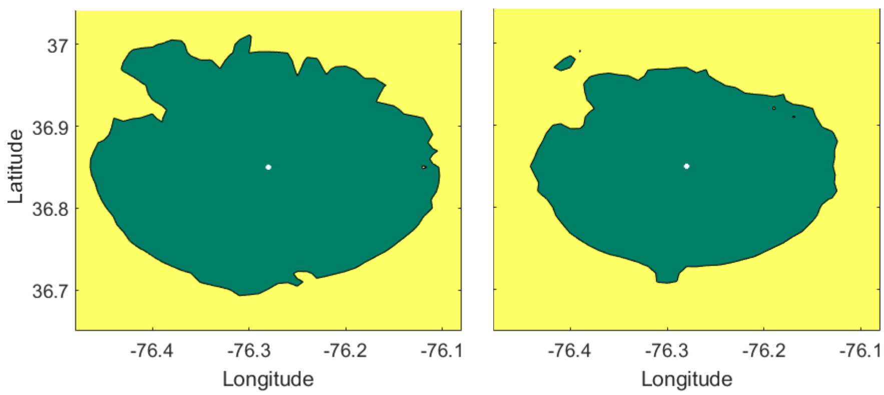
and,

$$P(P_L \leq P_{th}^{(r)}) = 1 - p_r \tag{5.6}$$

where, $P_{th}^{(n)} = P_{tx} - P_N - S_{th}$ and $P_{th}^{(r)} = P_{tx} - P_{I+N} - S_{th}$.

Finally, we can use Equations (5.5) and (5.6) to compute the coverage region of an NB-IoT cell. We define the coverage region as the zone where the path loss is less than $P_{th}^{(n)}$ (or $P_{th}^{(r)}$ in case of radar interference) with $1 - p_n$ (or $1 - p_r$ in case of radar interference) reliability. Using this definition in the ITM-PTP mode, we can compute the coverage region for both cases, where the right-hand sides of Equations (5.5) and (5.6) are specified as reliability levels.

Figures 5.1(a) and 5.1(b) show the coverage maps of NB-IoT cell (assumed to be located at Norfolk, Virginia) in the absence and presence of radar



(a) Without radar interference. (b) With radar interference.

Figure 5.1: Coverage area (shown in green) of NB-IoT eNodeB.

interference respectively. The coverage maps were generated for the following set of values: $P_N = -120$ dBm, $P_I = -116$ dBm, $P_{tx} = 23$ dBm, and $B_{th} = 10\%$. The value of S_{th} (-3 dB) corresponding to B_{th} was obtained from Figure 4.1 and used in the coverage analysis. We used ITM in PTP mode with reliability levels obtained from CDF curves of SINR (Figure 4.2) to compute the path loss around the eNodeB, which is located at the center of our analysis area. Note that, for accurately analyzing the NB-IoT cell coverage region, an additional path loss of 10 dB, on average, should be added to the path loss values computed by ITM-PTP in order to account for the losses caused due to indoor attenuation (ITM-PTP computes outdoor losses only). From the figures, it is clear that NB-IoT coverage area is smaller when radar interference is present.

We further study the change in NB-IoT coverage area (in square kilometers) for different levels of peak radar interference power, P_I, at the eNodeB.

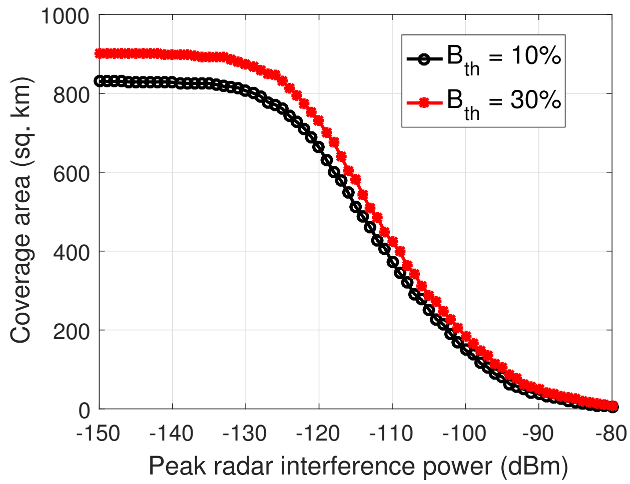


Figure 5.2: Effect of radar interference on NB-IoT coverage.

The value of P_I is varied from -150 dBm to -80 dBm and the coverage area of NB-IoT eNodeB is calculated. Figure 5.2 summarizes the results. Clearly, when the peak radar power is high, the NB-IoT uplink BLER (and SINR) deteriorates, resulting in smaller coverage area. Also, as expected, the coverage of NB-IoT eNodeB shrinks when the minimum required uplink BLER, B_{th}, is small (recall that small B_{th} ensures a longer batter life). Thus, our results show that we can compromise coverage for improving the battery life of NB-IoT UEs.

Furthermore, the capacity of an NB-IoT cell is directly proportional to its coverage area. Given a coverage area in sq. kms, A_{cov}, an average density of households per sq. km, ρ, and the average number of NB-IoT devices in each household, N_H, the total capacity, C_{NB-IoT}, is given as, $C_{NB-IoT} = A_{cov} \times \rho \times N_H$. This value, however, may not always be achievable when capacity is limited by the total available PHY/MAC-layer resources in the system.

Chapter 6

Conclusion

In this paper, we presented an extensive experiments-based feasibility study on the co-existence of NB-IoT with S-band radars when NB-IoT uses the shared channel in the uplink. We showed that, given a battery-life requirement of NB-IoT UEs in terms of the maximum tolerable BLER, the coverage of a NB-IoT system is affected by the presence of radar interference. Our analysis show that the NB-IoT system can co-exist with S-band radars; however, at the cost of increased block error rate (and hence, reduced battery-life performance) for users at the cell-edge.

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