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Link adaptation for Coverage Enhancement in NB-IoT

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Abstract-The cellular connectivity problems are rectified by the Narrowband Internet of Things (NB-IoT) and this NB-IoT introduced by the Third Generation Partnership Project (3GPP) under release-13 (R-13). The main application of the NB-IoT is to connect the massive number of IoT devices for both low complexity and low power devices. The main goal of the NB-IoT is to enhance the coverage when compared to traditional short-range communication devices such as Bluetooth, Wi-Fi, ZigBee, etc. To enhance the coverage in NB-IoT, we introduce three techniques namely, Resource Unit Alteration, Bandwidth Alteration, Repetitions Alteration by employing Signal to Noise ratio (SNR), Bandwidth Utilization (BWU), and Energy per transmitted bits (ETb) and also,studythe effect of Bandwidth, Repetitions, the transmission time for concerning Maximum Coupling Loss (MCL). Furthermore, we proposed to implement theuplink adaptation mechanism to enhance the coverage in the NB-IoT.

Keywords: NB-IoT, Coverage Enhancement Techniques, Transmission Time, MCL, Link adaptation Mechanism.

I. Introduction

An initial idea for the Internet of Things (IoT) is introduced by Kevin Ashton in 1999 [1]. The main goal of the IoT is to connect various things (sensors, actuators, extenders, etc.) by using the internet. At the end of the year 2020, 20 billion IoT devices will be connected with the exchange data rate of around 40 Zettabytes [2]. Worldwide, the application of IoT technologies and devices are personal, commercial, logistics, smart cities, smart homes, smart agriculture, etc. In the current IoT world, there will be a lot of technical issues due to lack of infrastructure, data rate, latency, coverage, energy consumption because, in many years, the sender conveys information to the receiver via the cloud by using traditionalshort-range communication devices such as Bluetooth, Wi-Fi, and ZigBee, etc.

To avoid the above drawbacks, we use Low Power Wide Area Networks (LPWANs). The LPWANs are used to transfer the information with low power over a long distance. The LPWANs are divided into two types namely, infrastructure-less LPWANs and infrastructure LPWANs respectively. The infrastructure-lessLPWANs are LoRa (Long Range), SigFoX, and Random Phase [3] Multiple Access (RPMA) and the infrastructure LPWANs are Long Term Evaluation-M (LTE-M), Narrow Band-Internet of Things (NB-IoT), andExtended Coverage-GSM-Internet of Things (EC-GSM-IoT). The infrastructure-less LPWANs are not secured one so anyone can access this network without permission from the service provider but in the case of infrastructure, LPWANs are a secured network so we need permission from the service provider to access the networks.

Among infrastructure-less LPWANs,Sigfox is an Ultra Narrow Band RF transmission network and it offers extreme coverage with low energy consumption and low data rate and also, it is not suitable for downlink reception. Sigfox is one of the proprietary networks and it is only applicable for use cases. SigFox communication modules are applicable for low bandwidth. The application of the Sigfox modules is location monitoring, smart metering, basic alarm systems, etc [4].

LoRais an unlicensed version of the LPWANs. In Europe, the operating frequency of the LoRais 169 MHz, 433 MHz, 868 MHz,and 915 MHz in the case of North America [5]. The LoRa network contains two parts such as physical layer protocol, Long Range Wide Area Network (LoRaWAN) and LoRaWAN is one of the top Medium Access Control (MAC) layers [6]. LoRaWAN is used to communicate between LPWAN gateways and User Equipment using routing protocol and it is operated by the LoRa alliance. LoRaWAN is a new Wi-Fi wireless communication device is used to communicate between various IoT devices by employing various platforms [7]. The application of the LoRais deep mining, logistics, renewable energy, industrial, smart agriculture, smart cities, etc. [8].

The NB-IoT is one of the benchmarking networks and is a licensed LPWANs. It is released by the Third Generation Partnership Party (3GPP) under Release-13 (R-13). It is one of the novel radio frequencies

(RF) cellular IoT network technology [6]. The NB-IoT provides more coverage for low throughput devices and also, it provides low energy consumption, low latency, low device cost and the lifetime of the battery is very high because it consumes low energy.

Andres-Maldonado et al. [11], devised expressions after analysis for the minimumSNRreq, BWU, and ETb based on the factors influencing them (i.e., number of RU, bandwidth, and repetitions) in NB-IoT. Thereafter, the paper discusses an adjustment algorithm that uses different approaches for transmission. Changsheng et al [12] introduced two link adaptation algorithms namely, inner loop and outer loop link adaptation. An inner loop link adaptation is designed to adjust the number of repetitions to guarantee the Block Error Rate (BLER) for enhancing coverage in NB-IoT and an outer loop link adaptation used to guarantee the BLER by adjusting the Modulation and Coding Scheme (MCS). MarwaChafii et al. [13], proposed a solution for enhancing coverage based on machine learning algorithms that also helps reduce power consumption instead of using a random procedure method.

The main aim of the article to enhance the coverage in NB-IoT by using three techniques namely, [9] RU Alteration, Bandwidth Modification, and vary the number of repetitions in terms of SNRreq,BWU, andETb and, also study the effect of BW, the number of repetitions, the transmission timeconcerning Maximum Coupling Loss (MCL). Furthermore, we proposed to implement link adaptation algorithms for enhancing the coverage in NB-IoT systems.

The organization of the article includes, the background of the NB-IoT in section 2, system considerations will see in section 3, the system analysis in section 4, link adaptation algorithm of the system in section 5, results, and its discussion in section 6, and lastly, conclude the article in section 7.

II BACKGROUND

The NB-IoT works in the LTE band with an occupying Bandwidth (BW) of 180 kHz. It offers three deployment flexibility modes [6] such as Stand-alone, in-band, and Guard band and also, supports Half Duplex-Frequency Division Duplex (HD-FDD). In downlink NB-IoT reception, Orthogonal Frequency Division Multiple Access (OFDMA) is used with 3.75 kHz Sub Carrier Spacing (SCS) similarlySingle Carrier Frequency Division Multiple Access (SC-FDMA) used in uplink transmission and its SCS is 15 kHz or 3.75 kHz under single tone [9]. In uplink transmission, the NB-IoT uses both single tone and multi-tone configurations. Specifically, 12 tones, 6 tones, or 3 tones are used in the uplink. The above tones are deployed in 15 kHz SCS[14].

III SYSTEM CONSIDERATIONS

NB-IoT can either coexist with GSM or LTE licensed bands, considering the NB-IoT band to be employed alongside the LTE band. The User Equipment (UE) requires to transmit a block of data with ‘b’ bits over a noisy channel with path loss ‘L’. As path loss is the most significant among other losses, [10] we take maximum coupling loss (MCL) to be equal to L, i.e., MCL = L. The receiver is an eNodeB (E-UTRAN Node B or Evolved Node B) which is a unit similar in functionality to a base transceiver station (BTS) in GSM networks. For the UE to transmit data successfully, it is required to follow some specifications set by eNodeB namely: allocated bandwidth (BW), number of Resource Units (nRUs), and number of Repetitions(nR). Each value of the nRUs, a defined Modulation, and the Coding Scheme (MCS) level is present which possesses the information about the modulation scheme to be used. The modulation scheme to be used can be BPSK, QPSK, 16 bit-QAM, or 64 bit-QAM, as shows in Figure 1.

Figure 1. System Model

When the UE receives the set of values for the above four factors, the rate of transmission of bits can be formulated as,

$$R_b = \frac{b + CRC}{nRU.\, T(nRU)} \qquad (1)$$

R_b denotes the data rate of transmission, CRC represents the number of bits used for Cyclic Redundancy Check to detect the error at the receiver side (eNodeB), nRU is the number of Resource Units to be sent in a single transmission, T(nRU) is the time duration of each RU and b is the Transport Block Size[14] (TBS).NB-IoT deploys a multiplexing scheme known asSC-FDMA during uplink transmission which is a simplified version of OFDMAsending each data symbol at a time instead of parallel transmission. Hence, we can transfer multi-tone signals over the allocated bandwidth.From the above statement, we incur that as the number of tones increases, the value of T(nRU) decreases, and when tones are less, T(nRU) increases, thereby making it a factor dependent on bandwidth.

The number of signal bits allowed to be transmitted in one single transmission is determined by the Transport Block Size (TBS) table [14] as shown in Table 1. For single transmission, the TBS table decides to allow the maximum bits during transmission. This value is determined by the MCS level or the modulation scheme being used along with the number of resource units we wish to transfer.

Table 1. Transport Block Size Table

MCS	**Number of RU**							
	1	2	3	4	5	6	8	10
0	16	32	56	88	120	152	208	256
1	24	56	88	144	176	208	256	344
2	32	72	144	176	208	256	328	424
3	40	104	176	208	256	328	440	568
4	56	120	208	256	328	408	552	680
5	72	144	224	328	424	504	680	872
6	88	176	256	392	504	600	808	1000
7	104	224	328	472	584	712	1000	1224
8	120	256	392	536	680	808	1096	1384
9	136	296	456	616	776	936	1256	1544

IV SYSTEM ANALYSIS

To measure the efficiency of particular uplink transmission, we require some parameters depending upon the factors discussed in the previous section to draw a comparison when those values are varied. Also, the analysis being done should concur with Shannon's Theorem. Signal to Noise Ratio (SNRreq) for successfully decoding the data. The SNRreq can be calculated by picking up the value of each factor, i.e. MCS, RU, R, Bandwidth.We first analyse the effect of the number of repetitions on SNR considering an ideal channel,

Under Shannon's Theorem, SNR for a single transmission can be given as,

$$SNR_{eff} = \sum^{R} SNR_{req} = nR.\, SNR_{req}$$

$$\therefore SNR_{req} = \frac{SNR_{eff}}{nR}$$

$$SNR_{eff} = 2^{R_b\,(nRU,BWmax,1)/BWmax} - 1$$

For nR repetitions,

$$SNR_{req}\,(nRU, BW, nR) = \frac{2^{Rb\,(nRU,BWmax,nR)/BWmax} - 1}{nR}$$

$$= \frac{2^{\frac{b+mCRC}{BWmax\,.\,nRU\,.\,T(nRU)}} - 1}{nR} \qquad (2)$$

Following the required SNR derivation, the equation for the second parameter, i.e. Bandwidth Utilization (BWU) can be formulated as,

$$\mathrm{BWU(nRU, BWmax, nR)} = \frac{R_b\,\mathrm{(nRU, BWmax, nR)}}{\mathrm{nR\,.\,BWmax}} = \frac{\mathrm{b+mCRC}}{\mathrm{nR\,.\,BWmax\,.\,nRU\,.\,T(nRU)}} \quad (3)$$

ETb which is our third parameter for evaluation of the transmission can be calculated if we know that,

$$\frac{E_b}{N_0} = \frac{SNR_{req}}{BWU}$$

$$\mathrm{ETb(nRU, BWmax, nR)} = \frac{E_b}{N_0}\mathrm{(nRU, BWmax, nR)\,.\,MCL\,.\,RNF\,.\,TND} = \frac{2^{\frac{\mathrm{b+mCRC}}{\mathrm{BWmax\,.\,nRU\,.\,T(nRU)}}}-1}{\frac{\mathrm{b+mCRC}}{\mathrm{BWmax\,.\,nRU\,.\,T(nRU)}}}\mathrm{.\,MCL\,.\,RNF.\,TND} \quad (4)$$

In Resource Unit alteration in the uplink transmission, consider the bandwidth (BW_{max}) as 15 kHz and the repetition (nR) as 1 and vary the number of RUs. Similarly, let us consider the bandwidth reduction in the uplink, in this case, we fix the nRU and nR as 1 and change the bandwidth. Here, bandwidth is the product of Sub Carrier Spacing (SCS) and the number of tones (BW=SCS*Nt). We use either 15kHz or 3.75 kHz SCS in the uplink. Lastly, we consider the impact of the number of repetitions. The received signal combined with the eNodeB when applying repetitions. Here, we consider the number of resource units as 1 and BW_{max} as 15 kHz. Hence, the RU alteration, BW reduction, and repetition alteration techniques are applied in equation (2), (3), and (4). From the equations (2), (3), and (4), we observe that, if nRUis enhanced then the remaining of theparameters SNRreq, BWU, and ETb are decreased. Similarly, in the case of bandwidth reduction techniques, the resource unit duration T(nRU) is equal to the reduction in the bandwidth when applying multi-tone configurations. Hence, the NB-IoT User Equipment retains a multi-tone. Finally, the consumption of power is reduced when applying the bandwidth reduction technique. In repetition analysis, we observe that the energy per transmitted bit remains unaffected by the number of repetitions, however, it is also evident from the above equations that an increase in the repetitions not only decreases the required SNR value but also reduces the bandwidth utilization, therefore R should be chosen such that a trade-off is achieved between the two.

Furthermore, for plotting the number of tones possible for transmission as a function of the Maximum Coupling Loss (MCL) [15] is expressed as,

$$\mathrm{MCL = Tx.\,Power - RNF - TND} - SNR_{req} - 10\log_{10}\mathrm{(BWmax)} \quad (5)$$

The power transmitted (Tx.Power) for an uplink signal cannot exceed 23dB.The receiver noise figure (RNF) for uplink transmission is around 3dB, which will help us evaluate the required SNR (SNR_{req}) value subsequently helping us calculate the number of tones and repetitions required. The TND represents the thermal noise density and its value around -174 dBm/Hz and the value of the Bandwidth (BW_{max}) is 15000 Hz in uplink transmission.

TheBW, repetitions (R), and Tx. Time is derived from equation (2) and these equations are expressed as

$$\mathrm{BW} = \frac{\mathrm{B + mCRC}}{\mathrm{nRU.\,T}(nRU)\mathrm{.}\log_2\left(\mathrm{nR.\,10}^{\frac{\mathrm{SNR\ req}}{10}} + 1\right)} \quad (6)$$

$$\mathrm{R} = \left(2^{\frac{\mathrm{B+mCRC}}{\mathrm{BWmax\,.nRU\,.T(nRU)}}}-1\right).\left(10^{\frac{-\mathrm{SNR\ req}}{10}}\right) \quad (7)$$

$$\mathrm{Tx.\,Time} = \frac{\mathrm{B + mCRC}}{\mathrm{BWmax.\,nRU}\log_2\left(\mathrm{nR.\,10}^{\frac{\mathrm{SNRreq}}{10}} + 1\right)} \quad (8)$$

In equations (6), (7), and (8). BW_{max} is Maximum Bandwidth, B is Packet Size, mCRC is the Maximum number of Cyclic Redundancy CheckCodeto detect the error at the receiver side and its value is 24, nRU is the number of Resource Unit as 1, T(nRU) is the duration of RU as 1ms for one RU, nR is the number of repetitions as 128 in uplink transmission and $SNR_{req}$is the required SNR values from equation (2) and BW_{max} value is 15000 Hz in equation (7) and (8).

V LINK ADAPTATION ALGORITHM

Using the previous section, calculate the SNRreq using equation (2) for each value of Transport Block Size shown in Table 1 and these values are compared with the input SNR and the number of b (bits) and the TBS values and SNRreq values are greater than input SNR and b then store the SNR values to the SNRreq array and also store the IMCS, IRU, Ri, C to their array. From the SNRreq array, select the minimum SNRreq based on the optimum value of the IMCS, IRU, Ri, and C. By using the minimum SNRreq value, evaluate the transmission time using equation (8) with different packet size.Table 2 gives a brief about the values of the NB-IoT standard used for our evaluation [11].

Table 2. Standard values of parameters used in NB-IoT uplink transmission

Parameter	Value(s)	Description
MCL	164	Maximum Coupling Loss (dB)
RNF	3	Receiver Noise Figure(dB)
TND	-174	Thermal Noise Density (dBm/Hz)
C	[15,30,90,180]	Current Bandwidth (kHz)
mCRC	24	Max. Cyclic Redundancy Check in bits
nRU	[1,2,3,4,5,6,8,10]	Number of Resource Units
nR	[1,2,4,8,16,32,128]	Number of repetitions
T(nRU)	[1, 2, 4, 8, 32]	Duration of RUs (ms)

The UE uplink transmission is then adapted based on the values received from eNB that are in turn obtained by our link adaptation algorithm.

Algorithm:

Inputs: Minimum required SNR in dB (SNRin), number of bits to be transmitted (b).
Output: Optimum Point (IMCS, IRU, Ri, C)

```
1. Initialize IMCS – index of MCS value
2. Initialize IRU – index of the number of RUs
3. Initialize Ri – index of the number of repetitions
4. Initialize C – current bandwidth
5. Initialize TBS table
6. for i in values (C):
 for j in values (Ri):
for k in values (IMCS):
   for l in values (IRU):
    calculate SNRreq
    if TBS [IMCS, IRU] >= b and SNRreq>= SNRin:
     add SNR value to SNR_req array
     add values of C, Ri, IMCS, IRU to Points array
    else:
     continue
7. Obtain the minimum value of SNR from the SNR_req array
8. Evaluate the transmission time for the corresponding minimum value of SNR
Return the corresponding values of MCS, RU, R, and C
```

In User Equipment of NB-IoT, the link adaptation mechanism shows the impact of the coverage in terms of the Maximum Coupling Loss (MCL) shown in Figure 5. In this mechanism, the UE coverage is struggling at larger packet size then the transmission time increases between eNodeB and UE similarly the UE coverage is enhanced when in small packet size. Hence, the transmission time between eNodeB and UE is decreased. Therefore, the MCL for the small packet size is less than the larger packet size in this link adaptation mechanism.

VI RESULT AND DISCUSSION

The earlier sections discuss based on the Shannon theorem relating the uplink transmission evaluation parameters, i.e., SNRreq, BWU, andETb, to the variable factors namely RU number, MCS, andrepetitions. To get a deeper insight into these expressions, we visualize the equations as graphical plots which makes it easier for us to conclude the transmission characteristics.

Figures 2, 3, 4, and 5 are analysed the transmission properties such as SNRreq, BWU, and ETbconcerning Transport Block Size (TBS) in bits. Theanalysed transmission methods show that the comparison of RUs alteration with the number of tones. From the analysis, if the number of RUs is enhanced, then the energy per transmitted bit (ETb) is reduced for a given Transport Block Size (TBS) similarly in the case of SNRreq if the number of RUs is increased then the required SNR values are decreased and also if the number of tones is increased, then the SNRreq values are decreased. In BWU, the number of RUs and tones is increased then the BWU is decreasedwhich means we can increase the spectral efficiency under the small number of tones.

Figure 6 and 7 shows that the impact ofBW and the number of repetitions concerning on the Maximum Coupling Loss (MCL). For Packet size (B) 16,the coverage between BS and the eNodeB is enhanced, then the MCL is decreased which results in latency is less. Likewise, the coverage between BS and UEs is less in the case of 32packet size (B)which results in higher MCL and latency. From the analysis, we can get the worst coverage when used larger B values at lower MCLs than the small B values.

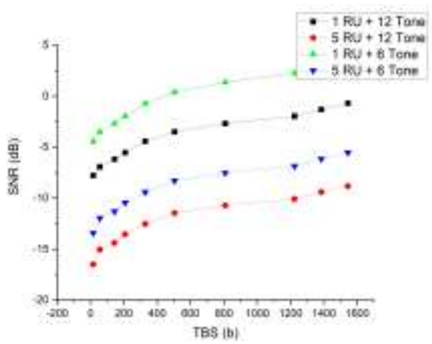


Figure 2. Required SNRconcerningTBS

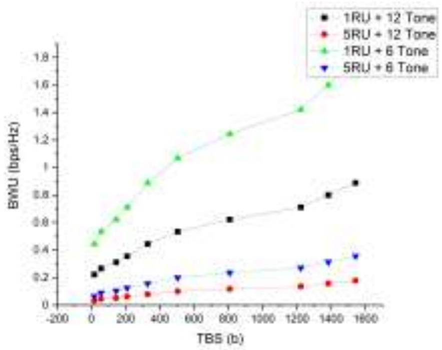
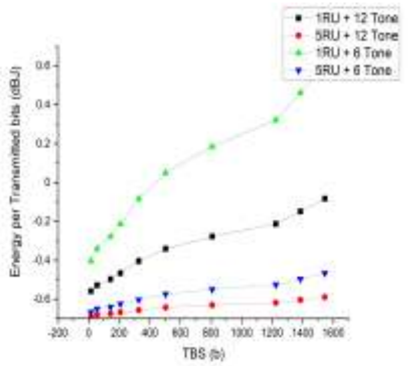


Figure 3. Bandwidth Utilization for the TBS



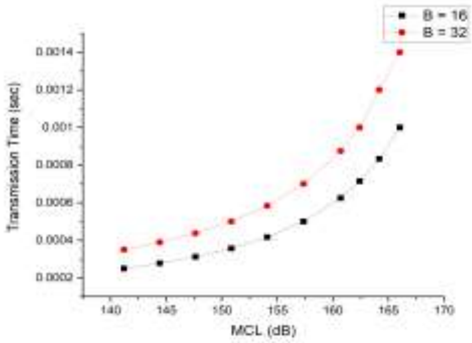
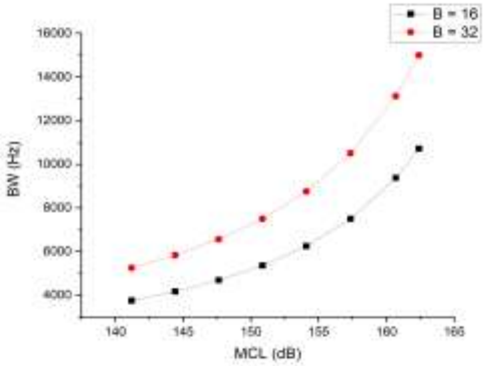


Figure 4. Energy per transmitted bit concerning TBSFigure 5. Transmission Time as the function of the MCL



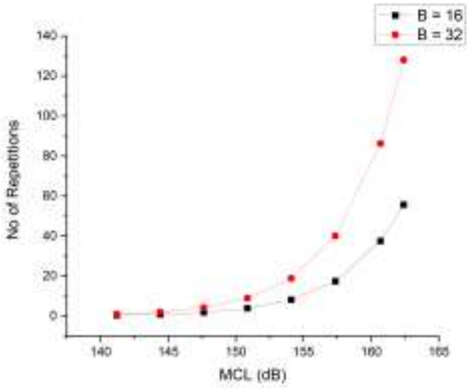


Figure 6. BW is a function of MCLFigure 7. Required Repetitions as a function of MCL

VII Conclusion

In this article, we studied LPWANs for both unlicensed and licensed and also, discussed the background of the NB-IoT in detail. The coverage analysis was analysedunderthe Shannon theorem. This coverage is enhanced by the techniques such as Resource Unit alteration, Bandwidth reduction, and repetitions by employing SNRreq, BWU, andETb and also analysed the impact of BW, transmission time, and repetitions on the MCL. Furthermore, we search minimum required SNR based on the optimum value of MCS index, Resource Unit index, repetition index, and current bandwidth (C) and evaluated the transmission time for the corresponding minimum SNR that enhances the coverage in NB-IoT using link adaption mechanism.

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