ANALYSIS OF RANDOM ACCESS IN NARROW-BAND INTERNET OF THINGS

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **Analysis of Random access in Narrow-band Internet of Things**, submitted by **Chaturasan Ramineni**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology (Dual Degree)**, is a bona fide record of the project work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: NB-IoT, Random Access, Throughput ,Random access Delay

Internet of Things (IoT) is a set of technologies enabling connectivity of devices. Low power wide area network (LPWAN) is one of those technologies. 3GPP introduced a new standard called Narrow Band Internet of Things (NB-IoT) for LPWAN. In NB-IoT, due to coverage enhancement levels (CE levels) throughput analysis of random access is different from analysis in other OFDMA technologies. This thesis presents an analytical model to estimate throughput of NB-IoT based on Markov chain analysis for User Equipments (UEs) by considering the CE level, preamble transmission attempt and size of back-off window as state variables under steady state conditions. Markov chains are modelled as per the UE initial random access CE level. This model is verified by simulations for different set of parameters. For controlling the random access channel overload, 3GPP introduced two access barring mechanisms access class barring (ACB) and extended access barring (EAB). In NB-IoT only extended access barring mechanism is adapted. In this thesis we also show that broadcasting access barring factor and barring time in system information block-2 (SIB-2) improves random access success probability to traditional back-off method through simulations under transient conditions.

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ABBREVIATIONS

IoT	Internet of Things
NB-IoT	Narrow-band Internet of Things
3GPP	3rd Generation Partnership Project
UE	User Equipment
CE level	Coverage Enhancement level
NPRACH	Narrow-band Physical Random Access Channel
RSRP	Measured Reference Signal received Power
MIB	Master Information Block
SIB-2	System Information Block-2
ACB	Access Class Barring
EAB	Extended Class Barring

CHAPTER 1

INTRODUCTION

Internet of Things (IoT) is the network of the physical objects that are capable of connecting to each other and exchange data. Over the years the number of IoT devices have been increasing at a dramatic pace in various fields. In terms of range, IoT is divided into short-range and wide area networks [1]. Short-range IoT is enabled by technologies such as Z-wave, Bluetooth, ZigBee and Wi-Fi which are all unlicensed radio technologies. While wide-area IoT is enabled by cellular technologies [2] as well as by unlicensed radio technologies like SigFox, LoRa. Wide-Area IoT network is further divided based on applications requirements into massive and critical segments IoT [3]. Critical IoT addresses applications which require high reliability and low latency, such as Intelligent Transportation System [4]. Massive IoT refers to low-cost and latency tolerant devices that consumes less power, have low data rates and requires ubiquitous connectivity e.g. Environment sensors [5].

Narrow-Band Internet of Things (NB-IoT) [6] is Massive IoT technology proposed by 3rd Generation Partnership Project (3GPP) in release 13 for Low Power Wide Area Network (LPWAN) [5]. NB-IoT is ideal for low-throughput, delay-tolerant, wide coverage use cases with low mobility support [7], such as smart meters, remote sensors, smart parking, smart buildings etc. By 2020 NB-IoT will be dominant LPWAN technology due to global cellular connectivity compared to non-3GPP technologies like SigFox and LoRa [8]. Due to massive number of devices, random access procedure of NB-IoT plays a crucial role in determining its performance.

1.1 Aim of the Project

Aim of this work is divided into two parts. 1) Modeling and analyzing the throughput of random access procedure of NB-IoT under steady state conditions. 2) Showing the necessity of Access Class Barring in NB-IoT.

1.2 Contribution of the Thesis

1.2.1 Part I

In NB-IoT coverage area is divided into 3 coverage enhancement levels (CE levels) those are normal coverage, extended coverage and extreme coverage. The User Equipments (UEs) in lower CE levels can access network and transfer data in higher CE levels [9]. Due to this, previous works modeling throughput in other Orthogonal Frequency Division Multiple Access (OFDMA) systems cannot be used in NB-IoT case so this work contributes modeling and analysis of throughput for UEs according to their initial CE level.

1.2.2 Part II

3GPP adopted Access Barring mechanisms, Access class barring (ACB) and Extended access barring (EAB) in LTE/LTE-A but considers only EAB [10] in NB-IoT. This work explains the necessity of ACB in NB-IoT through simulations under transient conditions.

1.3 Organization of thesis

Rest of the thesis is as follows.

1. In Chapter 2, brief background of NB-IoT architecture, random access procedure and previous works on throughput modeling in NB-IoT and OFDMA systems are presented.
2. In chapter 3, analytical model for random access in NB-IoT is presented and the formulas required for throughput calculation are derived.
3. In chapter 4, the analytical model is validated with the help of simulations and the limitations of the model are presented.
4. In chapter 5, access barring mechanisms are explained and the improvement of performance of random access by inclusion of ACB is presented.
5. Finally in chapter 6, thesis is concluded discussing the possible future works.

CHAPTER 2

BACKGROUND AND LITERATURE SURVEY

NB-IoT is introduced by 3GPP in release 13 for LPWAN aiming massive connectivity along with enhanced coverage.3GPP has defined three coverage enhancement (CE) levels, CE levels 0, 1 and 2, based on the coverage conditions such as range and path loss experienced by different UEs. CE level 0, 1 and 2 corresponds to the normal coverage, the robust coverage and the extreme coverage in each cell [11]. User Equipments (UEs) determine their CE level based on the measured reference signal received power (RSRP) thresholds. UEs in the lowest CE level have the highest RSRP while UEs in the highest CE level have the lowest RSRP. Radio signal information and data are repeated several times based on the CE level for better reliability at eNB. [11].

2.1 Random Access Procedure

The Random Access Procedure in NB-IoT is similar to that of in LTE however with a different sets of parameters for each CE level. NB-IoT follows contention-based random access. The UE performs random access procedure during initial access of network wherein it acquires the uplink resources for data transmission. Initially when a UE powers-on or turns-on from sleep mode, it synchronizes with the downlink by decoding the primary and secondary synchronization signals. Then UE decodes the master information block (MIB) and determines the periodicity and timing details of system information blocks (SIB). After acquiring SIBs UE begins the random access procedure. Random access in NB-IoT consists of four steps

2.1.1 Random Access Preamble Transmission (step 1)

System information block-2 (SIB-2) which is periodically broadcasted in downlink carries RSRP thresholds and narrow band physical random access channel (NPRACH) configuration information. NPRACH is the uplink channel which is used for preamble transmission. In frequency domain, the uplink bandwidth of 180KHz is divided into 48 sub-carrier of 3.75 KHz. In NPRACH those 48 sub-carriers are further divided into 4 groups of 12 sub-carriers each since the hoping pattern spans over 12 sub-carriers. Each CE level should have a minimum of 12 sub-carriers. Therefore the possible combinations of different sub-carriers in different CE levels are {12,12,12} or {12,12,24} or {12,24,12} or {24,12,12} .

After the determination of CE level and parameters of NPRACH, the UE takes the first step in random access procedure as follows. UE transmits a preamble in NPRACH by randomly selecting a sub-carrier from the set of sub-carriers allocated to its CE level. A preamble consists of four symbol groups which are repeated according to the number of repetitions defined for the CE level. Each preamble group consists of one cyclic prefix plus five symbols. The four symbols groups are transmitted over four sub-carriers with hoping pattern over the 12 sub-carriers. The hopping pattern is for estimating timing of arrival (ToA) at eNB [12].

2.1.2 Random Access Response (step 2)

Up on receiving the preamble sequence, eNB replies with Random Access response (RAR) containing the Random Access preamble Identifier, the timing advance, a temporary cell radio network identity (TC-RNTI) and some scheduling messages.The UE maintains a counter to keep of the number of preamble attempts. UE expects the RAR with in expiration of RAR timer, which is started immediately after transmitting the preamble. If the timer expires with no response received then the preamble attempt counter is incremented by one and UE re-transmits the preamble after waiting for the back-off time. Back-off time is decided from the SIB-2 parameters by uniformly selecting a random value ranging from zero to the back-off window value broadcasted in SIB-2. UE continues to re-transmit the preamble until the preamble attempt counter reaches the maximum value or the RAR is successfully received.

Due to multiple CE levels, NB-IoT adapted a new counter along with original preamble attempt counter, introduced in Release 13. The new counter counts the number of preamble attempts in the current CE level. If the new counter reaches maximum number of attempts in the current CE level before the original preamble attempt counter reaches its maximum value then the new counter resets to zero and UE switches to next higher CE level and starts transmitting preamble in that CE level. This process continues until original counter reaches the maximum value or the random access is successful.

2.1.3 Scheduled Transmission (step 3)

In step 3 the UE requests for the RRC connection by transmitting TC-RNTI through the resources allocated in uplink by eNB during RAR. In case of data transmission, some medium access control (MAC) layer information is sent along with TC-RNTI. The MAC layer information is used for knowing the size of data packet and for allocating uplink resources for data transmission. In case two or more UEs select the same initial sub-carrier during preamble transmission then those UEs will receive the same TC-RNTI. As a result those UEs will transmit the TC-RNTI through the same resources allocated during random access response. This leads to a collision and the collided UEs need to re-transmit the preamble again after waiting for the back-off time period.

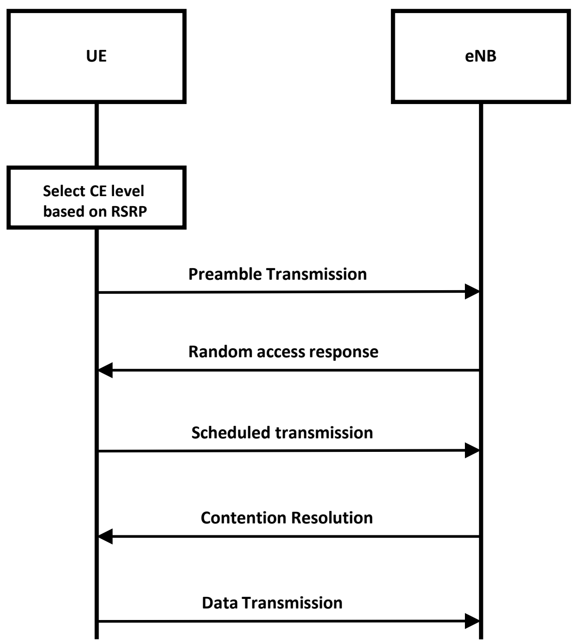

Figure 2.1: Random access procedure and data transmission

2.1.4 Contention Resolution (step 4)

In the final step, eNB responds with decoded TC-RNTI. If UE receives the decoded TC-RNTI before the contention resolution timer expires, then the random access is successful and data transmission is started. Else if no response is received from eNB, UE waits for back-off time and re-transmits the preamble until the maximum attempts are reached. This concludes the random access procedure.

2.1.5 Related Work

We now briefly survey the literature on the performance analysis of the random access procedure in LTE and NB-IoT. Random access procedure in LTE is generally modelled as multi-channel slotted ALOHA since preambles act as virtual channels in each time slot. Throughput [13],[14] and mean delay[15] have been studied quite extensively in multi-channel slotted ALOHA. However analytical results of multi-channel slotted ALOHA cannot directly be applied to NB-IoT random access due to the presence of multiple CE levels. So R.u Harwahyu [16] modelled the random access procedure in NB-IoT as multi-band multi-channed slotted ALOHA and optimized the parameters for better access probability under transient conditions [17]. Y. Sun [18] analyzed the throughput of random access in NB-IoT by considering a queue model for UE's buffer. They combined the back-off mechanism and FIFO queue based on Markov chain, through which system throughput is modeled and analyzed. Y.Zhao [19] proposed a classification back-off method for capacity optimization in NB-IoT through simulation. F.Chiti [20] derived the mean access rate per CE level of NB-IoT based on Markov chain approach.

Most of the works [18] have analyzed the throughput and access probability considering the whole system and have not differentiated the performance of UEs based on their initial CE levels. In contrast our work models and analyze the throughput according to UEs initial CE level under steady state conditions. We also study the effect of migration of UEs from one CE level to higher CE level after reaching the maximum number of preamble transmission attempts in the current CE level.

Our work differs from other closely related work as follows. Harwahyu [16] has analyzed the access mechanism of NB-IoT using combinatorics and probability theory and no Markov chain model has been developed. Further [16] treatment is for transient condition while we analyze the steady state condition. F.Chiti [20] have developed a simplistic Markov chain model for each CE level but each chain has only three states. Further migration of UEs to higher CE levels are not accounted for.

We have studied the effect of packet generation rate, preamble attempts and division of sub-carriers in each CE level.

CHAPTER 3

Analysis of Throughput in Steady State

In this section we model NB-IoT random access procedure by treating NPRACH as multi-band multi-channel slotted ALOHA [17]. We develop three 2-dimensional Markov chains one for each CE level and derive the steady state throughput of UEs according to their initial CE level. In NB-IoT case, band means CE level and the channel corresponds to the sub-carrier allocated to NPRACH in each CE level.

3.1 Assumptions and Notations

Let us consider N stationary UEs distributed over the three CE levels. Let the number of sub-carriers allocated to CE level 0,1 and 2 be denoted as S_0, S_1 and S_2 respectively. Packet arrival at each UE follows Poisson process with rate λ. In addition to these some general assumptions are made

1. Let the initial number of UEs in 'CE level i' be denoted as N_i. In practical scenario the CE level of an UE is decided based on RSRP thresholds. All UEs are identical and independent. Based on the distribution of UEs over the NB-IoT network, we can find p_i, the probability that an UE maps onto CE level i. It follows that $\sum_{i=0}^{2} p_i = 1$, and $N_i = Np_i$
2. Time is divided into equal sized slots with slot length being the NPRACH periodicity. The NPRACH periodicity corresponds to the duration it takes for the four steps of random access to occur as well as the data transmission. NPRACH periodicity in each CE level depends on the corresponding number of preamble and data repetitions.
3. Collision probability of a preamble transmission made by a UE in each CE level is constant and independent of number of preamble attempts made at that CE level, but dependent only on its current CE level and the initial CE level of that UE.
4. To evaluate the maximum achievable throughput at the MAC layer, we assume an ideal PHY layer.In other words there is no physical loss of packet due to channel errors.

Notations used in this chapter are summarized in Table 3.1

Table 3.1: NOTATIONS OF VARIABLES AND PARAMETERS

Notation	Definition
N	Number of UEs in the cell
λ	Arrival rate (packets/s)
δ_i	NPRACH periodicity in CE level i
N_i	Initial number of UEs in CE level i
S_i	Number of sub-carriers allocated to CE level i
M	Maximum number of attempts in all CE levels
R_i	Maximum number of attempts per preamble that are allowed in CE level i
R_{ij}	Maximum number of attempts per preamble in CE level j for UE initially in CE level i
p_{sij}	Successful transmission of packet in CE level j for UE initially in CE level i
p_{ij}	Collision probability for every (re)transmission of preamble in CE level j for UE initially in CE level i
τ_{ij}	(Re)transmission probability of preamble in CE level j for UE initially in CE level i in every slot
W_i	Maximum number of back-off windows in CE level i
T_i	Throughput corresponds to the UEs that are initially in CE level i

3.2 System Model

We propose three 2-dimensional discrete time Markov chain models based on UE's initial CE level. Our modelling is along the lines of the Markov chain model for LTE developed by X. Yang [21]. The Markov chain models for the UE's whose initial CE levels are 0, 1 and 2 are respectively shown in figures 3.2,3.3 and 3.4. The states of the Markov chain model are defined as 3-tuples (i,j,k), where i denotes the CE level, j denotes the counter value for preamble attempts, and k denotes the value of the back-off window counter. The state transition duration of the Markov chain is equal to one random access slot (NPRACH period). The size of the back-off counter window, denoted as W_i is in units of slot. The value of j is incremented by one whenever the preamble transmitted by that UE collides. The value of k is chosen uniformly from 0 to $W_i - 1$ and is decrements by one per slot during back-off. A preamble transmission is attempted when k reaches zero. The maximum number of attempts in CE level y, for UEs which are initially in CE level x is given by,

$$R_{xy} = \max\{0, \min\{R_y, R_2 - \sum_{b=x}^{b=y-1} R_b\}\} \quad \forall\, 0 \leq x < y \leq 2 \tag{3.1}$$

Under the assumption that the system can reach steady state, let the steady state probability be denoted as '$\pi_{i,j,k}$'. The subsequent sub-sections show the derivation of formulas for transmission probability, success probability and throughput.

In a typical IoT application, most of the time the UEs will be in the sleep state to conserve power. Whenever the UE gets a packet, they wakeup and contend to transmit the packet to the eNB. To model this scenario, we assume the Poisson arrival rate of the packet λ to the UE to be small such that the inter arrival duration of the packets is much larger than the packet transmission time. In our Markov chain we model this by introducing an Idle state. After a successful transmission the UE gets into an Idle state and wait for packet arrival. We now invoke the Bernoulli approximation to the Poisson process, which is valid when the arrival rate, and time interval for arrival is small. Then the probability of a packet arrival in a time slot δ_i in the Idle state is given by $\lambda\delta_i$.

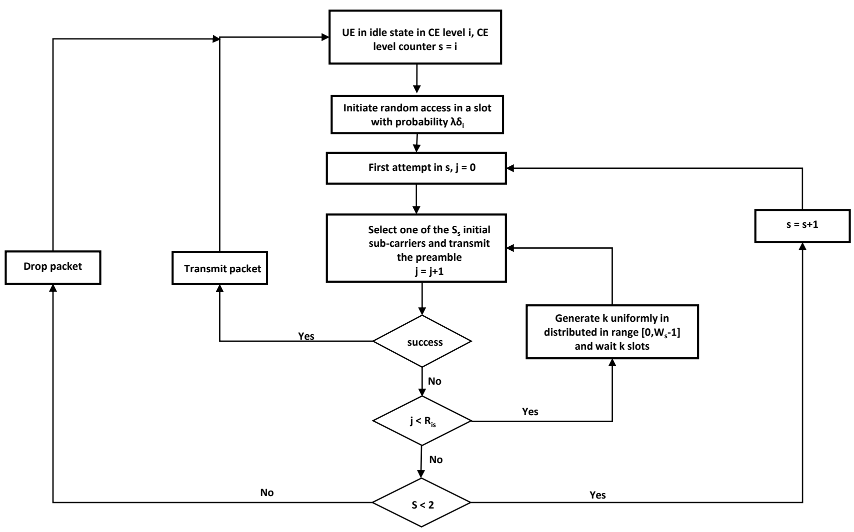

Figure 3.1: Flow diagram of random access in NB-IoT

3.2.1 Markov chain model for UEs initially in CE level 0

The Markov chain for UEs which begin their initial random access in CE level 0 is shown in figure 3.2. There are three stages of preamble transmissions for UEs initially in CE level 0 i.e preamble transmission in CE level 0, CE level 1 and CE level 2. In figure 3.2, (0,0,0) is idle state for the UEs initially in CE level, wherein the UE is waiting for the arrival of a packet. The stage (0,1,0) represent first transmission of preamble in CE level 0. Relationship between states for $(0,0,0)$, $(0,1,0)$, and $(0,2,0)$ are given by

$$\pi_{0,1,0} = \pi_{0,0,0}\lambda\delta_0 \tag{3.2}$$

$$\pi_{0,2,0} = \pi_{0,1,0}p_{00} \tag{3.3}$$

$$\pi_{0,2,0} = \pi_{0,0,0}p_{00}\lambda\delta_0 \tag{3.4}$$

For i=0, j $\in$ (2,R_{00}) & k $\in$ (0,$W_0 - 1$), from Markov chain

$$\pi_{0,j,k} = \pi_{0,j,k+1} + \pi_{0,j-1,0}\frac{p_{00}}{W_0} \tag{3.5}$$

$$\pi_{0,j,k} = \pi_{0,j,k+2} + 2\pi_{0,j-1,0}\frac{p_{00}}{W_0} \tag{3.6}$$

$$\pi_{0,j,k} = \frac{(W_0 - k)}{W_0}\pi_{0,j-1,0}p_{00} \tag{3.7}$$

By substituting equations Equations 3.2 and 3.4 in 3.7 following equation is derived

$$\pi_{0,j,k} = \frac{W_0 - k}{W_0}p_{00}^{j-1}\lambda\delta_0\pi_{0,0,0} \tag{3.8}$$

Now consider the states $(1, j, k)$ in figure 3.2 i.e UE reached maximum number of attempts in CE level 0 and started re-transmission in CE level 1. For the first transmission in CE level 1, the relation between states of CE level 0 and $(1, 1, 0)$ is given by

$$\pi_{1,1,0} = p_{00}\pi_{0,R_{00},0} \tag{3.9}$$

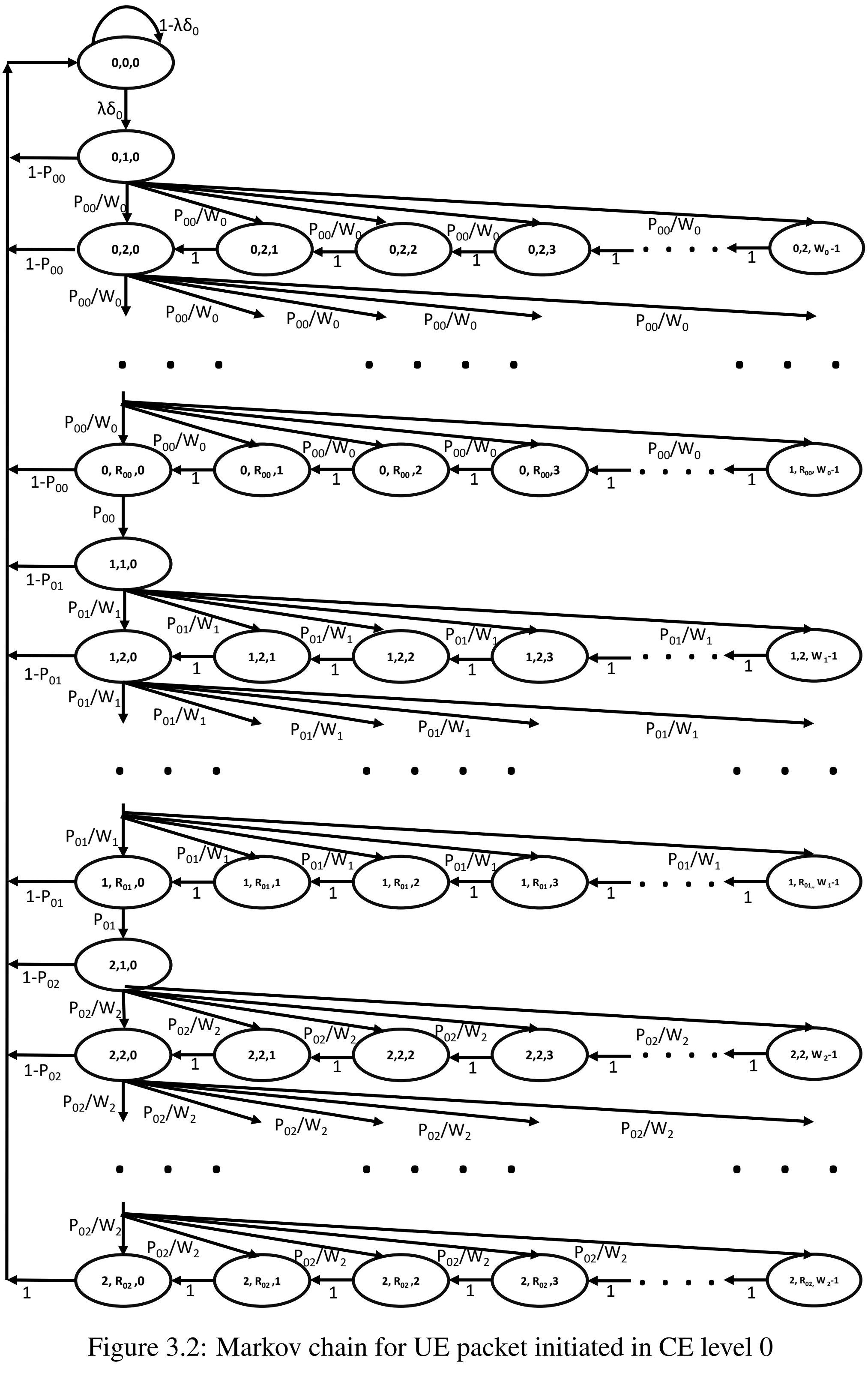

Figure 3.2: Markov chain for UE packet initiated in CE level 0

In equation 3.8 by substituting k = 0 and j = R_{00}

$$\pi_{0,R_{00},0} = p_{00}^{R_{00}-1}\lambda\delta_0\pi_{0,0,0} \tag{3.10}$$

From equation 3.9 and 3.10

$$\pi_{1,1,0} = p_{00}^{R_{00}}\lambda\delta_0\pi_{0,0,0} \tag{3.11}$$

For i=1, j ∈ (2,R_{01}) & k ∈ (0,$W_1 - 1$)

$$\pi_{1,j,k} = \frac{W_1 - k}{W_1} p_{01}^{j-1} p_{00}^{R_{00}}\lambda\delta_0\pi_{0,0,0} \tag{3.12}$$

Similarly for transmission in CE level 2 $(i = 2)$ which happens after maximum attempts in CE level 1 are exhausted, following the derivation of equations for CE level 0 $(i = 0)$ and CE level 1 $(i = 1)$

$$\pi_{2,1,0} = p_{00}^{R_{00}} p_{01}^{R_{01}}\lambda\delta_0\pi_{0,0,0} \tag{3.13}$$

and for j ∈ (2,R_{02}), k ∈ (0,$W_2 - 1$)

$$\pi_{2,j,k} = \frac{W_2 - k}{W_2} p_{02}^{j-1} p_{01}^{R_{01}} p_{00}^{R_{00}}\lambda\delta_0\pi_{0,0,0} \tag{3.14}$$

Thus, by relations 3.2, 3.4, 3.8, 3.11, 3.12, 3.13 and 3.14 all state occupancy probabilities can be expressed in terms of $\pi_{0,0,0}$. In turn $\pi_{0,0,0}$ can be derived from the normalization condition,

$$\pi_{0,0,0} + \pi_{0,1,0} + \pi_{1,1,0} + \pi_{2,1,0} + \sum_{j=2}^{R_{00}}\sum_{k=0}^{W_0-1}\pi_{0,j,k} + \sum_{j=2}^{R_{01}}\sum_{k=0}^{W_1-1}\pi_{1,j,k} + \sum_{j=2}^{R_{02}}\sum_{k=0}^{W_2-1}\pi_{2,j,k} = 1 \tag{3.15}$$

$$\pi_{0,0,0}\Bigg(1+\lambda\delta_0+p_{00}^{R_{00}}\lambda\delta_0+p_{01}^{R_{01}}p_{00}^{R_{00}}\lambda\delta_0+\sum_{j=2}^{R_{00}}\sum_{k=0}^{W_0-1}\frac{W_0-k}{W_0}p_{00}^{j-1}\lambda\delta_0$$
$$+\sum_{j=2}^{R_{01}}\sum_{k=0}^{W_1-1}\frac{W_1-k}{W_1}p_{01}^{j-1}p_{00}^{R_{00}}\lambda\delta_0+\sum_{j=2}^{R_{02}}\sum_{k=0}^{W_2-1}\frac{W_2-k}{W_2}p_{02}^{j-1}p_{01}^{R_{01}}p_{00}^{R_{00}}\lambda\delta_0\Bigg)=1 \quad (3.16)$$

$$\pi_{0,0,0}\Bigg(1+\lambda\delta_0\Big(1+\sum_{j=2}^{R_{00}}\frac{W_0+1}{2}p_{00}^{j-1}\Big)+p_{00}^{R_{00}}\lambda\delta_0\Big(1+\sum_{j=2}^{R_{01}}\frac{W_1+1}{2}p_{01}^{j-1}\Big)$$
$$+p_{01}^{R_{01}}p_{00}^{R_{00}}\lambda\delta_0\Big(1+\sum_{j=2}^{R_{02}}\frac{W_2+1}{2}p_{02}^{j-1}\Big)\Bigg)=1 \quad (3.17)$$

$$\pi_{0,0,0}\Bigg(1+\lambda\delta_0\Big(1+\frac{W_0+1}{2}\Big(\frac{1-p_{00}^{R_{00}}}{1-p_{00}}-1\Big)\Big)+p_{00}^{R_{00}}\lambda\delta_0\Big(1+\Big(\frac{1-p_{01}^{R_{01}}}{1-p_{01}}-1\Big)\Big)$$
$$+p_{01}^{R_{01}}p_{00}^{R_{00}}\lambda\delta_0\Big(1+\Big(\frac{1-p_{02}^{R_{02}}}{1-p_{02}}-1\Big)\Big)\Bigg)=1 \quad (3.18)$$

$$\pi_{0,0,0}\Bigg(1+\lambda\delta_0\Big(\frac{1+\frac{W_0-1}{2}p_{00}-\frac{W_0+1}{2}p_{00}^{R_{00}}}{1-p_{00}}\Big)+p_{00}^{R_{00}}\lambda\delta_0\Big(\frac{1+\frac{W_1-1}{2}p_{01}-\frac{W_1+1}{2}p_{01}^{R_{01}}}{1-p_{01}}\Big)$$
$$+p_{01}^{R_{01}}p_{00}^{R_{00}}\lambda\delta_0\Big(\frac{1+\frac{W_2-1}{2}p_{02}-\frac{W_2+1}{2}p_{02}^{R_{02}}}{1-p_{02}}\Big)\Bigg)=1 \quad (3.19)$$

$$\pi_{0,0,0}=\frac{2(1-p_{00})(1-p_{01})(1-p_{02})}{\begin{aligned}2(1-p_{00})(1-p_{01})(1-p_{02})+\lambda\delta_0\Big(1+\big(W_0-1\big)p_{00}-\big(W_0+1\big)p_{00}^{R_{00}}\Big)\\+p_{00}^{R_{00}}\lambda\delta_0\Big(1+\big(W_1-1\big)p_{01}-\big(W_1+1\big)p_{01}^{R_{01}}\Big)\\+p_{01}^{R_{01}}p_{00}^{R_{00}}\lambda\delta_0\Big(1+\big(W_2-1\big)p_{02}-\big(W_2+1\big)p_{02}^{R_{02}}\Big)\end{aligned}} \quad (3.20)$$

To summarize, the steady state probability of idle state has been derived and all states have been expressed in terms of idle steady probability.

3.2.2 Markov chain model for UEs initially in CE level 1

Figure 3.3 shows the Markov chain model for UEs which initiated their random access in CE level 1. For UEs initiating their random access in CE level 1 has two stages, transmission in CE level 1 ($i = 1$) and in CE level 2 ($i = 2$). Relationship between different states are given below.

$$\pi_{1,1,0} = \pi_{1,0,0}\lambda\delta_1 \tag{3.21}$$

$$\pi_{1,2,0} = \pi_{1,1,0}p_{11} \tag{3.22}$$

$$\pi_{1,2,0} = \pi_{1,0,0}\lambda\delta_1 p_{11} \tag{3.23}$$

For i=1, j $\in$ (2,R_{11}) & k $\in$ (0,$W_1 - 1$) owing to chain regularities

$$\pi_{1,j,0} = \frac{W_1 - k}{W_1} p_{11}^{j-1}\lambda\delta_1\pi_{1,0,0} \tag{3.24}$$

Consider the case $i = 2$ where preamble attempts has reached maximum value in CE level 1 and started transmitting the preamble in CE level 2. In CE level 2, the state (2,1,0) corresponds to first transmission in CE level 2.

$$\pi_{2,1,0} = \pi_{1,R_{11},0}\lambda\delta_1 \tag{3.25}$$

$$\pi_{2,1,0} = \pi_{1,0,0}p_{11}^{R_{11}}\lambda\delta_1 \tag{3.26}$$

The steady state probabilities for i=2, j $\in$ (2,R_{12}) & k $\in$ (0,$W_2 - 1$)

$$\pi_{2,j,0} = \frac{W_2 - k}{W_2} p_{11}^{j-1}\lambda\delta_1\pi_{2,1,0} \tag{3.27}$$

$$\pi_{2,j,0} = \frac{W_2 - k}{W_2} p_{11}^{j-1}p_{11}^{R_{11}}\lambda\delta_1\pi_{1,0,0} \tag{3.28}$$

Now all steady state probabilities in figure 3.3 are expressed in terms of idle state probability $\pi_{1,0,0}$. Normalized condition leads to

$$\pi_{1,0,0} + \pi_{1,1,0} + \pi_{2,1,0} + \sum_{j=2}^{R_{11}}\sum_{k=0}^{W_1-1}\pi_{1,j,k} + \sum_{j=2}^{R_{12}}\sum_{k=0}^{W_2-1}\pi_{2,j,k} = 1 \tag{3.29}$$

$$\pi_{1,0,0}\left(1+\lambda\delta_1\left(\frac{1+\frac{W_1-1}{2}p_{11}-\frac{W_1+1}{2}p_{11}^{R_{11}}}{1-p_{11}}\right)+p_{11}^{R_{11}}\lambda\delta_1\left(\frac{1+\frac{W_2-1}{2}p_{12}-\frac{W_2+1}{2}p_{12}^{R_{12}}}{1-p_{12}}\right)\right)=1 \tag{3.30}$$

$$\pi_{1,0,0}=\frac{2(1-p_{11})(1-p_{12})}{2(1-p_{11})(1-p_{12})+\lambda\delta_1\Big(1+\big(W_1-1\big)p_{11}-\big(W_1+1\big)p_{11}^{R_{11}}\Big)+p_{11}^{R_{11}}\lambda\delta_1\Big(1+\big(W_2-1\big)p_{12}-\big(W_2+1\big)p_{12}^{R_{12}}\Big)} \tag{3.31}$$

The idle steady state probability of UE initially in CE level 1 is given in equation 3.31 will be used in deriving the transmission probabilities in CE level 2 and CE level 1 for UEs initially in CE level 1

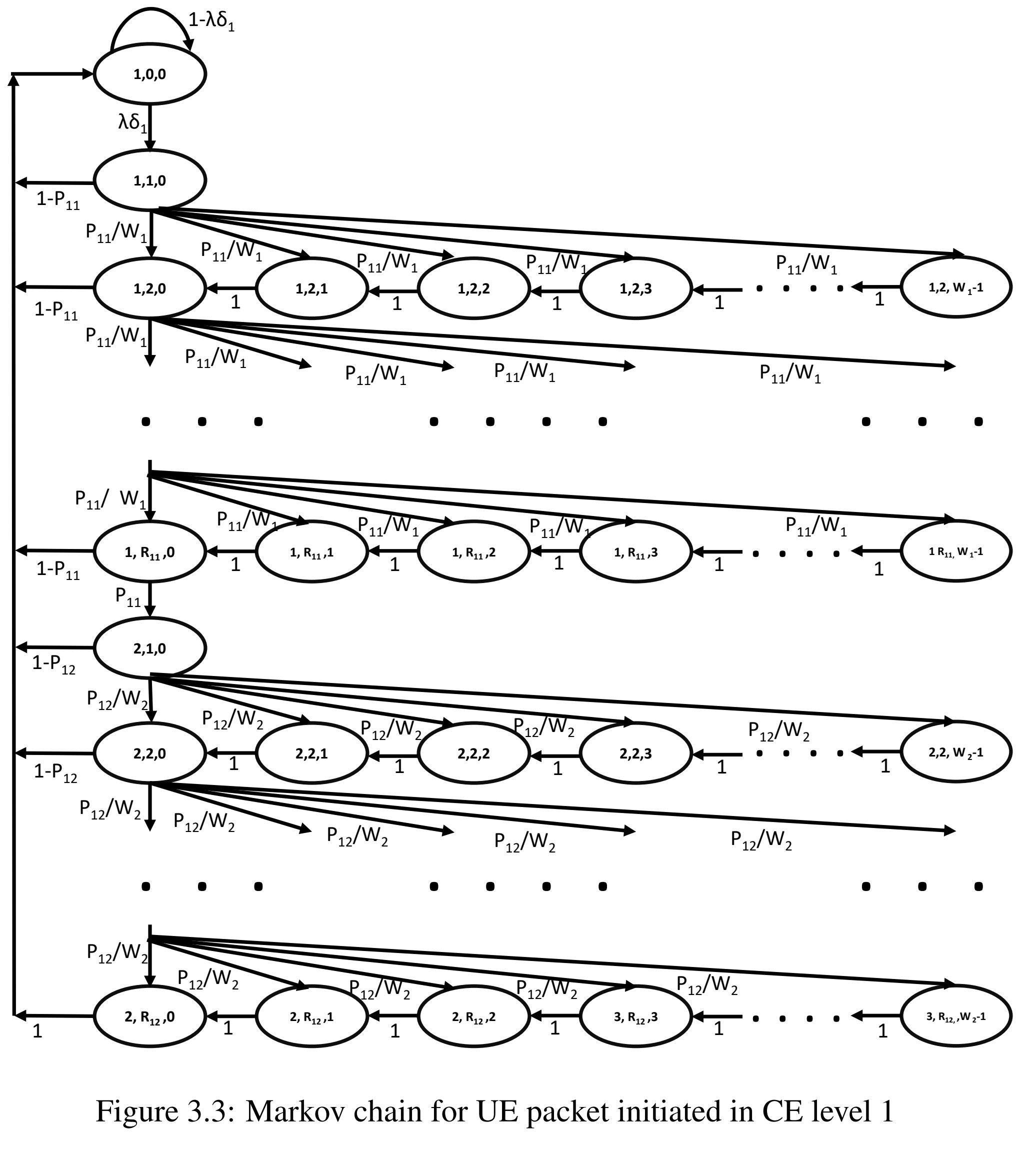

Figure 3.3: Markov chain for UE packet initiated in CE level 1

3.2.3 Markov chain model for UEs initially in CE level 2

For UEs initially in CE level 2 the maximum number of attempts in CE level 2 is equal to the total maximum number of attempts since there is no CE level higher than 2. Markov chain model for UEs initially in CE level 2 is shown in the figure 3.4. Idle state for UE in CE level 2 is (2,0,0). Relationship between different states are derived in similar manner as for the UE initially in CE level 1 and 0.

$$\pi_{2,1,0} = \pi_{2,0,0}\lambda\delta_2 \tag{3.32}$$

$$\pi_{2,2,0} = \pi_{2,1,0}p_{22} \tag{3.33}$$

$$\pi_{2,2,0} = \pi_{2,0,0}p_{22}\lambda\delta_2 \tag{3.34}$$

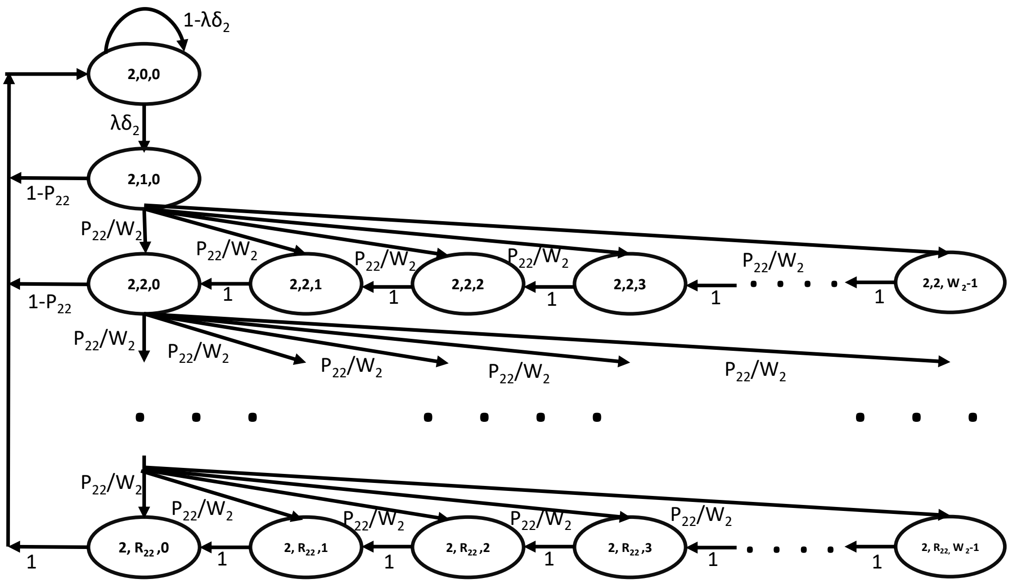

Figure 3.4: Markov chain for UE packet initiated in CE level 2

Relationship between states of the UE after completing the first preamble transmission i.e for $j \in$ (0,R_{22}) and $k \in$ (0,W_2-1) is given by

$$\begin{aligned} \pi_{2,j,k} &= \frac{(W_2 - k)}{W_2}\pi_{2,j-1,0}p_{22} \\ \pi_{2,j,0} &= \frac{W_2 - k}{W_2}p_{22}^{j-1}\lambda\delta_2\pi_{2,0,0} \end{aligned} \tag{3.35}$$

Normalizing the sum of all state probabilities to one

$$\pi_{2,0,0} + \pi_{2,1,0} + \sum_{j=2}^{R_{22}} \sum_{k=0}^{W_2-1} \pi_{2,j,k} = 1 \tag{3.36}$$

By taking the idle state probability as a common factor and solving for it leads to

$$\pi_{2,0,0}\left(1 + \lambda\delta_2\left(\frac{1 + \frac{W_2-1}{2}p_{11} - \frac{W_2+1}{2}p_{22}^{R_{22}}}{1 - p_{22}}\right)\right) = 1 \tag{3.37}$$

$$\pi_{2,0,0} = \frac{2(1 - p_{22})}{2(1 - p_{22}) + \lambda\delta_2\Big(1 + \big(W_2 - 1\big)p_{22} - \big(W_2 + 1\big)p_{22}^{R_{22}}\Big)} \tag{3.38}$$

All steady state probabilities are expresses in terms of their UE idle state probability so in succeeding sections transmission probabilities, success probabilities and throughput are derived.

3.3 Transmission Probabilities

Transmission or re-transmission of preamble happens only when the back-off counter value is zero so only the states with $k = 0$ contribute to the transmission or re-transmission probabilities. Recall that τ_{ij} denote the transmission probability of preamble in every slot in CE level j for UE initially in CE level i. In the next few sub-section the derivation of transmission probabilities of UEs in their initial CE level and the higher CE level are presented.

3.3.1 Transmission probabilities for UEs initially in CE level 0

Transmission in CE level 0

Transmission or re-transmission probabilities in CE level 0 is given by sum of states when $i = 0$, $k = 0$ and $j \in (1, R_{00})$

$$
\begin{aligned}
\tau_{00} &= \sum_{j=1}^{R_{00}} \pi_{0,j,0} \\
\tau_{00} &= \frac{1 - p_{00}^{R_{00}}}{1 - p_{00}} \lambda \delta_0 \pi_{0,0,0}
\end{aligned}
\tag{3.39}
$$

Transmission in CE level 1

Re-transmission probability in CE level 1 for UEs whose initial random access is in CE level 0 is given by

$$
\begin{aligned}
\tau_{01} &= \sum_{j=1}^{R_{01}} \pi_{1,j,0} \\
\tau_{01} &= \frac{1 - p_{01}^{R_{01}}}{1 - p_{01}} p_{00}^{R_{00}} \lambda \delta_0 \pi_{0,0,0}
\end{aligned}
\tag{3.40}
$$

Transmission in CE level 2

Similarly re-transmission probability in CE level 2 for UEs whose very first preamble transmission happened in CE level 0 is

$$
\begin{aligned}
\tau_{02} &= \sum_{j=1}^{R_{02}} \pi_{2,j,0} \\
\tau_{02} &= \frac{1 - p_{02}^{R_{02}}}{1 - p_{02}} p_{01}^{R_{01}} p_{00}^{R_{00}} \lambda \delta_0 \pi_{0,0,0}
\end{aligned}
\tag{3.41}
$$

3.3.2 Transmission probability for UE initially in CE level 1

Transmission in CE level 1

States contributing to the transmission probability in CE level 1 are $(1, j, 0)$ where $j \in (1, R_{11})$. Formula for transmission of preamble in CE level 1 is given by

$$\begin{aligned} \tau_{11} &= \sum_{j=1}^{R_{11}} \pi_{1,j,0} \\ \tau_{11} &= \frac{1 - p_{11}^{R_{11}}}{1 - p_{11}} \lambda \delta_1 \pi_{1,0,0} \end{aligned} \tag{3.42}$$

Transmission in CE level 2

When the preamble attempts reached the maximum value in CE level 1 then UE changes its CE level to 2 and starts transmitting there, so states contributing to re-transmission are $(2, j, 0)$ where j ∈ (1,R_{12})

$$\begin{aligned} \tau_{12} &= \sum_{j=1}^{R_{12}} \pi_{2,j,0} \\ \tau_{12} &= \frac{1 - p_{12}^{R_{12}}}{1 - p_{12}} p_{11}^{R_{11}} \lambda \delta_1 \pi_{1,0,0} \end{aligned} \tag{3.43}$$

3.3.3 Transmission probabilities for UEs initially in CE level 2

For UEs initially in CE level 2 has the only possibility of transmitting the preamble to transmit in CE level 2. Similar as in cases of CE level 1 and 0 only states account for transmission probability are when back-off counter is zero so transmission probability is given by

$$\begin{aligned} \tau_{22} &= \sum_{j=1}^{R_{22}} \pi_{2,j,0} \\ \tau_{22} &= \frac{1 - p_{22}^{R_{22}}}{1 - p_{22}} \lambda \delta_2 \pi_{2,0,0} \end{aligned} \tag{3.44}$$

Now all transmission probabilities have been derived and expressed in terms of collision probability. For finding the transmission probability we need to know collision probability. So in next section success probabilities are presented from which collision probabilities are derived.

3.4 Success probabilities

In this section success probabilities of random access procedure are derived for UEs in different CE levels. Lets consider a generalized case of L UEs. Since all UEs are identical let us observe a representative UE that has transmitted a preamble in an arbitrary slot. The probability that this given transmission is successful depends on the number of UEs contending in the random access slot, out of $L-1$ UEs let l UEs transmit in that slot with transmission probability τ is given by

$$P(l/L-1) = \binom{L-1}{l}\tau^l(1-\tau)^{L-l-1} \tag{3.45}$$

Let S be the number of sub-carriers available, the observed UE random access procedure is successful only if the other l contending UEs do not select the sub-carrier selected by the observing UE. So The probability that this given transmission is successful is given by

$$\begin{aligned} P(success/l) &= \sum_{s=0}^{S}\frac{1}{S}\Big(1-\frac{1}{S}\Big)^l \\ P(success/l) &= \Big(1-\frac{1}{S}\Big)^{l-1} \end{aligned} \tag{3.46}$$

Now combining equations 3.45 and 3.46 we get success probability of observed UE

$$\begin{aligned} P(success) &= \sum_{l=0}^{L-1} P(success/l)P(l/L-1) \\ &= \sum_{l=0}^{L-1}\Big(1-\frac{1}{S}\Big)^l\binom{L-1}{l}\tau^l(1-\tau)^{L-l-1} \\ &= \sum_{l=0}^{L-1}\binom{L-1}{l}\tau^l\Big(1-\frac{1}{S}\Big)^l(1-\tau)^{L-l-1} \\ &= \Big(\tau-\frac{\tau}{S}+1-\tau\Big)^{L-l-1+l} \\ &= \Big(1-\frac{\tau}{S}\Big)^{L-1} \end{aligned} \tag{3.47}$$

Like derivation of equation 3.47, the probability that this given transmission is successful for UEs in different CE levels can be derived

3.4.1 UEs initially in CE level 0

Transmission in CE level 0

There are N_1 UEs initially in the CE level, S_0 sub-carriers are available and transmission probability is τ_{00} so success probability will be

$$\begin{aligned} p_{s00} &= \sum_{n_0=0}^{N_0-1} \left(1-\frac{1}{S_0}\right)^{n_0} \binom{N_0-1}{n_0} \tau_{00}^{n_0} (1-\tau_{00})^{N_0-n_0-1} \\ &= \left(1-\frac{\tau_{00}}{S_0}\right)^{N_0-1} \end{aligned} \tag{3.48}$$

so collision probability from the figure 3.2 and equation 3.48 is given by

$$\begin{aligned} p_{00} &= 1 - p_{s00} \\ &= 1 - \left(1-\frac{\tau_{00}}{S_0}\right)^{N_0-1} \end{aligned} \tag{3.49}$$

Transmission in CE level 1

In this case not only the UEs from CE level 0 transmit the preamble but also UEs in CE level 1. So for UEs initially in CE level 0 to successfully transmit a packet in CE level 1 will be

$$\begin{aligned} p_{s01} &= \sum_{n_0=0}^{N_0-1} \sum_{n_1=0}^{N_1} \binom{N_0-1}{n_0} \tau_{01}^{n_0} (1-\tau_{01})^{N_0-n_0-1} \binom{N_1}{n_1} \tau_{11}^{n_1} (1-\tau_{11})^{N_1-n_1} \left(1-\frac{1}{S_1}\right)^{n_0+n_1} \\ &= \sum_{n_0=0}^{N_0-1} \sum_{n_1=0}^{N_1} \binom{N_0-1}{n_0} \tau_{01}^{n_0} (1-\tau_{01})^{N_0-n_0-1} \left(1-\frac{1}{S_1}\right)^{n_0} \left(1-\frac{\tau_{11}}{S_1}\right)^{N_1} \\ &= \left(1-\frac{\tau_{01}}{S_1}\right)^{N_0-1} \left(1-\frac{\tau_{11}}{S_1}\right)^{N_1} \end{aligned} \tag{3.50}$$

where N_0 and N_1 are the initial number of UEs in CE level 0 and 1, S_1 is the number of sub-carriers available in CE level 1, τ_{01} and τ_{11} are the transmission probabilities in

CE level 1 for UEs initially in CE level 0 and CE level 1. Collision probability for UEs from CE level 0 in CE level 1 denoted as p_{01} is given by

$$\begin{aligned} p_{01} &= 1 - p_{s01} \\ &= 1 - \left(1 - \frac{\tau_{01}}{S_1}\right)^{N_0 - 1}\left(1 - \frac{\tau_{11}}{S_1}\right)^{N_1} \end{aligned} \tag{3.51}$$

Transmission in CE level 2

Aside N_2 initial UEs in CE level 3 there are N_0 from CE level 0 and N_1 from CE level 1. The success probability of UEs from CE level 0 in CE level 2 is given by

$$\begin{aligned} p_{s02} = \sum_{n_0=0}^{N_0-1}\sum_{n_1=0}^{N_1}\sum_{n_2=0}^{N_2} \binom{N_0-1}{n_0}\tau_{02}^{n_0}(1-\tau_{02})^{N_0-n_0-1}\binom{N_1}{n_1}\tau_{12}^{n_1}(1-\tau_{12})^{N_1-n_1} \\ \binom{N_2}{n_2}\tau_{22}^{n_2}(1-\tau_{22})^{N_2-n_2}\left(1-\frac{1}{S_2}\right)^{n_0+n_1+n_2} \end{aligned}$$

$$P_{s02} = \left(1 - \frac{\tau_{02}}{S_2}\right)^{N_0-1}\left(1 - \frac{\tau_{12}}{S_2}\right)^{N_1}\left(1 - \frac{\tau_{22}}{S_2}\right)^{N_2} \tag{3.52}$$

Collision probability p_{02} is

$$\begin{aligned} P_{02} &= 1 - p_{s02} \\ &= 1 - \left(1 - \frac{\tau_{02}}{S_2}\right)^{N_0-1}\left(1 - \frac{\tau_{12}}{S_2}\right)^{N_1}\left(1 - \frac{\tau_{22}}{S_2}\right)^{N_2} \end{aligned} \tag{3.53}$$

3.4.2 UE initially in CE level 1

For the observed UE which is initially in CE level 1, the successful transmission probability of preamble can be derived in a similar manner as in the case of UEs initially in CE level 0 Derivation is same as in equation 3.50

$$\begin{aligned} p_{s11} &= \sum_{n_0=0}^{N_0}\sum_{n_1=0}^{N_1-1}\binom{N_0}{n_0}\tau_{01}^{n_0}(1-\tau_{01})^{N_0-n_0}\binom{N_1-1}{n_1}\tau_{11}^{n_1}(1-\tau_{11})^{N_1-n_1-1}\left(1-\frac{1}{S_1}\right)^{n_0+n_1} \\ &= \left(1-\frac{\tau_{01}}{S_1}\right)^{N_0}\left(1-\frac{\tau_{11}}{S_1}\right)^{N_1-1} \end{aligned} \tag{3.54}$$

Collision probability p_{11}

$$\begin{aligned} p_{11} &= 1 - p_{s11} \\ &= 1 - \left(1 - \frac{\tau_{01}}{S_1}\right)^{N_0} \left(1 - \frac{\tau_{11}}{S_1}\right)^{N_1 - 1} \end{aligned} \tag{3.55}$$

Transmission in CE level 2

$$p_{s12} = \sum_{n_0=0}^{N_0} \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2} \binom{N_0}{n_0} \tau_{02}^{n_0} (1-\tau_{02})^{N_0-n_0} \binom{N_1-1}{n_1} \tau_{12}^{n_1} (1-\tau_{12})^{N_1-n_1-1} \binom{N_2}{n_2} \tau_{22}^{n_2} (1-\tau_{22})^{N_2-n_2} \left(1 - \frac{1}{S_2}\right)^{n_0+n_1+n_2}$$

$$P_{s12} = \left(1 - \frac{\tau_{02}}{S_2}\right)^{N_0} \left(1 - \frac{\tau_{12}}{S_2}\right)^{N_1-1} \left(1 - \frac{\tau_{22}}{S_2}\right)^{N_2} \tag{3.56}$$

Collision probability p_{12}

$$\begin{aligned} p_{12} &= 1 - p_{s12} \\ &= 1 - \left(1 - \frac{\tau_{02}}{S_2}\right)^{N_0} \left(1 - \frac{\tau_{12}}{S_2}\right)^{N_1-1} \left(1 - \frac{\tau_{22}}{S_2}\right)^{N_2} \end{aligned} \tag{3.57}$$

3.4.3 UE initially in CE level 2

$$p_{s12} = \sum_{n_0=0}^{N_0} \sum_{n_1=0}^{N_1} \sum_{n_2=0}^{N_2-1} \binom{N_0}{n_0} \tau_{02}^{n_0} (1-\tau_{02})^{N_0-n_0} \binom{N_1}{n_1} \tau_{12}^{n_1} (1-\tau_{12})^{N_1-n_1} \binom{N_2-1}{n_2} \tau_{22}^{n_2} (1-\tau_{22})^{N_2-n_2-1} \left(1 - \frac{1}{S_2}\right)^{n_0+n_1+n_2}$$

$$P_{s22} = \left(1 - \frac{\tau_{02}}{S_2}\right)^{N_0} \left(1 - \frac{\tau_{12}}{S_2}\right)^{N_1} \left(1 - \frac{\tau_{22}}{S_2}\right)^{N_2-1} \tag{3.58}$$

Collision probability p_{22}

$$\begin{aligned} p_{22} &= 1 - p_{s22} \\ &= 1 - \left(1 - \frac{\tau_{02}}{S_2}\right)^{N_0} \left(1 - \frac{\tau_{12}}{S_2}\right)^{N_1} \left(1 - \frac{\tau_{22}}{S_2}\right)^{N_2 - 1} \end{aligned} \tag{3.59}$$

In above formulas, for large number of UEs $N-1$ can be approximated as N ($N-1 \approx N$) which leads to $p_{01} \approx p_{11}$ and $p_{02} \approx p_{12} \approx p_{22}$.

3.5 Throughput Analysis

In this section we finally derive the throughput of the packets transmitted by the UEs in different CE level. Packet transmission that happens after step 4 of random access procedure will be successful if there is no preamble collision in step 1. Therefore throughput is nothing but the average number of random access requests that become successful per slot. So throughput is average number of UEs trying to access the network in any slot multiplied by success probability. All UEs are considered as identical and independent.

3.5.1 UE initially in CE level 0

Since UEs initially from CE level 0 can transmit in CE level 1 and CE level 2. So success in CE level 1 and CE level 2 contribute to throughput of UEs initially in CE level 0.

$$\begin{aligned} T_0 = \sum_{n_0=0}^{N_0} n_0 \binom{N_0}{n_0} \tau_{00}^{n_0} (1 - \tau_{00})^{N_0 - n_0} p_{s00} + \sum_{n_0=0}^{N_0} n_0 \binom{N_0}{n_0} \tau_{01}^{n_0} (1 - \tau_{01})^{N_0 - n_0} p_{s01} \\ + \sum_{n_0=0}^{N_0} n_0 \binom{N_0}{n_0} \tau_{02}^{n_0} (1 - \tau_{02})^{N_0 - n_0} p_{s02} \end{aligned} \tag{3.60}$$

$$
\begin{aligned}
T_0 = N_0\tau_{00} \sum_{n_0=1}^{N_0} \binom{N_0-1}{n_0-1} \tau_{00}^{n_0-1}(1-\tau_{00})^{N_0-n_0} p_{s00} \\
+N_0\tau_{01} \sum_{n_0=1}^{N_0} \binom{N_0-1}{n_0-1} \tau_{01}^{n_0-1}(1-\tau_{01})^{N_0-n_0} p_{s01} \\
+N_0\tau_{02} \sum_{n_0=1}^{N_0} \binom{N_0-1}{n_0-1} \tau_{02}^{n_0-1}(1-\tau_{02})^{N_0-n_0} p_{s02}
\end{aligned} \tag{3.61}
$$

Since above equation 3.61 is addition of binomial expansion terms, it can be written as

$$
T_0 = N_0\tau_{00}p_{s00} + N_0\tau_{01}p_{s01} + N_0\tau_{02}p_{s02} \tag{3.62}
$$

3.5.2 UE initially in CE level 1

Throughput of packets for UEs initially in 1 has two possible cases 1) successful transmission in CE level 1 and successful transmission in CE level 2. Derivation is similar of equation 3.62

$$
\begin{aligned}
T_1 &= \sum_{n_1=0}^{N_1} n_1 \binom{N_1}{n_1} \tau_{11}^{n_1}(1-\tau_{11})^{N_1-n_1} p_{s11} + \sum_{n_1=1}^{N_1} n_1 \binom{N_1}{n_1} \tau_{12}^{n_1}(1-\tau_{12})^{N_1-n_1} p_{s12} \\
&= N_1\tau_{11}p_{s11} + N_1\tau_{12}p_{s12}
\end{aligned} \tag{3.63}
$$

3.5.3 UE initially in CE level 2

Throughput for UEs initially in CE level is solely from success in CE level 2

$$
\begin{aligned}
T_2 &= \sum_{n_2=0}^{N_2} n_2 \binom{N_2}{n_2} \tau_{22}^{n_2}(1-\tau_{22})^{N_2-n_2} p_{s22} \\
&= N_2\tau_{22}p_{s22}
\end{aligned} \tag{3.64}
$$

All formulas for transmission probabilities, success probabilities and throughput have been derived. The formulas show that success probabilities and transmission probabilities are inter-dependent. They can be solved numerically. Further it is found that there exist only one solution. The analysis results are validated with the simulations.

CHAPTER 4

Results and Validations

4.1 Configuration of parameters for Simulation

The analytical model proposed in chapter 3 is verified by the simulations. Simulations are done using C++ language in Linux platform while numerical computations of analytical model are done in MATLAB. First we configure the parameters for the simulation. According to 3GPP, the number of repetitions in uplink can go up to 128 in powers of 2 i.e {1,2,4,8,16,32,64,128} [9]. In this we considered repetitions of 2,4 and 16 for preamble and data in CE level 0,1 and 2 respectively.

Table 4.1: CONFIGURATION OF PARAMETERS

Parameter	**Value**
M	10
R_0,R_1,R_2,	4,4,10
δ_0,δ_1,δ_2	80ms,160ms,320ms
$N_0 : N_1 : N_2$	1 : 1 : 1
W_0, W_1, W_2	8,8,8
S_0, S_1, S_2	12,12,24

Number of UEs (N) are varied from 900, 3000 to 48000 in steps of 3000.

4.2 Varying Packet Generation Rate

Following the parameters mentioned in table 4.1, we vary the packet generation rate such that mean inter-arrival times between any two packets i.e $1/\lambda$ are {5,12,30,60,120} minutes. Figures 4.1, 4.2 and 4.3 shows the throughput for UEs which begin their random access in CE level 0, 1 and 2 respectively. Analytical results are expressed by

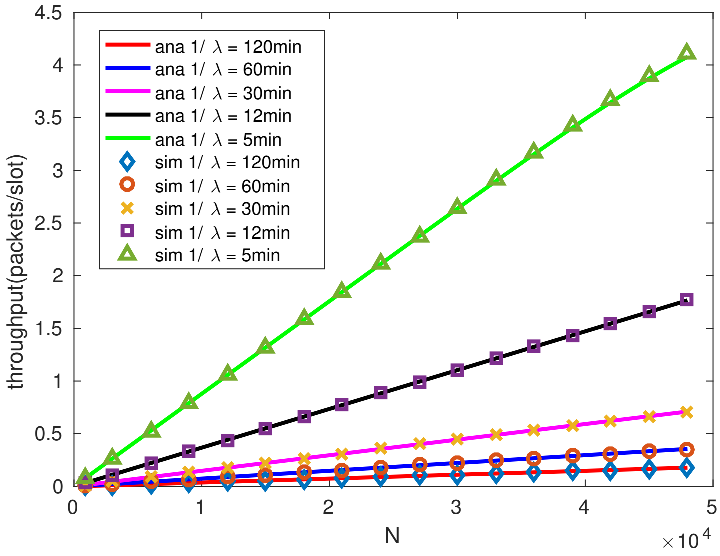

Figure 4.1: Throughput for UEs initially in CE level 0 for maximum preamble attempts {4,4,10} and sub-carrier division {12,12,24}

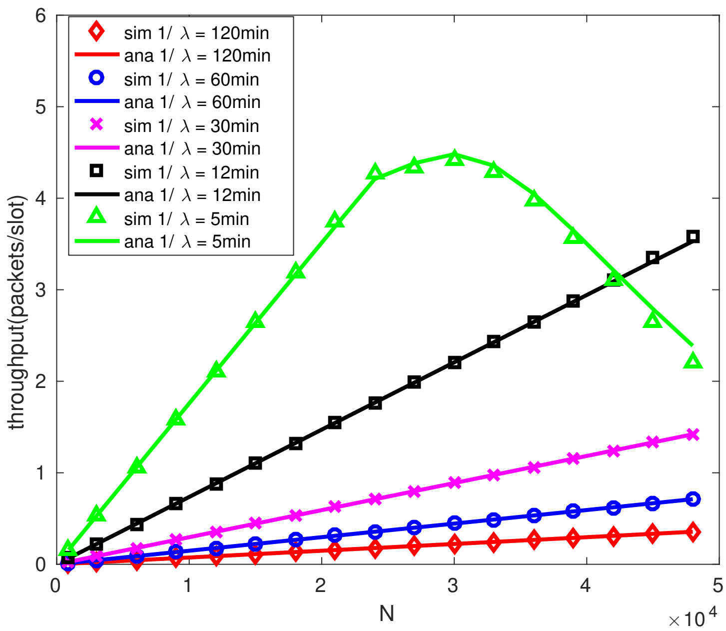

Figure 4.2: Throughput for UEs initially in CE level 1 for maximum preamble attempts {4,4,10} and sub-carrier division {12,12,24}

curves and simulation results are expressed by markers. From the figures 4.1, 4.2 and 4.3 it can observed the packet generation rate effects throughput. If inter-arrival time of packets is large collisions are less but throughput increases at slower rate. As inter-arrival time decreases throughput starts increasing at higher rate. From simulations it is observed that throughput increases till average traffic per slot is equal to the number

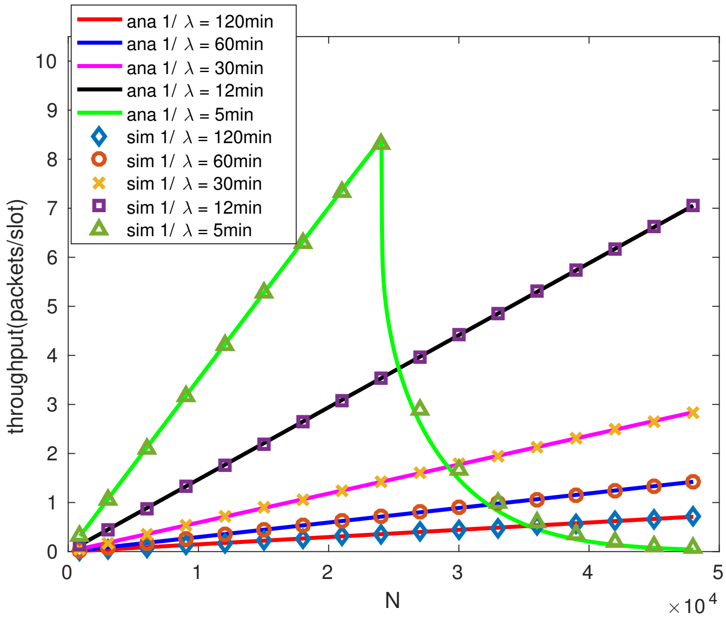

Figure 4.3: Throughput for UEs initially in CE level 2 for maximum preamble attempts {4,4,10} and sub-carrier division {12,12,24}

of sub-carriers and then decreases depending on the collision rate. It can be witnessed for case the $1/\lambda$ = 5min in plot 4.3, the throughput for UEs initially in CE level 2 increases till number of UEs approximately 24000 and starts decreasing exponentially due to average traffic load per slot increasing dramatically due to continuous collisions in every slot. This phenomenon can be explained as follows. Given the arrival rate as $\frac{1}{5} packets/min$, the slot length of CE level 2 as $320ms$ for about 24000 UEs the number of packets per slot is approximately 24 which becomes equal to the number of sub-carriers in CE level 2. Since arrival rate becomes equal to the service rate at this point the queue becomes unstable beyond this point [22]. Similar thing can be observed for throughput of UEs initially in CE level 0 and 1 when average random access requests cross the number of sub-carriers.

4.3 Varying the maximum number of attempts

The effect of changing the maximum number of attempts in each CE level has been observed by plotting the graphs for the inter-arrival time of 5 and 12min. Graphs are plotted for two cases of maximum preamble number attempts in each CE level to be {10,6,10}, {10,10,10} with parameters being the same as in table **??**. Figures 4.1,

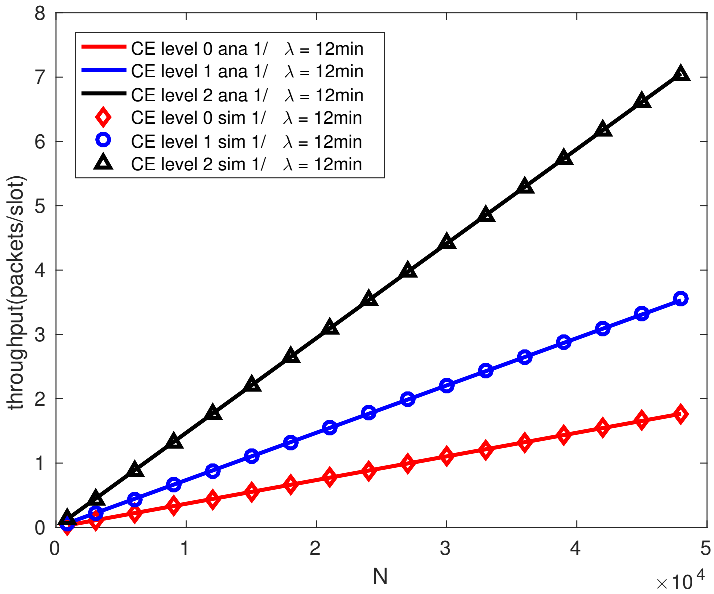

Figure 4.4: Throughput for UEs in all CE level for maximum preamble attempts {10,6,10} and sub-carrier division {12,12,24} for $1/\lambda = 12min$

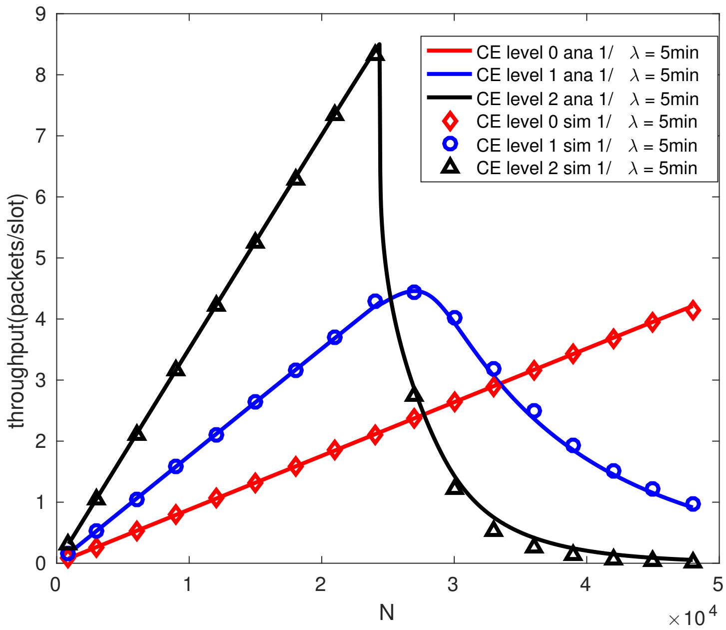

Figure 4.5: Throughput for UEs in all CE levels for maximum preamble attempts {10,6,10} and sub-carrier division {12,12,24} for $1/\lambda = 5min$

4.2 and 4.3 themselves can be used to observe respectively for CE level 0,1, and 2, the throughput for the case of maximum preamble attempts in each CE level being {4,4,10}
.

From the plots 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6 it is observed that if average traffic

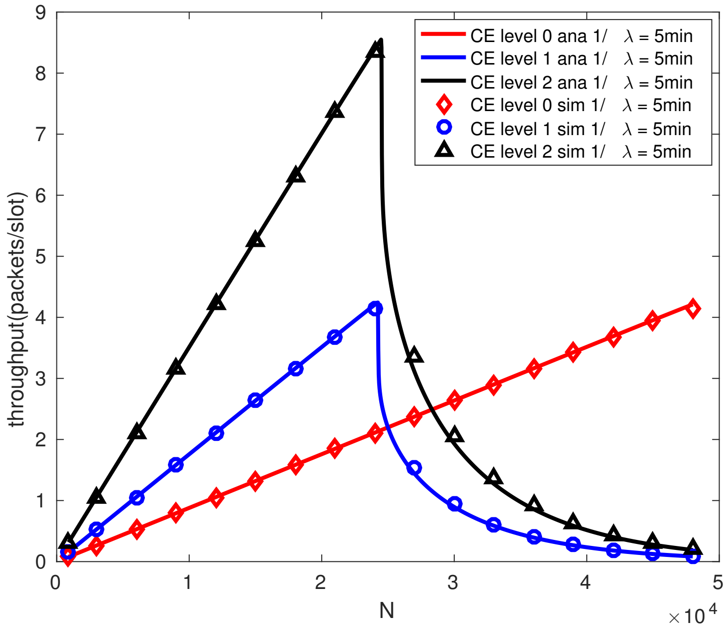

Figure 4.6: Throughput for UEs in all CE levels for maximum preamble attempts {10,10,10} and sub-carrier division {12,12,24} for $1/\lambda = 5min$

load per slot is less that the number of sub-carriers in that CE level then the division of preamble attempts does not matter much (refer figure 4.4). In case of average traffic load becomes greater than the number of sub-carriers allocated to that CE level it is better to have certain attempts in higher CE level so that load decreases in the current CE level and throughput decreases at slower rate as shown in the plot 4.5 compared to throughput in plot 4.6 for the case of UEs initially in CE level 1

4.4 Varying the number of sub-carriers

As the number of variations of sub-carrier allocation to different CE levels are limited, we exploited all possibilities of allocation of number of sub-carriers. There are total 4 cases {12,12,12},{24,12,12},{12,24,12} and {12,12,24}. Figure 4.1 to 4.6 shows the graphs for the case {12,12,24}. For case {12,12,12} there is no much change in throughput of UEs initially in CE level 0 and 1 but throughput of UEs initially in CE level 2 decreased drastically compared to the case {12,12,24}. Therefore {12,12,12} sub-carriers allocation can be used only in the case of large mean interval-arrival time e.g in case of $1/\lambda = \{30min, 60min, 120min\}$ for better utilization of radio resources.

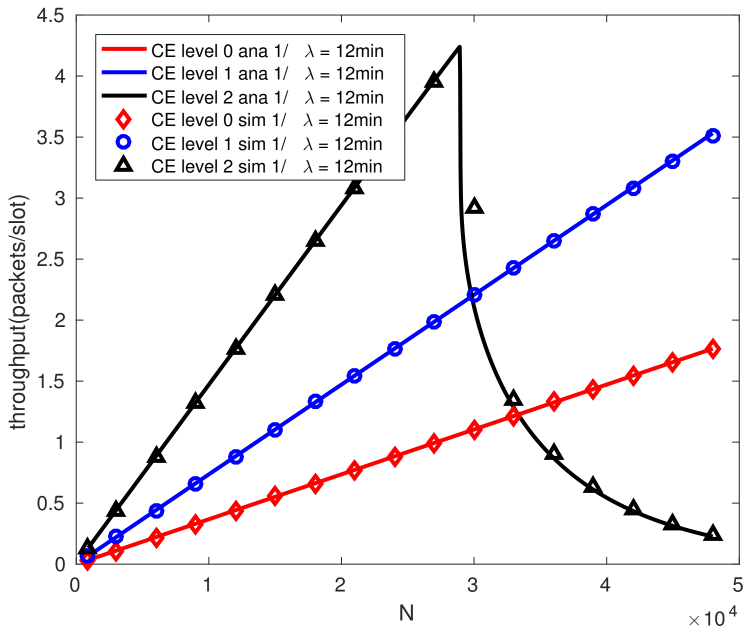

Figure 4.7: Throughput for UEs in all CE levels for maximum preamble attempts {10,6,10} and sub-carrier division {12,24,12} for $1/\lambda = 12min$

For the case {24,12,12} as throughput in CE level 0 is same as in case of {12,12,12} for $1/\lambda = 5min, 12min, 30min, 60min, 120min$. Only when most of the UEs concentrated in CE level 0 it is better to use sub-carrier allocation {24,12,12} .

Increasing the number of sub-carriers allocated to CE level 1 there is considerable increase of throughput for UEs initially in CE level 1 for case $1/\lambda = 5min$ but throughput for UEs in CE level 2 is worse in case of uniform division of UEs. In plot 4.7 even throughput for UEs initially in CE level 1 does not change. So allocation of sub-carriers highly depends on the number of UEs initially in CE levels.

4.5 Variation of distribution of UEs in CE levels

The initially distribution of UEs in CE levels are simulated for two cases $N_0 : N_1 : N_2 = 5 : 3 : 2$ and $N_0 : N_1 : N_2 = 3 : 5 : 2$. The graphs are drawn for the sub-carriers allocation {12,24,12}.It can be observed from the figure 4.8 that the throughput of CE level 1 is more than that of CE level 0 and CE level 2 because more number of UEs are initially in CE level 1. But it does not mean that throughput will be always high for the CE level in which initial UEs are more, it is evident in figure 4.9 where initial UEs are

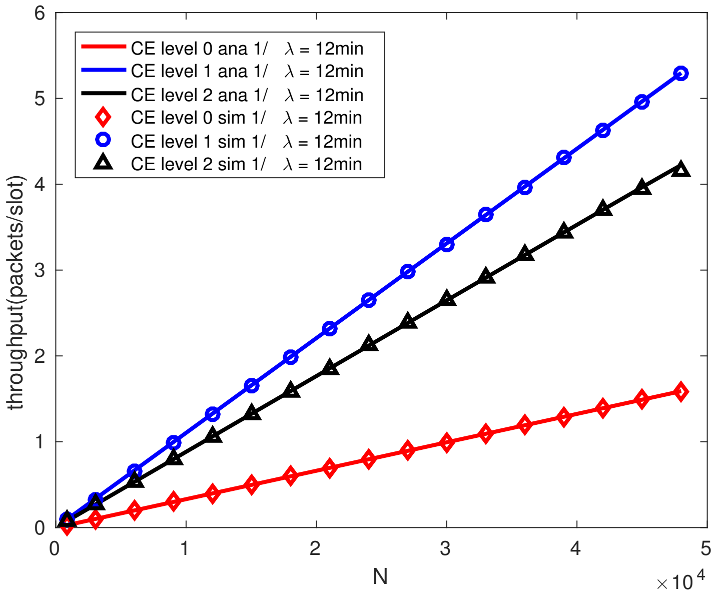

Figure 4.8: Throughput for UEs in all CE levels for maximum preamble attempts {10,6,10}, sub-carrier division {12,24,12} and UEs division {3,5,2} for $1/\lambda = 12min$

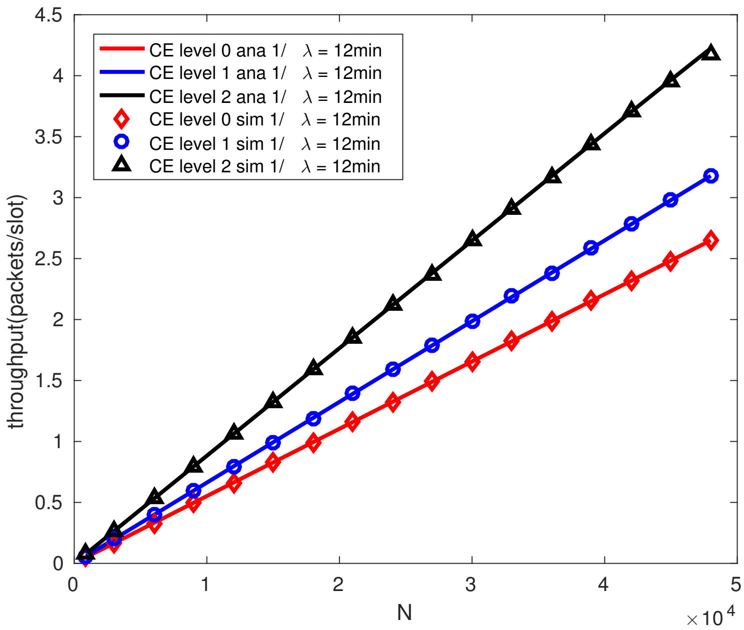

Figure 4.9: Throughput for UEs in all CE levels for maximum preamble attempts {10,6,10}, sub-carrier division {12,24,12} and UEs division {5,3,2} for $1/\lambda = 12min$

larger in CE level 0 but throughput is higher for CE level 2. Reason being for a given arrival rate the number of arrivals per slot vary due to the variations in the slot length across CE levels.

CHAPTER 5

Impact of Access Barring Factor in NB-IoT Random Access

NB-IoT deals with huge number of devices hence there will severe congestion. In literature, for congestion reduction in LTE/LTE-A many solutions are proposed such as access class barring (ACB), extended access barring (EAB), separate resources for MTC, Dynamic allocation of RACH resources, back-off specific schemes, slotted access and pull based RA proposed by 3rd Generation Partnership Project (3GPP) [23]. There are also non-3GPP based solutions self-optimization overload control (SOOC) RA [24], prioritized RA [25], group-Based RA [26], spatial-group-based reusable preamble allocation [27], reliability guaranteed RA [28], non-aloha-based RA [29] and collision-resolution-based RA [30]. 3GPP adapted ACB and EAB for LTE/LTE-A but in NB-IoT only EAB is considered. So the objective of this chapter is to show that broadcasting access barring factor and barring time in system information block-2 (SIB-2) improves the access probability when considered to traditional back-off method.

Access Barring (AB) Mechanism is used for regulating the access request traffic by barring some UEs from accessing the network for certain interval of time. Access Class Barring (ACB) and Extended Access Barring (EAB) are the access barring mechanisms adapted by 3GPP [10]. They are combinedly used in LTE/LTE-A.

5.1 Access Class Barring (ACB)

In Access Class Barring, a barring factor (α) and a barring time (T_{acb}) are broadcasted by eNB in SIB-2 from the available set of barring factors and barring times. If ACB parameters are not present in SIB-2 all UEs are allowed to access the network. When parameters are present UEs randomly generate a value (p) in between 0 and 1, if $p < \alpha$ then UE is able to access the network else it is barred and has to wait for the time

$T_{barring} = (0.7 + 0.6 \times random) \times T_{acb}$, where random is uniformly distributed in between 0 and 1. This process is repeated until the UE generates random value $p < \alpha$.

5.2 Extended Access Barring (EAB)

UEs are divided into 10 classes numbered from 0 to 9 based on the number stored in subscriber identity module (SIM). There are other classes 11 to 15 which are allocated for emergency cases. In EAB, a bitmap is broadcasted in SIB-14 with 10 bits. The UEs belonging to class with bit indicated one can access the network while other class UEs are barred from access the network. EAB activates only in case of high traffic load. EAB activation is indicated by a bit in SIB-14. Only when EAB activation bit is set to one, the bitmap is broadcasted.

There are many works analyzing ACB and EAB in LTE. In [31], authors presented an EAB algorithm analytical model in LTE. In [32], they explained the limiting factors of EAB algorithm. While the impact of barring rates and barring time of ACB on network performance is studied in [33]. Recently in literature there are few works comparing EAB and ACB. In [34], authors showed that optimal performance of ACB is better than EAB in terms of energy consumption.

NB-IoT system adopted only the EAB mechanism and the UEs in NB-IoT system reads SIB-14 only when the access barring bit is set to one in Master Information Block (MIB) [10]. During bursty arrivals if access barring bit is set to 0 then collision happens before access bit is set to one and activation of EAB. Even if EAB is activated if there are large number of UEs belonging to same class then also congestion is high. So we show that combining ACB with back-off method improves access probability.

5.3 Simulation and Comparison

The simulations are done using C++ language in linux platform. For simulation random access in NB-IoT is modelled as multi-band multi-channel slotted ALOHA as in [17]. Considering no physical losses and physical channel errors. UE re-transmits the preamble only when collision happens due to initial sub-carrier selection. Notations are explained in table 5.1

Table 5.1: NOTATIONS USED IN THIS CHAPTER

Symbols	**Definition**
N	Number of UEs in the cell
δ_i	NPRACH periodicity in CE level i
N_i	Initial number of UEs in CE level i
S_i	Number of sub-carriers allocated to CE level i
M	Maximum number of attempts in all CE levels
R_i	Maximum number of attempts per preamble that are allowed in CE level i
W_i	Maximum number of back-off windows in CE level i
α	Access barring factor
T_{acb}	Access barring time
P	Success access probability
D	Mean delay of the successfully accessed UEs

5.3.1 Configuration of parameters and Traffic Models

The basic configuration of the variables are taken from the paper [17].

Table 5.2: BASIC CONFIGURATION OF PARAMETERS

Parameter	**Value**
M	10
R_0,R_1,R_2,	5,5,10
δ_0,δ_1,δ_2	80ms,160ms,640ms
$N_0 : N_2 : N_3$	1 : 1 : 1
W_0, W_1, W_2	512ms,1024ms,4096ms
S_0, S_1, S_2	12,12,12

For showing the advantage of ACB, static access barring factor and time i.e they do not change with load . Simulations are done for above parameters in three traffic models [17]

1. One-shot communication i.e all 'N' UEs access the network at the same time.

2. Uniform arrivals over some interval, 'N' UEs arrive uniformly over first 5s.
3. Beta arrivals over some interval, 'N' UEs arrive over first 5s with beta distribution

One-shot traffic occurs during group paging, uniform traffic is considered as a realistic scenario and beta traffic is considered as an extreme scenario [23]. For simulations, N is varied from 60 to 1200 in steps of 60.

5.3.2 Plots and Inference

The graphs of success access probability and the mean delay (average delay of successful UEs) are plotted in case of three traffic models for three different values of α and T_{acb} {(0.9,4s), (0.7,8s) and (0.5,16s)} [34] .

One Shot Traffic Model

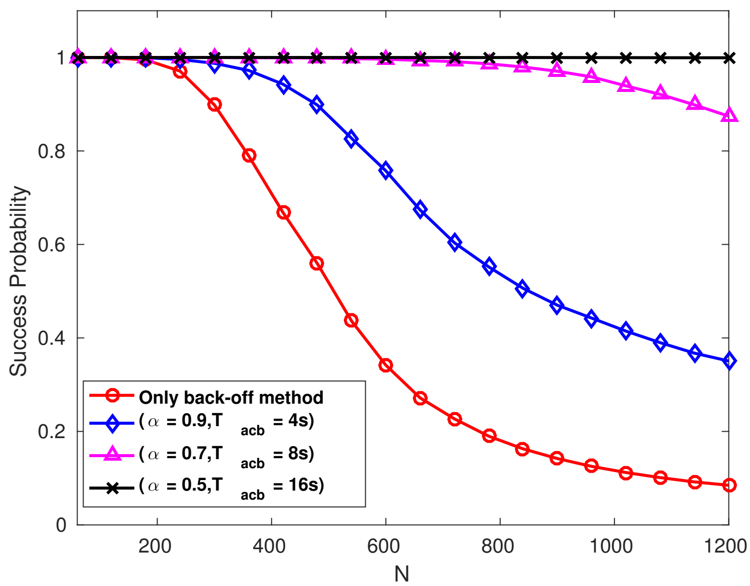

Figure 5.1: Success probability of UEs in random access in one-shot model

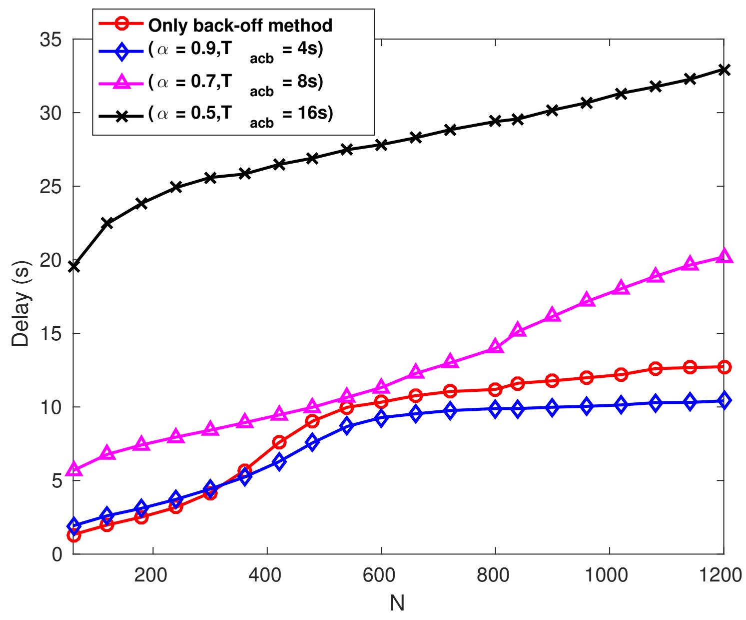

Figure 5.2: Average delay of random access for successful UEs in one-shot model

Uniform Traffic Model

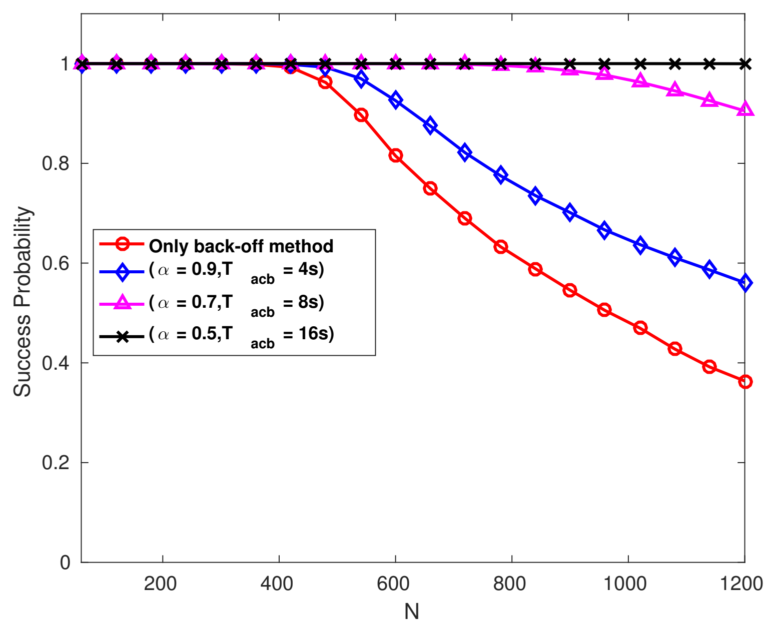

Figure 5.3: Success probability of UEs in random access in uniform model

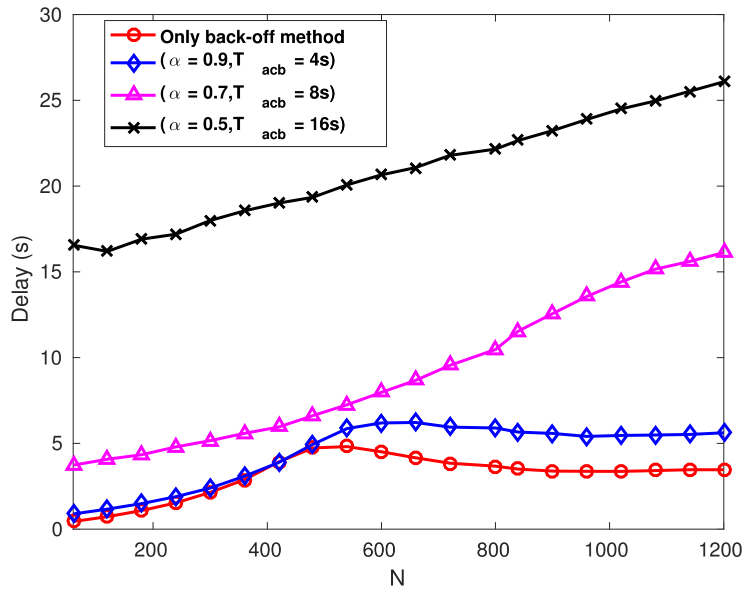

Figure 5.4: Average delay of random access for successful UEs in uniform model

Beta Arrivals Traffic Model

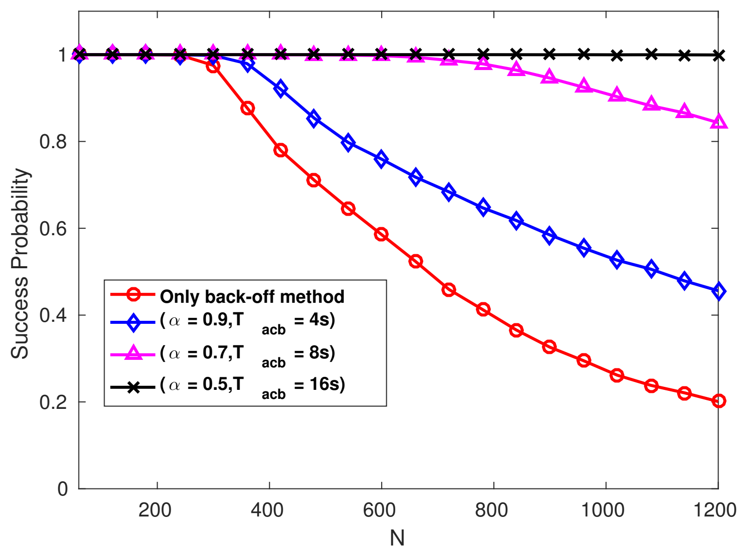

Figure 5.5: Success probability of UEs in random access in beta model

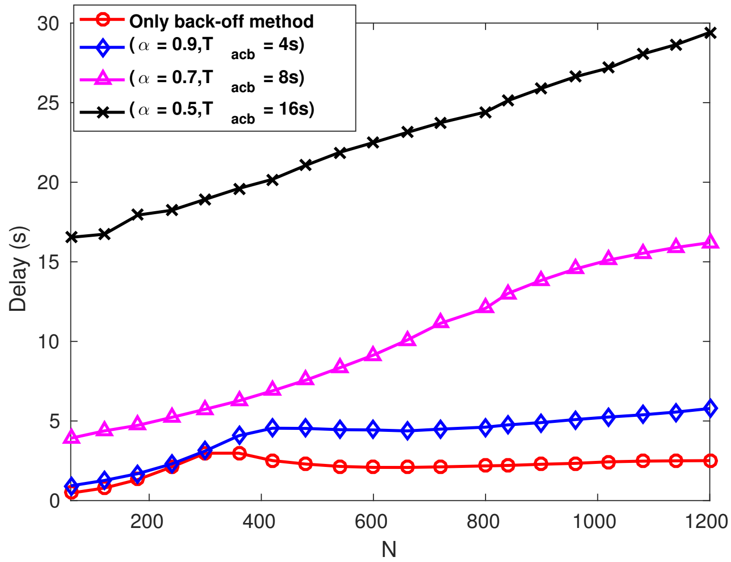

Figure 5.6: Average delay of random access for successful UEs in beta model

Figures 5.1, 5.2 shows the plots for success access probability and delay in case of One-shot traffic model. Similarly 5.3, 5.4 in uniform traffic model and 5.5, 5.6 in beta traffic model. In all the traffic models there is increase in success probability compared to only back-off method for all three sets of α and T_{acb}. In case of (0.5,16) almost all UEs successfully accessed the network in all three traffic models. There was also increase in the average delay for accessing the network. Since NB-IoT is mainly for the delay-tolerant devices it is okay to have increase in delay compared to only back-off method. The trade-off between delay and success probability can be achieved by adjusting the parameters of α and T_{acb}.

Table 5.3: Success probability and delay for different sets of α and T_{acb} in beta traffic model for N=1500

α	T_{acb} = 2s		T_{acb} = 4s		T_{acb} = 8s		T_{acb} = 16s	
	P	$D(s)$	P	$D(s)$	P	$D(s)$	P	$D(s)$
0.5	0.71	8.07	0.82	14.74	0.98	22.21	0.999	29.008
0.7	0.57	4.90	0.69	7.85	0.79	14.49	.95	23.49
0.9	0.40	2.83	0.49	4.25	0.57	7.05	0.64	13.17

Some of the adjustments are presented are in table 5.3. The values in table 5.3 are obtained for $N = 1500$ in beta traffic model. As T_{acb} increases, the barring time will have wide range and congestion will be less so success access probability increases. It can be observed in the table. The back-off values also effects the values of barring factor and barring time. Optimal adjustment of α and T_{acb} is not discussed in this thesis it is left for future work. Finally we have showed that inclusion of barring factor and barring in SIB-2 dramatically increases the success access probability in the system at high number of UEs. In case of low number of UEs there is no much difference in success probability but is better to have α and small T_{acb} to be broadcasted in SIB-2 so that congestion due to sudden arrival of UEs can be mitigated.

CHAPTER 6

Conclusion and Future Works

In this section we conclude the above work and discusses about the future possibilities. We have analyzed the throughput according to UEs initial random access. It is observed that preamble attempts division does not matter if average traffic load per slot is less to the sub-carriers. It is better to have certain number of preamble attempts in higher CE level for high traffic load. The allocation of sub-carriers depends on the number of UEs initially in each CE level. In future, we may analyze the delay of a packet that is transmitted successfully and the probability of dropping a packet. From impact of access barring factor we have showed that the necessity of broadcasting access barring factor and access barring time in SIB-2 for better performance of random access channel. We also showed that increasing access barring time for fixed barring factor increases access probability. Optimal adjustment and dynamic adjustment of access barring factor and barring time are left for future. This concludes the thesis

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