Evaluating Steady-state Performance in Narrowband Internet of Things (NB-IoT)

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Abstract—Next generation wireless communication technology of Internet of Things (IoT) nowadays is already used in many use cases. In 2016 3GPP (3rd Generation Partnership Project) started introducing a new technology called Narrowband Internet of Things (NB-IoT). Targeting to serve the market of IoT devices, NB-IoT is designed to be better in dealing with massive number of devices in a cell, compared to the existing cellular technologies. The biggest challenge to serve massive number of devices in wireless technologies is the random access. This paper presents a simulation result of NB-IoT’s random access procedure under massive number of devices in steady-state condition. A backoff mechanism with retry limit is considered with one coverage enhancement level. The result shows that a probability of transmitting packet also has a role in performance.

Keywords—nb-iot, performance, steady-state, slotted aloha, transmission, collision

I. INTRODUCTION

With the use of wireless or known as the Internet of Things (IoT) that alters the process of human activity between the aspects that exist between digital and physical, creating a wide network of interconnected with artificial intelligence. By 2020, the development of the IoT communication system is expected to be connected over twenty-five billion [1]. IoT technology can help realize stable economic growth because the technology can be used for inspection of goods, arrangements, and other costs. Next generation wireless communication technologies, such as beyond third generation (B3G) and 4G are beginning to emerge. The IEEE 802.16 [2] for high data rate fixed wireless services and the IEEE 802.20 [3] for mobile broadband wireless access service already have working groups in place for development of B3G systems.

In the middle of 2016, 3GPP introduced a technology called Narrowband Internet of Things (NB-IoT). The goal is to be able to handle devices connected to a large number of NB-IoT radio networks and battery life with good (sleeping) beds. NB-IoT uses the existing LTE-A OFDMA infrastructure technology and requires only 180 KHz of capacity for downlink and uplink. The features offered by NB-IoT enable operators to provide services to customers much better, no wonder if this technology will be part of the 5G technology system. The operator can use a carrier frequency to say the GSM carrier frequency (200 KHz) - useful for Physical Resource Block (PRB) generation of 180 KHz under normal circumstances on LTE or to use unused blocks on LTE. The downlink transmission is based on conventional orthogonal frequency-division multiple access (OFDMA) with 15 kHz subcarrier spacing. Both single tone and multi-tone transmissions are supported in the uplink. The subcarrier spacing for the single tone transmission can be either 15 kHz or 3.75 kHz. The multi-tone transmission is based on single-carrier frequency division multiple access (SCFDMA) with 15 KHz uplink subcarrier spacing [4].

NB-IoT devices Message and message delivery from the anchor carrier. In LTE, the device works with RA (NPRACH) from the anchor carrier to explore power data to transmit data. This paper focus on the NB-IoT physical random-access channel (NPRACH). NPRACH refers to the time frequency resource on which random access preambles are transmitted. Transmitting a random access preamble is the first step of random access procedure that enables a user equipment (UE) to establish a connection with the network. Acquiring uplink timing is another main objective of random access in OFDMA systems. The acquired uplink timing is used to command the UE to perform timing advance to achieve uplink synchronization in OFDMA systems. It helps fulfill the important performance objectives of IoT such as long battery lifetime and extended coverage [5].

This paper discusses RA NB-IoT with backoff and mobile users with up to 200 users. In chapter 2 will be discussed about literature study, chapter 3 methodology, chapter 4 simulation, and chapter 5 conclusion.

II. LITERATURE STUDY

A. Narrowband physical RA channel (NPRACH)

All devices receive synchronization signals and broadcasting messages from an anchor carrier. As in LTE, a device performs random access (RA) through narrowband physical RA channel (NPRACH) [6] from the anchor carrier to acquire uplink resource for data transmission. NPRACH is a set of consecutive subcarriers in a time interval specially reserved for preamble transmission [7]. Preamble consists of four symbol groups which are repeated several times. The base station chooses a proper number of repetitions for different CE
levels to ensure good signal quality at the receiver. NPRACH duration in each

CE level is set to accommodate this repetition [8]. The first repetition is randomly chosen from a set of subcarriers available in the NPRACH of the CE level.

Sometimes the collision while transmitting is occurred. The collision occurs when two or more UEs choose the same initial subcarrier. The UE shall perform random backoff and retransmit a new attempt in a newly chosen initial subcarrier in the next NPRACH.

The access mechanism in NPRACH in each CE level is based on multi-channel slotted ALOHA system. The access mechanism in each NPRACH can be modelled by a multi-channel slotted ALOHA system by considering maximum number of preamble transmissions, size of backoff windows, and number of subcarriers in each CE level [7].

On the paper Xingqin Lin, et al [9] which focused on NPRACH design, stated that the random-access preamble design is based on single subcarrier transmission with frequency hopping within a configured NPRACH band within the OFDM resource grid, as illustrated in Figure 1.

![Figure 1 Illustration of 3GPP NB-IoT physical random-access channel design [9]](image)

We can see that the hopping consists of both inner layer fixed size hopping and outer layer pseudo-random hopping. Outer layer pseudorandom hopping is applied between groups of 4 symbol groups. Inner layer fixed size hopping is applied within every 4 symbol groups.

- First level single-subcarrier hopping is used between the first and the second and between the third and the fourth symbol groups. Further, the two single-subcarrier hoppings are mirrored, i.e., if the first hopping is “UP”, the second hopping is “DOWN”, and vice versa.
- Second level 6-subcarrier hopping is used between the second and the third symbol groups.

Samuele Foni et al [10] aims of the paper is to know also to serve the LENA structure and to develop a real NB-IOT system. The research have been made to create a module on uplink and downlink on NB-IOT through the NB-IOT master block information (MIB) and NB-IOT block information system (SIB), where both systems use different systems from LTE systems. MIB NB-IOT and SIB NB-IOT are essential for the NB-IOT system as it is one of the requirements required to connect the new one before connecting to the interface.

The main focus of the paper is Radio Resource Control (RRC) and Physical Layer. The RRC has functions in the settings between eNB and User Equipment and vice versa, and also in fixing between uplink and downlink.

NB-IOT works on 180 KHz frequency. NB-IOT has five physical paths used for communication are 3 downlink lines (NPBCH, NPDCCH, NPDSCH) and 2 uplink lines (NPUSCH and NPRACH). In the figure 2 below describes the architecture that has been created on the NB-IOT system, where in the drawing the logic module between the LENA module and the modification must be made using the NS-3 code.

![Figure II-2 The Architecture on NB-IoT [10]](image)

The paper has tested the exchange of messages between MIB NB-IOT and SIB NB-IOT where exchanges were made between PRC and EU. The test results show that the encapsulation process has been in accordance with the scenario. In addition, testing is also done with the exchange of PRC with physical paths, including multiplexing and demultiplexing on the NB-IOT runs well. In future research, the paper hopes the module can be equipped with features of sphinx and doxygen [10].

B. Multichannel Slotted ALOHA

Multichannel slotted ALOHA systems are a system containing parallel multi-channel slotted ALOHA systems operating in different frequency bands which have been widely used to model the random-access channel of a cellular network. Several analytical models have been proposed to investigate the performance of the multichannel slotted ALOHA systems, the multichannel slotted Aloha is analyzed for fixed bandwidth per channel or fixed total bandwidth, which is designed for multichannel satellite communication. In this system, each UE is assigned to an initial band. A UE transmits a packet by randomly selecting a sub-channel form its initial band. When the time is slotted, each transmission is aligned to the slot which is assumed that the UE knows whether the transmission is successful or failed immediately. The duration on each slot in all bands are synchronized. There are some possibilities that collision will occur. It happens
if two or more UEs transmitting a packet simultaneously in the same slot through the same sub-channel. Collided UEs retransmit the packet. The maximum number of transmissions in each band is band-specific and total number of transmissions that a UE can perform is limited. When UE’s last attempt in a band is collided, it retransmits at the next higher band until its maximum number of attempts is reached. The UE drops the packet if it still fails in its very last attempts.

The random-access protocol has also been modified for various environments, the retransmission probability is dynamically adjusted according to the transmission result in the previous slot. Redundant transmissions are exploited to meet a user’s deadline requirement. Random-access protocol is analyzed when long-range dependent traffic is transmitted over random access channels [11].

III. METHODOLOGY

This research uses an analytical model to simulated NB-IoT technology on 1 base station using backoff method for 10 minutes (T) and use 1 coverage enhancement (CE) with 200 users (M). A packet will be transmitted to 24 sub carriers (Nc) randomly within three probabilities to generate uplink packet (Ppkt) 10%, 20%, and 30% running on a maximum transmitted power. Our assumption a Transmitted ACK (TACK) consume 2 slots while a Delivered ACK (DACK) consume 1 slot, and backoff window (W BO) use 10 slots, where each slot has a time to transmit 5ms. In addition, the graph to be analyzed is the Ppkt sent based on the increase of user (multiple of 5 up to 200) with the resulting packet. There are several components that checked are:

a. Normalized throughput: the number of packets sent successfully (ΣPACK) divided by the total number of generated packages (ΣPgen)

\[ NT = \frac{\sum P_{ACK}}{\sum P_{gen}} \]

d. Average delay: delay rate for all successful packets sent. Time when packet in ACK (\(t_{ACK}\)) minus time when packet is generated (\(t_{gen}\))

\[ D = t_{ACK} - t_{gen} \]

c. Resource efficiency: number of packets sent successfully divided by the number of slot during simulation time.

\[ \eta_r = \frac{\sum P_{ACK}}{\sum P_{gen} \times \sum t_{slot}} \]

d. in addition to these three components we also measuring the difference between the generated and ACKed packets. Our assumption of maximum packet loss is not more than 50%. Our purpose is to find an optimal condition for each Ppkt and best possibility of the NB-IoT performance.

\[ L = \frac{(t_{gen} - t_{ACK})}{t_{gen}} \times \% \]

For a better result we have run a simulation for 1000 times and try to make it similar to NB-IoT mechanism. This research uses C programming language that runs on Debian Linux operating system 9 and PCG Random (pcg-random.org) for random number generator. While its built on Linux environment, this program also compatible with Windows and MacOS Operating System.

IV. SIMULATION

Simulation start with \(T_m\) defined to 10 minutes converted into 120.000 slots (\(T_{slot}\)) then, it starts to generate a random access to \(N_c\) for each \(P_{pkt}\) and \(M\) multiple of five, a user who has no package (already successfully sent or already dropped), is not waiting backoff, and is not waiting for ACK declare as an idle user, where for not idle user is declare as backlogged user. At any time, each idle user has a probability to generate an uplink packet of \(P_{pkt}\), first transmission or retransmission is preceded by a backoff. For a package, retransmission can be done as much as \(NPT_{max} - 1\) times (excludes first transmission). At the end of simulation, we capture all the four components result and analyzed the output.

A. Normalized throughput

From our simulation result we have found a normalized throughput graph is directly proportional to the number of users as seen in figure IV-1. The \(P_{pkt}\) 10% has higher throughput and much stable curve than the other.

\[ \text{Figure IV-1 Normalized throughput} \]

B. Average delay

An average delay seen to be flat but in general is directly proportional to the number of users. We also add another 500 times simulation for the oddity of the result just to make sure it was not an error from the random generator. The \(P_{pkt}\) 10% has lower average delay than the other since it has lower probability of user for transmitting package.

\[ \text{Figure IV-2 Average delay} \]
C. Resource efficiency
From Figure IV-3 we found a resource efficiency graph is directly proportional to the number of users, the $P_{pkt}$ 30% has a lower efficiency compare to the other.

![Resource Efficiency Graph](image)

**Figure IV-3 Resource Efficiency**

D. Number of ACKed and Generated packets
From the simulation result we have found that $P_{pkt}$ 10% has more efficient than the other, a different space in result as shown in Figure IV-4 has more gap than $P_{pkt}$ 20% between $P_{pkt}$ 30%.

![Number of ACKed packets](image)

**Figure IV-4 Number of ACKed packets**

While on generated packets it does not has a big different beside $P_{pkt}$ 10% is higher than the other and the number of generated packets nearly overlapping one and another as seen in Figure IV-5.

![Number of generated packets](image)

**Figure IV-5 Number of generated packets**

E. Percentage of packets loss
Our final analysis is measuring the percentage of packet loss, shown in the table that the maximum $M$ for $P_{pkt}$ 10% is 50, 40 for $P_{pkt}$ 20%, and 35 for $P_{pkt}$ 30%. From tables below we able to determine a performances of NB-IoT as shown on Figure IV-6, most of the $P_{pkt}$ have an issue when $M$ reach around 50 users while $P_{pkt}$ 10% has a constant increment.

**TABLE IV-1 Excerpt of $P_{pkt}$ 10% packets loss**

<table>
<thead>
<tr>
<th>Users</th>
<th>ACKed packets</th>
<th>Generated packets</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>50.6040</td>
<td>54.9270</td>
<td>8%</td>
</tr>
<tr>
<td>10</td>
<td>57.5260</td>
<td>65.9560</td>
<td>13%</td>
</tr>
<tr>
<td>15</td>
<td>55.5780</td>
<td>68.2950</td>
<td>19%</td>
</tr>
<tr>
<td>20</td>
<td>54.6510</td>
<td>71.6810</td>
<td>24%</td>
</tr>
<tr>
<td>25</td>
<td>54.1740</td>
<td>75.6680</td>
<td>28%</td>
</tr>
<tr>
<td>30</td>
<td>53.3520</td>
<td>79.4000</td>
<td>33%</td>
</tr>
<tr>
<td>35</td>
<td>51.8090</td>
<td>82.4470</td>
<td>37%</td>
</tr>
<tr>
<td>40</td>
<td>49.7220</td>
<td>84.9350</td>
<td>41%</td>
</tr>
<tr>
<td>45</td>
<td>47.9040</td>
<td>88.1120</td>
<td>46%</td>
</tr>
<tr>
<td>50</td>
<td>46.9640</td>
<td>91.6300</td>
<td>49%</td>
</tr>
<tr>
<td>55</td>
<td>46.2120</td>
<td>95.6480</td>
<td>52%</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>200</td>
<td>17.4360</td>
<td>214.4170</td>
<td>92%</td>
</tr>
</tbody>
</table>

**TABLE IV-2 Excerpt of $P_{pkt}$ 20% packets loss**

<table>
<thead>
<tr>
<th>Users</th>
<th>ACKed packets</th>
<th>Generated packets</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>47.3460</td>
<td>51.9340</td>
<td>9%</td>
</tr>
<tr>
<td>10</td>
<td>49.2090</td>
<td>58.4960</td>
<td>16%</td>
</tr>
<tr>
<td>15</td>
<td>47.0440</td>
<td>61.250</td>
<td>23%</td>
</tr>
<tr>
<td>20</td>
<td>44.7180</td>
<td>63.4800</td>
<td>30%</td>
</tr>
<tr>
<td>25</td>
<td>43.3710</td>
<td>66.8550</td>
<td>35%</td>
</tr>
<tr>
<td>30</td>
<td>41.8930</td>
<td>70.2770</td>
<td>40%</td>
</tr>
<tr>
<td>35</td>
<td>39.8440</td>
<td>72.9310</td>
<td>45%</td>
</tr>
<tr>
<td>40</td>
<td>38.9400</td>
<td>76.7990</td>
<td>49%</td>
</tr>
<tr>
<td>45</td>
<td>36.2620</td>
<td>79.1220</td>
<td>54%</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>200</td>
<td>9.6620</td>
<td>208.8090</td>
<td>95%</td>
</tr>
</tbody>
</table>

**TABLE IV-3 Excerpt of $P_{pkt}$ 30% packets loss**

<table>
<thead>
<tr>
<th>Users</th>
<th>ACKed packets</th>
<th>Generated packets</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>43.7300</td>
<td>48.5850</td>
<td>10%</td>
</tr>
<tr>
<td>10</td>
<td>44.6310</td>
<td>54.2700</td>
<td>18%</td>
</tr>
<tr>
<td>15</td>
<td>42.8460</td>
<td>57.3260</td>
<td>25%</td>
</tr>
<tr>
<td>20</td>
<td>41.6250</td>
<td>61.0050</td>
<td>32%</td>
</tr>
<tr>
<td>25</td>
<td>38.6160</td>
<td>62.8920</td>
<td>39%</td>
</tr>
<tr>
<td>30</td>
<td>37.1980</td>
<td>66.3470</td>
<td>44%</td>
</tr>
<tr>
<td>35</td>
<td>34.7340</td>
<td>68.8930</td>
<td>50%</td>
</tr>
<tr>
<td>40</td>
<td>33.4390</td>
<td>72.4750</td>
<td>54%</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>200</td>
<td>6.8860</td>
<td>206.5730</td>
<td>97%</td>
</tr>
</tbody>
</table>

**TABLE IV-4 Excerpt of $P_{pkt}$ 30% packets loss**

**Figure IV-6 Percentage of packets Loss (L)**

![Percentage of packets Loss Graph](image)
V. CONCLUSION

Based on the simulation result, it can be concluded that the probability to generate uplink package is important in NB-IoT performance. Backoff windows able to minimize a collision and reduce packet loss. NB-IoT has decent performance with one CE and a small-to-medium users, we propose to use multiple CE and allocate more sub carriers for high density environment usage.

This analysis verified by computer simulation model and still needs further development, especially on random generator function and testing on simulation for a better result. Our next project is developing a simulator to produce more result but not limited:

1. the average number of new packages generated in each slot
2. the average number of packets sent (including transmission and retransmission) in each slot
3. the average number of packets collide in each slot
4. the average number of empty sub-carrier (not selected by any user) in each slot

REFERENCES