Random Access Preamble Detection for Narrowband IoT Systems

A Seminar Report

submitted in partial fulfillment of the requirements for the award of the degree of

Master of science

in

Electrical Engineering

by

Praveen Kumar N
(Roll No: 201082001)

With the guidance of
Dr. Naveen M B

॥ सा विद्या या विमुक्तये ॥
भारतीय प्रौद्योगिकी संस्थान धारवाड़
Indian Institute of Technology Dharwad

to the

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOOGY, DHARWAD
DHARWAD, KARNATAKA-580011 (INDIA)

Dec, 2020

Abstract

Narrowband IoT (NB-IoT) is a low-power wide-area network (LPWAN) technology standard developed to provide improved coverage for massive number of low-throughput low-cost devices with low device power consumption in delay-tolerant applications. A new single tone signal with frequency hopping has been designed for NB-IoT Physical Random Access CHannel (NPRACH). When multiple uplink users attempt to attach simultaneously, the base station receives superimposed NPRACH preambles and must detect all users and acquire their synchronization parameters: time-of-arrival (ToA) and residual carrier frequency offset (RCFO). Here we discuss receiver techniques for user detection and estimation of ToA and RCFO for detected users.

Contents

List of Figures

Chapter 1

Introduction

1.1 Low Power Wide Area(LPWA) technologies:

- Internet of Things (IoT) has undergone a drastic change in the last few years. The number of IoT devices are increasing at a phenomenal rate and several new IoT applications related to vehicles, logistics, power grid, agriculture, metering, etc. have sprung up.
- Machine type communications (MTC) can be categorized into three folds 1) Short-distance MTC (distance $\leq$10 m), 2) Medium-distance MTC (distance ranges among [10 m, 100 m]), and 3) Long-distance MTC (distance $\geq$100 m).[1]

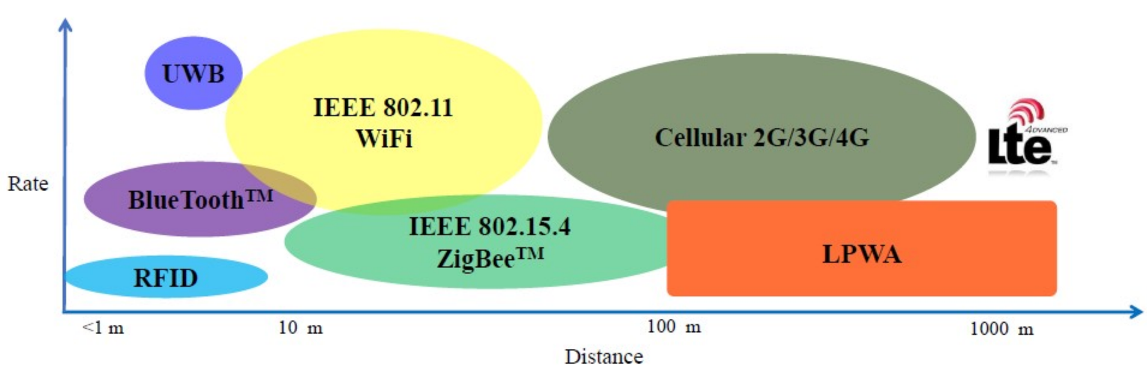

Figure 1.1: Coverage and transmission rate comparisons among wireless communication technologies.[1]

- Long-distance low-rate MTC is a new ongoing area, and is applicable in scenarios such as meters, tracking, smart parking, smart agriculture and so on and There are ample IoT use cases, where applications/deployments often battery-powered 'things' need cheap, mobile, low-power and long-range connectivity, whereby low bandwidth (low bit rate) is more than enough. Low power wide area (LPWA) technologies is a promising solution for long range and low power Internet of Things (IoT) and machine type communication (MTC) applications. The LPWA networks have critical requirements for long battery life, extended coverage, high scalability, and low device and deployment costs.

- The LPWA technologies can be cellular or non-cellular wireless technologies. The cellular technologies include LTE-M (LTE-machine type communication) which include eMTC(enhanced MTC),EC-GSM-IoT (Enhanced Coverage-GSM-IoT) and Narrowband Internet of Things (NB-IoT), which uses licensed spectrum. whereas non-cellular technologies uses unlicensed spectrum(e.g:LoRa(Longe Range) and SigFox).[7]

Parameters/Technologies	LoRa	SigFox	eMTC	NB-IoT
Spectrum	unlicensed	unlicensed	licensed	licensed
Modulation	CSS	UL:DBPSK DL:GFSK	UL:SC-FDMA DL:OFDMA	UL:SC-FDMA DL:OFDMA
Bandwidth	7.8 kHz-500 kHz	200 kHz	1.08 MHz (1.4 MHz carrier bandwidth)	180 kHz (1200 kHz carrier bandwidth)
Range	urban:2∼5 km suburban:∼ 15 km	urban:3∼10 km suburban:30∼50 km	urban:∼ 5 km suburban:∼ 17 km	urban:1∼8 km suburban:∼ 25 km
Data rate	<50 bps	<100 bps(EU) <600 bps(USA)	<1 Mbps	160∼250 kbps(DL) 160∼200 kbps(UL)
Battery Life	>10 years	8∼10 years	5∼10 years	>10 years
Price	<$5	∼ $10	<$10	<$5

Figure 1.2: Comparisons among LoRa, SigFox, eMTC and NB-IOT.[1]

1.2 Introduction to Narrowband-IoT (NB-IoT):

- NB-IoT is a LPWA technology which was proposed by 3GPP in September, 2015 and was eventually standardized by 3GPP in June, 2016.The advantage of narrowband transmission lies in providing both coverage and capacity extension. The architecture of NB-IoT is extensively derived from legacy LTE. NB-IoT technology is appropriate for users transmitting low, infrequent, and delay-tolerant data. Furthermore, ubiquitous coverage, scalability, and coexistence with LTE network has made the deployment of NB-IoT simpler and faster.[7]

1.2.1 Use cases of NB-IoT:

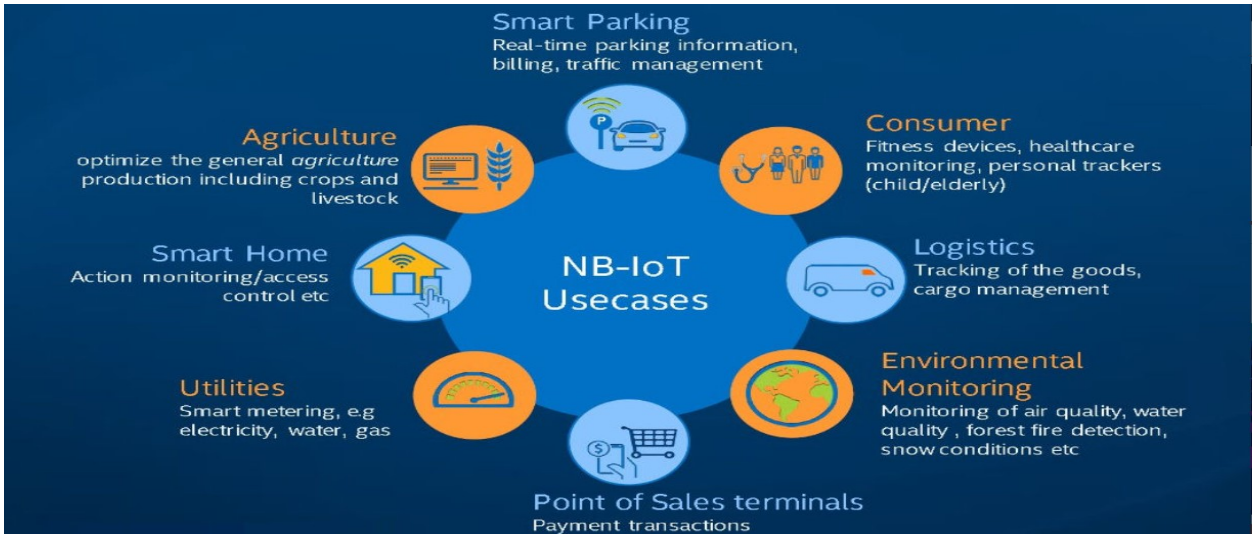

Figure 1.3: Use cases of NB-IoT

1.2.2 Objectives of NB-IoT:

- NB-IoT system aims to provide both indoor and out- door deep coverage. The coverage of NB-IoT is up to 20 dB more when compared to the legacy LTE network. While conventional LTE supports a Maximum Coupling Loss (MCL) of 144 dB, NB-IoT supports an MCL of 164 dB.[7]

- To serve UEs having different ranges of path loss, there are three coverage enhancement levels (CE0, CE1, CE2).CE level 0 corresponds to normal coverage, and CE level 2 to the worst case, where the coverage may be assumed to be very poor.A maximum of 2048 repetitions for Downlink (DL) and 128 repetitions for Uplink (UL) are defined.

- However, there are two trade-offs of increasing the coverage. Bandwidth reduction decreases the data rate while a large number of repetitions increases data transmission latency and device's energy consumption[7]

- NB-IoT devices are designed to have more than 10 years of battery life. To ensure a long battery life of NB- IoT devices, 3GPP has introduced Power Saving Mode (PSM) and enhanced Discontinuous Reception (eDRX) modes.
- In NB-IoT communication model, users send only low, infrequent, and delay-tolerant data. So, a massive number of devices can be catered simultaneously by a single cell.
- NB-IoT reuses the LTE design extensively, including the numerologies, downlink orthogonal frequency-division multiple-access (OFDMA), uplink single-carrier frequency-division multiple-access (SC-FDMA), channel coding, rate matching, interleaving, etc. This significantly reduces the time required to develop full specifications.[3]

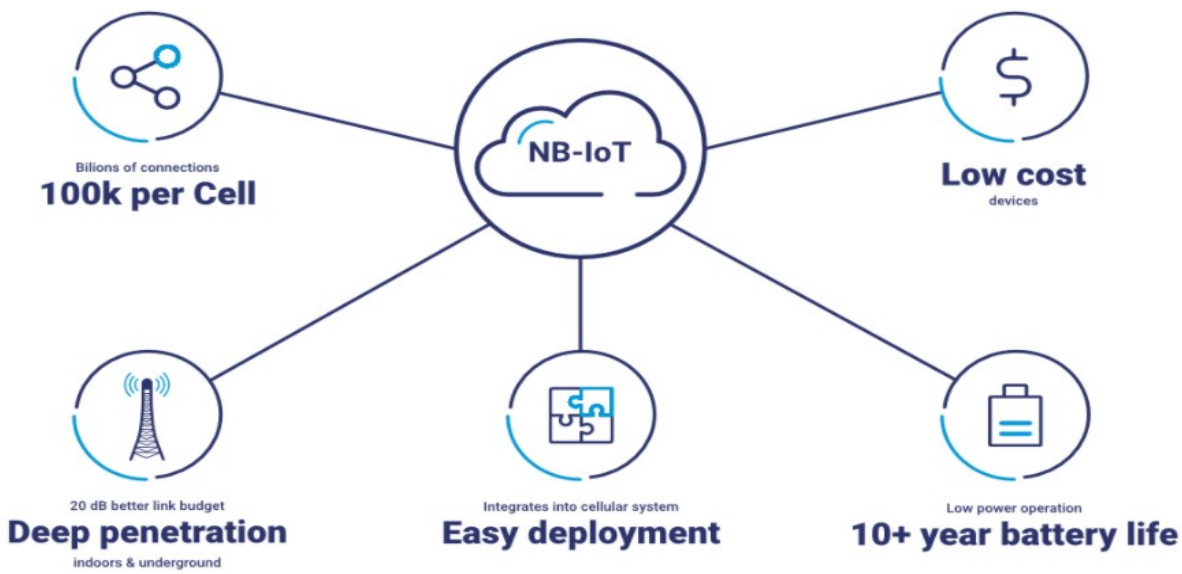

Figure 1.4: Objectives of NB-IoT

1.2.3 NB-IoT Deployment scenarios:

- NB-IoT has a channel bandwidth of 200 kHz but occupies only 180 kHz. This is equal to one resource block in LTE (1 RB). With this selection, the following operation modes are possible:

  Stand alone operation: A possible scenario is the utilization of currently used GSM frequencies. With their bandwidth of 200 kHz there is still a guard interval of 10 kHz remaining on both sides of the spectrum.

Guard band operation: utilizing the unused resource blocks within a LTE carrier's guard-band.

In-band operation: utilizing resource blocks within an LTE carrier.[4]

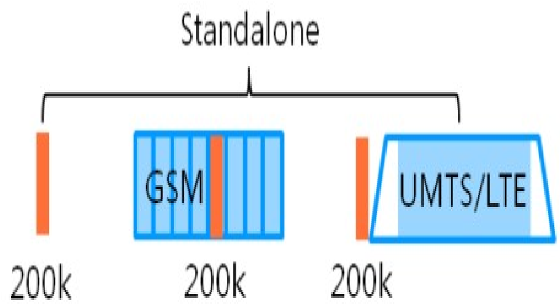

Figure 1.5: Three deployment scenarios of NB-IoT.[2]

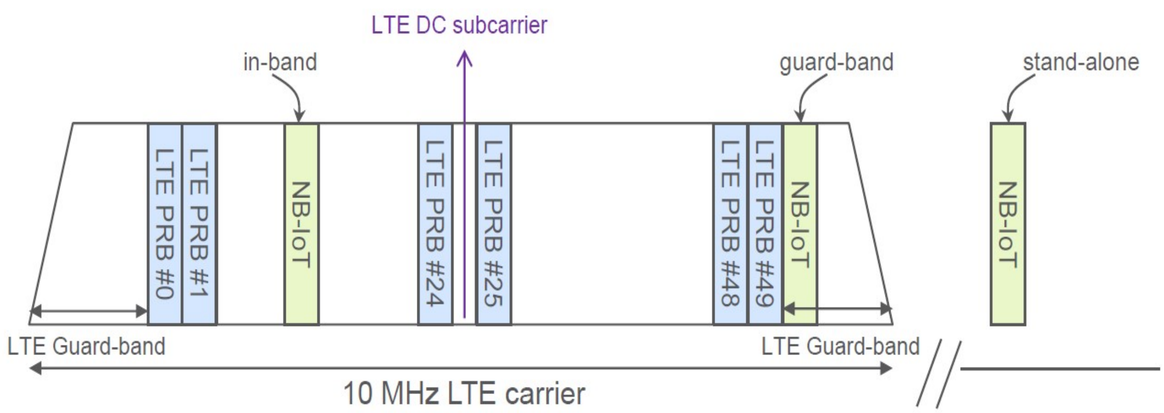

Figure 1.6: Examples of NB-IoT stand-alone, LTE in-band and guard-band deployments.[3]

Chapter 2

Physical Layer in NB-IoT:

2.1 Downlink:

2.1.1 Frame and slot structure:

- The downlink (DL) is the same as in LTE but has limiting simplifications. The downlink uses OFDMA with a carrier spacing of 15 kHz. NB-IoT uses only 12 carriers, which leads to an occupied bandwidth of 180 kHz. One slot consists of seven OFDMA symbols. This produces the following grid, which is exactly equal to one resource block (1 RB) in LTE. A resource element (RE) is one subcarrier in one OFDMA symbol and is shown as one square in the figure. NB-IoT defines only QPSK modulation in the downlink. Each of these resource elements carries a complex value with values according to the modulation scheme. [4]
- These slots are summed up into subframes and radio frames in the same way as for LTE.

2.1.2 Physical channels and signals:

- NB-IoT defines three physical channels with the same designation as in LTE:
  - **NPBCH** - the narrowband physical broadcast channel carries the narrowband master information block (MIB-NB)

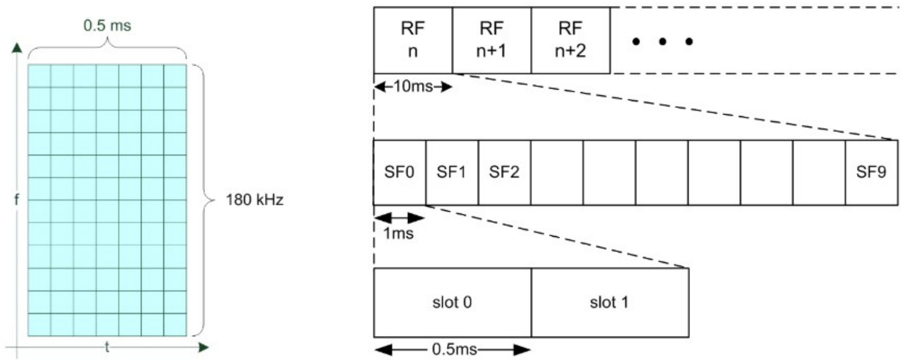

Figure 2.1: Downlink slot and frame structure.[4]

  - **NPDCCH** – the narrowband physical downlink control channel provides the UE with two important pieces of information: (i) Which data are directed towards the UE in the downlink (NPDSCH) (ii) What resource the UE can use in the uplink.
  - **NPDSCH** - the narrowband physical downlink shared channel transports user data in the downlink.[4]

- As in LTE, NB-IoT provides the UE with Reference and synchronization signals in the downlink. Synchronization signals help the UE to perform cell search, which includes time and frequency synchronization,and cell identity detection(NCellID-Narrowband physical cell ID).
  - Narrowband primary synchronization signal (**NPSS**)
  - Narrowband secondary synchronization signal (**NSSS**)
- The narrowband reference signal (**NRS**) helps the UE to estimate the channel.[4]

2.2 Uplink:

- In the uplink (UL), two different possibilities are defined. It can use either a single carrier or multiple carriers.
  - Single-tone: each user only uses one subcarrier at a time, with 15 kHz or 3.75 kHz carrier spacing.

– Multitone: SC-FDMA with 15 kHz carrier spacing. multiple subcarriers are simultaneously used by the same user.[8]

- Again there are 7 SC-FDMA symbols within a slot. With a carrier spacing of 15 kHz, 12 carriers are available; 3.75 kHz spacing yields 48 carriers.The symbol duration for 3.75 kHz subcarrier spacing has four times the duration compared to 15 kHz, which results in a slot length of 2 ms.

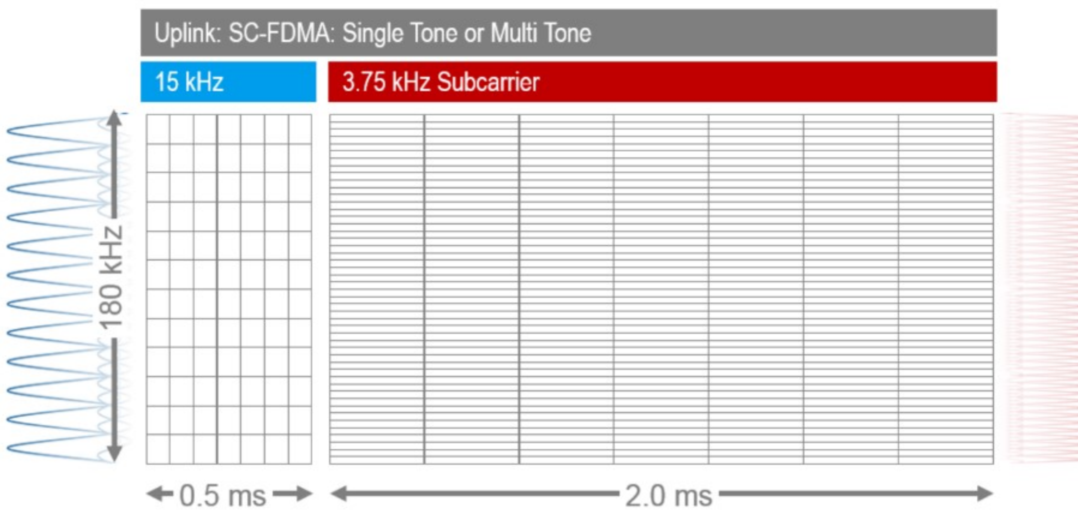

Figure 2.2: Resource element grid for one slot in the uplink.[4]

2.2.1 Physical channels and signals:

- NB-IoT defines two physical channels and a demodulation reference signal (DMRS).
  - **NPUSCH** – Narrowband Physical Uplink Channel.
    - Physical UL shared channel(UL-SCH) NPUSCH transports two types of information: 1) The actual data in the uplink (NPUSCH format 1) 2) Uplink control information (UCI) (NPUSCH format 2)
    - The smallest unit to map a transport block is the resource unit (RU). Its definition depends on the PUSCH format and subcarrier spacing. table below provides an overview of possible RU's.
    - Repetitions of user data block over a specified number of slots is the key technique allowed for NB-IoT to achieve deep penetration in excessive bad

radio conditions. In the case of NPUSCH, the number of repetitions depends on the CE level and is chosen from the set $(1, 2, 4, 8, 16, 32, 64, 128)$.[8]

NPUSCH format	Transport channel	Δf in kHz	Number of carriers	Number of slots	T^{slot} in ms	T^{RU} in ms
1	UL-SCH	3.75	1	16	2	32
		15	1	16	0.5	8
			3	8	0.5	4
			6	4	0.5	2
			12	2	0.5	1
2	UCI	3.75	1	4	2	8
		15	1	4	0.5	2

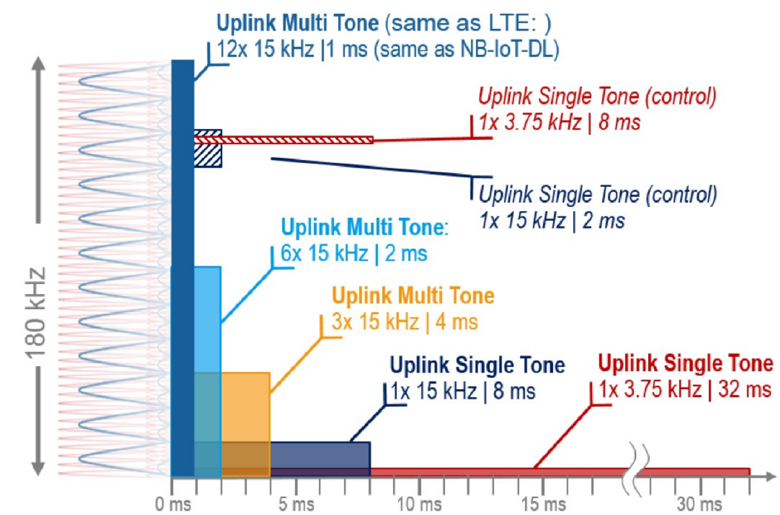

Figure 2.3: Overview of possible resource units(RU's).[4]

– **NPRACH** – Narrowband Physical Random Access Channel.

Chapter 3

Random Access Channel (NPRACH):

3.1 Preamble design and hopping pattern

- The Random Access Channel (NPRACH) uses a single tone with frequency hopping and 3.75 kHz subcarrier spacing.
- The preamble is based on symbol groups on a single subcarrier. preamble transmission comprises of 4 symbol groups transmitted without gaps While each group uses a single subcarrier, it can hop across 12 subcarriers and each symbol group has a cyclic prefix (CP) followed by 5 symbols.
- Different NPRACH resource configurations can be deployed in a cell, each corresponding to a different coverage class. Each one is described through periodicity, the number of repetitions, starting time, frequency location, and the number of subcarriers.[5]
- Two preamble formats are defined, **format 0** and **format 1**, which differ in their CP length. The CP length is 66.67s (format 0) for cell radius up to 10 km and 266.7s (format 1) for cell radius up to 40 km.[3]
- The five symbols have a duration of $T_{SEQ} = 1.333ms$ prepended with a CP of $T_{CP} = 67\mu s$ for format 0 and $267\mu s$ for format 1, giving a total length of $1.4ms$ and $1.6ms$, respectively. A single NPRACH preamble lasts either $5.6ms$ or $6.4ms$, when format 0 or format 1 is applied,respectively.
- Depending on the coverage level, the cell may indicate that the UE shall repeat the preamble 1, 2, 4, 8, 16, 32, 64, or 128 times, using the same transmission power on

each repetition.Each repetition consists of symbol groups transmitted at four different subcarriers (within a band of 12 subcarriers) that follow a predefined frequency hopping pattern

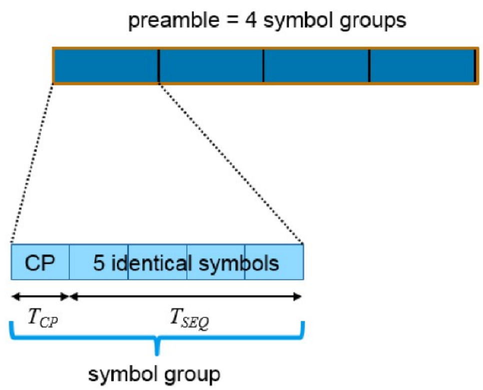

Figure 3.1: NPRACH preamble.[4]

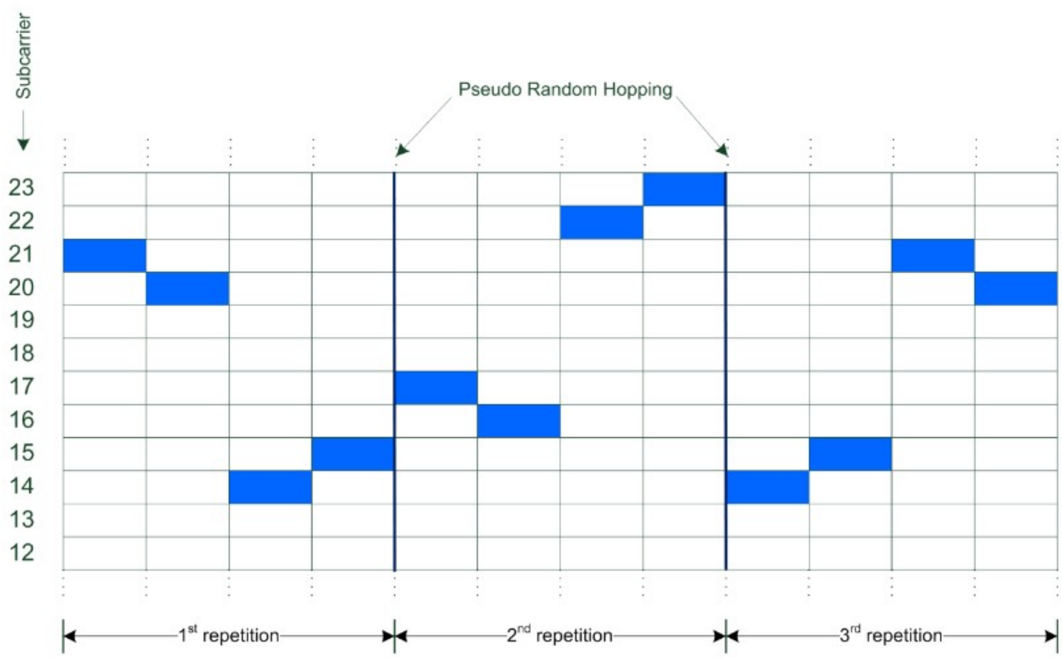

Figure 3.2: An illustration of NPRACH frequency hopping.[4]

- The UE selects the subcarrier for the transmission of the first preamble symbol group.The subcarriers for next 3 symbol groups are determined by an algorithm which depends only on the location of the first one. For the subcarrier selection of the first symbol group of the next repetition, a pseudo-random hopping is applied, where NCellID and the repetition number are used as input.

- The choice of the subcarrier for preamble transmission is random and independent of the choice made by other devices. If more than one devices from the same CE level select the same initial subcarrier in the same PRACH occasion, it results in a collision.

- The frequency hopping algorithm is designed in a way that different selections of the first subcarrier lead to hopping schemes which never overlap. Hence there are as many different congestion free preambles as there are subcarrier allocated to the NPRACH.The preamble sequence is built upon a Zadoff-Chu sequence, which depends on the subcarrier location.

- With the subcarrier spacing of 3.75 KHz, the NPRACH is a set of 48 subcarriers with a basic sub-carrier allocation unit of 12 sub-carriers. Thus, 12, 24, 36 or 48 orthogonal preamble sequences are possible.[5]

Figure 3.3: Two different preamble sequences[5]

3.2 Transmitted and received signals

- Let N be the FFT size and N_{cp} be the number of cyclic prefix samples. Therefore a symbol group consists of $N_{cp} + \eta N$ samples($\eta = 5$). $N_{cp} = N/4$ for preamble format 0 and $N_{cp} = N$ for preamble format 1.

- A random access preamble consists of L symbol groups. The length L of the preamble is determined by the target operating signal-to-noise ratio (SNR) or target coverage level. $L = 8, 32$ and 128 for CE1,CE2 and CE3 respectively.

- Lets denote the subcarrier index used by symbol group m as $\Omega(m)$, $m = 0 \ldots L - 1$, where $\Omega(.)$ is a generic mapping from symbol group index to the subcarrier index. for e.g. it can be the multi-level hopping pattern adopted in NPRACH.

- Let $u[m]_{m=0}^{L-1}$ denote the sequence of random access preamble.The baseband equivalent digital signal for the random access preamble transmission can be written as

$$s[n;m] = \frac{\sqrt{E}}{N} \sum_{k} S[k;m] e^{j2\pi \frac{k}{N} n}, \quad n = -N_{cp}, \dots, N-1$$

where $s[n;m]$ is $n-th$ sample of $m-th$ symbol group and $S[k;m]$ denotes symbol on $k-th$ subcarrier during $m-th$ symbol group.

- For the narrow random access hopping range that is not larger than 45 kHz(12 subcarriers) the channel can be sufficiently modeled using single channel coefficient $h[n;m]$ at the $n-th$ sample of the $m-th$ symbol group

$$h[n;m] = a[m]\delta[n],$$

where $a[m]$ is the channel gain at $m-th$ symbol group

- For each symbol group receiver discards first N_{cp} samples and performs FFT on remaining ηN samples. the $i-th$ received symbol in symbol group m is given by

$$\tilde{y}[i;m] = B(\Delta f, D) a[m] u[m] e^{j2\pi \Delta f(m(N_{cp}+\eta N)+iN)} e^{-j2\pi \frac{\Omega m}{N} D} + \tilde{v}[i;m].$$

$$B(\Delta f, D) = \sqrt{E} \frac{sin(N\pi\Delta f)}{Nsin(\pi\Delta f)} e^{j2\pi\Delta f(\frac{N-1}{2}-D)}$$

where D is time of arrival (ToA) to be estimated and $D \in [0, N_{cp}-1]$, Δf is the residual carrier frequency offset (CFO) and $\tilde{v}[i;m]$ is a complex AWGN with zero mean and variance N_0.[6]

3.2.1 Preamble detection and estimation

- Based on the received signal, The problem at the base station is to detect the presence of the active UEs and for each detected UE, estimate its ToA and CFO parameters accurately and efficiently.

- Here we make the simplifying approximation of a block fading model: $a[m]_{m=0}^{L-1}$ do not change in a block of Q symbol groups but change independently over the blocks. here Q is chosen such that L/Q is an integer.

$$a[m] = \tilde{a}_g$$

where $\tilde{a}_g$ is the channel coefficient for block g, and $(\tilde{a}_g)_{g=0}^{L/Q-1}$ are independent.

- With the block fading assumption, ToA and residual CFO can be jointly estimated as

$$\begin{aligned}(D^*, \Delta f^*) &= \arg\max_{D,\Delta f} J(D, \Delta f) \\ &= \arg\max_{D,\Delta f} \sum_{g=0}^{L/Q-1} |J_g(D, \Delta f)|^2\end{aligned}$$

where,

$$J_g(D, \Delta f) = \sum_{m=gQ}^{(g+1)Q-1} \sum_{i=0}^{\eta-1} \tilde{y}[i;m]u^*[m]e^{-j2\pi\Delta f(m(N_c p+\eta N)+iN)}e^{j2\pi\frac{\Omega(m)}{N}D}.$$

here $(D^*, \Delta f^*)$ is the one that yeilds maximum correlation of transmitted preamble symbols and the received symbols whose phase shift due to ToA and CFO is corrected by the estimate. [6]

- We can express the above equation in the form of 2D DTFT, as a result the search for $(D^*, \Delta f^*)$ is efficiently carried out using 2D FFT.i.e, we define

$$W_g[p, q] = \sum_{n=0}^{M_1-1} \sum_{k=0}^{M_2-1} w_g[n, k]e^{-j2\pi\frac{n}{M_1}p}e^{-j2\pi\frac{k}{M_2}q}$$

where,

$$w_g[n, k] = \begin{cases} z[i;m] & if\, n = (m - gQ)(\eta + 1) + i, k = \Omega(m); \\ 0 & \text{otherwise.} \end{cases}$$

$$z[i;m] = \tilde{y}[i;m]u^*[m]. \tag{3.1}$$

Now point of maximum correlation is given by

$$(p^*, q^*) = \arg\max_{p,q} \tilde{J}(p, q)$$

$$where, \quad \tilde{J}[p, q] = \sum_{g=0}^{L/Q-1} |W_g[p, q]|^2$$

Now from this we can get estimated ToA and CFO as follows,

$$\Delta f^* = \begin{cases} \frac{1}{NM_1} p^* & if p^* < \frac{M_1}{2}; \\ \frac{1}{NM_1}(p^* - M_1) & \text{otherwise.} \end{cases} \quad D^* = \begin{cases} -\frac{N}{M_2} q^* & if p^* < \frac{M_2}{2}; \\ -\frac{N}{M_2}(q^* - M_2) & \text{otherwise.} \end{cases}$$

- Given the joint estimate $(D^*, \Delta f^*)$, next step is to determine the presence of the preamble. here if the correlation result exceeds some predetermined threshold, the base station declares the presence of preamble otherwise not.
  The overview of the preamble detection and estimation algorithm is given below

Algorithm 1: NPRACH Detection: 2D FFT Method

Result: Residual Frequency Offset and Time-of-Arrival Estimation
y = Received Signal;
y = removeCP(y);
Y = FFT(Received Signal);
Z = Y * conj(U);
W = PickUserSpecificSpectralComponents(Z, Nsc);
J = FFT2(W, M1, M2);
(P, Q) = maxIndex(J);

if $P \geq \frac{M_1}{2}$ **then**

$$\Delta F = \frac{(P - M_1)}{N * M_1}$$

else

$$\Delta F = \frac{P}{N * M_1}$$

end
if $Q \geq \frac{M_2}{2}$ **then**

$$D = \frac{-(Q - M_2) * N}{M_2}$$

else

$$D = \frac{-Q * N}{M_2}$$

end
if $J[P, Q] \geq threshold$ **then**

$$UAD = 1$$

else

$$UAD = 0$$

end

Figure 3.4: Detection and estimation Algorithm.[6]

References

[1] J. Chen, K. Hu, Q. Wang, Y. Sun, Z. Shi, and S. He. Narrowband internet of things: Implementations and applications. *IEEE Internet of Things Journal*, 4(6):2309–2314, 2017.

[2] Huawei. White paper on nb-iot. 2016.

[3] Y. . E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman, and H. S. Razaghi. A primer on 3gpp narrowband internet of things. *IEEE Communications Magazine*, 55(3):117–123, 2017.

[4] Rohde and schwarz. White paper on nb-iot. 2016.

[5] Mamta Agiwal, Mukesh Kumar Maheshwari, and Hu Jin. Power efficient random access for massive nb-iot connectivity. *Sensors*, 19(22):4944, 2019.

[6] X. Lin, A. Adhikary, and Y. . Eric Wang. Random access preamble design and detection for 3gpp narrowband iot systems. *IEEE Wireless Communications Letters*, 5(6):640–643, 2016.

[7] Eshita Rastogi, Navrati Saxena, Abhishek Roy, and Dong Ryeol Shin. Narrowband internet of things: A comprehensive study. *Computer Networks*, 173:107209, 2020.

[8] Md Ali, Yu Li, Song Chen, and Fujiang Lin. Narrowband internet of things: Repetition-based coverage performance analysis of uplink systems. *Journal of Communications*, 13:293–302, 06 2018.

[9] J. Hwang, C. Li, and C. Ma. Efficient detection and synchronization of superimposed nb-iot nprach preambles. *IEEE Internet of Things Journal*, 6(1):1173–1182, 2019.