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Master Thesis

Random Access in Mobile Networks with Beamforming

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Abstract

In the fifth generation (5G) of mobile networks, high data rate and low latency services are supported. In order to fullfill these two requirements, the frequency above 6 GHz is one of options to be used. The frequency above 6 GHz is called frequency range two (FR2) in 3GPP 38 series specification. The attentuation is a critical problem in high frequency system, so beamforming technology is adopted to overcome this problem. For control plane procedure with beamforming, more time is needed to do synchronization and random access procedure with beamforming. This paper proposes random access procedure with beamforming model, and shows the impact of different number of beams, different beam residence times and different TDD patterns. Furthermore, we propose an analytical model to evaluate the performance of the random access procedure with beamforming model by estimating the access success probability and average access delay. The simulations results show the accuracy of the performance metrics derived analytically.

Pátá generace (5G) mobilních sítí umožňuje služby s vysokou rychlostí přenosu dat a nízkou latencí. Jednou z možností jak těchto požadavků dosáhnout je využití frekvencí nad 6GHz. Tyto frekvence jsou v sérii 38 specifikací 3GPP nazývány frekvencemi druhého pásma (FR2). Ve vysokofrekvenčním systému je však problémem útlum, a tak je pro jeho překonání adaptována technologie formování paprsků. Procedura řídící roviny při formování paprsků vyžaduje více času na synchronizaci a vykonání metody náhodného přístupu s formováním paprsků. Tato práce navrhuje model náhodného přístupu s technologií formování paprsků a ukazuje dopady využití různých množství paprsků, dob jejich pobytů a různých vzorů TDD. Nadále navrhujeme analytický model k vyhodnocení výkonu modelu náhodného přístupu s technologií formování paprsků pomocí odhadování pravděpodobnosti úspěšného přístupu a průměrné prodlevy přístupů. Výsledky simulací ukazují přesnost analyticky derivovaných metrik výkonu.

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List of Abbreviations

3GPP	**3**rd **G**eneration **P**artnership **P**roject
eMBB	**e**nhance **M**obile **B**roadband
mMTC	**m**assive **M**achine **T**ype **C**ommunication
URLLC	**U**ltra **R**eliable **L**ow **L**atency **C**ommunication
m-MIMO	**m**assive **M**ultiple **I**nput **M**ultiple **O**utput
M2M	**M**achine **t**o **M**achine
D2D	**D**evice **t**o **D**evice
mmWave	**m**illi**m**eter **W**ave
TDD	**T**ime **D**ivision **D**uplex
FR2	**F**requency **R**ange **T**wo
SSB	**S**ynchronization **S**ignal **B**lock
RSRP	**R**eference **S**ignals **R**eceived **P**ower
RMSI	**R**emaining **M**inimum **S**ystem **I**nformation
MIB	**M**aster **I**nformation **B**lock
PRACH	**P**hysical **R**andom **A**ccess **CH**annel
PDCCH	**P**hysical **D**ownlink **C**ontrol **CH**annel
PDSCH	**P**hysical **D**ownlink **S**hared **CH**annel
PUCCH	**P**hysical **U**plink **C**ontrol **CH**annel
PUSCH	**P**hysical **U**plink **S**hared **CH**annel
RAR	**R**andom **A**ccess **R**esponse
ACK	**ACK**owledgement
NACK	**N**egative **ACK**owledgement

Chapter 1

Introduction

The next generation 5G networks serves different services, including low latency, high data rate and so on. There are three kinds of use cases for 5G mobile networks, enhance mobile broadband(eMBB), massive machine type communications(mMTC) and ultra-reliable low latency communications (URLLC) [1]. There are serval potential solutions which are used in 5G networks, like massive Multiple-Input Multiple-Output (mMIMO), device-to-device communication (D2D), machine-to-machine communication (M2M), or millimeter wave (mmWave) [2]. Papers [3][4] give an overview of the essentials of the Third Generation Partnership Project (3GPP) New Radio (NR) specifications representing the technique of 5G mobile networks. Also, 3GPP NR specifications include distinct procedures in order to overcome the main limitations of mmWave communications [5] and large bandwidth operation [6]. Large bandwidths are available at high frequency (e.g. mmWave), but the propagation loss is huge in mmWave system [7]. That is the reason why the multi-beam operation for mmWave communications in NR is one of the key features that differentiates NR from LTE, and assists in fulfilling the 5G requirements [8].

The establishment between base station (BS) and user equipment (UE) is called controll plane procedure which includes synchronization phase and initial access phase. In synchronization phase, UE gets downlink synchronization signal to know the timing from BS. In initial access phase, it is also called random access procedure. The purpose for random access procedure is to get uplink synchronization and establish the connection between UE and BS. After the UE successfully compelets random access procedure, the connection between UE and BS is established successfully. In LTE system, control plane procedure is performed on omnidirectional channels. Beamforming or other directional transmissions can only be performed after the connection between UE and BS is established [9]. In NR, there are several control plane procedures for mmWave communications, including exhaustive search and iterative search for synchronization and initial access phase. Synchronization procedure in NR is described in paper [10], and the different methods for synchronization phase with beamforming technology are showed in papers [11][12], including exhaustive search and iterative search. Exhaustive search among all possible BS beam/UE beam pairs and iterative (two-stage) BS beam training is discussed [13]. There are serveral papers which discuss analog beamforming, hybrid beamdorming [14] or digital beamforming technology. In paper [11], number of analog and digital beams both at BS side and UE side is considered. For random access procedure with beamfoming, the UE has to wait for the BS to schedule the Random Access Channel (RACH) opportunity towards the best direction that the UE has determined. The UE performes random access procedure according to the RACH information which is obtained from the optimal beam of the BS. In papers [15][16], the number of beams both at BS and UE side to evaluate access delay and successful probability for initial access phase is considered. Moreover, random access preamble design by carrying beam ID is described.

In paper [17], basic mechanism for four-step random access procedure in LTE system is showed and different maximal number of preamble transmissions to analyze the performance metrics, like access success probability and average access delay, by using slotted aloha model is considered. An optimization of the access to radio resources by massive MTC devices in LTE is called distributed queuing mechanism. Distributed queuing is based on a m-ary tree spitting algorithm with a simple set of rules to organize devices in virtual queues during an access procedure. One of the example of distributed queuing is Distributed Queuing-based Random Access Procedure (DQRAP), proposed in [18]. By the distributed scheduling of the MTC devices accessing the channel in time domain, DQRAP provides an efficient channel utilization regardless of the number of accessing MTC devices and reduces the average access delay comparing with the standard-LTE procedure. Consequently, DQRAP also reduces an energy consumption and blocking probability for a massive number of simultaneously accessing devices. Another improvement of access success probability is called two-phase random access procedure (TPRA)[19]. The random access procedure is spiltted into two phases. In the first phase, an additional access resources to separate the devices into several groups by the access resources they selected. In the second phase, the standard LTE random access procedure is independently performed in each group. To access performance of proposed algorithm, analytical model for the access success probability and access delay are developed in [19]. In TPRA, the eNB can immediately adjust the number of preamble is reserved for the first phase based on the instantons offered load. Thus, TPRA makes the system more flexible in order to arrange the unexpected bursty arrivals.

Beam management procedure is to design directional random access procredure. Avoiding severe path loss in mmWave system is important, and beam management procedure has been already defined as follows [20]:

- **Beam determination** : The UE determines which SSB (beam) is used to perform random access procedure.
- **Beam measurement** : The UE measures Reference Signals Received Power (RSRP) of each SSB (beam)
- **Beam reporting** : The UE reports the information of beam measurement.
- **Beam sweeping** : The BS sweeping all the beams which are equipped in the BS.

Synchronization phase with beamforming is showed according to the papers [11][12], but there is no paper about random access procedure with beamforming. In this thesis, we focus on random access procedure in mmWave system by following beam management procedure in order to show the impact of random access procedure with beamforming. We show a possible beam management action for random access procedure in this thesis. Moreover, we consider serveral kinds of factors which affects random access procedure, like TDD pattern, beam residence time .. and so on. Also, this thesis provides slotted aloha based analytical model to analyze random access procedure with beamforming.

The remainder of this thesis is organized as follows. In Section II, the standard LTE random access procedure is described and then the NR random access procedure with beamforming is introduced. The system model is presented in Section III. In Section IV, the proposed system model is analytically formulated. Simulation and analytical results are presented and discussed in Section V to verify the accuracy of models. Last, major conclusions and potential future research directions are given in Section VI.

Chapter 2

Random Access Procedure

In this section, random access procedures for LTE and NR with beforming are introduced.

2.1 LTE Random Access Procedure

In LTE, there are two types of random access procedures: contention based and contention free. Usually, contention-free random access procedure is used on some special cases, like handover to ensure zero or low collision probability. Contention-based random access procedure including RACH preamble (Msg. 1), random access response (Msg. 2), RRC connection request (Msg. 3) and RRC connection setup (Msg. 4) is supported in LTE as shown in *Figure 2.1*.

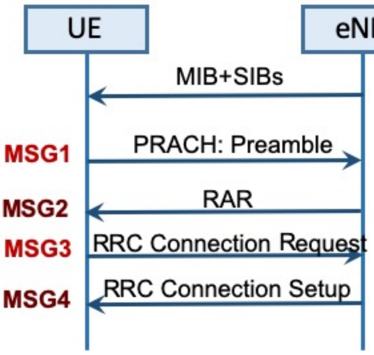


FIGURE 2.1: LTE random access procedure

In first step, the UE accesses the channel by randomly selecting preamble and transmitting it. The Msg1 is transmitted on PRACH and one or more reserved PRACHs in one frame. Frame is the fixed 10 msec value in LTE systemm, and there are 10 subframes in each frame. PRACH in time domain is located at specific subframe according to $PRACH\ configuration\ index$ which is obtained from SIB2. In second step, if eNB detects the preamble which is transmitted by UEs, the eNB replies Msg2 (random access response) on Physical Downlink Shared CHannel (PDSCH). The RAR contains the identity of preamble(s) and uplink time adjustment, dedicated uplink resource to transmit Msg3. Each RAR contains one Media Access Control (MAC) header and one or more MAC RAR(s). In MAC header, there are serveral sub-headers indicating the RAR corresponding to individual preamble. There is back-off parameter inside the subheader which is denoted as Backoff Indicator (BI), and it is carried for (i) the UE whose preamble is not detected by the eNB, (ii) the UE whose preamble is collide with the preamble select by other UE(s), or (iii) the UE can not be accomodated due to insufficient RAR capacity. In third step, after the

UE receives RAR within random access response window size (W_{RAR}), the UE(s) transmits Msg3 and start contention timer (T_{CR}). Otherwise, it re-transmits pramble (Msg1) after waiting a random backoff time(W_{BO}). The Msg3 carries UE identity and the cause of connection establishment in dedicated resource on Physical Uplink Shared CHannel (PUSCH). The UE identity is a random value or a Temporary Mobile Subscriber Identity (TMSI). When more than two UE transmit Msg3 on the same dedicated resource, the collision happens. Non-adaptive HARQ is enabled to protect the reliable message exchange. After the UE transmits Msg3, it waits for T_{HARQ} to receive acknowledgment (ACK) or negative-acknowledgment (NACK) from eNB. If the eNB receives Msg3 successfully, it replies ACK. Otherwise, it repies NACK to the UE. When the UE receives NACK, it waits for processing time to re-transmit Msg3 until the maximal number of HARQ is reached (N_{HARQ}). In last step, eNB waits for processing time (T_{A_M4}) to transmit Msg4 after transmit ACK of Msg3. Similarity, if the UE receives Msg4 successfully, it replies ACK to eNB. If the ACK is not received by eNB, eNB waits for T_{HARQ} time to retransmit Msg4 [17].

2.2 NR Random Access Procedure with beamforming

In NR, it is similar to LTE. There are also two type of random access procedures: contention based and contention free. About contention based random access procedure in NR, four messages exchange is used as same as LTE. Besides, beam management is followed for random access procedure with beamforming as shown in *Figure 2.2* .

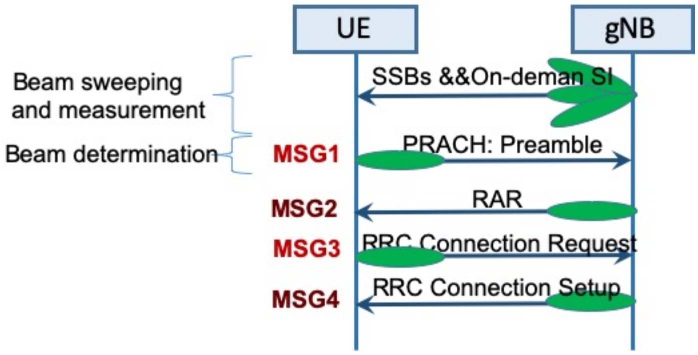


FIGURE 2.2: 5G random access procedure with beamforming

Before random access procedure is performed, the UE needs to do beam sweeping to select the best SSB (beam) according to RSRP(beam measurement) during cell searching. After the UE selects the beam (beam determination), the UE decodes the information of SSB and know the PRACH configuration from selected SSB (beam). After the UE gets PRACH configuration, the UE starts to perform random access procedure.

In first step, the preamble is transmitted through PRACH channel on PRACH occasion in one slot by using selected beam. In NR, frame is the length of 10 msec and subframe is the length of 1 msec. There are serveral slots in each subframe. Slot is the flexible duration according to subcarrier spacing (SCS). For example, the length of slot is 0.25 msec if the SCS is 60kHz. the UE randomly selects random access preamble from a group of preambles reserved for the PRACH occasion, and transmits preamble on PRACH occasion.

In second step, the gNB detects preamble from the UE and knows which beam is used by the the UE. After that, the gNB transmits Msg2 when gNB's beam aligns to the UE's beam. Each random access response (Msg2) carries backoff indicator (BI) to indicate the backoff parameter value. The UE waits for the processing time (T_{RAR}) for the gNB to detect the preamble from the UE.

In third step, once the UE receives Msg2 from the gNB to adjust uplink timing during RAR window (W_{RAR}), the UE waits for at least T_{MSG3} and transmits Msg3 on the assigned dedicated uplink resource which is obtained from Msg2 by using the same beam as transmitting Msg1. T_{MSG3} is the minimum processing time for the UE to transmit Msg3. However, the UE may wait some time to transmit Msg3 until gNB's beam aligns to the UE's beam. The gNB sends an HARQ ACK or NACK after the minmum processing time ($\overline{T_{HARQ}}$). Due to TDD system, adaptive and asynchronous HARQ is applid. Asynchronous HARQ means that the duration of transmitted HARQ ACK/NACK is not fixed, and adaptive HARQ means that the frequency resource location of HARQ ACK/NACK is not the same as the first time transmitted HARQ ACK/NACK.

In last step, similarly, the gNB waits for at least T_{A_M4} until gNB' s beam aligns to UE' s beam and transmits Msg4 after the gNB replies ACK of Msg3 to the UE. If Msg4 is successfully received, the UE waits for the minmum processing time ($\overline{T_{HARQ}}$) and sends ACK of Msg4 to the gNB.

Random access procedure is considered as failure if the UE doesn't receive messages before timer expires or collision happens on transmitting Msg3. When the UE fails in random access procedure, the UE reselects SSBs or uses the same SSB to transmit preamble according RSRP of SSBs. The UE does the backoff action and waits for W_{BO}. After backoff window, the UE won' t directly retransmit preamble until gNB's beam is aligned to UE's selected beam. After UE retransmits preamble, UE does the actions which are mentioned before.

Chapter 3

System Model

This thesis considers M_k fixed devices which simultaneously perform random access procedure (RAP) at the k-th beam of a millimeter wave (mmWave) system operated under time division duplex (TDD) mode ($1 \leq k \leq K$) as shown in *Figure 3.1.* It is assumed that the gNB is equipped with number of beams (K) and thus, the k-th beam is transmitted in the kth direction with residence time T_k.

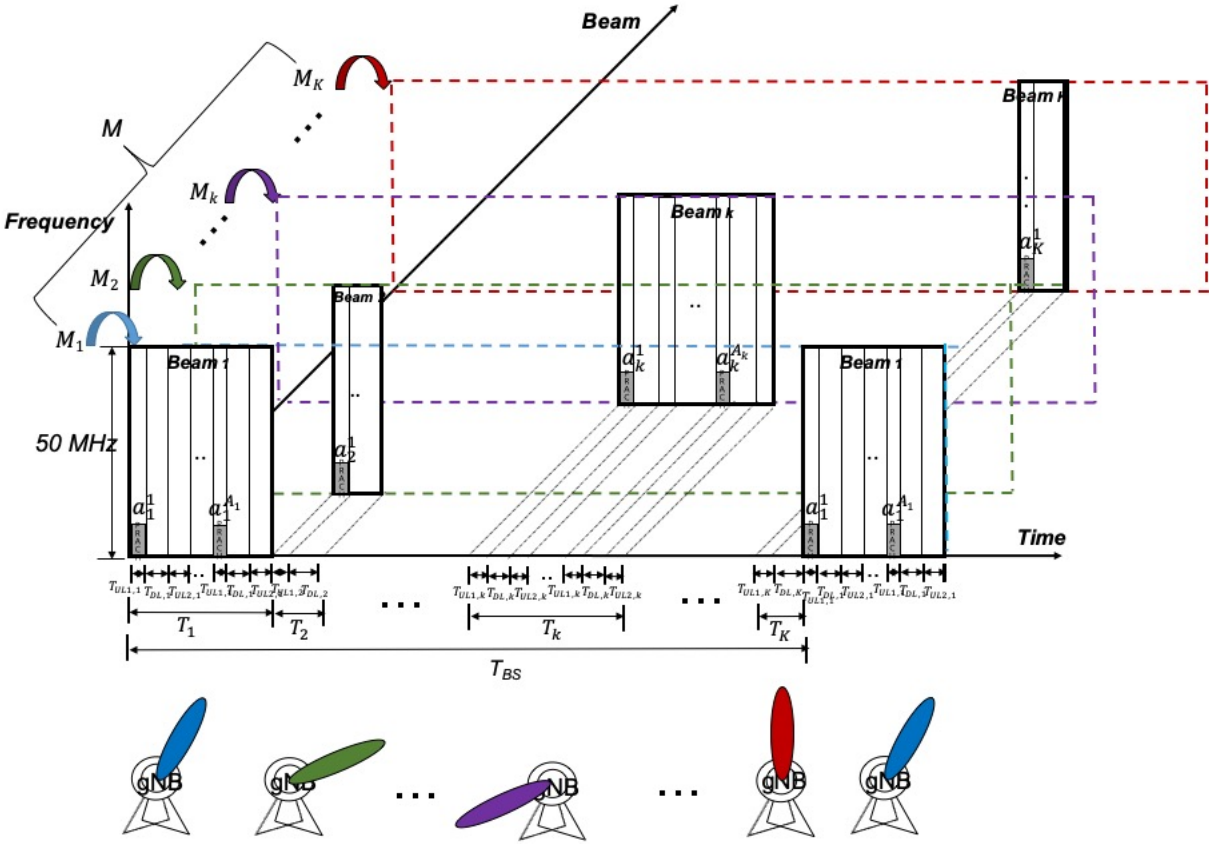


FIGURE 3.1: 5G NR for multiple beams in TDD system

The beam sweeping time (T_{BS}) from beam 1 to beam K for gNB is $T_{BS} = \sum_{k=1}^{K} T_k$. A_k is the number of PRACH slot within T_k, so we can know that $T_k = A_k * T_{RA\_REP}$, and k-th beam residence time (T_k) is the interval for gNB and devices to transmit or receive the k-th beam data. a_k^i is the index i of physical random-access channel (PRACH) slot for k-th beam as shown in *Figure 3.1.* According to TDD mmWave system, there are downlink time ($T_{DL,k}$) and uplink time ($T_{UL,k} = T_{UL1,k} + T_{UL2,k}$) within the configured TDD period (P). $T_{DL,k}$ is the downlink time for the k-th beam within P, and $T_{UL,k}$ is the uplink time for the kth-beam within P. Within T_k, we can know that the total downlink/uplink time for the k-th beam by $\frac{T_k}{P}$. T_{slot} is the time unit system according to configured subcarrier spacing (SCS).

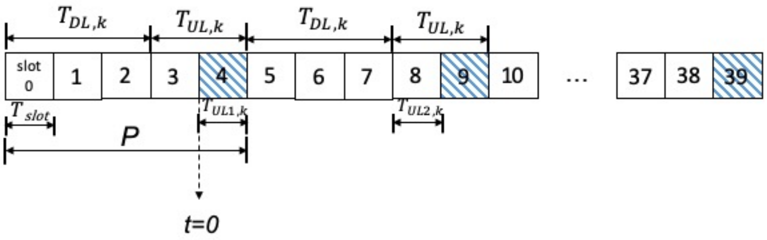


Figure 3.2: TDD pattern

In *Figure 3.2*, we set the starting time at the beginning of first PRACH slot, so there are two TDD uplink time ($T_{UL1,k}$ and $T_{UL2,k}$) and one TDD downlink time ($T_{DL,k}$).

Without loss of generality, it is assumed that the detection probability of preamble is 100%. N_{PTmax} is the maximal number of preamble transmission. The devices retransmits preamble according to N_{PTmax}. N_{PTmax} affects the period of random access procedure (average access delay). Also, the access succss probability is higer if the value of N_{PTmax} is higher. N_{RAR} is the maximal number of preambles acknowledged in random access response (RAR) messages. N_{RAR} affects that the number of Msg3 is assigned on dedicated resource. We limit the dedicated resource for Msg3 (contention request) according to this value N_{RAR}.

In this system, the gNB has sufficient amount of the dedicated resource for transmission of contention setup and acknowledge of contention request and contention setup messages.

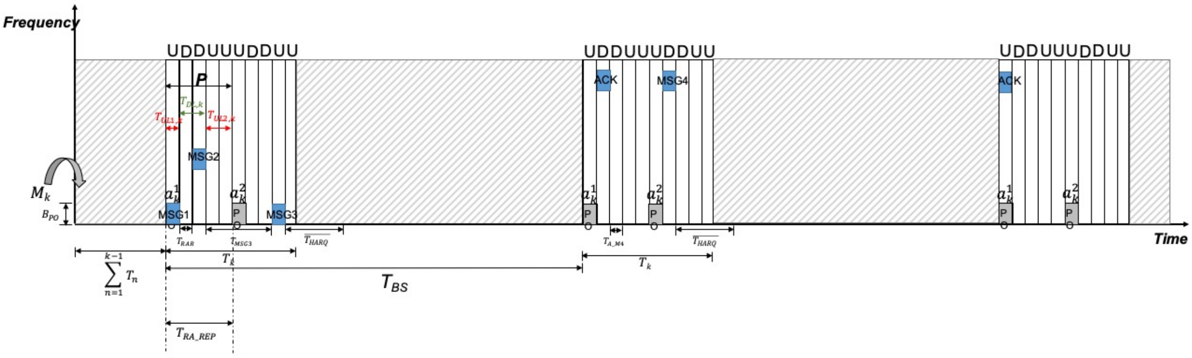


Figure 3.3: 5G NR for beam k ($1 \leq k \leq K$)

We capture k-th beam part from *Figure 3.1* to form *Figure 3.3* and set $A_k = 2$. k-th beam devices (M_k) means that the devices in area covered by the gNB's beam k. In *Figure 3.3*, k-th beam devices (M_k) can transmit preamble in each PRACH occasion; B_{PO} is the bandwidth for PO; R is the number of preambles reserved in each PRACH occasion, and which can be reused in each beam for devices.

Figure 3.4 shows NR random access procedure for k-th beam devices. In Msg1 (preamble), the preamble is transmitted through PRACH channel shared by k-th beam devices. The device randomly selects random access preamble from a group of

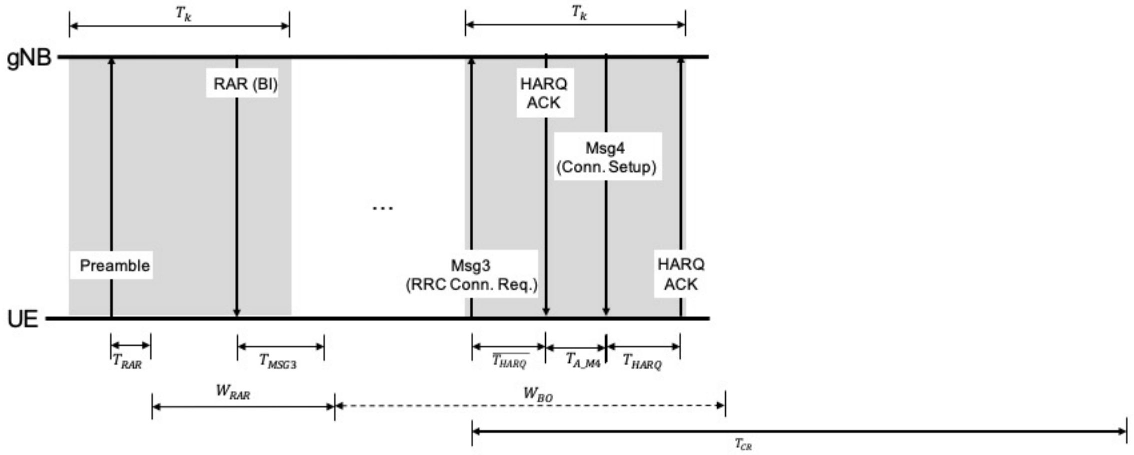


Figure 3.4: Random Access Procedure

preambles reserved for the RACH, and transmits preamble on PRACH occasion which is scheduled by the gNB. The gNB detects preamble from k-th beam device(s) and transmits Msg2 (random access response) when gNB’s beam aligns to device’s beam. Each random access response (Msg2) carries backoff indicator (BI) to indicate the backoff parameter value. T_{RAR} is the processing time for gNB to detect the preamble from device, and W_{BO} is the backoff window for device to retransmit preamble when device doesn’ t receive Msg2 during RAR window (W_{RAR}). After backoff window, device won’ t directly retransmit preamble until gNB’ s beam is aligned to device’ s beam. After the device transmits preamble, device monitors Msg2 inside random access response window (W_{RAR}). Once the device receives Msg2 from the gNB to adjust uplink timing, the device waits for T_{MSG3} and transmits Msg3 on the assigned dedicated uplink resource. The gNB sends an HARQ ACK or NACK after ($\overline{T_{HARQ}}$) . The gNB waits that gNB’ s beam aligns to device’ s beam and transmits Msg4 after it replies ACK of Msg3 to device. If Msg4 is successfully received, the device waits for ($\overline{T_{HARQ}}$) and sends ACK of Msg4 to gNB.

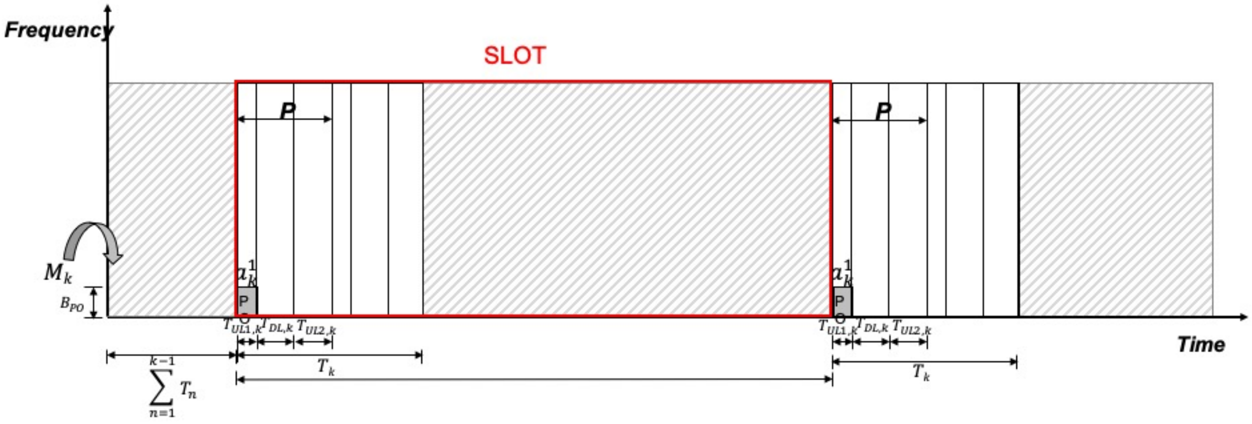


Figure 3.5: Slotted ALOHA for beam k ($1 \leq k \leq K$)

From *Figures 3.3* to *Figure 3.5*, we assume there is only one PRACH occasion within k-th beam residence time (T_k), and then we can model the 5G NR for k-th beam system to slotted aloha for k-th beam system. Due to this approximation, the error rate is getting higher if A_k is increased.

We want to dynamically adjust K to maximize the access success probability Ps subject to a given number of devices in the gNB cell system. Also, we want to find access success probability ($P_{s,k}$) and average access delay ($\overline{D}_{a,k}$) for k-th beam devices according different number of beams.

Chapter 4

Analytical Model

In this section, we propose analytical model by using slotted aloha model to estimate the access success probability for kth beam $P_{s,k}$ and the average access delay for kth beam $\overline{D_{a,k}}$ according to paper [17]. There are two difference points between paper [17] and this thesis. One is to consider beam domain. The other is to consider TDD system. Only the devices successfully finishing four messages exchange without exceeding maximal number of preamble tranmsission N_{PTmax} is counted into successful devices. Thus, we use fixed duration $I_{max,k}$ to estimate the performance for kth beam devices. $I_{max,k}$ is the number of PRACH slot within the investigated period for kth beam. The devices retransmit a new preamble for $N_{PTmax} - 1$ times if random access fails. For each preamble transmission, the devices spend up to $T_{RAR} + W_{RAR} + W_{BO}$ before retransmit a new preamble. $I_{max,k}$ can be determined as

$$I_{max,k} = 1 + (N_{PTmax} - 1) * \lceil \frac{(T_{RAR} + W_{RAR} + W_{BO})}{T_{BS}} \rceil \tag{4.1}$$

Let $M_{i,k}[n]$ be the number of kth beam devices that transmit the nth preambles at ith slot and successfully finish preamble transmission. That is $(1 \leq n \leq N_{PTmax})$,

$$M_{i,k} = \sum_{n=1}^{N_{Ptmax}} M_{i,k}[n] \tag{4.2}$$

We show that the number of kth beam devices who does not collide for $M_{i,k}$ and R which is number of preamble reserved at random access slot can be expressed as $\frac{-M_{i,k}}{R}$ The total number of kth beam devices can received random access response messages if kth beam devices do not exceed $N_{UL,k}$. Otherwise, gNB randomly sends random access response messages to kth beam devices. Hence, $M_{i,k,S}[n]$ can be express as

$$M_{1,k,S}[n] = \begin{cases} N_{UL,k}, & if\ n = 1 \& M_{1,k} * e^{\frac{-M_{1,k}}{R}} \geq N_{UL,k} \\ M_{1,k} * e^{\frac{-M_{1,k}}{R}}, & if\ n = 1 \& M_{1,k} * e^{\frac{-M_{1,k}}{R}} < N_{UL,k} \\ 0, & if\ n \neq 1 \end{cases} \tag{4.3}$$

$$M_{i,k,S}[n] = \begin{cases} M_{i,k}[n] * e^{\frac{-M_{i,k}}{R}}, & if\ \sum_{n=1}^{N_{PTmax}} M_{i,k}[n] * e^{\frac{-M_{i,k}}{R}} < N_{UL,k} \\ \frac{M_{i,k}[n] * e^{\frac{-M_{i,k}}{R}}}{\sum_{n=1}^{N_{PTmax}} M_{i,k}[n] * e^{\frac{-M_{i,k}}{R}}} * N_{UL,k}, & Otherwise \end{cases} \tag{4.4}$$

$N_{UL,k}$ is the maximal number of kth beam devicess that can be acknowledged within RAR window. Due to TDD mmWave system, gNB replies RARs during downlink slots. It can be expressed as

$$N_{UL,k} = (A + B + C) * N_{RAR} \tag{4.5}$$

$$A = \begin{cases} \frac{(T_k - T_{RA\_REP}) * T_{DL,k}}{P * T_{slot}}, & if\ 0.25 + T_{RAR} + W_{RAR} \geq T_k \\ \frac{(0.25 + T_{RAR} + W_{RAR} - T_{RA\_REP}) * T_{DL,k}}{P * T_{slot}}, & otherwise \end{cases} \tag{4.6}$$

$$B = \begin{cases} \frac{(T_{DL,k} - T_{RAR})}{T_{slot}}, & if\ T_{DL,k} \geq T_{RAR} \\ 0, & otherwise \end{cases} \tag{4.7}$$

$$C = \begin{cases} 0, & if\ 0.25 + T_{RAR} + W_{RAR} \geq T_k \\ \frac{(0.25 + T_{RAR} + W_{RAR}) - \lfloor \frac{(0.25 + T_{RAR} + W_{RAR})}{P} \rfloor * T_{RA\_REP}}{T_{slot}}, & otherwise \end{cases} \tag{4.8}$$

The number of failed kth beam devices that transmit the nth preambles at ith slot can be calculated by

$$M_{i,k,F}[n] = M_{i,k}[n] - M_{i,k,S}[n] \tag{4.9}$$

The number of kth beam devices that transmit the nth preambles at ith slot can be expressed as

$$M_{i,k}[n] = \sum_{a=A_{min,k}}^{A_{max,k}} a_{k,a,i} * M_{a,k,F}[n-1] \tag{4.10}$$

$M_{a,k,F}[n-1]$ represents that kth beam devices that transmit the $(n-1)$th preambles at a_kth slot, and they failed to complete preamble transmission. $a_{k,a,i}$ is the portion of backoff interval of ath random access slot $(A_{min,k} \leq a_k \leq A_{max,k} < i_{th,k})$ that overlaps with the transmission interval of i_kth random access slot for kth beam as shown in *Figures 4.1*. In *Figures 4.1*,

For kth beam devices, the minimum value of $a_k(A_{min,k})$ is obtained when the right boundary of the a_kth random access slot backoff interval reaches the left boundary of the $i_{th,k}$th random access slot transmission interval $(\sum_{n=1}^{k-1} T_n + (a_k - 1) * T_{BS} + T_{RAR} + W_{RAR} + W_{BO} \geq \sum_{n=1}^{k-1} T_n + (i_{th,k} - 2) * T_{BS} + 0.25)$, and the maximum vlaue of $a_k(A_{max,k})$ is obtained when the left boundary of the a_kth random access slot backoff interval exceeds the right boundary of the $i_{th,k}$th random access slot transmission interval $(\sum_{n=1}^{k-1} T_n + (a_k - 1) * T_{BS} + T_{RAR} + W_{RAR} + 0.25 \leq \sum_{n=1}^{k-1} T_n + (i_{th,k} - 1) * T_{BS})$.

$$A_{min,k} = \lceil (i_{th,k} - 1) + \frac{0.25 - T_{RAR} - W_{RAR} - W_{BO}}{T_{BS}} \rceil \tag{4.11}$$

$$A_{max,k} = \lfloor i_{th,k} - \frac{0.25 + T_{RAR} + W_{RAR}}{T_{BS}} \rfloor \tag{4.12}$$

$a_{k,a,i}$ can be determined based on three cases as shown in *Figure 4.1*. For first case, the right boundary of the backoff interval is within the transmission interval $(\sum_{n=1}^{k-1} T_n + (i_{th,k} - 1) * T_{BS} \geq \sum_{n=1}^{k-1} T_n + (a_k - 1) * T_{BS} + T_{RAR} + W_{RAR} + W_{BO} \geq \sum_{n=1}^{k-1} T_n + (i_{th,k} - 2) * T_{BS} + 0.25)$ In this case, $A_{min,k} \leq a_k \leq i_{th,k} - \frac{T_{RAR} + W_{RAR} + W_{BO}}{T_{BS}}$ and the overlapped region starts from the left boundary of transmission interval and end at the right boundary of backoff interval. For second case, the transmission

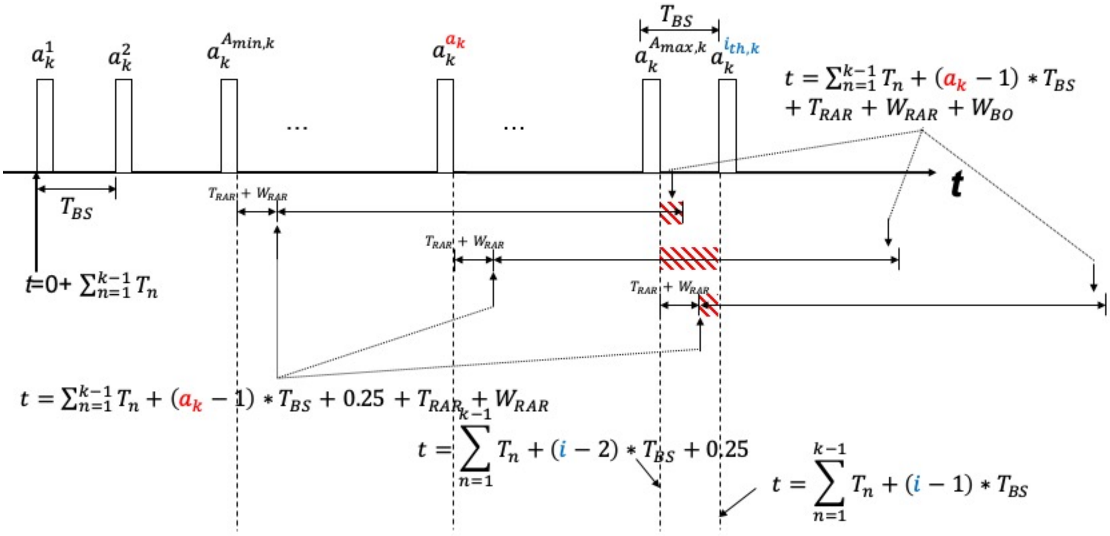


FIGURE 4.1: Backoff timing diagram for k-th beam devices

interval is fully overlapped with the backoff interval. Thus, the lenght of overlapped region is T_{BS}. For last case, the left boundary of the backoff interval is within the transmission interval ($\sum_{n=1}^{k-1} T_n + (i_{th,k} - 2) * T_{BS} + 0.25 \leq \sum_{n=1}^{k-1} T_n + (a_k - 1) * T_{BS} + T_{RAR} + W_{RAR} + 0.25 \leq \sum_{n=1}^{k-1} T_n + (i_{th,k} - 1) * T_{BS}$)

$$a_{k,a,i} = \begin{cases} \frac{(a_k-1)*T_{BS}+T_{RAR}+W_{RAR}+W_{BO}-(i_{th,k}-2)*T_{BS}}{W_{BO}}, & if\ A_{min,k} \leq a_k \leq i_{th,k} - \frac{T_{RAR}+W_{RAR}+W_{BO}}{T_{BS}} \\ \frac{T_{BS}}{W_{BO}}, & if\ i_{th,k} - \frac{T_{RAR}+W_{RAR}+W_{BO}}{T_{BS}} \leq a_k \leq (i_{th,k} - 1) - \frac{T_{RAR}+W_{RAR}}{T_{BS}} \\ \frac{(i_{th,k}-1)*T_{BS}-((a_k-1)*T_{BS}+T_{RAR}+W_{RAR})}{W_{BO}}, & if\ (i_{th,k} - 1) - \frac{T_{RAR}+W_{RAR}}{T_{BS}} \leq a_k \leq A_{max,k} \end{cases} \tag{4.13}$$

Let $T_{i,k}$ be access delay of kth beam devices that transmit preamble at ith random access slot and successfully complete preamble and message transmission. According to TDD pattern and A_k value, $T_{i,k}$ will be different. TDD pattern affects downlink and uplink messages position and A_k value affects the beam residence time for kth beam.

$$T_{i,k} = \begin{cases} \sum_{n=1}^{k-1} T_n + (i-1) * T_{BS} + 3 * T_{BS}, & if\ A_k = 1\ \&\ T_{DL,k} = 0.75\ \&\ T_{UL,k} = 0.5 \\ \sum_{n=1}^{k-1} T_n + (i-1) * T_{BS} + T_{BS} + 2 * P, & if\ A_k = 2\ \&\ T_{DL,k} = 0.75\ \&\ T_{UL,k} = 0.5 \\ \sum_{n=1}^{k-1} T_n + (i-1) * T_{BS} + T_{BS}, & if\ A_k = 4\ \&\ T_{DL,k} = 0.75\ \&\ T_{UL,k} = 0.5 \\ \sum_{n=1}^{k-1} T_n + (i-1) * T_{BS} + 4 * P + 0.25 + T_{DL,k}, & if\ A_k = 8\ \&\ T_{DL,k} = 0.75\ \&\ T_{UL,k} = 0.5 \\ \sum_{n=1}^{k-1} T_n + (i-1) * T_{BS} + 4 * T_{BS}, & if\ A_k = 1\ \&\ T_{DL,k} = 0.5\ \&\ T_{UL,k} = 0.75 \\ \sum_{n=1}^{k-1} T_n + (i-1) * T_{BS} + 2 * T_{BS}, & if\ A_k = 2\ \&\ T_{DL,k} = 0.5\ \&\ T_{UL,k} = 0.75 \\ \sum_{n=1}^{k-1} T_n + (i-1) * T_{BS} + T_{BS} + P + 0.25 + T_{DL,k}, & if\ A_k = 4\ \&\ T_{DL,k} = 0.5\ \&\ T_{UL,k} = 0.75 \\ \sum_{n=1}^{k-1} T_n + (i-1) * T_{BS} + 5 * P + 0.25 + T_{DL,k}, & if\ A_k = 8\ \&\ T_{DL,k} = 0.5\ \&\ T_{UL,k} = 0.75 \end{cases} \tag{4.14}$$

For performance metrix, we use access success probabitliy ($P_{s,k}, P_s$)and average access delay ($\overline{D}_{a,k}, \overline{D}_a$) for kth beam and system devices.

$$P_{s,k} = \frac{\sum_{i=1}^{I_{max,k}} \sum_{n=1}^{N_{PTmax}} M_{i,s,k}[n]}{M_k} \tag{4.15}$$

$$P_s = \frac{\sum_{n=1}^{K} P_{s,n} * M_n}{\sum_{n=1}^{K} M_n} \tag{4.16}$$

$$\overline{D}_{a,k} = \frac{\sum_{i=1}^{I_{max,k}} \sum_{n=1}^{N_{PTmax}} M_{i,s,k}[n] * T_{i,k}}{\sum_{i=1}^{I_{max,k}} \sum_{n=1}^{N_{PTmax}} M_{i,s,k}[n]} \tag{4.17}$$

$$\overline{D}_a = \frac{\sum_{n=1}^{K} \overline{D}_{a,n} * M_n}{\sum_{n=1}^{K} M_n} \tag{4.18}$$

Chapter 5

Numerical Result

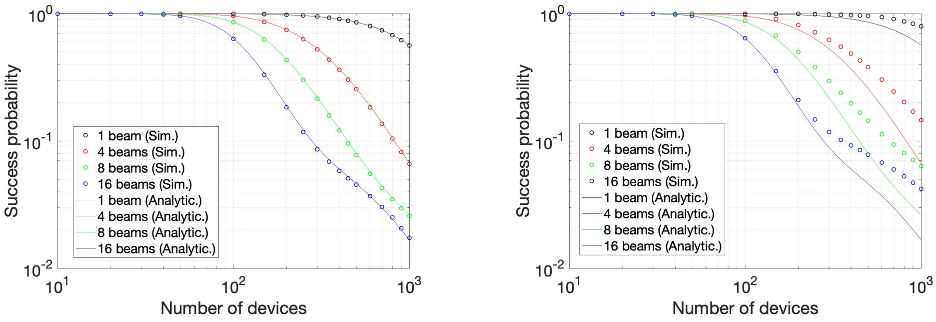
Computer simulation is based on C-programming to verify the effectivieness of the proposed analytical model. In simulation, each point is obtained by averaging results of 10^4 simulation drops. Each drop is to run random access procedure from Msg1 to Msg4 within investigated period ($I_{max,k}$) for k-th beam devices. We fix the total number of preambles (R) and do simulation for number of beams (K) to see the performance metrix ($P_{s,k}, \overline{D}_{a,k}$). All simulation parameters are listed in *Table 5.1*.

Table 5.1: Simulation settings.

Notations	**Descriptions**	**Values**
T_{slot}	Time unit according to SCS=60kHz (unit: msec)	0.25
M_k	Numbers of UEs in beam k	10-1000
T_k	Beam k's residence time (unit: msec)	A_k*T_{RAREP}
A_k	Number of PRACH slot within T_k	1/2/4/8
a_k^i	the index i of PRACH slot within T_k	$1/2/../A_k$
T_{RA_REP}	Interval between two successive PRACH slots (unit: msec)	1.25 if PRACH conf. ind. = 83
P	TDD configuration period (unit: msec)	1.25
$T_{DL,k}$	TDD downlink time of P period within T_k (unit: msec)	0.5/0.75
$T_{UL1,k}$	TDD uplink time for front part of P period within T_k (unit: msec)	0.25
$T_{UL2,k}$	TDD uplink time for rear part of P period within T_k (unit: msec)	0.5/0.25
$T_{UL,k}$	TDD uplink time of P period within T_k (unit: msec)	$T_{UL1,k} + T_{UL2,k}$
K	Number of gNB’ s beams	1/4/8/16
N_{PTmax}	Maximal number of preamble transmission	3/5/10
R	Total number of preambles in a PRACH occasion	56
N_{RAR}	Maximal number of RAR that can be carried in response time	5
BI	Backoff indicator	20/40/80/160
W_{BO}	back-off window size (unit: msec)	BI+0.25
W_{RAR}	RAR window (unit: msec)	2/2.5/5/10
T_{BS}	Beam sweeping time from beam 1 to beam K (unit: msec)	$\sum_{k=1}^{K} T_k$
B_{PO}	Bandwidth of PRACH occasion (unit: subcarrier)	18
T_{CR}	Contention resolution timer (unit: msec)	64
T_{RAR}	Processing time required by gNB to detect Msg1 (unit: msec)	0.25
T_{MSG3}	Minimum processing time required by a UE to transmit Msg3 (unit: msec)	1.25
$\overline{T_{HARQ}}$	Minimum average processing time for receiving HARQ ACK (unit: msec)	1
T_{A_M4}	Gap of monitor Msg4 (unit: msec)	0.25

Three kinds of parameters are considered in this thesis, and the result for the parameters adjustment is showed in the figures. One parameter is different number of beams (K). Another parameter is different number of preamble transmission (N_{PTmax}). The other parameter is different TDD pattern ($T_{DL,k}, T_{UL,k}$).

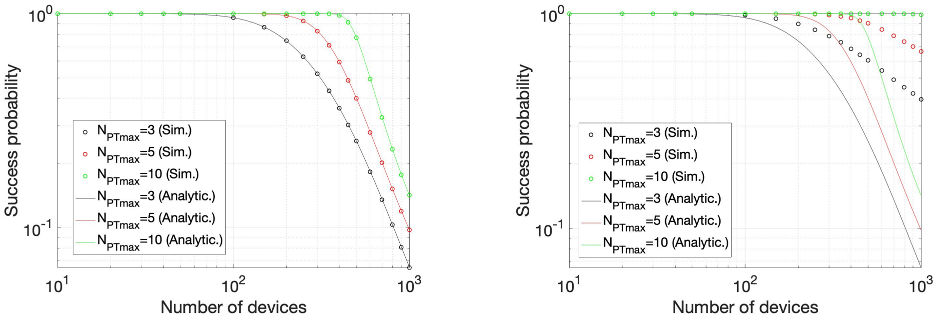
In *Figure 5.1*, different number of beams (K) is showed. In *Figure 5.1a*, it shows the access success probability with slotted aloha simulation. In *Figure 5.1b*, it shows the access success probability with real case simulation. When number of beams increases, the access succss probability is lower. The beam sweeping time (T_{BS}) increases, so backoff devices have higher probability to contend the same PRACH occasion. The error rate between slotted aloha and real case simulation is caused by A_k value. In slotted aloha, there is only one PRACH occasion within k-th beam residence time. However, there are A_k PRACH occasions within k-th beam residence time in real case simulation. That is the reason why the access success probability of real case simulation is higer that the access success probability of slotted aloha. The result of *Figure 5.1b* shows that it is accuracy when number of k-th beam devices are less than 200. If the number of devices is less, the collision probability is lower. If the collision probability is lower, the backoff devices are less. The effect of A_k is not obvious.



(a) slotted aloha (b) real case

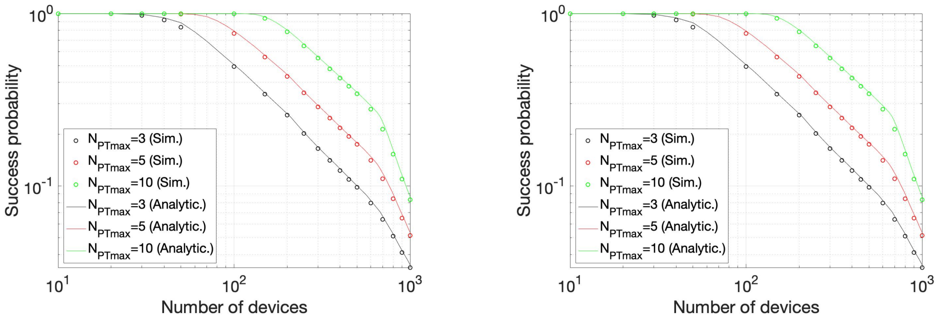
FIGURE 5.1: Access success probability with A_k=2 & $T_{DL,k}$=0.75 & N_{PTmax}=3

In *Figure 5.2* and *Figure 5.3*, different number of preamble transmission (N_{PTmax}) is showed. In *Figure 5.2a* and *Figure 5.3a*, it shows the access success probability with slotted aloha simulation. In *Figure 5.2b* and *Figure 5.3b*, it shows the access success probability with real case simulation. When number of preamble transmission increases, the succss probability becomes higer because N_{PTmax} provides devices with more chance to access the channel. Compared to *Figure 5.3*, there is error rate between slotted aloha and real case simulation in *Figure 5.2*. The value of A_k is larger than 1, so there is error rate between slotted aloha and real case simulation. When the value of A_k is equal to 1, there is only one PRACH occasion within k-th beam residence time. There is no error rate between slotted aloha and real case simulation. On the other hand, the error rate between slotted aloha and real case simulation is getting higer when the value of A_k increases.



(a) slotted aloha (b) real case

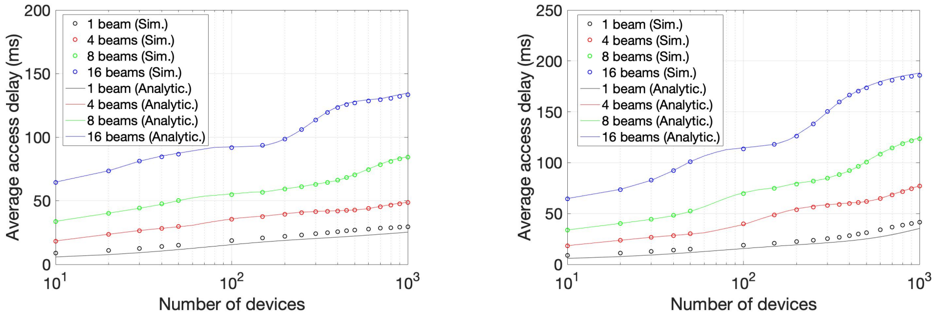
FIGURE 5.2: Access success probability with A_k=8 & $T_{DL,k}$=0.5 & K=4



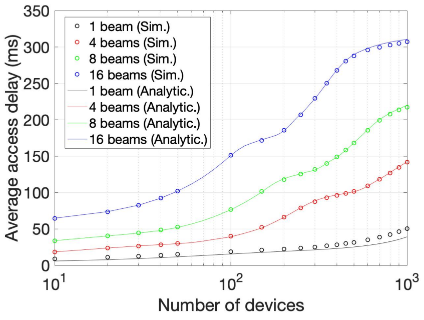
(a) slotted aloha (b) real case

FIGURE 5.3: Access success probability with A_k=1 & $T_{DL,k}$=0.5 & K=4

In *Figure 5.4* and *Figure 5.5*, three different N_{PTmax} values are showed. Although the access succss probability increases, the devices need to spend more time to complete random access procedure. In *Figure 5.4* and *Figure 5.5*, it is obivous to see the tradeoff between access succss probability and average access delay accordign to different N_{PTmax} values. Although the result of *Figure 5.4* shows that the average access delay is better when number of beams is less, it is at k-th beam devices side to observe the result. If we observe the result of average access delay at gNB side, we have to consider all the beams and calculate the average access delay of gNB system ($\overline{D}_a$). Similarly, if we want to observe the result of access success probability at gNB side, we have to consider all the beams and calculate the access success probability of gNB system (P_s).

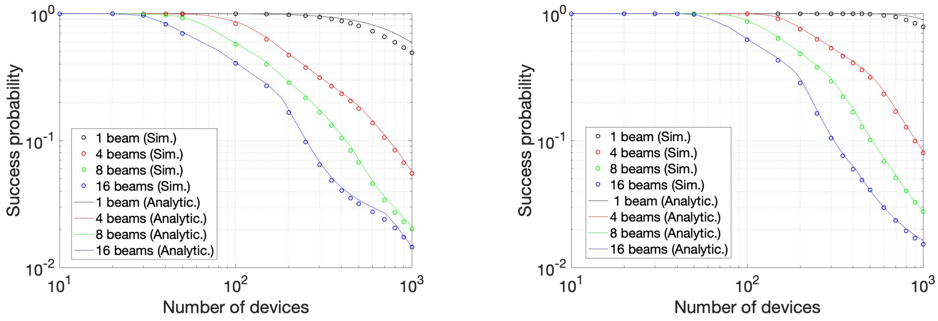


(a) N_{PTmax}=3 (b) N_{PTmax}=5

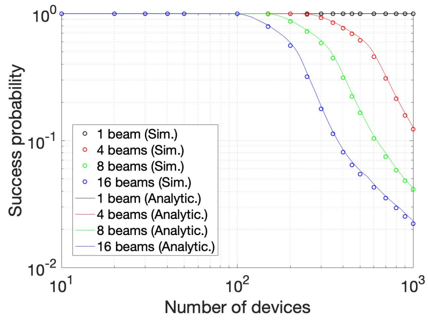


(c) N_{PTmax}=10

FIGURE 5.4: Average access delay with A_k=1 & $T_{DL,k}$=0.75



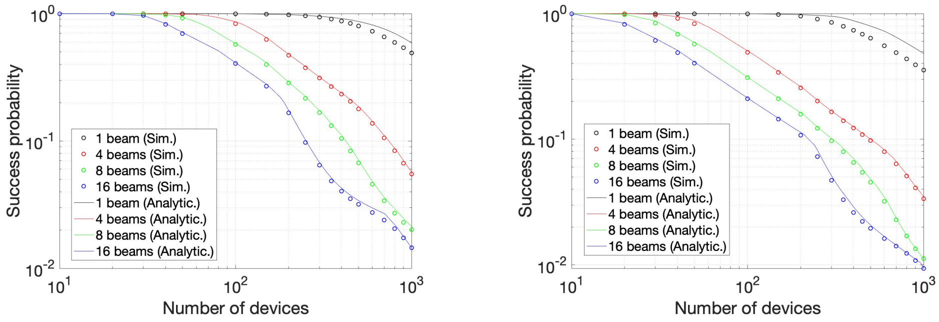
(a) N_{PTmax}=3 (b) N_{PTmax}=5



(c) N_{PTmax}=10

FIGURE 5.5: Access success probability with A_k=1 & $T_{DL,k}$=0.75

In *Figure 5.6*, two different TDD patterns are showed. In *Figure 5.6a*, it shows the access success probability with $T_{DL,k}$=0.75 & $T_{UL,k}$=0.5 situation. In *Figure 5.6b*, it shows the access success probability with $T_{DL,k}$=0.75 & $T_{UL,k}$=0.5 situation. We can see that different TDD pattern affects the succss probability. Because more downlink resource can be used for gNB to schedule more RARs, it makes more devices transmit Msg3. That is the reason why the access success probability with $T_{DL,k}$=0.75 & $T_{UL,k}$=0.5 situation is better.

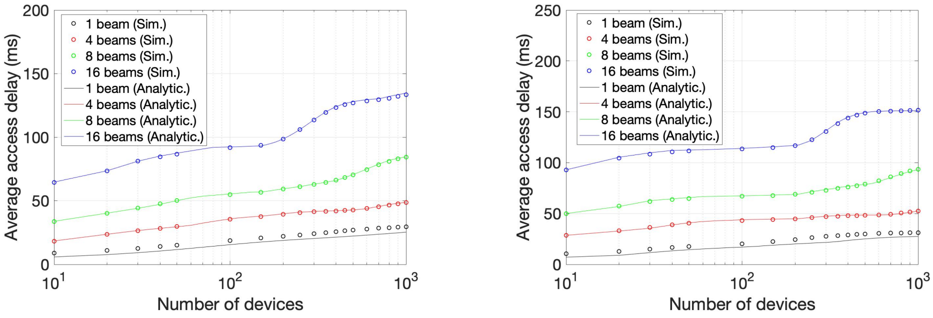


(a) $T_{DL,k}$=0.75 & $T_{UL,k}$=0.5 (b) $T_{DL,k}$=0.5 & $T_{UL,k}$=0.75

FIGURE 5.6: Access success probability with A_k=1 & N_{PTmax}=3

In *Figure 5.7*, two different TDD patterns are showed. In *Figure 5.7a*, it shows the average access delay with $T_{DL,k}$=0.75 & $T_{UL,k}$=0.5 situation. In *Figure 5.7b*, it shows the average access delay with $T_{DL,k}$=0.75 & $T_{UL,k}$=0.5 situation. We can see that different TDD pattern affects the average access delay. Actually, the reason is the same as access success probability. Because more downlink resource can be used for gNB to transmit more RARs, the less devices do backoff action when the downlink resource is not enough.

From *Figure 5.6* and *Figure 5.7*, we know that the average access delay is reduced by increasing $T_{DL,k}$ value. Similarly, the access succss probability increases when $T_{DL,k}$ value is increased.



(a) $T_{DL,k}$=0.75 & $T_{UL,k}$=0.5 (b) $T_{DL,k}$=0.5 & $T_{UL,k}$=0.75

FIGURE 5.7: Average access delay with A_k=1 & N_{PTmax}=3

Chapter 6

Conclusion and Future Work

In this thesis, analytical model for random access procedure with beamforming in 5G TDD mmWave system has been proposed From numerical result, we consider the access success probability and average access delay for k-th beam devices. We know that the beam sweeping time is higher if number of beams (K) is more. From aspect of k-th beam devices, the better access success probability and average access delay are showed when number of beams (K) is less. In fact, more number of beams is used, the gNB's area is divided into K small areas. The access success probability of the devices in each small area increases but the small area devices need to wait more time to transmit/recieve messages. This is the tradeoff between access success probability and average access delay.

We use slotted aloha model to analyze the situation of random access procedure with beamforming. In numberical result shows that there is error when $A_k > 1$ because we remove other PRACH occasions. It causes that the success probability of real case is higher than the success probability of slotted aloha case. We can improve the error rate by increasing number of preambe (R) to make analytical model more accuracy.

In the future, the model proposed in this thesis can be used to study the impact of different number of beams during the random access procedure. Also, the model can be extended to design the beam residence time and TDD pattern configuration.

Bibliography

[1] K. S. Kim et al., *Ultrareliable and Low-Latency Communication Techniques for Tactile Internet Services,* in Proceedings of the IEEE, vol. 107, no. 2, pp. 376-393, Feb. 2019.

[2] N. Al-Falahy and O. Y. Alani, *Technologies for 5G Networks: Challenges and Opportunities,.* in IT Professional, vol. 19, no. 1, pp. 12-20, Jan.-Feb. 2017.

[3] X. Lin, J. Li, R. Baldemair, T. Cheng, S. Parkvall, D. Larsson, H. Koorapaty, M. Frenne, S. Falahati, A. Grövlen, K. Werner, *5G New Radio: Unveiling the Essentials of the Next Generation Wireless Access Technology,.* to be published.

[4] S. Y. Lien, S. L. Shieh, Y. Huang, B. Su, Y. L. Hsu and H. Y. Wei, *5G New Radio: Waveform, Frame Structure, Multiple Access, and Initial Access,.* in IEEE Communications Magazine, vol. 55, no. 6, pp. 64-71, 2017.

[5] M. Rebato, M. Polese, and M. Zorzi, *Multi-Sector and Multi-Panel Performance in 5G mmWave Cellular Networks,* to be published.

[6] J. Jeon, *NR Wide Bandwidth Operations,.* in IEEE Communications Magazine, vol. 56, no. 3, pp. 42-46, March 2018.

[7] M. Giordani, M. Polese, A. Roy, D. Castor and M. Zorzi, *A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies,* in IEEE Communications Surveys & Tutorials, vol. 21, no. 1, pp. 173-196, Firstquarter 2019.

[8] J. Liu et al., *Initial Access, Mobility, and User-Centric Multi-Beam Operation in 5G New Radio,.* in IEEE Communications Magazine, vol. 56, no. 3, pp. 35-41, MARCH 2018.

[9] M. Giordani, M. Polese, A. Roy, D. Castor and M. Zorzi, *Standalone and Non-Standalone Beam Management for 3GPP NR at mmWavess,.* to be published.

[10] A. Omri, M. Shaqfeh, A. Ali and H. Alnuweiri, *Synchronization Procedure in 5G NR Systems,* in IEEE Access, vol. 7, pp. 41286-41295, 2019.

[11] L. Wei, Q. C. Li and G. Wu, *Initial Access Techniques for 5G NR: Omni/Beam SYNC and RACH designs,.* 2018 International Conference on Computing, Networking and Communications (ICNC), Maui, HI, 2018, pp. 249-253.

[12] M. Giordani, M. Polese, A. Roy, D. Castor and M. Zorzi, *Initial Access Frameworks for 3GPP NR at mmWave Frequencies,.* 2018 17th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), Capri, 2018, pp. 1-8.

[13] M. Giordani, M. Mezzavilla, C. N. Barati, S. Rangan and M. Zorzi, *Comparative analysis of initial access techniques in 5G mmWave cellular networks,.* 2016 Annual Conference on Information Science and Systems (CISS), Princeton, NJ, 2016, pp. 268-273.

[14] I. Ahmed et al., *A Survey on Hybrid Beamforming Techniques in 5G: Architecture and System Model Perspectives,*. in IEEE Communications Surveys & Tutorials, vol. 20, no. 4, pp. 3060-3097, Fourthquarter 2018.

[15] T. Wang, H. Guo and L. Ruan, *Low Complexity Random Access Detection for 5G Millimeter Wave Communications,*. 2018 IEEE 87th Vehicular Technology Conference (VTC Spring), Porto, 2018, pp. 1-5.

[16] J. M. P. Arana, K. M. Saquib and Y. S. Cho, *Random access preamble design for 5G millimeter-wave cellular systems with multiple beams,*. 2017 Ninth International Conference on Ubiquitous and Future Networks (ICUFN), Milan, 2017, pp. 378-380.

[17] C. Wei, R. Cheng and S. Tsao, *Performance Analysis of Group Paging for Machine-Type Communications in LTE Networks,*. in IEEE Transactions on Vehicular Technology, vol. 62, no. 7, pp. 3371-3382, Sept. 2013.

[18] R. Cheng, Z. Becvar and P. Yang, *Modeling of Distributed Queueing-Based Random Access for Machine Type Communications in Mobile Networks,*. in IEEE Communications Letters, vol. 22, no. 1, pp. 129-132, Jan. 2018.

[19] R. Cheng, Z. Becvar, Y. Huang, G. Bianchi and R. Harwahyu, *Two-Phase Random Access Procedure for LTE-A Networks,*. in IEEE Transactions on Wireless Communications, vol. 18, no. 4, pp. 2374-2387, April 2019.

[20] 3GPP TR 38.912, *Study on New Radio (NR) access technology,*. ver.15.0.0, Jun. 2018.

[21] 3GPP TR 38.211, *NR;Physical channels and modulation,*. ver.15.4.0, Dec. 2018.

[22] 3GPP TR 38.213, *NR;Physical layer procedures for control,*. ver.15.4.0, Dec. 2018.

[23] 3GPP TR 38.214, *NR;Physical layer procedures for data,*. ver.15.4.0, Dec. 2018.

[24] 3GPP TR 38.321, *NR;Medium Access Control (MAC) protocol specification,*. ver.15.4.0, Dec. 2018.

[25] 3GPP TR 38.331, *NR;Radio Resource Control (RRC) protocol specification,*. ver.15.4.0, Dec. 2018.