CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Electrical Engineering

Department of Telecommunication Engineering

Random Access Procedure for Machine Type Communication in Mobile Networks

Ing. Programme: Communication, Multimedia and Electronics
Specialisation: Electronic Communication Networks

May 2017

Author: Bc. Yi-Shin Huang
Supervisor: doc. Ing. Zdeněk Bečvář, Ph.D
Prof. Ray-Guang Cheng

I hereby declare that this master’s thesis is completely my own work and that I used only the cited source in accordance with the instruction about observance of ethical principles of preparation of university final projects.

Prague, May 26, 2017

……………….………

Signature

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Huang** Jméno: **Yi-Shin** Osobní číslo: **465907**

Fakulta/ústav: **Fakulta elektrotechnická**

Zadávající katedra/ústav: **Katedra telekomunikační techniky**

Studijní program: **Komunikace, multimédia a elektronika**

Studijní obor: **Sítě elektronických komunikací**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Procedura náhodného přístupu k médiu pro komunikaci strojů v mobilních sítích

Název diplomové práce anglicky:

Random Access Procedure for Machine Type Communication in Mobile Networks

Pokyny pro vypracování:

Study principles of Random Access Procedure (RAP) in LTE-A cellular networks. Investigate possible extensions of the RAP conventionally utilized in mobile networks towards an efficient access of massive machine type devices as envisioned in future mobile networks. Propose an improvement of the conventional RAP in LTE-A to overcome high collision probability and consequent high access delay. Consider a possibility to split the RAP into two-phases for the devices with colliding preambles. Evaluate performance of the proposed solution analytically and by means of simulations.

Seznam doporučené literatury:

[1] A. Laya, L. Alonso, and J. Alonso-Zarate, "Contention Resolution Queues for Massive Machine Type Communications in LTE," IEEE PIMRC workshop on Machine-to-Machine Communications, July 2015.
[2] A. Samir, M. M. Elmesalawy, A. S. Ali, and I. Ali, "An Improved LTE RACH Protocol for M2M Applications" Mobile Information Systems, Vol. 2016, July 2016.
[3] R. G. Cheng, C. H. Wei, and S. L. Tsao, "Iterative contending-user estimation method for OFDMA wireless networks with bursty arrivals," IEEE Symposium on Computers and Communications (ISCC), Croatia, June 2013.

Jméno a pracoviště vedoucí(ho) diplomové práce:

doc. Ing. Zdeněk Bečvář Ph.D., katedra telekomunikační techniky FEL

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) diplomové práce:

Datum zadání diplomové práce: **20.02.2017** Termín odevzdání diplomové práce: **26.05.2017**

Platnost zadání diplomové práce: **30.09.2018**

Podpis vedoucí(ho) práce | Podpis vedoucí(ho) ústavu/katedry | Podpis děkana(ky)

III. PŘEVZETÍ ZADÁNÍ

Diplomantka bere na vědomí, že je povinna vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

.

Datum převzetí zadání | Podpis studentky

ACKNOWLEDGEMENT

I appreciated my supervisor doc. Ing. Zdeněk Bečvář, Ph.D for his help and instructions on all administrative matters, courses studying and my master thesis during my Double-Degree study in CVUT. I am sincerely grateful for Prof. Ray-Guang Cheng for the opportunity to study in CVUT and his continuous encouragement throughout my master study and careful teach on my working attitude, research methodology.

My thanks also belong to BMW lab mates, who supported me when I was confused. Thanks to my parents, and sister for their encouragement, support, and concerns.

ABSTRACT

Machine-type communication (MTC) can generate numerous connection requests and bring explosive load within small time interval. A massive amount of simultaneous random access attempts results in a high collision probability and intolerable access delay because more devices contend in shared random access channels (RACH) with limited capacity. Thus, this thesis addressed a novel mechanism, denoted as two-phase random access (TPRA) procedure, for MTC in mobile networks to relieve the load of RACH. The proposed TPRA reduces probability of collision among the MTC devices when accessing radio resources by separation of the massive number of devices into small groups. The proposed concept allows a base station to adjust the number of additional access channels according to their current load. Furthermore, we propose an analytical model to evaluate the performance of the proposed TPRA by estimating the access success probability and average access delay. The simulations results validate the accuracy of the performance metrics derived analytically. The results further demonstrate that the proposed TPRA can improve the access success probability by 9% and reduce the access delay by 50% for a high density of the MTC devices comparing to the standard LTE-A random access procedure.

Keywords- **Random access, machine-type communications, mobile networks, analytical analysis.**

ANOTACE

Komunikace strojů (Machine-type communication, MTC) v mobilních sítích může vést k velkému množství požadavků na přístup k médiu a způsobit tak krátkodobá, ale častá přetížení sítě. Velké množství MTC zařízení přistupujících náhodně k radiovému kanálu vede k vysoké pravděpodobnosti kolize a neúnosné době přístupu k médiu, jelikož velké množství MTC zařízení přistupuje ke sdílenému kanálu pro náhodný přístup (Random Access Channel, RACH), který má však omezenou kapacitu. Tato diplomová práce se zabývá novou procedurou dvoufázového náhodného přístupu (Two-Phase Random Access, TPRA). Navržená procedura TPRA pro přístup MTC zařízení v mobilních sítích umožňuje snížit zátěž kanálu pro náhodný přístup tím, že redukuje pravděpodobnost kolize mezi MTC zařízeními při jejich přístupu k radiovým prostředkům. Toho je dosaženo rozdělením všech zařízení do malých skupin. Navržený koncept umožňuje základnové stanici přizpůsobit počet přístupových kanálů podle jejich aktuálního zatížení. V práci je dále navržen analytický model k vyhodnocení výkonnosti navržené procedury TPRA ve smyslu pravděpodobnosti úspěšného přístupu a doby přístupu. Výsledky simulací potvrzují přesnost těchto metrik odvozených analyticky. Výsledky dále ukazují, že TPRA umožnuje zvýšit pravděpodobnost úspěšného přístupu o 9% a zároveň snížit dobu přístupu o 50% pro vysokou hustotu MTC zařízení v porovnání se standardní LTE-A procedurou náhodného přístupu.

***Klíčová slova-* Náhodný přístup, Komunikace strojů, mobilní sítě, analytická analýza.**

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

MTC	Machine-Type Communications
M2M	Machine-to-Machine
3GPP	3rd Generation Partnership Project
RAN	Radio Access Network
H2H	Human-to-human
RACHs	Random Access Channels
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
UE	User equipment
eNB	Evolved Node B
UE-ID	UE Identity
GID	Group identity
RAP	Random Access Procedure
ACB	Access Class Barring
DQRAP	Distributed Queueing-based Random Access procedure
RAR	Random Access Response
MAC	Medium Access Control
BI	Backoff Indicator
HARQ	Hybrid Automatic Repeat Request
RRC	Radio Resource Control
ACK	Acknowledgment
NACK	Negative-acknowledgment
PRACH	Physical Random Access Channel
PUSCH	Physical Uplink Shared Channel
PDSCH	Physical Downlink Shared Channel
SIB	System Information Block
TMSI	Temporary Mobile Subscriber Identity
TPRA	Two-Phase Random Access
C-PRACH	Common- Physical Random Access Channel
D-PRACH	Dedicated- Physical Random Access Channel

I. INTRODUCTION

Machine-type communication (MTC), also known as machine-to-machine (M2M) communication, is a new service defined by standardization organization the 3rd Generation Partnership Project (3GPP) in current Long Term Evolved-Advanced (LTE-A) networks [1]. MTC introduces a communication from MTC devices to other MTC devices, a central MTC server or a set of MTC servers [2] without human intervention. Machine-type communication usually considers a huge number of devices deployed in the world interacting with each other, and with human-beings. In order to transmit data, the MTC device requests the resources for uplink data transmission. To that end, the MTC device sends a request to access radio channel. Unfortunately, the technologies that can support MTC are currently incapable of fulfilling the demand for ubiquitous access of a massive number of devices to the communication systems [3]. The concurrent access requests from the massive number of devices may congest the radio access network (RAN) and cause a high probability of collision in radio access among devices. The high probability of collision results in intolerable access delay, packet losses or even service unavailability to human-to-human (H2H) communication services. Hence, RAN overload control is identified as the first priority improvement area by 3GPP [1]. In [1], 3GPP aims to improve the usage of RAN resources efficiently, and handle high MTC access load with the minimal changes of existing specifications and small impaction of H2H communication. 3GPP further classifies the RAN overload control scheme into two categories: push-based and pull-based [4].

In push-based approaches, the devices can transmit data to the network automatically whenever they have data to be sent. Examples of solutions for push-based RAN overload control schemes are: Access class barring (ACB) [5][6], separated Random Access Channel (RACH) resources for MTC [7][8], dynamic allocation of RACH resource, MTC specific backoff scheme [9], or slotted access. In the ACB scheme [10][11], the network divides the MTC devices into several access classes and assigns an ACB factor to each access class. Each device then selects a random number before accessing RAN. The MTC devices can only transmit data when the random number selected by the device exceeds the ACB factor. Thus, the network can control the channel access probability of a specific MTC access class by setting the ACB factor. In the separated RACH scheme [7][8], the network assigns a distinct set of dedicated RACH resources to MTC and H2H devices to offer them different probabilities of the collision during radio resource access. In the dynamic allocation of RACH resource scheme [9], the network can dynamically increase or decrease the number of resources allocated to the access of the MTC devices (by means of the number of RACHs) by forecasting the access load from the MTC devices. In the MTC specific backoff scheme

[10], the network can delay a retransmission of the random access attempts of the MTC devices by assigning MTC-specific random backoff parameters. In the slotted access scheme [1], each MTC device is associated with a dedicated access cycles/slots through its identity. Each MTC device can transmit the random access attempt only at its random access slot.

The devices in pull-based approaches can only transmit data when they are invited to do so by the network. Therefore, the network with the pull-based approaches may more properly control the MTC traffic load than with pushed-based approaches. In pulled-based approaches, the network may properly handle the MTC traffic load by activating the appropriate number of devices to prevent RAN overload [12]. Paging and group paging are potential pull-based RAN overload control schemes [13][14]. In LTE, a downlink paging channel is defined to transmit the paging information from an evolved Node B (eNB) to a user equipment (UE). The paging channel informs the UEs about an update of system information and provides emergency notifications. The eNB may transmit a paging message to trigger a specific UE at the UE's paging occasion. The paging occasion of each UE is determined based on its UE identity (UE-ID). The paging mechanism that was originally designed for H2H services can only page up to 16 devices with a single paging message and only two paging occasions are available per 10 ms radio frame [14]. Therefore, the eNB have to spend a long period transmitting several paging messages to trigger a huge number of MTC devices. Thus, a group paging mechanism is proposed to overcome this limitation by sending just one single group paging message to trigger a group of MTC devices [1]. In the group paging, each MTC device is assigned with a distinct group identity (GID) after camping on a network and joining a group. All of the MTC devices in the same group listen to the same paging channel at the same paging occasion. The paging occasion is derived from the GID [15]. The MTC devices belonging to the same group should simultaneously perform the standard LTE random access procedure to access the network after finding their GID in the group paging message sent by the eNB.

Another pull-based approach based on paging scheme is described below. An optimization of the access to radio resource 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 [17]. DQRAP is the random access procedure in LTE and it is based on a combination of a tree-spitting algorithm and the distributed queuing mechanism. 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 [17]. The performance analysis and an analytical model for DQRAP can be found in [17] and [18], respectively.

Another implementation of distributed queuing idea, denoted as Distributed Queuing Access for LTE (DQAL) presented in [8]. DQAL not only divides the channel resources into H2H part and MTC part, but also separates the radio access resources for the MTC devices into a number of groups. Thus, DQAL can perform distributed queuing mechanism in both time domain and frequency domain by assigning different group of access resources to the different groups of devices. DQAL reduces the collision probability and enhances both the access success probability and access delay for MTC. Furthermore, it guarantees the non-machine equipment can access the network without any modification.

In the thesis, a novel solution of random access procedure is proposed. The novelty consists in splitting the access procedure into two phase. In the first phase, an additional selection of access resources is added to separate the devices into several groups by the access resources they selected; in the second phase, the standard LTE-A 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. The results of analysis are compared with the simulations to validate the accuracy of the analytical model.

The remainder of this thesis is organized as follows. In Section II, the standard LTE-A random access procedure is described and then the proposed two-phase random access procedure is introduced. The system model is presented in Section III. In Section IV, the proposed mechanism is analytically formulated. The metrics for performance assessment are described in Section V. Simulation and analytical results are presented and discussed in Section VI to verify the accuracy of models and to compare the performance of the proposed access procedure with other approaches. Last, major conclusions and potential future research directions are given in Section VII.

II. RANDOM ACCESS PROCEDURE

In this section, the standard LTE random access procedure is briefly outlined and then the two-phase random access procedure proposed in this thesis is described.

A. *LTE-A Random Access Procedure*

In LTE-A, there are two types of the random access procedure: contention-based and contention-free. Usually, the contention-free random access is used in some special cases like handover and related management ensures low or no probability of collisions [19] . Thus, this sub-section is focused on the contention-based random access procedure (RAP) defined for LTE-A network.

LTE-A RAP is composed of four steps, represented by messages exchanged between the UE and the eNB, as shown in Figure 1. In the first step, the device, which is willing to access the channel for communication randomly selects the RA preamble and transmits it in Msg1. In LTE-A, time is divided into fix-length frames with a duration of 10s and each frame consists of 10 sub-frames [20]. One PRACH consists of 72 continuous carriers, i.e., six Resource Blocks (RBs) with the duration of one sub-frame [20]. The Msg1 is transmitted on the shared Physical Random Access Channel (PRACH) and one or more PRACHs are reserved in the frame for the RAP. The location of the PRACH in time domain is defined by the parameter *PRACH Configuration Index* broadcasted by the eNB in *System Information Block 2* (*SIB 2*) [20]. If the eNB detects the preamble(s) transmitted by the devices, it replies with the Msg2, denoted as Random Access Response (RAR), on a Physical Downlink Shared Channel (PDSCH). This response is sent just after a processing time required by the eNB to detect the preambles. The RAR contains the identity of the detected preamble(s), an uplink timing alignment, and dedicated uplink resources reserved for the accessing devices to transmit following message, i.e., Msg3. Each RAR carries one Medium Access Control (MAC) header, and one or more MAC RAR(s). In MAC header, there are several sub-headers indicating the RAR corresponding to the individual preambles. Then, one optional backoff parameter value, denoted as Backoff Indicator (BI), is carried for: i) the devices whose preamble is not detected by the eNB, ii) the devices whose preamble is collided with the preamble selected by other device(s), or iii) the devices that cannot be accommodated due to insufficient RAR capacity. After the device receives RAR within the RAR window size (W_{RAR}), it can continue to the next step; otherwise, it re-transmits a new random preamble (Msg1) and restarts the random access procedure after waiting a random backoff time BI indicated in the RAR. The procedure continues until the maximal number of preamble transmission is reached. If the maximal number of transmissions is reached, the MAC layer will indicate a Random Access problem to an upper layer in real networks [21]. In our model, additional attempts of the device are blocked if the maximum number of preamble transmissions is reached and we leave the interaction with the upper layers for future research.

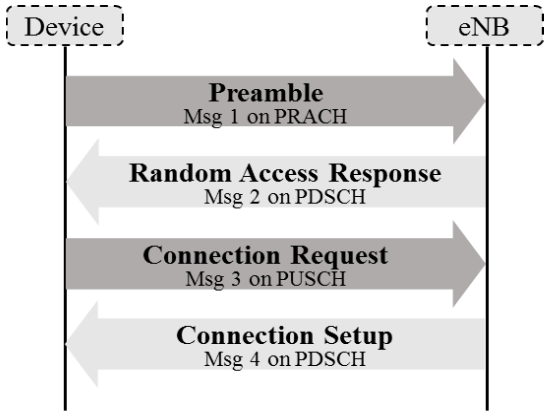

Figure 1. LTE-A four-step RA procedure

After the device receives the RAR from the eNB, it transmits the Radio Resource Control (RRC) Connection Request message (Msg3) and starts a Contention Resolution timer. The Msg3, carrying the UE identity and the reason of connection establishment, is transmitted in the dedicated uplink resource on the Physical Uplink Shared Channel (PUSCH) indicated in the Msg2. The UE identity is either a Temporary Mobile Subscriber Identity (TMSI) or a random value generated by the UE if the UE is not registered into the current cell [21]. Note that the devices transmitting the same preamble, which is detected by the eNB may still receive the RAR. However, these devices collide with each other because of transmitting the Msg3 with different content (UE identity) on the identical uplink resources. Non-adaptive Hybrid Automatic Repeat Request (HARQ) is enabled to protect the reliable message exchange [21]. After the device transmits the Msg3, it waits for a HARQ acknowledgement (ACK) or a negative- acknowledgment (NACK) from the eNB within the time interval required for receiving the HARQ ACK (denoted as T_{HARQ} with unit: sub-frame) [12]. If the eNB receives the Msg3 successfully, it replies with the ACK; otherwise, it replies with the NACK. When the device receives the NACK, it waits for T_{M3} sub-frames before re-transmitting the Msg3 again. This process is repeated until the device correctly receives the ACK.

As the last step, the eNB waits for T_{A_M4} sub-frames (after the ACK of the Msg3) and transmits Msg4. The Msg4 indicates that the Msg3 is successfully received. Similarly, the eNB receives another ACK in T_{HARQ} sub-frames if the Msg4 is successfully received by the device; otherwise, the eNB waits for the ACK within T_{HARQ} sub-frames. If the ACK is not received within T_{HARQ} sub-frames, the eNB re-transmits the Msg4 again after T_{M4} sub-frames. The number of re-transmission of the Msg3 and the Msg4 are limited to N_{HARQ}.

B. Two-phase Random Access Procedure (TPRA)

In this subsection, we provide detailed description of TPRA. The message sequence chart of the proposed two-phase random access procedure is shown in Figure 2. Comparing to the conventional LTE-A RAP, TPRA is composed of two phases. Two messages (pre-Msg1 and pre-Msg2) are defined in Phase-I to separate devices into smaller groups and assign each group a dedicated channel. We denote the two messages as the pre-Msg1 and the pre-Msg2 since they share the same functionality as the Msg1 and the Msg2 in LTE-A RAP. The preambles are used to indicate the pre-Msg1 and the Msg1. For differentiation, we use a preamble-I and a preamble-II to denote the preamble used for the pre-Msg1 in the Phase-I and the Msg1 in the Phase-II, respectively. In the Phase-I, the devices transmit a randomly chosen preamble-I (pre-Msg1) on a shared common-PRACH (C-PRACH). Note that the C-PRACH in TPRA utilizes the same PRACH as those used in the standard LTE-A RAP. Thus, the position of C-PRACH in time-frequency domains is defined by *PRACH Configuration Index* as it is done in the standard LTE RAP. This ensures compatibility of the proposed solution with the LTE-A procedure. In the second step of the Phase-I, the eNB replies with the RAR-I (pre-Msg2) over the PDSCH carrying a dedicated-PRACH (D-PRACH) allocated to the detected preamble-I. Note that the C-PRACH and the D-PRACH utilize the PRACH and PUSCH defined in LTE-A, respectively. The allocation of PRACH is fixed (i.e., defined in SIB2) and the allocation of PUSCH can be dynamically adjusted. One D-PRACH is made up of the same number of continuous RBs as the PRACH in LTE-A.

After the devices successfully receive the RAR-I indicating the preamble-I they sent in the pre-Msg1, they transmit the preamble-II (Msg1) on the assigned D-PRACH and start a modified four-step RAP. A key aspect and a difference with respect to the standard LTE four-step RAP, is that the resources assigned by the eNB to the devices on the D-PRACH are not the same for all devices. The eNB groups the devices according to their selected preamble-Is in the Phase-I. The devices grouped together then continue the Phase-II at the dedicated resources, but do not compete with the devices in other groups. Thanks to this grouping, the probability of collisions in the Phase-II is significantly lowered due to less competing devices at the same resources. The remaining processes in the Phase-II are similar to the processes in the standard LTE-A RAP, but take advantage of the split of devices onto groups during the Phase-I.

The devices, which fail in the Phase-I (due to the failure of the pre-Msg2) or in the Phase-II (due to the failure of the Msg2, Msg3, or Msg4) should perform the random backoff and start over the RAP from the Phase-I at the next available C-PRACH. The process repeats until the number of attempts exceeds the preamble-I transmission limitation. Thus, the maximal number of assignable D-PRACHs is restricted not only to the maximal number of the acknowledged RAR-I, but also to the amount of available PUSCH resources at the eNB. Note that the selection of the preamble-I in the Phase-I divides devices into multiple groups and all devices in the same group contend in the same dedicated D-PRACH in the Phase-II. The devices from different groups do not contend with each other.

The benefit of TPRA consists in the flexibility of the PRACH allocation. In LTE-A RAP, the PRACH is periodically allocated by the eNB. The allocation may be based on mean arrival rate of the access requests, which is inflexible in supporting MTC services. In TPRA, the C-PRACH is periodically allocated and the D-PRACH can be dynamically allocated based on the instantaneous access requests injected in the C-PRACH.

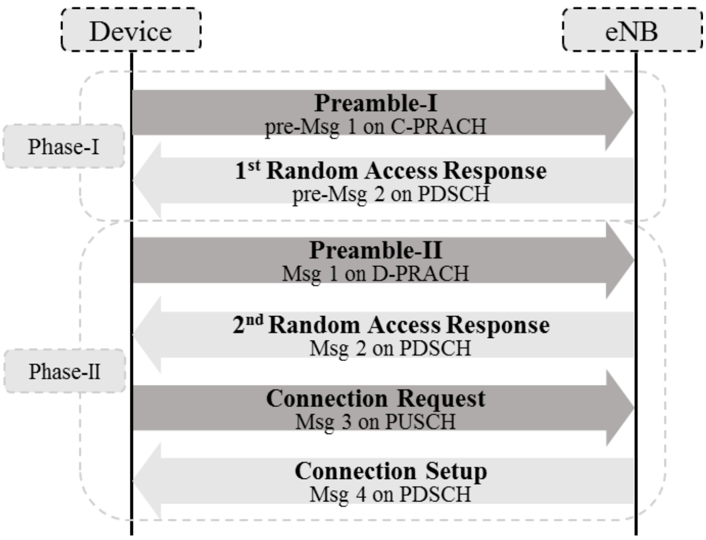

Figure 2. Proposed TPRA procedure

III. SYSTEM MODEL

This work considers M MTC devices in a paging area simultaneously performing the random access procedure after receiving a group paging massage in the LTE-A network. Once the group paging message is received from the eNB, all of M MTC devices establish the connection with the eNB by following the TPRA procedure. The performance of TPRA is investgated from the first C-PRACH to the I_{max}-th C-PRACH, where I_{max} is the number of C-PRACH within the investigated interval and is calculated by the maximal number of preamble transmissions. Let T_{CP} is the periodicity of C-PRACHs; R_C and R_D are the number of preamble-I and preamble-II reserved for C-PRACH and D-PRACH, respectively. For simplicity, it is assumed that all D-PRACHs are allocated in different sub-carriers at the same sub-frame. Therefore, the maximal number of assignable D-RPACH is restricted to the bandwidth of uplink defined in LTE-A and to the maximal number of RARs which can be acknowleged by the eNB within one RAR window size. We assumed that eNB is available to assigned the maximal number of D-PRACH to the devices in each C-PRACH. The common parameters used in both LTE-A RAP and TPRA are summarized as follows:

- T_{RAR} is the time required for receiving RAR after the preamble transmission;
- N_{UL} is the maximal number of RARs, which can be acknowledged by the eNB;
- T_{HARQ} is the time interval required for reception of the acknowledgement of the Msg3 and the Msg4;
- T_{A_M4} is the time for monitoring the Msg4.

The relationship among T_{CP}, T_{RAR}, T_{HARQ}, and T_{A_M4} is illustrated in Figure 3. The arrow represents the colliding attempts, i.e., the situation requesting a retransmisison of the preamble due to followng problems: i) the preamble-Is and the preamble-IIs are not indicated in the pre-Msg2 or in the Msg2, respectively; ii) the preamble-IIs coliding in the Phase-II. All devices, which collides perform backoff mechanism with a Backoff window size (W_{BO}). Note that the proposed model can be easily extended to accommodate a general arrival process based on the technique shown in [8].

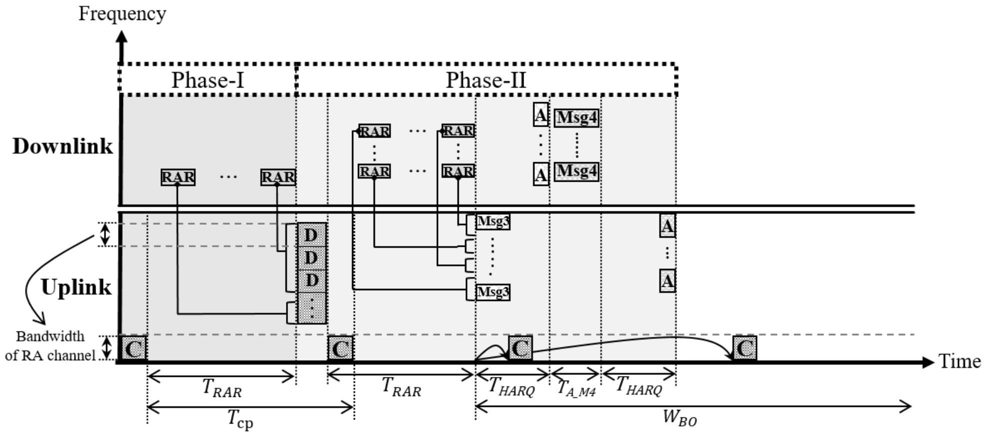

Figure 3. Timing diagram of TPRA

IV. ANALYTICAL MODEL

In this section, an analytical model is presented to estimate the access success probability P_S and the average access delay $\overline{D_a}$ for the proposed TPRA. Both performance metrics for TPRA are derived based on the estimation of the number of contending devices in each C-PRACH, and the number of successful and failed devices after the reception of Msg2. Only the device successfully accessing the channel without exceeding the maximal number of preamble transmissions (N_{PTmax}) can be counted into successfully accessing devices. Thus, we investigate the performance within an interval of a fix duration. The duration, denoted as I_{max}, is decided by the maximal number of preamble-I transmission (N_{PTmax}). I_{max}, is the maximal duration for the devices that succeed to access the channel by transmitting the maximal number of preamble-I transmissions (N_{PTmax}). It represents a situation when the device transmits preamble-I with $(N_{PTmax} - 1)$ times and each of preamble-I transmission are failed before successfully accessing the channel, and the device consumes the longest possible duration for each failed transmission. The longest duration for each failed transmission means that the device selects the maximal value of backoff time (W_{BO}) and with the fixed value $2\times(T_{RAR}+W_{RAR})+1$ where 1 is the time for D-PRACH; $2\times(T_{RAR}+W_{RAR})$ is the time for learning the result of the C-PRACH and the D-PRACH transmissions. I_{max} is expressed in the number of C-PRACH because the following formulas are derived with the number of C-PRACH. Thus, I_{max} equals to the sum of 1 (the successful attempt at the last transmission) and $\left(N_{PTmax}-1\right)\times\left\lceil\frac{2\times(T_{RAR}+W_{RAR})+1+W_{BO}}{T_{CP}}\right\rceil$ (the number of C-PRACH within $(N_{PTmax} - 1)$ times failed transmissions). Thus, I_{max} can be derived as

$$I_{max}=1+\left(N_{PTmax}-1\right)\times\left\lceil\frac{2\times(T_{RAR}+W_{RAR})+1+W_{BO}}{T_{CP}}\right\rceil. \tag{1}$$

Let N_{DP} *is the number of assigned D-PRACH,* $M_i[n]$ is the number of devices contending at the i-th C-PRACH with the n-th preamble-I transmission, $M_{i,S}[n]$ is the average number of MTC devices that transmit the n-th preamble-I at the i-th C-PRACH and learn the successful preamble transmission after receiving the Msg2 with the specified RAR, $M_{i,F}[n]$ is the average number of MTC devices that transmit the n-th preamble-I at the i-th C-PRACH, but fail in this transmission because of the failure of receiving the pre-Msg2 or the Msg2, M_i is the total number of MTC devices that transmit their preamble-I at the i-th C-PRACH. Thus, the total number of contending devices in each C-PRACH is the sum of the n-th preamble-I transmission at the i-th C-

PRACH that $1 \le n \le N_{PTmax}$. That is,

$$M_i = \sum_{n=1}^{N_{PTmax}} M_i[n]. \tag{2}$$

All transmissions of the preamble-II are detected by the eNB with the preamble-II detection probability $p_n = 1 - \frac{1}{e^n}$ where n is the number of the preamble-I transmission [1]. However, we assume the eNB is able to detect all transmissions of the preamble-I because of the simplification of equation (4). According to [22], the $M_{i,s}[n]$ of the group paging in LTE is approximated by

$$M_{i,S}[n] = \begin{cases} M_i[n] e^{-\frac{M_i}{R}} p_n, & \text{if } \sum_{n=1}^{N_{PTmax}} M_i[n] e^{-\frac{M_i}{R}} p_n \le N_{UL}, \\ \frac{M_i[n] e^{-\frac{M_i}{R}} p_n}{\sum_{n=1}^{N_{PTmax}} M_i[n] e^{-\frac{M_i}{R}} p_n} N_{UL}, & \text{otherwise.} \end{cases} \tag{3}$$

In TPRA, all contending devices are divided into R_C group in the Phase-I and we assume to always assign the maximal number of D-PRACH (N_{DP}) in each procedure. Therefore, only N_{DP} of R_C groups can be assigned D-PRACHs when $R_C > N_{DP}$. Thus, the maximal number of assignable DPRACH is bounded by the number of acknowledged RARs within a RAR window (N_{UL}) and the channel bandwidth of uplink. The number of D-PRACHs is restricted to the channel bandwidth of uplink because we assumed that all D-PRACHs are at the same sub-frame but different subcarriers. Thus, let N_{RB} is the number of available continuous RBs at the same sub-frame in the PUSCH. Each D-PRACH occupies 72 continuous subcarriers (i.e., 6 RBs) as the PRACH in LTE-A. Thus, $N_{DP} = \min\left(N_{UL}, \frac{N_{RB}}{6}\right)$. Thus, one D-PRACH in TPRA is the same as one standard four-step RAP in LTE-A and there are $\frac{M_i[n]}{R_C}$ contending devices in each D-PRACH. Then, $M_{i,S}[n]$ can be determined as:

$$M_{i,S}[n] = \begin{cases} \frac{M_i[n]}{R_C} \times e^{\frac{-M_i}{R_C \times R_D}} \times p_n \times N_{DP}, & \text{if } \sum_{n=1}^{N_{PTmax}} \frac{M_i[n]}{R_C} \times e^{\frac{-M_i}{R_C \times R_D}} \times p_n \le N_{UL} \\ \frac{\frac{M_i[n]}{R_C} \times e^{\frac{-M_i}{R_C \times R_D}} \times p_n}{\sum_{n=1}^{N_{PTmax}} \frac{M_i[n]}{R_C} \times e^{\frac{-M_i}{R_C \times R_D}} \times p_n} \times N_{UL} \times N_{DP}, & \text{otherwise.} \end{cases} \tag{4}$$

All successfully accessing devices in a D-PRACH can receive the RARs if the total number of the successful devices in the D-PRACH does not exceed N_{UL} (i.e., $\sum_{n=1}^{N_{PTmax}} \frac{M_i[n]}{R_C} \times e^{\frac{-M_i}{R_C \times R_D}} \times p_n \leq N_{UL}$). Otherwise, the eNB replies with the RAR only to N_{UL} devices selected randomly. The number of the acknowledged RARs is proportional to the total number of the successful devices with the same number of preamble-I transmissions. The result is calculated for one D-PRACH. Therefore, the number of successful devices in one D-PRACH is multiplied with the number of assigned D-PRACH (N_{DP}) and then the total number of successful devices in both C-PRACH and D-PRACH transmission is acquired.

The number of devices, which fail in the preamble transmission is equal to the number of the contending devices minus the number of successful devices. That is

$$M_{i,F}[n] = M_i[n] - M_{i,S}[n] \tag{5}$$

$M_i[n]$ can be derived by recursive accumulation with $M_{i,S}[n-1]$ and $M_{i,F}[n-1]$:

$$M_i[n] = \sum_{k=K_{\min}}^{K_{\max}} \alpha_{k,i} M_{k,F}[n-1] + \sum_{j=J_{\min}}^{J_{\max}} \beta_{j,i} p_{e,MSG} M_{j,S}[n-1] \tag{6}$$

(6) contains two parts: the devices with failure in transmission at the C-PRACH or the D-PRACH and those who fail in the Msg3 or Msg4 transmission/reception. The first term in (6) ($\alpha_{k,i} M_{k,F}[n-1]$) represents the condition where the devices transmit the *(n-1)*-th preamble-I at the *k*-th C-PRACH, but they fail to accomplish the preamble-I or the preamble-II transmission. Among these devices with failed C-PRACH/D-PRACH transmissions, $\alpha_{k,i}$ of them perform random backoff and retransmit the *n*-th preamble-I at the *i*-th C-PRACH with backoff window (W_{BO}). K_{min} and K_{max} indicate the minimal and maximal value of *k*, respectively. Hence, we accumulate any *k* from K_{min} to K_{max} to acquire the number of devices with failed preamble-I or preamble-II transmission. The second term in (6) ($\beta_{j,i} p_{e,MSG} M_{j,S}[n-1]$) represents the condition where the devices transmit the *(n-1)*-th preamble-I at the *j*-th C-PRACH and finish both the preamble-I and the preamble-II transmissions, but fail in the Msg3 transmission or the Msg4 reception with the error probability $p_{e,MSG}$. Among these devices with failed Msg3 transmissions or Msg4 receptions, $\beta_{j,i}$ of them perform random backoff and

retransmit the n-th preamble-I at the i-th C-PRACH. J_{min} and J_{max} indicate the minimal and maximal value of j. Hence, we accumulate any j from J_{min} to J_{max} to acquire the number of devices failed in the Msg3 transmissions or the Msg4 receptions. Note that the Msg3 transmission or the Msg4 reception is failed when the number of Msg3 transmissions exceeds N_{HARQ}, or Msg3 transmission is successful, but the number of Msg4 transmission exceeds N_{HARQ}. Thus, $p_{e,MSG}$ can be determined by:

$$P_{e,MSG} = p_f^{\,N_{HARQ}} + \sum_{j=0}^{N_{HARQ}-1} p_f^{\,j}\left(1-p_f\right)p_f^{\,N_{HARQ}}. \quad (7)$$

Referring to [19] and [1], N_{HARQ} and p_f are set to 5, and 0.1, respectively (N_{HARQ}=5, p_f =0.1). With these parameters, the $P_{e,MSG}$ equals to 2×10^{-5}. Due to a small value of $p_{e,MSG}$ and $\beta_{j,i} \le 1$, the second term in (6) can be neglected. Therefore, $M_i[n]$ is simplified to:

$$M_i[n] = \sum_{k=K_{\min}}^{K_{\max}} \alpha_{k,i} M_{k,F}[n-1]. \quad (8)$$

The relationship among $\alpha_{k,i}$ K_{min} and $K_{\max}$ in (8) can be explained from Figure 4. The device, whose preamble-I or preamble-II transmission is failed at the k-th C-PRACH, may re-transmit a new preamble-I at the i-th C-PRACH only if the backoff interval of the k-th C-PRACH transmission is overlapping with the transmission interval of the i-th C-PRACH. Moreover, $\alpha_{k,i}$ is the portion of the backoff interval of the k-th C-PRACH that overlaps with the transmission interval of the i-th C-PRACH $(k<i)$. As illustrated in Figure 4, the devices transmitting the preamble at the k-th C-PRACH at time $(k-1)\times T_{CP}$ can recognize their preamble-I or preamble-II failure after $(2\times T_{RAR}+1)$ sub-frames. Each failed device starts to perform random backoff at time $(k-1)\times T_{CP}+2\times T_{RAR}+1+1$. Hence, the backoff interval of the k-th C-PRACH begins at time $(k-1)\times T_{CP}+2\times T_{RAR}+1+1$, and ends at time $(k-1)\times T_{CP}+2\times T_{RAR}+1+W_{BO}$. The devices transmit their preamble-I at the i-th C-PRACH if their random backoff counters reach zero during the interval between $(i-2)\times T_{CP}+1$ and $(i-1)\times T_{CP}$. The minimal value of k (K_{min}) is obtained when the right boundary of the random backoff interval of the k-th C-PRACH reaches the left boundary of the preamble transmission interval of

the i-th C-PRACH ($(i-2)\times T_{CP}+1$) (i.e., $(i-2)\times T_{CP}+1\le(K_{\min}-1)\times T_{CP}+2\times T_{RAR}+1+W_{BO}$). Therefore, K_{min} is expressed as:

$$K_{min}=\left\lceil (i-1)-(\frac{2\times T_{RAR}+\mathrm{W}_{\mathrm{BO}}}{T_{CP}})\right\rceil. \tag{9}$$

The maximal value of k (K_{max}) is obtained when the left boundary of the random backoff interval of the k-th C-PRACH exceeds the right boundary of the preamble transmission interval of the i-th C-PRACH ($(i-1)\times T_{CP}$) (i.e., $(i-1)\times T_{CP}\ge(K_{\max}-1)\times T_{CP}+2\times T_{RAR}+1$). Thus, K_{max} is expressed as:

$$K_{\max}=\left\lfloor i-(\frac{2\times T_{RAR}+1}{T_{CP}})\right\rfloor \tag{10}$$

$\alpha_{k,i}$ can be determined according to k in three conditions presented in Figure 4. In the first condition, the right boundary of the random backoff interval of the k-th C-PRACH is between the transmission interval of the i-th C-PRACH (i.e., $(i-2)\times T_{CP}+1\le(k-1)\times T_{CP}+2\times T_{RAR}+1+W_{BO}\le(i-1)\times T_{CP}$). In this case, $K_{min}\le k\le i-(\frac{2\times T_{RAR}+1+W_{BO}}{T_{\mathrm{CP}}})$ and the overlapped area starts from the left boundary of the transmission interval of the i-th C-PRACH and ends at the right boundary of the random backoff interval of the k-th C-PRACH. In the second condition, the transmission interval of the i-th C-PRACH fully overlaps with the random backoff interval of the k-th C-PRACH. Hence, the overlapping area is of the length of T_{CP}. In the third condition, the left boundary of the random backoff for the k-th C-PRACH is between the transmission interval of the i-th C-PRACH (i.e., $(i-1)\times T_{CP}\ge(k-1)\times T_{CP}+2\times T_{RAR}+1\ge(i-2)\times T_{CP}+1$). In this case, $(i-1)-\frac{2\times T_{RAR}}{T_{CP}}\le k\le K_{max}$ and the overlapping area starts from the left boundary of the random backoff interval for the k-th C-PRACH and ends at the right boundary of the transmission interval of the i-th C-PRACH. Thus, $\alpha_{k,i}$ is defined below:

$$\alpha_{k,i}=\begin{cases}\dfrac{(k-1)\times T_{CP}+2\times \mathrm{T}_{RAR}+1+W_{BO}-(i-2)\times T_{CP}}{W_{BO}}, & \text{if } K_{min}\le k\le i-(\dfrac{2\times T_{RAR}+1+W_{BO}}{T_{\mathrm{CP}}}),\\ \dfrac{T_{CP}}{W_{BO}}, & \text{if } (i-1)-\dfrac{2\times T_{RAR}}{T_{CP}}<k<i-(\dfrac{2\times T_{RAR}+1+W_{BO}}{T_{\mathrm{CP}}}),\\ \dfrac{(i-1)\times T_{CP}-(k-1)+2\times T_{RAR}+1}{W_{BO}}, & \text{if } (i-1)-\dfrac{2\times T_{RAR}}{T_{CP}}\le k\le K_{max},\\ 0, & \text{otherwise.}\end{cases} \tag{11}$$

At the beginning, all of the M devices transmit their first preamble-I at the first C-PRACH. Thus, the initial conditions are: M_1=M_1[1]=M, and M_1[n]=0, for n ≠ 1. Let i=1 in (3), then, we derive

$$\mathrm{M}_{1,\mathrm{S}}[\mathrm{n}]=\begin{cases}\dfrac{\mathrm{M}}{\mathrm{R}_C}\times \mathrm{e}^{\frac{\text{-M}}{\mathrm{R}_C\times \mathrm{R}_D}}\times p_n\times \mathrm{N}_{\mathrm{DP}} & \text{,if } n=1 \text{ and } 0<\dfrac{\mathrm{M}}{\mathrm{R}_C}\times \mathrm{e}^{\frac{\text{-M}}{\mathrm{R}_C\times \mathrm{R}_D}}\times p_n\le \mathrm{N}_{\mathrm{UL}}\\ \mathrm{N}_{\mathrm{UL}}\times \mathrm{N}_{\mathrm{DP}} & \text{,if } n=1 \text{ and } \dfrac{\mathrm{M}}{\mathrm{R}_C}\times \mathrm{e}^{\frac{\text{-M}_\mathrm{i}}{\mathrm{R}_C\times \mathrm{R}_D}}\times p_n>\mathrm{N}_{\mathrm{UL}}\end{cases} \tag{12}$$

and

$$\mathrm{M}_{1,\mathrm{F}}[\mathrm{n}]=\begin{cases}M(1-\dfrac{1}{R_C}\times e^{\frac{-M}{R_C\times R_D}}\times p_n)\times N_{DP} & \text{,if } n=1 \text{ and } 0<\dfrac{M}{R_C}\times e^{\frac{-M}{R_C\times R_D}}\times p_n\le N_{UL}\\ M-N_{UL}\times N_{DP} & \text{,if } n=1 \text{ and } \dfrac{M}{R_C}\times e^{\frac{-M_i}{R_C\times R_D}}\times p_n>N_{UL}\end{cases} \tag{13}$$

For $i\ge 2$, $M_{i,S}[n]$, $M_{i,F}[n]$ and M_i can be determined by recursive accumulation from (3), (4) and (5), respectively.

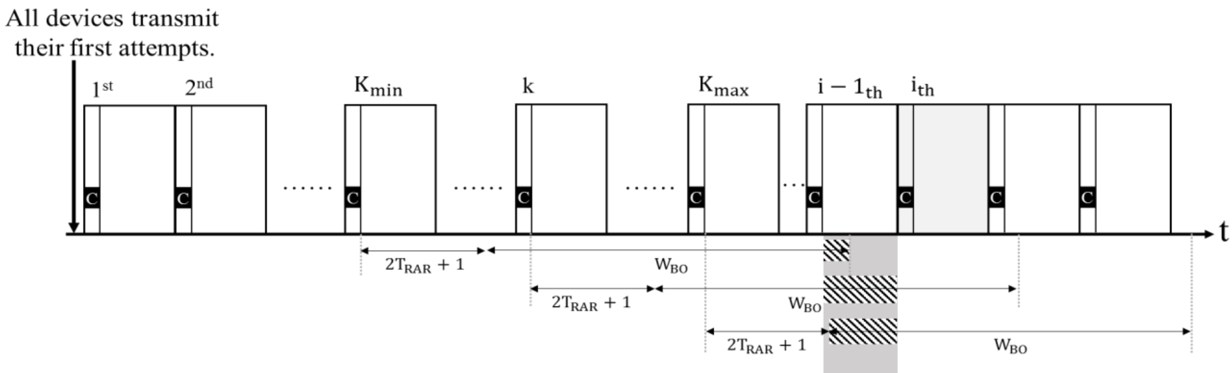

Figure 4. Demonstration for deriving (11)

V. PERFORMANCE METRIC

The access success probability and the average access delay are selected as the performance metrics to evaluate the performance of TPRA in this thesis. The access success probability P_s, defined as the probability of successful completion of the random access procedure within the maximal number of preamble transmissions [1]. Hence, P_s is the ratio between the number of devices, which success in access without exceeding the maximal number of preamble transmissions (N_{PTmax}) and within the investigated interval I_{max} and the total number of devices paged by the eNB in the beginning (M). The number of successful devices that transmit their n-th preamble-I at the i-th C-PRACH is equal to $M_{i,S}[n](1-p_{e,MSG})$. The total number of the successful devices is the sum of the devices successfully accessing the resources for each C-PRACH. Thus, P_s is expressed as:

$$P_s = \frac{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT\max}} M_{i,S}[n](1-p_{e,MSG})}{M} \tag{14}$$

The average access delay, $\overline{D_a}$, is the average time duration needed to complete the random access procedure for the successfully accessing devices (unit: sub-frame). $\overline{D_a}$ is the ratio of the total access delay for all successfully accessing devices to the total number of devices, which complete RAP successfully within investigated time interval I_{max}. The total access delay for all successfully accessing devices, which transmit their last preamble-I at the i-th C-PRACH is $\sum_{n=1}^{N_{PTmax}} M_{i,S}[n](1-p_{e,MSG})T_i$. Hence, $\overline{D_a}$ is expressed as

$$\overline{D_a} = \frac{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT\max}} M_{i,S}[n](1-p_{e,MSG})T_i}{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT\max}} M_{i,S}[n](1-p_{e,MSG})} = \frac{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT\max}} M_{i,S}[n]T_i}{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT\max}} M_{i,S}[n]} \tag{15}$$

Let T_i is the time required to access the network for the device that transmit the last preamble-I at the i-th C-PRACH and complete successfully the preamble transmission (preamble-I and preamble-II) and the Msg3/Msg4 transmission/reception. T_i starts from the first C-PRACH because all of devices transmit their first preamble-I at the first C-PRACH. Therefore, $(i-1)T_{CP}$ is the time before the last transmission of preamble-I at the *i*-th C-PRACH. The remaining parts are the time to transmit preamble-II (1 sub-frame), to receive the RAR-I and the RAR-II ($2T_{RAR}$) and to finish the Msg3/Msg4 transmission/reception ($\overline{T_{MSG}}$). That is

$$T_i = (i-1)T_{CP} + 2T_{RAR} + 1 + \overline{T_{MSG}} \tag{16}$$

where $\overline{T_{MSG}}$ is the average time required by the device to complete the transmission of the Msg3 and the reception of the Msg4. Consider a situation that the successful transmission of the Msg3 by using *u* HARQ transmissions and the successful transmission of Msg4 by using *v* HARQ transmissions. The time required to transmit *u* Msg3 and *v* Msg4 is equal to $1+(u-1)(T_{M3}+T_{HARQ})+T_{HARQ}$ and $T_{A\_M4}+(v-1)(T_{M4}+T_{HARQ})+T_{HARQ}$, respectively. The probability that the device that successfully transmits the Msg3 using *u* HARQ transmissions and receives the Msg4 using *v* HARQ transmissions is $P_f^{u-1}(1-P_f)P_f^{v-1}(1-P_f)$. Hence, $\overline{T_{MSG}}$ is expressed as

$$\begin{aligned}\overline{T_{MSG}} &= \sum_{u=1}^{N_{HARQ}} \sum_{v=1}^{N_{HARQ}} P_f^{u-1}(1-P_f)P_f^{v-1}(1-P_f)\begin{bmatrix}\left(1+(u-1)(T_{M3}+T_{HARQ})+T_{HARQ}\right) \\ +\left(T_{A\_M4}+(v-1)(T_{M4}+T_{HARQ})+T_{HARQ}\right)\end{bmatrix} \\ &= \sum_{u=1}^{N_{HARQ}} \sum_{v=1}^{N_{HARQ}} P_f^{u+v-2}(1-P_f)^2\left((u-1)T_{M3}+(v-1)T_{M4}+(u+v)T_{HARQ}+T_{A\_M4}+1\right).\end{aligned} \tag{17}$$

VI. NUMERICAL RESULTS

Computer simulations are conducted on top of a C-based simulator to verify the effectiveness of the proposed analytical model. In the simulation, each point is obtained by 10^5 samples. Each sample is acquired by preforming the random access procedure in an investigated interval. We adjust the parameters of number of devices (M), total number of preamble-I reserved for C-PRACH (R_C), total number of preambles reserved for D-PRACH (R_D), and maximal number of preamble-I transmission (N_{PTmax}) to evaluate the performance of the access success probability (P_S) and the average access delay ($\overline{D_a}$). The same random access preamble set as in LTE-A is used for R_D. Hence, R_D is fixed in all simulation. All of random access parameters refers to [12], and the setting values of all simulation parameters are summarized in Table 1.

Three scenarios are considered in this thesis. Scenario I is defined to verify the accuracy of the analytical models. We consider the case when the eNB reserves 5, 10 and 15 preambles for C-PRACH (R_C= 5, 10, 15) and 54 preambles for each D-PRACH (R_D=54) to page a group of a size of 10–1000 MTC devices (M=10–1000) with a different number of the maximal preamble-I transmission. The results of the maximal number of preamble-I transmission, which equals to 3, 5 and 10 (N_{PTmax}=3, 5, 10), are shown in the Figure 5 to Figure 10.

Scenario II is designed to evaluate an effect of the variable parameters setting and the tradeoff between R_C and N_{PTmax} with M=1000. The range we used in R_C is from 1 to 15 because the maximum number of D-PRACH is also set to 15 in our simulations. Thus, any higher number of the reserved R_C would cause more failures in the Phase-I because of lack of the D-PRACHs. The results are shown in Figure 11 and Figure 12.

Scenario III is presented to compare the group paging in proposed TPRA with group paging in the standard LTE RAP [12]. We take two cases (R_C=5 and 15) of the proposed TPRA into account. The value of the maximal number of preamble-I transmission is set to 10 for both LTE RAP and TPRA (N_{PTmax}=10). Figure 13 and Figure 14 show the comparisons of the access success probability and average access delay, respectively. Thus, Figure 15 and Figure 16 demonstrate the number of contending and successful devices for each C-PRACH in TPRA and each PRACH in LTE RAP.

Notation	Definition	Value
N_{RB}	System bandwidth for uplink [unit: GHz]	20
M	Number of initial devices	1-1000
R_C	Total number of preambles reserved for C-PRACH	5, 10 , 15, 30, 54
R_D	Total number of preambles reserved for D-PRACH	54
$\mathrm{N_{DPmax}}$	Maximal number of assigned D-PRACH	$\min(\mathrm{N_{UL}}, \frac{\mathrm{N_{RB}}}{6})$
N_{PTmax}	Maximal number of preamble-I transmission	3, 5, 10
W_{BO}	Backoff window size [unit: sub-frame]	21
N_{UL}	Maximal number of acknowledged RAR within the random access window size	15
T_{CP}	Interval between successive C-PRACH [unit: sub-frame]	10
T_{RAR}	Time required for receiving the RAR after preamble transmission (=processing time+ RAR window size) [unit: sub-frame]	7
T_{CR}	Contention resolution timer [unit: sub-frame]	48
p_f	Failed probability of HARQ transmissions for Msg3 and Msg4	0.1
N_{HARQ}	Maximal number of HARQ transmission for Msg3 and Msg4	5
p_n	Preamble detection probability of the *n*th preamble-I transmission	$p_n = 1 - \frac{1}{e^n}$
T_{HARQ}	Time interval required for receiving HARQ ACK [unit: sub-frame]	4
T_{M3}	Gap of Msg3 retransmission [unit: sub-frame]	4
T_{A_M4}	Gap of monitoring Msg4 [unit: sub-frame]	1
T_{M4}	Gap of Msg4 retransmission [unit: sub-frame]	1

Table 1. Simulation parameters

In Scenario I, the analytical and simulation results of P_S and $\overline{D_a}$ are shown in Figure 5 to Figure 10. Markers and lines in Figure 5 to Figure 10 are used to present simulation and analytical results, respectively. The analytical results of P_S and $\overline{D_a}$ are obtained based on (13), and (14), respectively. In Figure 5 to Figure 10, variable R_C is evaluated and three cases of N_{PTmax} are investigated including N_{PTmax}=3 for Figure 5 to Figure 6, N_{PTmax}=5 for Figure 7 to Figure 8, and N_{PTmax}=10 for Figure 9 to Figure 10. In Figure 5, the access success probability (P_S) is obviously increasing with R_C. However, in Figure 7 and Figure 9, all of the devices successfully complete the random access procedure (P_S=1) when the number of devices is below 600 (M≤600). For M>600, the access success probability (P_S) is still 1 (P_S=1) when N_{PTmax}=10, but it is getting smaller when N_{PTmax}=5. In Figure 6, Figure 8, and Figure 10, the average access delay ($\overline{D_a}$) is decreasing with increasing R_C. If we compare with the results in Figure 6, Figure 8, and Figure 10, the average access delay ($\overline{D_a}$) for the case of N_{PTmax}=3 is lower than the others because a small maximal number of preamble-I transmission causes less successful devices and influences the time required to succeed in the random access. In both Figure 8 and Figure 10, the average access delay for the case of R_C=10 has the same value as for the case of R_C=15. We can conclude that 5-times preamble-I transmission is enough to complete the random access procedure for cases of R_C=10 and 15 because the access success probability ($\overline{D_a}$) has already been 1 when N_{PTmax}=5. Although, the case for N_{PTmax}=3 reaches the lowest average access delay ($\overline{D_a}$), the access success probability (P_S) is much worse than for all other cases even with the high number of R_C. Thus, among these results, the accuracy can be verified by the perfect matching between the analytical and the simulation results.

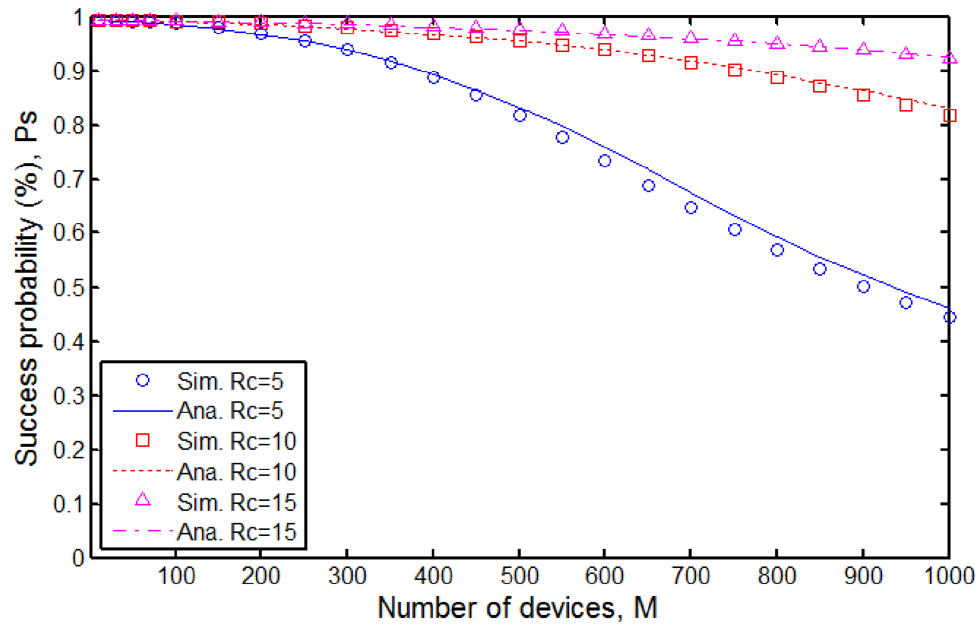

Figure 5. Access success probability (N_{PTmax}=3)

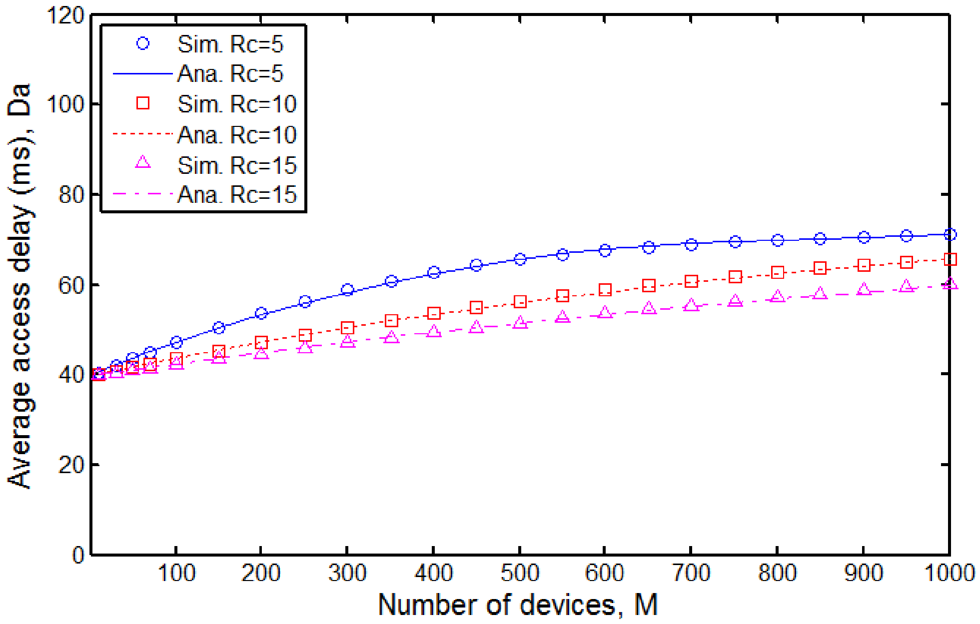

Figure 6. Average access delay (N_{PTmax}=3)

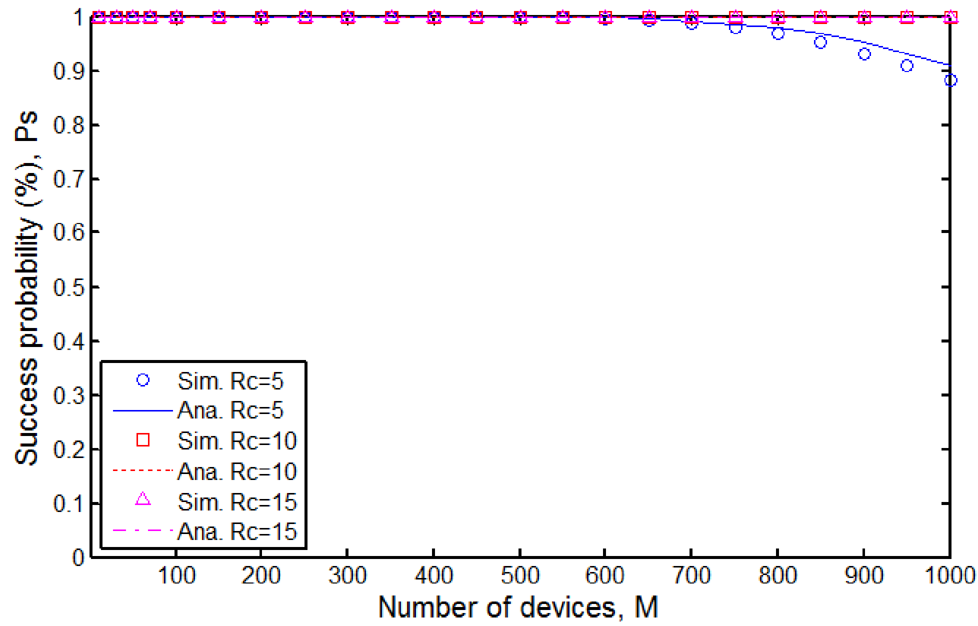

Figure 7. Access success probability (N_{PTmax}=5)

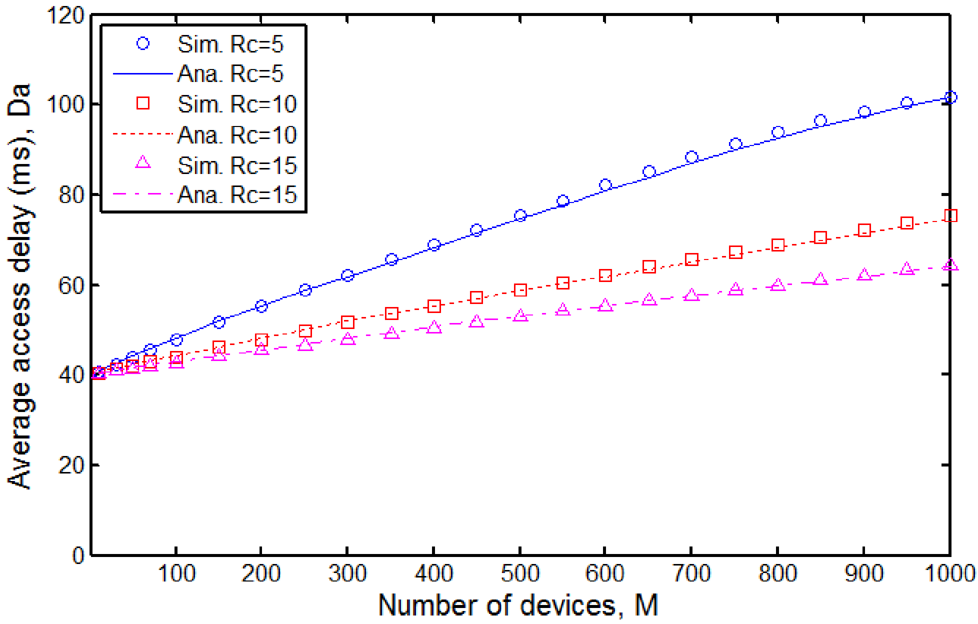

Figure 8. Average access delay (N_{PTmax}=5)

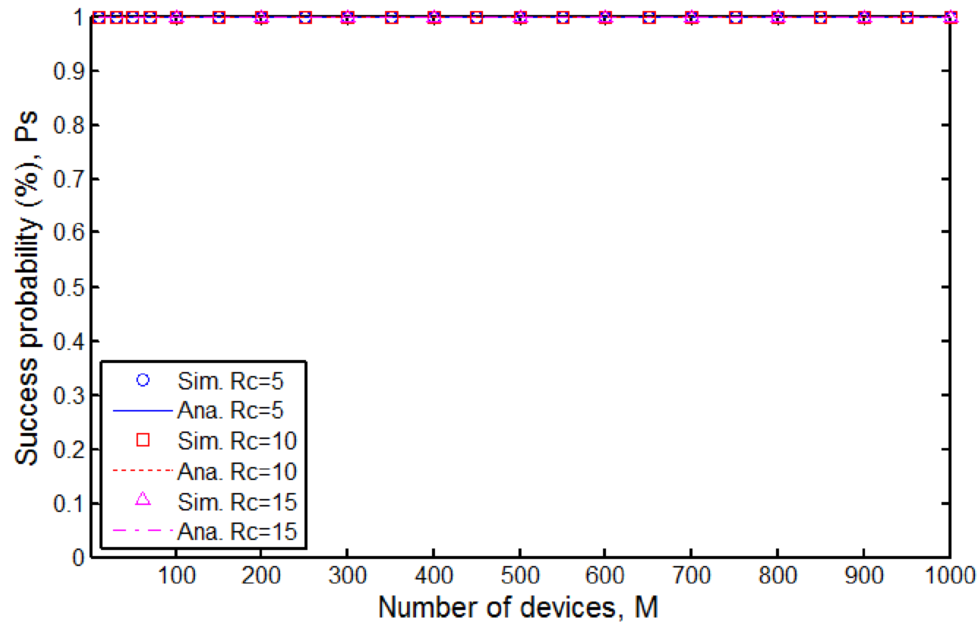

Figure 9. Access success probability (N_{PTmax}=10)

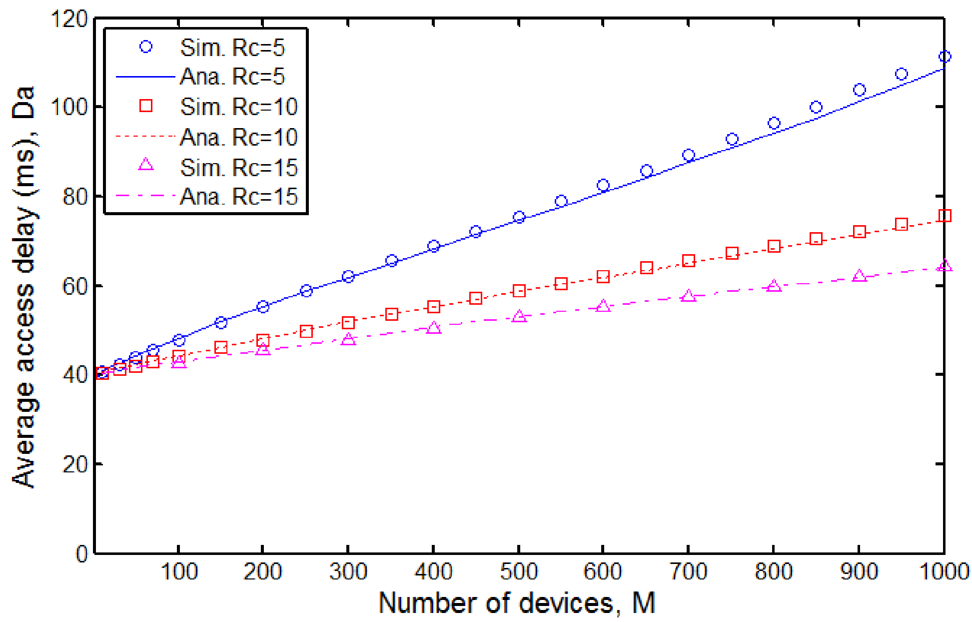

Figure 10. Average access delay (N_{PTmax}=10)

In Scenario II, the access success probability (P_S) and average access delay ($\overline{D_a}$) of the case for M=1000 with variable R_C ($1 \le R_C \le 15$) are presented in Figure 11 and Figure 12, respectively. We discussed three cases ($N_{PTmax} = 3$, $N_{PTmax} = 5$ and $N_{PTmax} = 10$) with R_C ranging from 1 to 15. Figure 11 shows that all devices can successfully access the channel in both cases ($N_{PTmax} = 5$ and 10) when $R_C \ge 8$ and $R_C \ge 3$, respectively. On the other hand, in the case with $N_{PTmax} = 3$, only around 90% of devices can successfully access the channel even when the eNB allocates 15 D-PRACHs. The access success probability for the three cases (N_{PTmax}=3, 5, and 10) are increasing with R_C until the access success probability equals to 1.

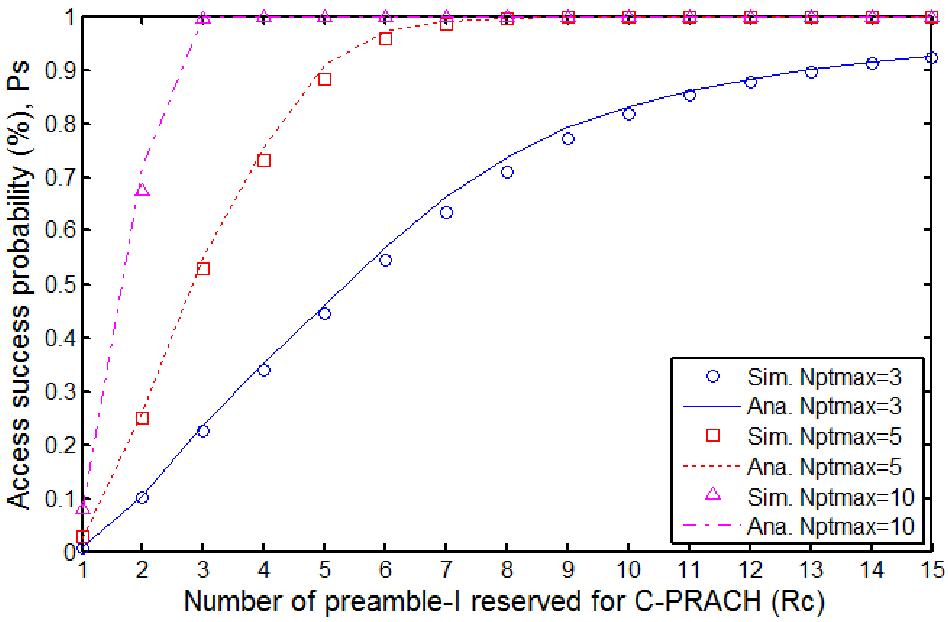

Figure 11. Access success probability with variable R_C ($1 \le R_C \le 15$)

Figure 12 shows that the average access delay is high when N_{PTmax}=5 and 10 with low R_C because a higher N_{PTmax} provides the devices with more chances to access the channel even for a low number of the preamble-I reserved in the C-PRACH. However, the most interesting conclusion in Figure 12 is that the results for two cases (N_{PTmax}=5 and 10) are converging to a low delay (below 60 ms) for a larger R_C (approximately for R_c>10) The reason is that R_C gradually increases to the optimal situation (P_S=1) and this means that it is not necessary to reserve more R_C. Thus, from Figure 11 and Figure 12, we can study the effect of the different combination of setting parameters N_{PTmax} and R_C according to the service quality constraints.

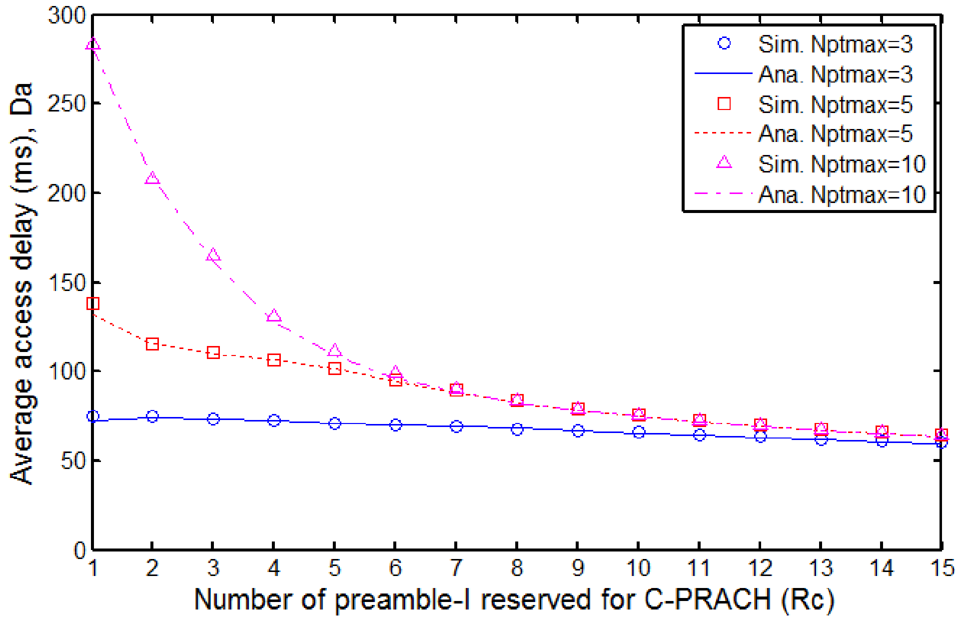

Figure 12. Average access delay with variable R_C $(1 \leq R_C \leq 15)$

In scenario III, a comparisons of the access success probability (P_S) and the average access delay ($\overline{D_a}$) for the group paging in the standard LTE RAP and the group paging for TPRA with N_{PTmax}=10, and R_C=5, 15 are demonstrated (Figure 13and Figure 14).

Figure 13 shows that all the devices successfully access the network for both LTE RAP and TPRA when the number of initial devices in the first PRACH/C-PRACH (M) is up to 250. Then, the access success probability (P_S) in the case of LTE RPA drops down by 90% when the number of initial devices (M) increased to 1000. Obviously, the performance of the access success probability (P_S) in the case of TPRA is much higher than in the case of LTE RAP even though the eNB reserves only few preambles for the C-PRACH.

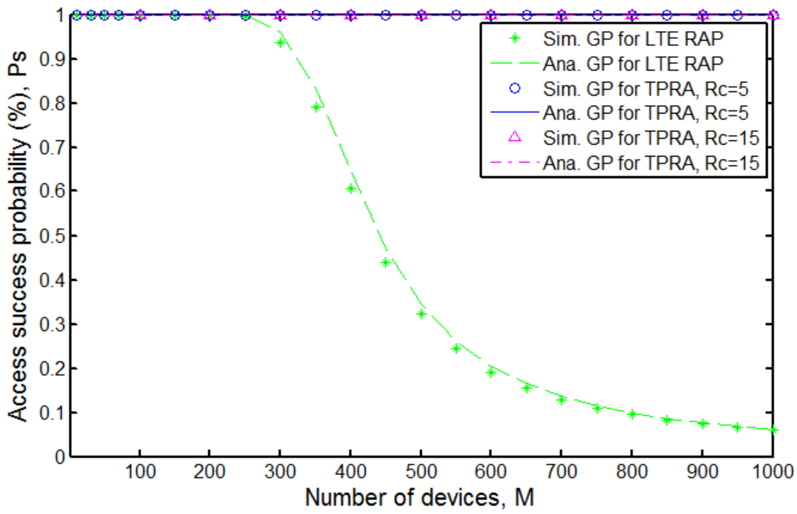

Figure 13. Comparison between group paging for LTE RAP and TPRA of success access probability

In Figure 14, we find that both values of R_C for TPRA (R_C=5 and 15) allows to reach a lower average access delay ($\overline{D_a}$) than the standard LTE RAP when the number of initial devices is higher than 70 (M>70). The access delay ($\overline{D_a}$) for the TPRA is slightly higher than the case of LTE RAP when the number of initial devices (M) is below 70 because an additional preamble-I transmission in TPRA is required and it causes a longer preamble transmission time. It is important to mention, that the proposed TPRA is intended for massive MTC and thus low number of devices are not expected.

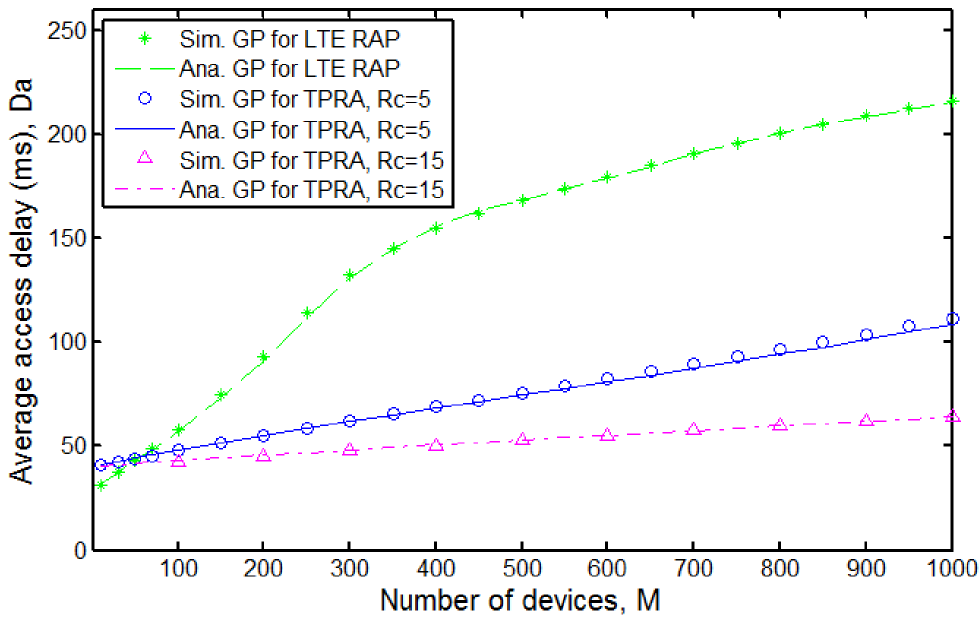

Figure 14. Comparison between group paging for LTE RAP and TPRA of average access delay

Figure 15 and Figure 16 show that the comparison of the number of contending devices and the number of successful devices in each C-PRACH/PRACH between LTE RAP and TPRA for the case *M*=1000. Figure 15 and Figure 16 show that the number of contending devices for the standard LTE RAP is high in most of the PRACHs because the number of successful devices is always small and most of the devices perform random backoff to re-transmit again. In Figure 15Figure 16, the number of the contending devices in the second C-PRACH in the both cases of TPRA is zero because the time to learn the failure of the preamble transmission (including preamble-I and preamble-II) in TPRA is longer than one C-PRACH interval (T_{CP}). Figure 16 shows that the number of successful devices for the two cases of TPRA in each C-PRACH does not exceed the maximal number of acknowledged RAR for all D-PRACHs. The maximal number of acknowledged RAR is calculated as $R_C \times N_{UL}$ if $R_C < N_{UL}$. Thus, the maximal numbers of the acknowledged RAR-I are 75 and 225 for R_C=5 and 15, respectively.

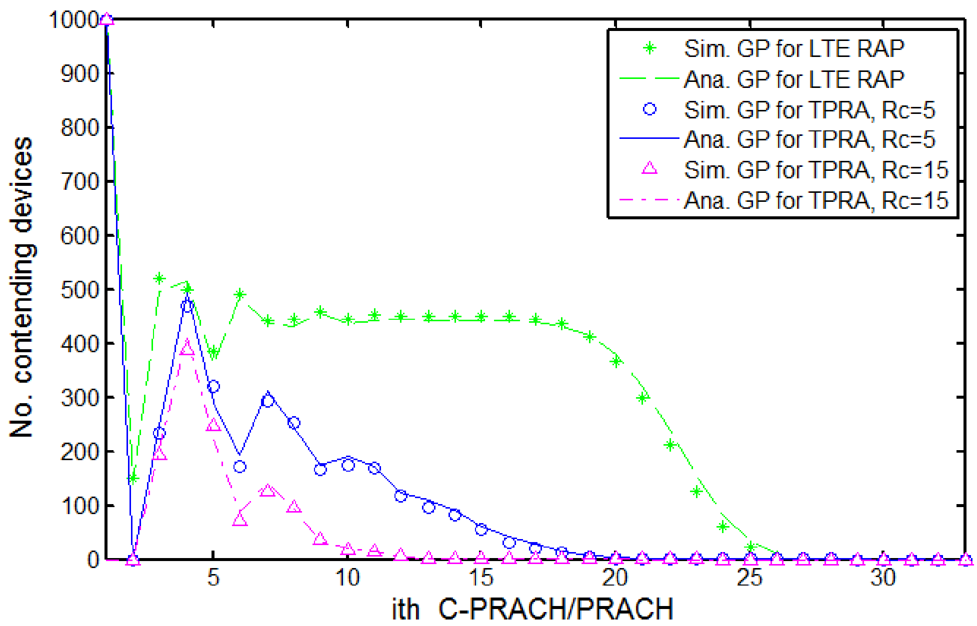

Figure 15. Number of contending devices in each C-PRACH and PRACH (*M*=1000, N_{PTmax}=10)

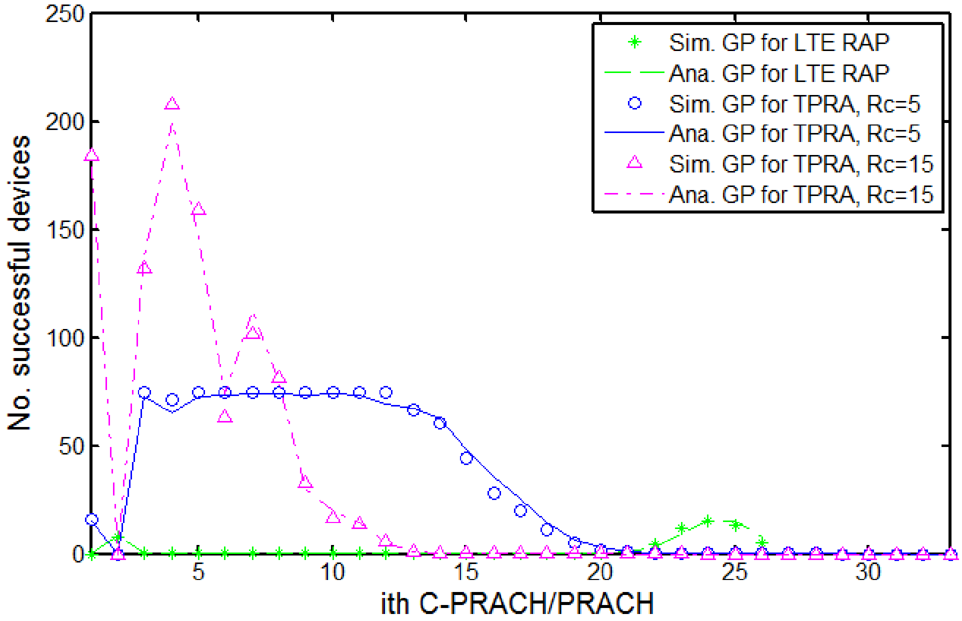

Figure 16. Number of successful devices in each C-PRACH and PRACH (M=1000, N_{PTmax}=10)

VII. CONCLUSIONS AND FUTURE WORKS

This thesis has proposed two-phase random access procedure for machine-type communication in LTE-A system. The proposed TPRA is based on the LTE-A RAP and extends it towards suitability for a simultaneous access of massive amount of MTC devices. Also, the analytical model is derived to estimate the access success probability and average access delay during the random access procedure considering the implementation constraints of the random access procedure. The accuracy of the analytical model is verified by the computer simulation and the numerical results show that the proposed TPRA can be applied for high density of the devices. In TPRA, the eNB can immediately adjust the number of preamble-Is reserved for the C-PRACH (R_C) based on the instantons offered load. Thus, TPRA makes the system more flexible in order to arrange the unexpected bursty arrivals. The numerical results demonstrate that, compare with the standard LTE-A RAP, the proposed TPRA can improve the access success probability by 9% and save around 50% of access delay, especially under high density of devices. Also, it shows that the two additional steps doesn’t bring negative influence to the performance.

In the future, the model proposed in this thesis can be widely adopted to study the impact of different system parameter configurations and consider the influences of the distribution of bursty arrival during the random access procedure. Also, the model can be extended to design the timely dynamic allocation mechanism for the D-PRACH to efficiently utilize the PRACH resources.

REFERENCES

[1] 3GPP TR 37.868, “RAN improvements for machine-type communications,” v. 11.0.0, Sep. 2011.

[2] T. Taleb and A. Kunz, "Machine type communications in 3GPP networks: potential, challenges, and solutions," IEEE Communications Magazine, vol. 50, no. 3, pp. 178-184, March 2012.

[3] Biral, M. Centenaro, A. Zanella, L. Vangelista, and M. Zorzi, “The challenges of M2M massive access in wireless cellular networks”, *Digital Communications and Networks* 1, pp. 1-19, Mar. 2015.

[4] 3GPP R2-104873, “Comparing push and pull based approaches for MTC,” Institute for Information Industry (III), Coiler Corporation, RAN2#71, Aug 2010.

[5] 3GPP R2-100182, “Access control of MTC devices,” CATT, RAN2#68bis, Valencia, Spain, Jan. 2010.

[6] J. P. Cheng, C. H. Lee and T. M. Lin, “Prioritized random access with dynamic access barring for RAN Overload in 3GPP LTE-A networks,” *IEEE GLOBECOM*, pp. 368-372, 2011.

[7] 3GPP R2-102780, “Discussion on RACH overload for MTC,” CATT, RAN2#70, May. 2010.

[8] A. Samir, M. M Elmesalawy, AS Ali, and I. Ali, “An Improved LTE RACH Protocol for M2M Applications”, *Mobile Information Systems*, Aug. 2016.

[9] Cheng, R.-G., Al-Taee, F., Chen, J., and Wei, C.-H., “A dynamic resource allocation scheme for group paging in LTE-advanced networks,” *IEEE Internet of Things Journal*, vol. 2, no. 5, pp. 427–434, Oct. 2015.

[10] 3GPP R2-103759, “Load distribution for MTC devices,” ALU/ASB, RAN2#70bis, July 2010.

[11] 3GPP R2-112250, ”Further study of access performance for MTC,” Alcatel-Lucent and Alcatel-Lucent Shanghai Bell, RAN2#73bis, Shanghai, China, April 2011.

[12] 3GPP R2-104930, “RACH load analysis for MTC in LTE,” Alcatel-Lucent and Alcatel-Lucent Shanghai Bell, RAN2#71, Aug. 2010.

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

[14] 3GPP R2-104870, “Pull based RAN overload control,” Huawei and China Unicom, RAN2#71, Aug. 2010.

[15] 3GPP R2-104004, “Group paging for MTC devices,” LG Electronics Inc., RAN2#70bis July 2010.

[16] H. Inaltekin, and S. Wicker, “The analysis of a game theoretic MAC protocol for wireless networks,” in *Proc. IEEE 3rd Communications Society on Sensor and Ad Hoc Communications and Networks,* pp. 296–305, Sep. 2006.

[17] A. Laya, L. Alonso, and J. Alonso-Zarate, “Contention Resolution Queues for Massive Machine Type Communications in LTE,” *IEEE Personal, Indoor, and Mobile Radio Communications (PIMRC) Workshop on Machine-to-Machine Communications*, pp. 2314-2318, Hong Kong, 2015.

[18] Y. P. Hsun, “Distributed Queuing-based Random Access Procedure in Mobile Networks” Master dissertation, Dept. Telec. Eng., Czech Technical Univ. in Prague, Prague, May 2016.

[19] 3GPP TS 36.300 “Evolved universal terrestrial radio access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN), Overall description,” v14.2.0, Mar. 2017.

[20] 3GPP TS 36.211 “Evolved universal terrestrial radio access (E-UTRA): Physical channel and modulation,” v13.0.0, Jau. 2016.

[21] 3GPP TS 36.321 “Evolved universal terrestrial radio access (E-UTRA): Medium access control (MAC) protocol specification,” ver. 14.2.2, Apr. 2017.

[22] C. H.Wei, R. G. Cheng, and S. L. Tsao, “Modeling and estimation of oneshot random access for finite-user multichannel slotted ALOHA systems,” *IEEE Commun. Lett.*, vol. 16, no. 8, pp. 1196–1199, Aug. 2012.