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MODELING CONTENTION BEHAVIOR OF MACHINE-TYPE DEVICES OVER MULTIPLE WIRELESS CHANNELS

Master of Science Thesis

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and
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ABSTRACT

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Machine-Type Communication (MTC) is expected to account for the largest proportion of the regular connected devices with a dramatic growth from 2 billion at the end of 2011 to 12 billion by the end of 2020. Leading the largest submarket within the Internet of Things (IoT) submarket, it has been one the most attractive research areas as it has received remarkable attention recently from both academic and industry. Deployments of unattended devices characterized by their small-size and infrequent data pattern over Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) have been focused in this Thesis.

MTC devices may utilize contention-based random access to transmit over the LTE network to have their data delivered. However, there has been limited attention to analytical characterization of contention-based behavior when unsaturated MTC traffic is considered. Furthermore, the existing efforts lack the analytical model capturing MTC contention behavior and utilizing it for MTC over LTE transmission use cases and scenarios. Thus, in this Thesis we focus on proposing a novel mathematical model which characterizes contention behavior in a multi-channel environment being applicable to various MTC over LTE scenarios. Further, the proposed mathematical model has been confirmed by extensive protocol-level simulations.

Regarding the performance evaluation, in this Thesis we have assessed two distinct variations of ALOHA-type algorithms to characterize the MTC contention behavior. Proposing a novel mathematical model which captures contention behavior based on the system attributes and entities, we have employed the ALOHA-type channel access methods and mathematical processes (e.g. Markov chain) to investigate analytically three performance metrics including average access delay, average throughput and average number of users in the system. Furthermore, the proposed analytical characterization in the multi-channel environment is shown to be useful in quantifying the performance of contention-based Physical Random Access Channel (PRACH) procedure in 3GPP LTE.

As a conclusion, the perfect convergence between analysis and simulation-level results confirms the rigorousness of the proposed model to be used for optimizing Random Access (RA) procedure or to be employed as a baseline in other relevant MTC over LTE research works.

PREFACE

The research work made in this Thesis was supported by TEKES and Ericsson (Finland) as part of Internet of Things program of DIGLE (Finnish Strategic Center for Science, Technology and Innovation in ICT). I hope that both simulation-level and analytical results presented in this Thesis will be sufficiently helpful for solving more sophisticated and challenging problems in such a way providing a reliable baseline for the future works.

Foremost, I would like to express my sincere gratitude to my supervisor Professor Yevgeni Koucheryavy for his excellent guidance, caring and providing me with an amazing and exciting atmosphere for doing research. Besides that, I would like to express my deepest appreciation to my co-supervisor Dr. Sergey Andreev for his patience, motivation and enthusiasm. He helped me in all terms from the beginning of this research work and truly he opened a new window of attitude in my research career. I appreciate his patience when I was asking him to explain the assigned tasks again. I do appreciate his responsibility for being available and carful about his student. I will never forget how much time you invested in teaching me how to deal with different kinds of challenges throughout the research work. I could not have imagined of having better supervisors for doing my Master's thesis.

Beside my supervisors, I would like to thank Researcher Olga Galinina for her motivation, kindness and patience. Undoubtedly, I have never been able to deal with formulations and mathematical analysis as one of the most novel parts in this work without your passionate encouragement and support.

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Last but not the least; I would like to thank my family: my father, Mostafa, who devoted his life to teaching me the true science since childhood. To my mother, Shokouh, who has been a source of inspiration to me throughout my life. To my sisters Shiva and Shabnam, who have actively supported me in my determination to find and realize my potential, and to make this work.

Tampere, 22.12.2014

Amir Mehdi Ahmadian Tehrani

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LIST OF ABBREVIATIONS

ALOHA	Wireless Network Protocol
BI	Backoff Indicator for RA procedure
CDMA 2000	Code Division Multiple Access Release 2000
eNodeB	Base Station
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GSM	Global System for Mobile Communications
H2H	Human-to-Human Communication
IoT	Internet of Things
LTE	Long Term Evolution
MAC	Medium Access Control
MTC	Machine Type Communication
Msg1	Message One
Msg2	Message Two
Msg3	Message Three
Msg4	Message Four
Multi-DFT-1	Multi Channel Delayed First Transmission Type1
Multi-DFT-2	Multi Channel Delayed First Transmission Type2
Multi-IFT	Multi Channel Immediate First Transmission
M2M	Machine-to-Machine Communication
OFDMA	Orthogonal Frequency-Division Multiple Access
PDCCH	Physical Downlink Control Channel
PRACH	Physical Random Access Channel
PUCCH	Physical Uplink Control Channel
RA	Random Access
RFID	Radio Frequency Identification
RRC	Radio Resource Control
Single-DFT-1	Single Channel Delayed First Transmission Type1
Single-DFT-2	Single Channel Delayed First Transmission Type2
Single-IFT	Single Channel Immediate First Transmission
SMS	Short Message Service
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
WoT	Web of Things
WSAN	Wireless Sensor and Actuator Networks
3GPP	Third Generation Partnership Project

LIST OF SYMBOLS

U	Number of identical Machine-Type devices
M	Number of preambles
$p(t)$	Channel access probability at time t
$N(t)$	Number of Machine-Type backlogged devices
σ	Machine-Type arrival probability per user frequency division duplex
π_i	Steady-state probability of the system being at state i
π	Steady-state probability vector
λ	Overall arrival rate
$p_{i,j}$	Transition probability from state i to j in Markov chain process
P	Transition probability matrix of Markov chain
S_{out}	Steady-state throughput
$\overline{S_{out}}$	Average MTC throughput in Single Channel
$\overline{N}$	Average number of M2M backlogged users in Single Channel
n	Instantaneous number of Machine-Type backlogged users in Single Channel
$\overline{D}$	Average MTC access delay in Single Channel system
a	Arrival to the system
S (c | n)	Probability of c successful transmissions out of n contending devices
$S_{IFT}(i)$	Steady-state throughput of being at state i in IFT system
$S_{DFT1}(i)$	Steady-state throughput of being at state i in DFT-1 system
$S_{DFT2}(i)$	Steady-state throughput of being at state i in DFT-2 system
$E[N(t)]$	Average number of Machine-Type users in Multi Channel
S_{IFT}	Average MTC throughput in Multi Channel IFT system
S_{DFT1}	Average MTC throughput in Multi Channel DFT-1 system
S_{DFT2}	Average MTC throughput in Multi Channel DFT-2 system
$E[T]$	Average MTC access delay in Multi Channel access systems
b	PRACH opportunity in milliseconds
L_1	Msg1 unsuccessful time
K_1	PRACH duration
K_0	eNodeB processing time
K	PRACH response window
W	PRACH backoff indicator
ω	Uniform backoff subframe
$\overline{\omega}$	Average interval backoff time encompassing the next PRACH waiting time
$E[\tau]$	Average access delay

CHAPTER 1: INTRODUCTION AND MOTIVATION

1.1. Internet of Things and Future Connected Devices

Third wave society and its characteristics seen from the last two decades (e.g. Cell phones, the Internet) on, undoubtedly confirms the emergence of various high technologies such as global communication networks and their positive effect on human life. Global communication networks have undergone various evolutions leading to provide connectivity facilitating human's life. It becomes more tangible when the cost of connectivity thanks to rapid technology development has been dropped remarkably since last decade. This opportunity has also created a new vision towards the so called today's globalized business world creating a new infrastructure mainly based on network to increase productivity and sustainability.

The advent of connected devices as an effective actor in networked globalized business has made three waves of evolution in connected devices development (Figure 1). When this fact is taken into deep consideration, it becomes clearly understandable to observe this evolution from the goal of improving reach of business players through the first wave complementing to improving the value of customer's life style and the process efficiency by means of networked industries (known as second wave). Further, the evolution of connected devices has been driven by the opportunities to expand the scope of connectivity from home to the industry. Therefore, we would need to comply with fully connected structure for the industry entities to increase the customer-based service quality and productivity.

The pace of connected devices has reached to where networks are considered as fundamental in the globalized business production today. Therefore, the development of the networked world will create a new ecosystem in coming future consisting of people, business and society aiming at making profound changes in their interactions. Emergence of such newborn movement in connected devices, developing the benefits of smart and efficient industrial processes can be utilized in human life as well. This will lead us approaching networked society (or networked everything) as the main phenomenon of the third wave. We may imagine this new phenomenon by giving an example of a smart vending machine which communicates remotely with the business owner to provide an efficient and dynamic customer loyalty programs, advertising and pricing by sending data and alerts when the shoppers start interaction. Therefore, we may face with a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols. This world of heterogeneous things is referred to as Internet of Things (IoT). The target of interconnected everything is based on the advances in various protocols and standards brought by the traditional Internet and telecommunications field. This vast and global connectivity of identified things operating in smart spaces using intelligent interfaces has been sufficient to industrial partner's being active in IoT to start working on such vast domain connectivity that will be serving a complex ecosystem in few years. As an example, *More than 50 billion connected devices vision* by Ericsson was published in February 2011 to recognize the impact on people, society and businesses interaction in this complex ecosystem. Envisioning more than 50 billion connected devices by 2020 provides an unbelievable massive connectivity which demands different business and technical approaches to meet both short term and long term solutions expectations [1].

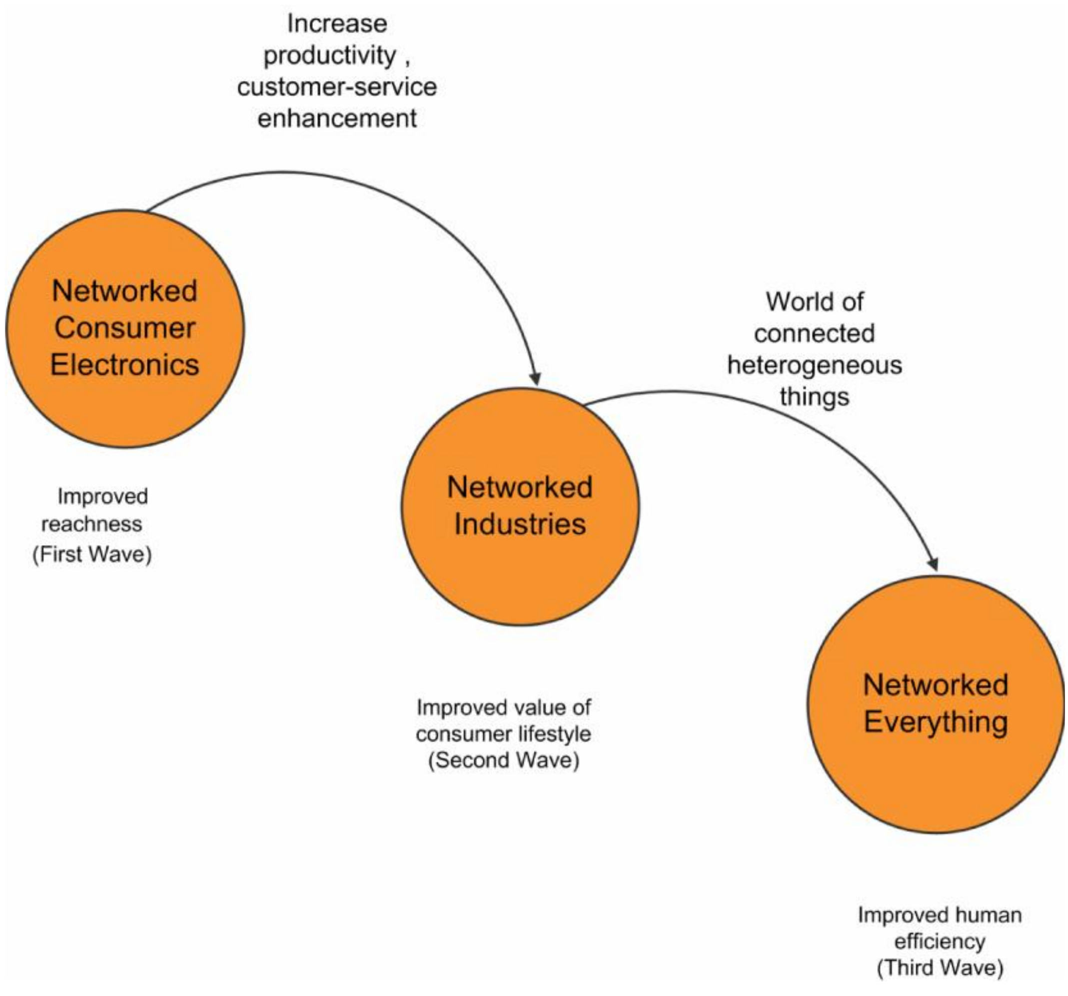

Figure 1. *Connected devices evolution*

The attractive revenue provided by this massive connectivity for the industries has been logically enough to specialize and categorize IoT technologies. These technologies are mostly tagging things, sensing things or embedded things [2]. There are several domains like radio-frequency identification (RFID), machine-type devices, wireless sensor and actuator networks (WSAN), ubiquitous computing and web-of-things (WOT) that have been proposed to develop these technologies [3].

Machine-Type Communication (MTC) is expected to account for the largest proportion of the regular connected devices having a dramatic growth from 2 billion at the end of 2011 to 12 billion by the end of 2020 (Figure 2) [4]. Thus, it is not far to expect the MTC market become the largest submarket within the IoT market [5].

Understanding the significance of MTC as the main entity in IoT, in this Thesis we focus on proposing the possible solutions to increase the future mobile broadband technologies performance through research and engineering. In other words, we believe that the outcome of this Thesis could help both industrial and academic partners to optimize future mobile broadband technologies which at the end will facilitate human interaction with society and business.

In the following sections, we firstly introduce MTC as a concept and afterwards, the current position of MTC in the recent mobile broadband technologies as well as the current research works on this filed are described.

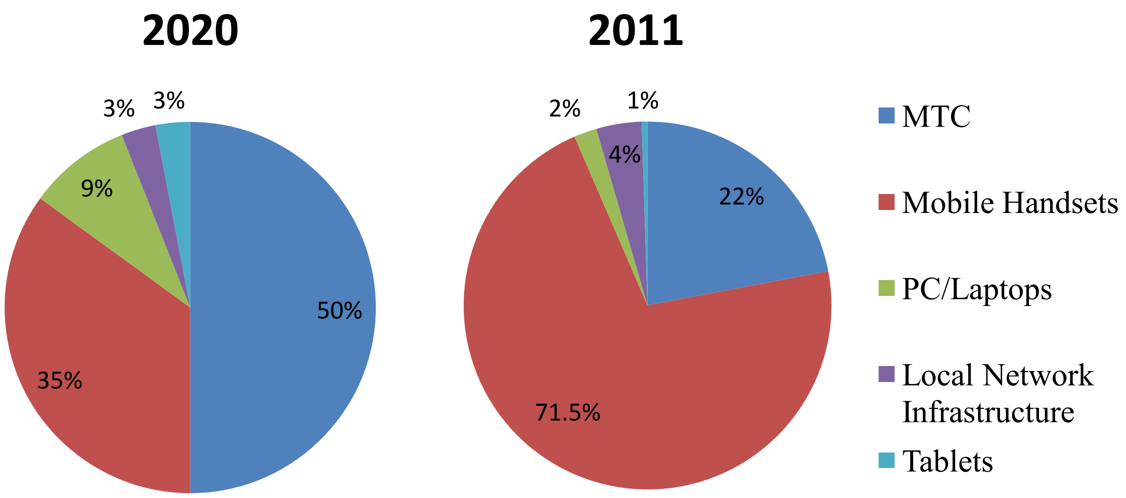

Figure 2. *Number of the connected devices and the expected growth*

1.2. Machine-Type Communication (MTC)

Machine-Type Communication (MTC) or what it is called mostly in American literature as Machine-to-Machine Communication (M2M) refers to a type of communication between two or more entities that do not necessarily need any direct human presence [6]. Machine-Type device mainly refers to an entity which records an event and translates it into meaningful information by means of embedded application. This information which might be transmitted through the interconnected network is infrequent and small in length when the main target of Machine-Type services is to automate communication processes. Thus, Machine-Type services play such a constructive role in the aforementioned complex ecosystem when such services will be filling with massive networked things via providing smart metering, environment sensing, triggering or automated actuation by means of different application domains. Knowing the existence of an object-identified connection capability along with the exploitation of data capture on one hand, and the vast possibilities offered by Machine-Type communication services on the other hand, it would become clear that human life quality will be affected dramatically. This fact reflects enough reason to believe Machine-Type communication as a hot bed of innovation which will make billions of things connected to billions of things to happen. The exciting opportunity represented by Machine-Type communication has made significant advances in smart grid technologies, smart sensors and actuators embedded hardware technologies and applications, green transportation and so on. Having a look at software applications development in this field, Recent *M2M Global Forecast & Analysis 2010-20* report has divided Machine-Type application groups into thirteen sectors from manufacturing applications to smart cities and transportation based on analysis of numerous applications (Figure 3). Such remote monitoring applications confirm the existence of an infrequent data transmission in a massive connected domain.

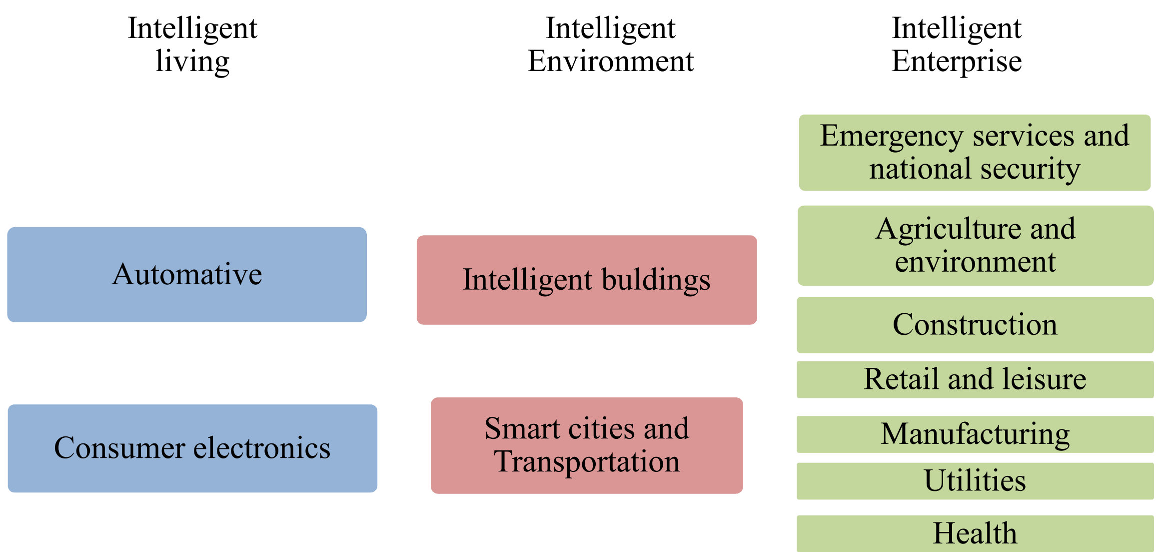

Figure 3. *Machine-Type application sectors*

The most conventional platform for Machine-Type services used to be fixed data networks (like public switched telephone networks) or leased lines [7]. However, wireless platforms have opened up a new vision toward having MTC connectivity any time, any place. There also have been various wireless technologies like ZigBee, WiMAX, WiFi utilized in different range of Machine-Type communication areas over the past decade. Cellular mobile network which consists of different air interface technologies has provided strong capabilities to expand and enforce Machine-Type services as well as conventional cellular mobile services. As such, in the world wide MTC market, Machine-Type device is not only used to increase the business owner revenue but also it could be helpful in retaining existing customers [8]. Irrespective of what type of cellular technologies might be used, conventional MTC solution would be such that the Machine-Type terminal acts similar to a mobile phone communicating with the base station on one hand, and with the MTC server or MTC gateway on the other hand. Typically, transmission from Machine-Type device to base station is termed as uplink and the transmission from base station to the Machine-Type device is termed as downlink.

Ubiquitous cellular broadband connectivity supporting MTC connectivity requires an infrastructure to fulfill the transmission of massive small data as well as mobile users' data volume requirements. Currently, Machine-Type communications are based on contemporary cellular technologies like Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), and Code Division Multiple Access 2000 (CDMA 2000) to fulfill the existing Machine-Type applications by offering the low-cost deployment. Based on the cellular networks generation, we could have various type of opportunities and quality of service. The majority of Machine-Type applications implemented in GSM is based on Short Message Service (SMS). Whereas, in the third generation where the IP based services enable access to a whole range of mobile Internet has removed some communication protocols limitations. Therefore, it provides new Machine-Type applications which require high data speeds like video surveillance [9].

The recent mobile cellular networks known as Long Term Evolution (LTE), are expected to support a wide range of applications and enable the networked everything to happen.

1.3. Long Term Evolution (LTE) and MTC

Long Term Evolution (LTE) as the recent standard of wireless communication developed by the Third Generation Partnership Project (3GPP) has been considered to fulfill mobile cellular (or human-to-human) users' requirements on high data rate, low delay, higher spectrum capacity and packet-oriented transmission scheme. Although the LTE domains of purpose at the beginning in 2004 had concentrated on human-to-human (H2H) efficient connectivity, the necessity of possibilities where LTE could provide optimized Machine-Type communication as well as H2H communication started to be considered gradually after Release 10. In fact, the main purpose of LTE augmentations through several work items defined on MTC has been to make the possibility of providing efficient Machine-Type services and to fill in the gap for Machine-Type applications diverse range of services which will be offered in coming future as well as numerous mobile cellular (or human-to-human) services [10]. LTE improvements for Machine-Type communications mostly include architectural enhancements to support either massive MTC connectivity or to fulfill Machine-Type service requirements or both above items together.

Going through the research efforts concerned, there have been quite many works proposed to facilitate Machine-Type data transmission over the LTE. Enumerating some of the hot topics, improving the energy-efficiency of MTC in the uplink utilizing power saving mechanisms and algorithms [11], radio resource allocation Machine-Type services as well as H2H services [12] and developing flexible MTC scheduling mechanisms considering the LTE scheduling frameworks [13] have had strong attention by far when it comes to MTC communication over LTE (Figure 4). In fact, the main reason paying such attention to Machine-Type transmission over LTE is that specific MTC characteristics (like small data, massive numbers and diverse range of applications) on one hand and LTE features mainly aiming at enhancing broadband applications on the other hand, have challenged both industry and academic to reduce the ratio between the payload imposed by MTC services and the required control information posed by LTE.

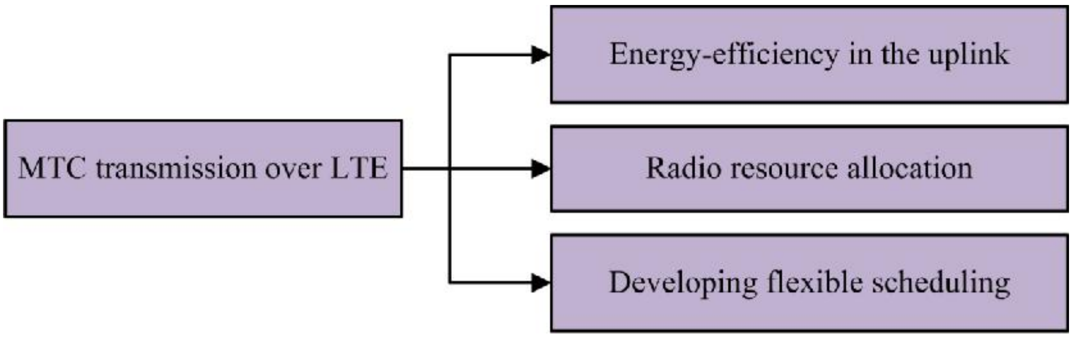

Figure 4. *Three most attractive research topics on MTC transmission over LTE*

1.4. Random Access Improvements for MTC

Approaching such high efficiency in dense network of Machine-Type devices imposes different challenges over the future LTE cellular networks. Over the recent years, different studies have been published to conceive how cellular networks need to evolve to be able to provide efficient access to Machine-Type devices where require a mentality shift on the way that cellular systems are designed [14]. Considerable amount of Machine-Type services are characterized by bulk arrivals which restrict the application of procedure to random access. Thus, one of the key challenges to provide such services over LTE is to enhance the random access channel performance which might suffer from overloading of massive number of MTC users. Random Access in LTE is defined as *contention-based* in which devices compete for the channel access or *contention-free* in which the base station allocates the access resource to the received requests based on their priorities.

Contention-based random access mechanisms plays a significant role in LTE improvements for MTC communication since it is basically used both for the initial association to the network before uplink data transmission as well as re-establishing a connection upon failure. The operation of uplink contention-based random access in LTE is referred to as Physical Random Access Channel (PRACH).

There have been alternatives proposed to improve the operation of PRACH procedure. Specifically, the improved version of PRACH in LTE Release 11 has made several research efforts. Utilizing OFDMA (Orthogonal Frequency-Division Multiple Access) technology [15] or performance evaluation of PRACH [16] can be considered as such examples. Apart from the above examples which have focused on mostly human-to-human traffic loads, there have been also efforts concentrating on handling numerous MTC requests when the PRACH is overloaded [17]. However, the existing PRACH evaluations are mostly simulation-based which leads to obtaining usually unreliable results. Therefore, building contention-based PRACH evaluation upon an analytical view helps us to not only enhance the reliability of simulation results but also it could fill in the gap of mostly simulation-based previous works.

The analytical view proposed through a novel mathematical model indicates a solution to explain under what conditions along with considering what specific parameters at the relevant time we will have what type of behaviors and reactions from the system. The proposed rigorous analytical characterization attempts to utilize the system behavior and characteristics in a way to increase the performance metrics effective and tangible in MTC random access procedure over LTE. The system behavior and actions will be explained comprehensively in the next chapter.

To sum up, we familiarized with the Internet of Things as a the new phenomenon which is about to revolutionize the future of information society in which the main entity circulating the information is not human but the networked connected devices distributed anywhere on earth. Machine-Type communication as a part of this world wide interconnected things plays a pivotal role in the society when it comes to smart metering applications, environment sensing or automated actuation. Therefore, this new domain of communication not only opens up new life style for the people in society but also it attempts to make billions of things connected to billions of things as the main purpose of

IoT leading to a significant change in existing communication technologies and concepts as well.

The image of future connectivity brought by MTC like similar phenomena has got considerable challenges and troubles which expect ICT experts to evaluate the possibilities and deploying the scenarios explaining how it can be useful through engineering and research. As we mentioned, medium access has attracted significant attention on MTC domain since LTE; the recent cellular wireless network is known as the main infrastructure for such massive connectivity. The main contribution of this Thesis is to focus on proposing a novel mathematical model which could be helpful to increase the MTC connectivity performance over the 3GPP LTE. Therefore, we will introduce the main entities and their interactions involved having an abstract view of the proposed analytical model in Chapter 2 and then we will go through explaining the tools and algorithms in used as well as the analytical approaches utilized for the model in Chapter 3. Chapter 4 concentrates on technological aspects of the Machine-Type transmission over LTE which describes the scenarios taken to verify the improvements for such massive connectivity when it comes to accessing the channel. This Thesis accomplishes with numerical results and final conclusion delivered in Chapter 4.

CHAPTER 2: SYSTEM OPERATION

This chapter focuses on providing essential information regarding to the behavior of system which is utilized as the infrastructure of the proposed model. In order to understand the process in which system reactions leading to form a structured model, the system characteristic are needed to be introduced as a baseline. Firstly, we would describe the system main entities and then we will continue with characterizing their interactions considering the existing constraints.

2.1. Entities and Interactions

User: In this model each of *U* identical Machine-Type devices sends small length uplink data over the equal size slotted communication channel(s) towards the single base station. Therefore, we consider Machine-Type devices as the users in the system.

Base Station: It refers to the entity which receives MTC requests for allocating radio resources. Base station response known as downlink data is not considered in this Thesis. Therefore, we only focus on the part in which Machine-Type devices request data are concerned and the single base station is assumed to respond mentioned requests error-free and immediately.

Transmission (communication) Channel: Generally it refers to what we consider as information signal conveyer which has a certain capacity for transmitting data [18]. Information signal might be sent from one or several senders (or transmitters) to one or several receivers. However, channel may characterize different terms [19]. In this Thesis channel refers to as an equal size slotted communication channel(s) in code sense where each user (which means MTC device in here) competes for taking available offered channel resources by picking available codes uniformly. In other words, each user sends its request through equal size slots over the coded channels in order to deliver required data to the base station (for example monitoring information) after resource allocation. More specifically, we focus on the part which is related to the channel access for each MTC request sent toward the base station. Moreover, each transmission takes only one slot and occurs at the beginning of the given slot. If there is more than one channel in the system for uplink transmission, the possible interference occurred between channels is neglected. Thus, we will not consider physical orthogonal but specifically coded channels which Machine-Type devices choose one out of *M* codes (not frequency channels) through a random process. The mechanism used as random process in which the communication channels are selected will be discussed in the following.

User Activation: It is referred to the process in which Machine-Type device generates new requests to be transmitted over the transmission channel(s). In order to facilitate the process of activation, in this system we have utilized Bernoulli distribution with the probability of $\sigma = \lambda / U$ per device, where λ denotes the overall arrival to the system. Therefore, each user based on the given arrival rate, becomes activated and then decides to attempt for channel access.

Successful Transmission: For each activated Machine-Type device successful transmission occurs when one out of M communication channel(s) is chosen randomly and channel access requests are transmitted to base station without any collision that might happen due to attempting the same slot from other device(s).

User deactivation: After each successful transmission, the equivalent Machine-Type device becomes *deactivated* and waits for the new packet generation which occurs according to its arrival probability.

Unsuccessful Transmission: Attempting for the same slot from two or more Machine-Type devices results in collision in the system. Each collision causes all the involved transmissions become failed and unsuccessful. This is when we call the involved devices to remain *backlogged.*

Retransmission: The process of retransmission occurs when the backlogged Machine-Type users are given another chance to transmit their data again. This process is fulfilled by using channel access probability $p(t)$ for overall existing backlogged users at instant time t. Therefore, the whole process will be continued with the access probability $p(t)$ until the transmission becomes successful. Moreover, each retransmission process is lossless meaning that any of $N(t)$ backlogged devices can retransmit in a different time slot or on a different transmission channel regardless of the given slot and channel in the previous attempt. Figure 5 illustrates an abstract view of the main functions applying to the system. It is seen that we are having a system containing activated users as input and successful transmissions as the output. In the case of unsuccessful transmission along with collision, the retransmission process continues till the backlogged user(s) randomly chosen the available codes and transmit(s) the generated packet successfully through the shared channel. In the next section a possible scenario which describes the system entities and their interactions is explained.

2.2. System Description

To perceive how the aforementioned entities would interact and affect the system operation, we describe the system operation through the following scenario (Figure 5) in which illustrates all the entities' rule and their effect to the system operation.

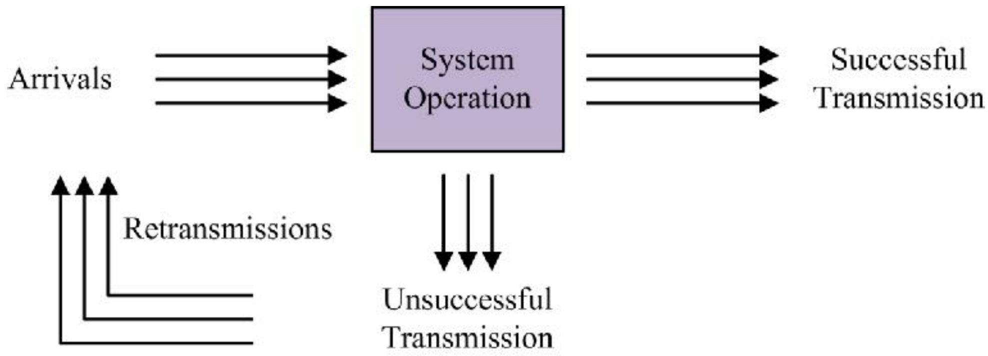

Figure 5. *Abstract view of the system main operation*

We assume 3 new activated Machine-Type users which are given 3 consecutive time slots in order to transmit their entries to the network. Knowing that there has been already 2 backlogged users at *N(t-1)*, we would have totally 5 backlogged users at *N(t)*. In this scenario we assume that each new arrival remains backlogged before transmitting over the channel and then it would apply the contention-based attempt for the channel access by employing the access probability *p(t)*. Therefore, there will be some delays imposed to the system comparing the case when each user attempts immediately for the channel access. The reason behind keeping users backlogged before contending for the channel will be discussed in the next section where we will be using different channel access algorithms for the proposed model.

Assuming access probability conditions are met, we would have transmission process over the *M* communication channels for all the 5 discussed packets.

As it can be seen in Figure 6, after transmission process some packets face with successful transmission and few of them remain backlogged at *N(t+1)* due to selecting the same channel at the same time slot.

Throughout the provided scenario, we observed different entities explained in the previous section and their effectiveness to the whole performance when it comes to system operation. In fact, familiarizing with the system main players and their rules would help us to utilize the sources and tools efficiently when the modeling process of any system is concerned. In the next chapter we will introduce the channel access algorithms which provide the baselines to the proposed model.

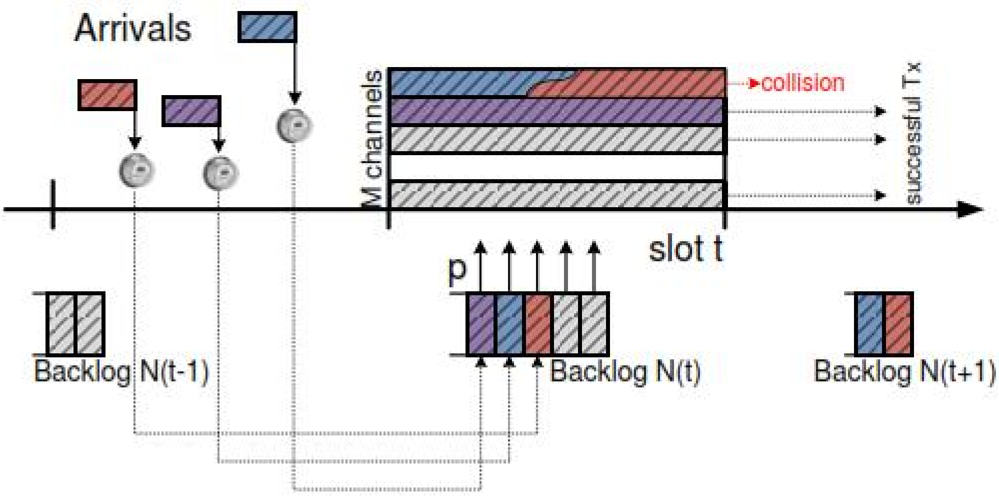

Figure 6. *System operation scenario*

2.3. Immediate First Transmission (IFT)

Prior to proposing the novel analytical model for LTE support of MTC, it requires introducing the two main analytical approaches that have been taken in this Thesis even though comprehensive description of analytical contention behavior is exclusively given in Chapter 3. Both of these approaches are based on ALOHA type algorithms. ALOHA is a simple channel access protocol in which provides immediate transmission in the next possible time slot to the user. Due to the possibility of simultaneous MTC transmissions, collision occurs where the collided packets cannot be detected and corrected.

Immediate first transmission provides the possibility of transmitting in the next available time slot whenever user is activated. Access probability in this type does matter only in the retransmission process. Thus, in the case of collision each backlogged user attempts to retransmit with respect to the probability *p(t)*. Figure 7 demonstrates a convenient flow chart of this basic random access algorithm. Each Machine-Type user becomes activated based on the arrival probability σ and immediately transmits over the channel. If the transmission has been successful (selecting unique code) the user becomes deactivated. Otherwise the user becomes backlogged and attempts retransmission based on *p(t)*. In other words, it tosses a biased coin and if the randomly generated number (illustrated as *a* in Figure 7) is lower than the access probability then the retransmission over the channel is applied. Therefore, if there will be another collision caused among new arrivals and backlogged users, all the involved users which selected the same channel would become backlogged. This process continues till all the users transmit their requests successfully.

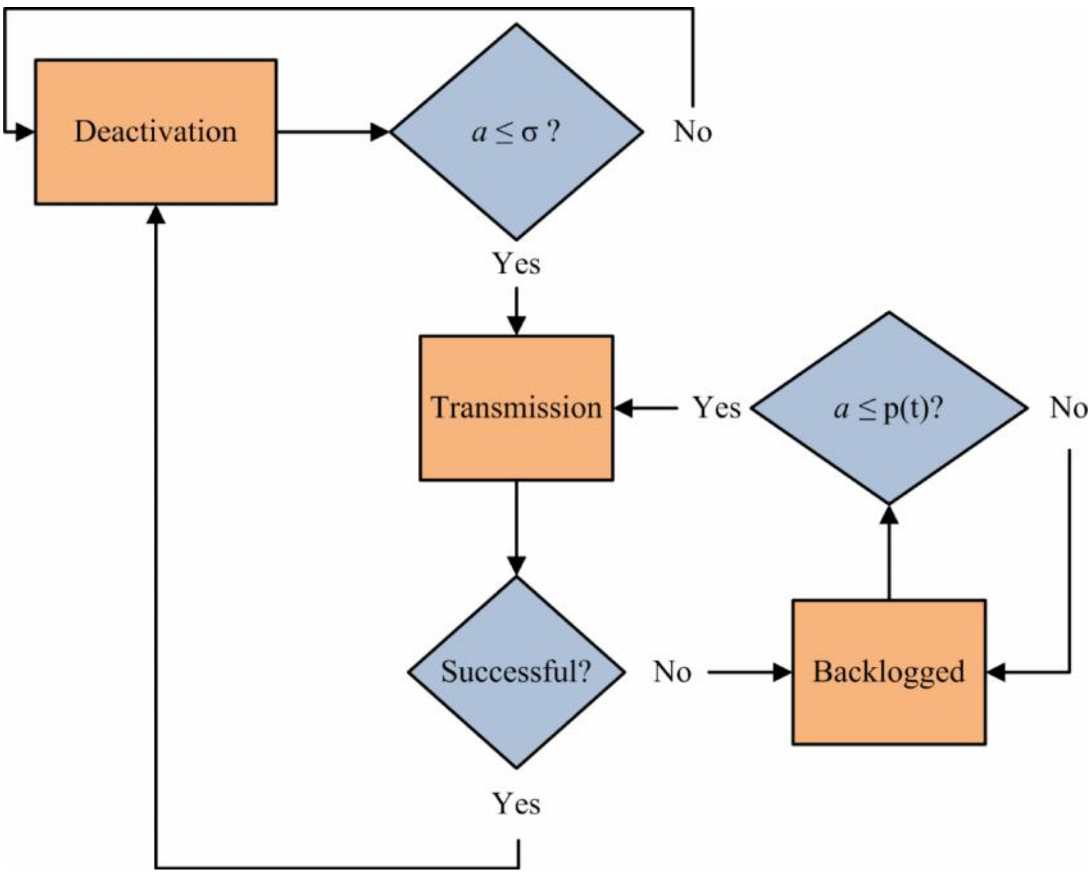

Figure 7. *Immediate First Transmission flow chart*

2.4. Delayed First Transmission Type 1 (DFT-1)

In contrast with IFT algorithm, there might be another type of ALOHA channel access algorithm to be used as the analytical approach. Delayed first transmission applies a pre back off before transmitting over the channel. In other words, whenever the user becomes activated based on the probability σ, it would get backlogged and then would try to access the channel by selecting a random probability lower than *p(t)*. If there is an unsuccessful transmission then the collided user is added to the backlogged users which includes new activated to the system as well.

When it comes to comparing the performance metrics between IFT and DFT like average throughput, the order of placing new arrivals and those which contend for the channel is significant. In other words, when we calculate the average throughput using IFT, transmission is performed at the beginning of slot either among already backlogged users or thinkers. Contrarily, in DFT method, it is essential to consider the number of deactivated users generating new packet first and then counting number of deciders to transmit which are selected among already backlogged and activated users.

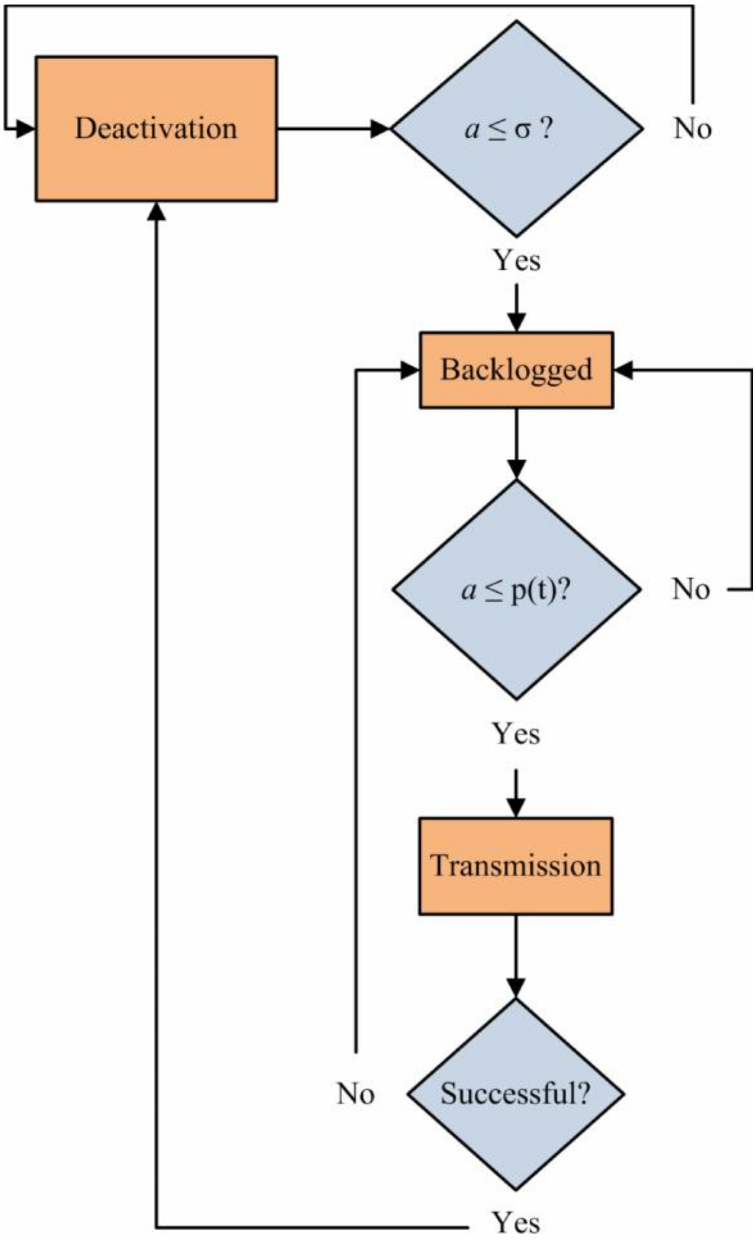

Figure 8. *Delayed First Transmission Type1 flow chart*

It is obvious that IFT channel access offers more realistic performance when it comes to random access in wireless communication. However, DFT type method could be utilized for specific real-life cases as well. We will see such use cases in Chapter 4.

2.5. Delayed First Transmission Type 2 (DFT-2)

If the sequence of transmission over the channel is replaced by the new generated packets in DFT Type 1 then we will have another type of delayed transmission which is known as Type 2 in this Thesis. Obviously, the operation and entities in the DFT second type is all the same as Type 1 except the order which changes the calculation process when it comes to performance metrics analysis. As it can be seen in Figure 9, contention for accessing the channel includes backlogged user in the first round and through the next step new traffic load would consider for the transmission attempt over the channel(s).

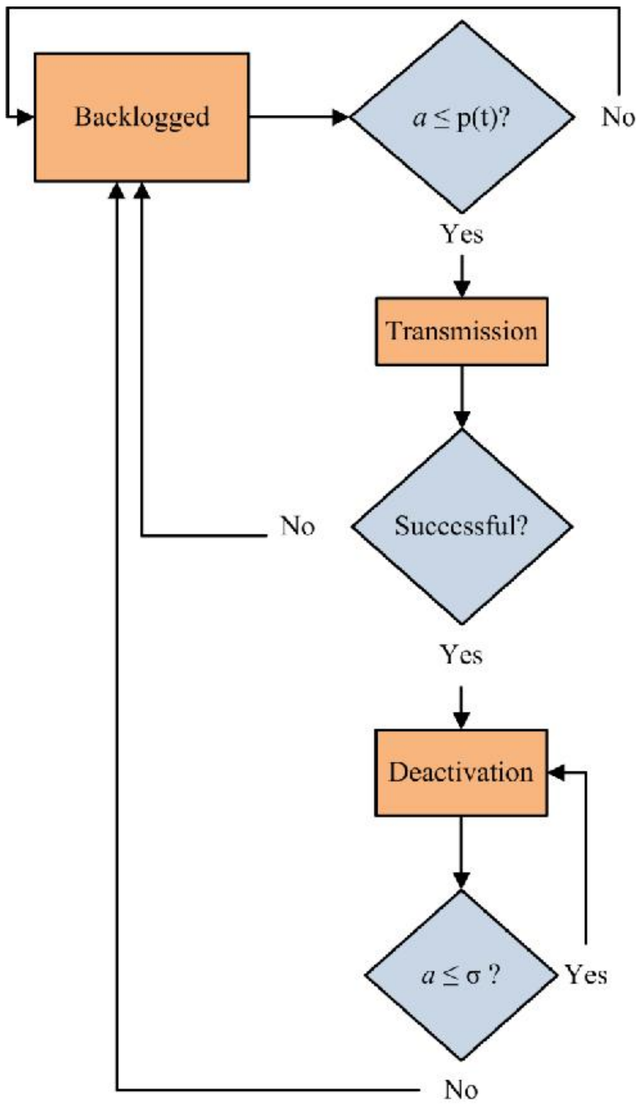

Figure 9. *Delayed First Transmission Type1 flow chart*

In Chapter 3 we will explain comprehensively the metrics that have been utilized for the proposed model based on these algorithms.

CHAPTER 3: APPROACHES & ALGORITHMS

This chapter presents core algorithms, assumptions and metrics utilized in the proposed model. Explaining the system operation and interactions in the previous chapter, the next step would be utilizing proper analytical tools and algorithms in order to define an appropriate process of interactions leading us to reach the main target. In other words, a set of approaches and procedures described in this chapter are required as a baseline to specify the essential interactions as well as sequences of events. In what follows, firstly we introduce two main ALOHA family protocols could be utilized for random access channel approach. Afterwards, we will specifically dig into the existing terminology of single slotted ALOHA channel as the basic analytical infrastructure of the proposed M2M random access analytical model considering the performance metrics. Eventually, multichannel slotted ALOHA approach as one of the main analytical contributions will be discussed.

3.1. ALOHA Protocols

Channel allocation problem has been always receiving much attention in wireless communication since network resources are often limited. Apart from the physical characteristics of the time-variant channel, wireless medium which controls channel access plays such vital role through impacting on system complexity, cost and determining the capacity of the wireless networks [20].

Over viewing *Media-Access Control (MAC)* protocols spanning cellular wireless networks, random access techniques (typically known as contention-type access protocols) have received high popularity in wireless communication control access in recent years [21]. In contrast with contention-free MAC protocols in which the entire channel bandwidth is divided based on equal subchannels like Frequency Division Multiple Access (FDMA) or equal time slots like Time Division Multiple Access (TDMA) to provide an *every guaranteed scheduled transmissions*, contention-based MAC protocols do not guarantee successful transmission in advance. In fact, the reason is due to the possibility of transmitting over the shared channel simultaneously from two or more users. As such, scheduling of each transmission can be regarded as the main concern of contention-based protocols where number of packet retransmissions may have to occur until they are eventually received.

One of the richest families of medium access protocols are ALOHA protocol families. In many literatures it is known as the first random access technique introduced. The first development of the ALOHA network was initiated in 1968 at the University of Hawaii under the leadership of Norman Abramson and others aiming at using low-cost commercial radio equipment to connect users on Oahu and other Hawaiian islands utilizing a central time-sharing computer on the main Oahu campus [22].

ALOHA channels were used limited in 1G mobile phones for the purpose of signaling and controlling after frequencies became available for mobile phones. Since then, ALOHA protocols and its variants have been causing different advances and novelties when it comes to channel access techniques in various wireless cellular technologies due to the simplicity of implementation and seniority [23].

Various ALOHA protocols analyzes have been proposed to present different aspects of transmission and retransmission schedules in parallel with adapting with different channel characteristics and circumstances [24]. In this section we overview few of these protocols and evaluate the performance metrics for single channel case before proposing the advanced approaches.

3.1.1. Single Channel Pure ALOHA

The most basic protocol in ALOHA family is called *Pure Aloha.* This fully-decentralized and simple protocol approach can be expressed as *"when you want to talk, just talk!"* As such, each new arrival is transmitted immediately with the hope of no interference by other arrivals. If any collision occurs, the retransmission schedules randomly some time in future to all the colliding users. Thus, at the end of each transmission we would have either successful or unsuccessful transmission. A very simple Pure ALOHA approach for single channel case is illustrated in Figure 10. As it can be seen the main problem of such network is the amount of time each user may expect an acknowledgment particularly when it comes to intensive networks where there are quite many users who want to transmit at the same time. Assuming t to be the time to send a packet, successful transmission occurs when there is only and only one scheduled user sending its data in the interval $(t-T,t+T)$ referred to as *vulnerable period* (See Figure 11). The reason behind this is due to preventing collisions might occur between t_0 and t_0+t (beginning time of shaded packet transmission) as well as t_0+t and t_0+2t (ending time of shaded packet transmission) caused by other packet sent by other users.

To analyze ALOHA-type systems tractable providing reliable predictions on their performance metrics, an appropriate mathematical distribution process is required to simulate scheduling point generation processes in such a way that retransmissions schedule uniformly as well as new arrival points which are randomly generated.

If we assume Poisson process as the best match to fulfill such requirements, the maximum throughput for Pure Aloha single channel case would take the value of $1/(2e) \approx 0.18$ as a function of offered load [25].

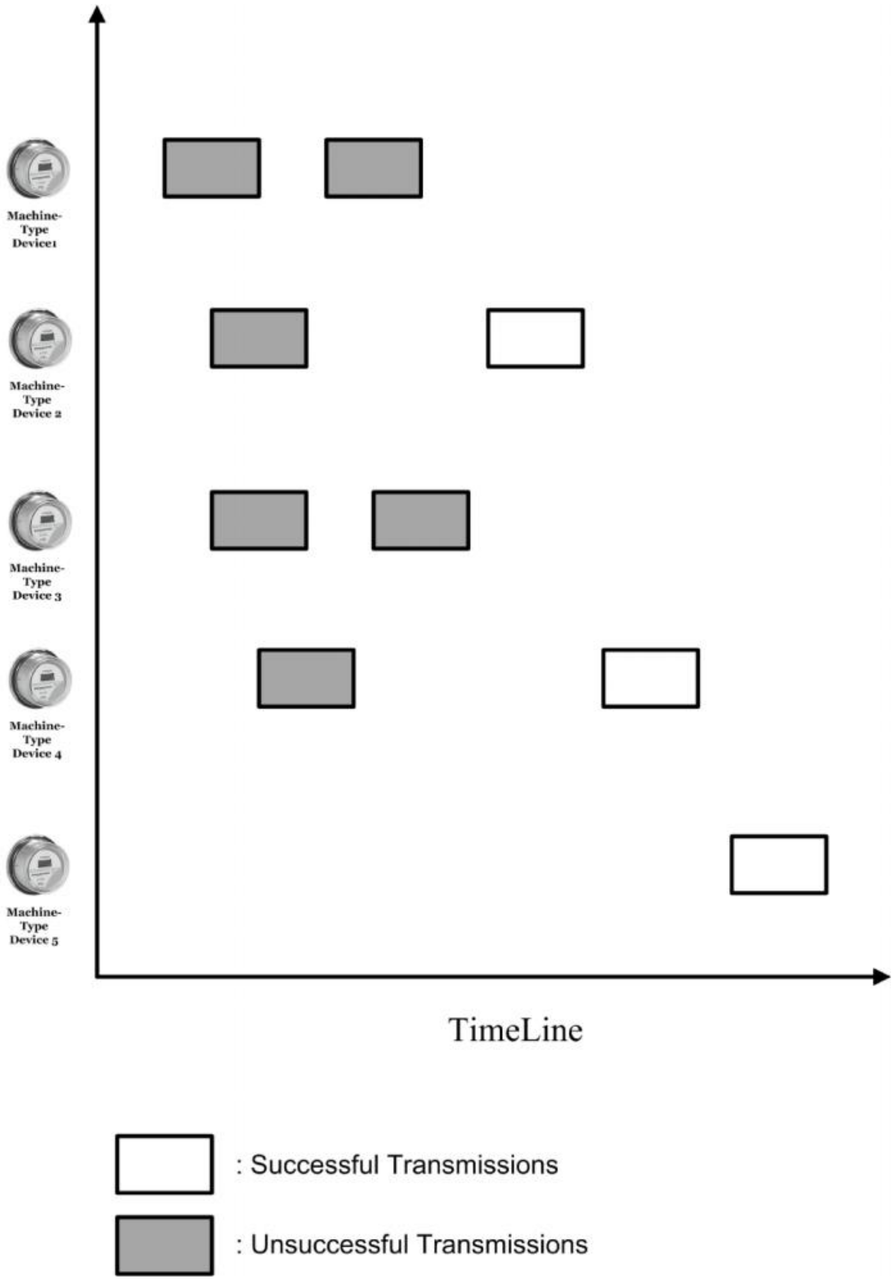

Figure 10. *Pure Aloha protocol principle*

3.1.2. Single Channel Slotted ALOHA

To improve the pure Aloha performance for when the load is quite high, Slotted Aloha approach was developed. In contrast with pure approach, the way transmissions take place is different in Slotted Aloha. In other words, each transmission should take place only at slot boundaries where timeline is divided into equal slots (See figure 12). In contrast with pure Aloha, vulnerable period occurs in the interval *(t,t+T)*. Therefore, the maximal channel capacity as a function of offered load would become increased (1/e ≈

0.36) [26] since each new arrival schedules in the previous slot before transmitting in the current slot.

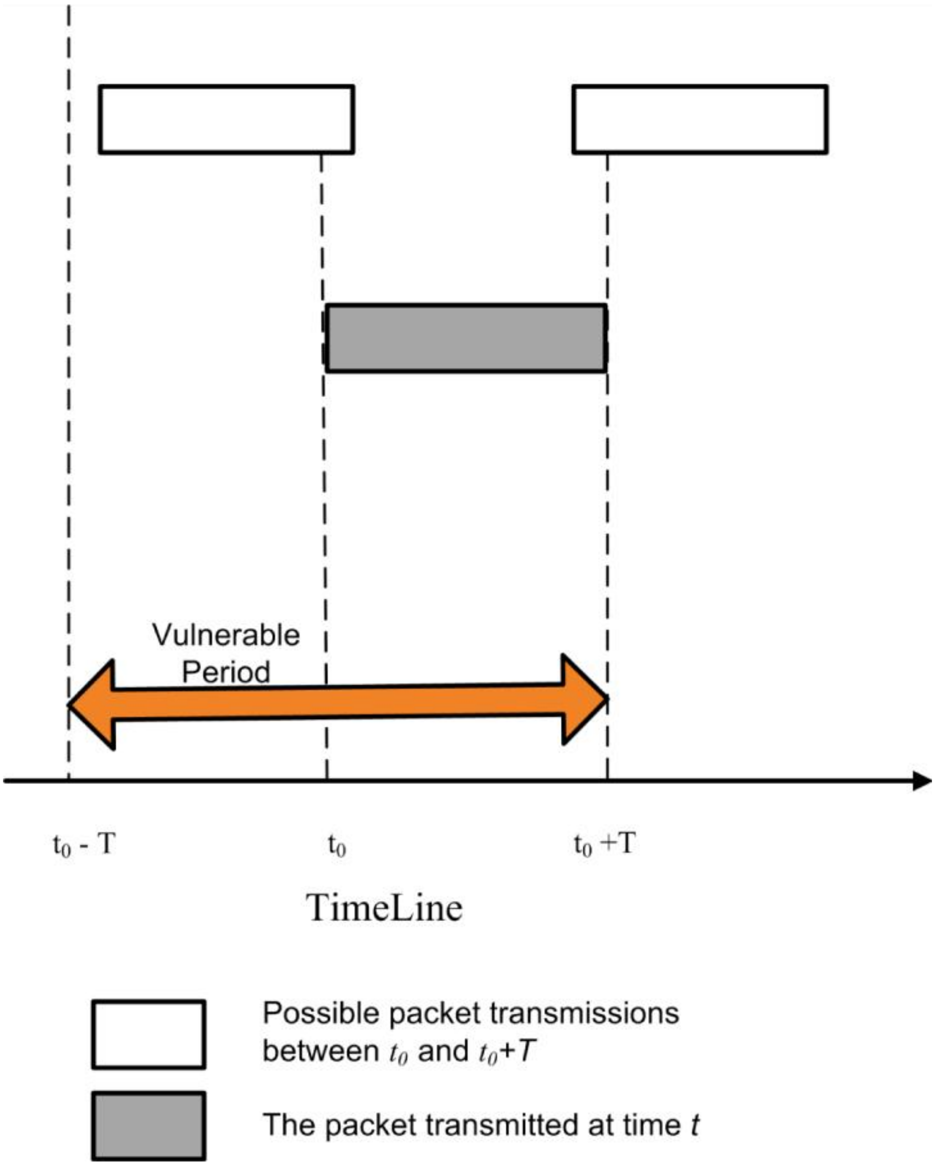

Figure 11. *Vulnerable period in Pure Aloha protocol*

Slotted Aloha approach has received much attention to facilitate random access for mobile communication irrespective of which network topology and air interfaces are considered due to its simplicity and seniority [27]. In other words, it can be seen that almost all the air interface technologies random access procedures are still inspired by such rather old protocol to fulfill the expectation on the channel access mechanism.

If we consider slotted Aloha approach as a regenerative process enabling us to analyze accessing channel in details, we could be able to simulate our system operation and entity behaviors described in the previous chapter. This regenerative process could have the following features to be used more flexible as a baseline in our system operation when single channel is shared between all the users:

- Slotted aloha is used by *U* number of users having the same size of packets and transmission time to send their data over the equally slotted channel.

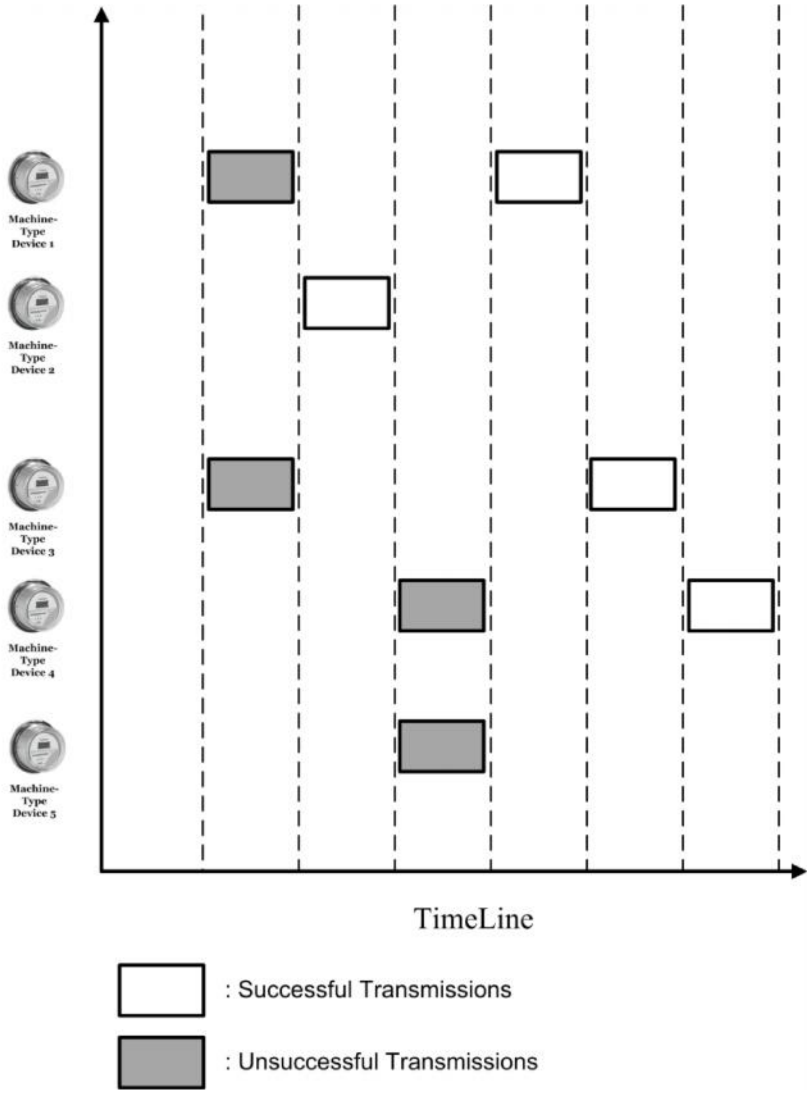

Figure 12. *Slotted Aloha protocol principle*

- To distinguish transmission from new users entered the system and those who attempt for retransmission, we would label users as *thinker* and *backlogged*. A user is called thinker when it does not take part to any transmission process and waits for the moment that it requires to get activated. By contrast, a user takes backlogged state if its transmission over the channel was not successful.

- Both arrival process (traffic generation) and retransmission process are assumed to be independently Bernoulli distributed. In other words, each thinking user decides to transmit with probability σ based on what described before to get activated regardless of the type of transmission attempt. Each backlogged user decides to retransmit in the next slot with respect to the access probability *p (t)* =1/ σ. Since this regenerative process is lossless, the retransmission process continues until the transmission is successful.
- The simplicity and well-defined features of this single slotted Aloha system could lead us to reach an appropriate mathematical tool analyzing such system behavior efficiently. This mathematical process is explained in further sections.

3.2. Single Channel Analysis

The principles of single channel analysis approach explained here are based on [28]. As we introduced slotted Aloha as an appropriate protocol used for random access over wireless channels which could be analyzed, we explain how this potential capability could be made into practice.

Considering the regenerative process based on Slotted Aloha described in previous section and the system operation introduced in Chapter 2, we could define the following algorithms for each transmission type to analyze the performance metrics of the single channel system:

- Single Channel Immediate Transmission First (Single-IFT): In this approach each thinking user transmits its packet over the channel right after packet generation. In other words, when the user is ready to transmit with respect to probability σ, it would do it irrespective of retransmission access probability p_t.

- Single Channel Delayed First Transmission Type 1 (Single-DFT-1): This algorithm does not follow any immediate transmission where it first assumes new activated users willing to transmit and then their attempts for transmission together with already backlogged users with respect to probability p_t is occurred.

- Single Channel Delayed First Transmission Type 2 (Single-DFT-2): Similarly to Type 1, there is no such immediate transmission in this algorithm as well. However, we would assume different possible order of the events mentioned in Type-1 algorithm. In other words, we would analyze transmission first and then new packet generations by thinkers will be considered.

As it was mentioned before, analyzing such system behavior based on an existing random access methodology requires us to utilize a comprehensive mathematical process. If we denote *N(t)* as the number of finite backlogged users at the beginning of slot (time *t*), then we could easily reach a Markov process turns out to be ergodic (See Appendix 1) where *N(t)* can be assumed as the system state where steady-state distribution exists.

Transition probabilities of being at specific state as result of this Markovian model could be characterized through the transition diagram for all the algorithms we have already defined even though each algorithm has its own transition matrix [28],[29]. If we denote π_i as the steady-state probability of the system being at state *i*, then we could define it as follows:

$$\pi_i = \lim_{t\to\infty} \text{Prob}\,[N(t) = i] \ . \qquad (1)$$

Further, if we denote $p_{i,j}$ as the transmission probability from state *i* to *j* as follows:

$$p_{i,j} = \lim_{t\to\infty} \text{Prob}\,[N(t+1) = j \mid N(t) = i] \ . \qquad (2)$$

If we let *P*= { $p_{i,j}$ } represent the matrix whose elements are denoted by $p_{i,j}$, the steady-state probability vector π which could guarantee the existence of a unique solution is expressed as:

$$\pi = \pi P \quad , \quad \sum_{i=0}^{U} \pi_i = 1 \ . \qquad (3)$$

It is obviously essential then to find matrix *P* as the first step and continue with obtaining the steady-state probability vector π through the solution to the finite set of linear equations. Transition probability matrix for each of mentioned algorithms is what requires next to be constructed separately and used to obtain the row vector. We will explain the significance of using this vector on the performance analysis in next section.

3.2.1. Single Channel Markovian Analysis

This section is focused on the analysis of random access algorithms explained in previous section. As we learnt how to reach steady-state probability vector, we do need to deal with three geometric processes introduced in previous section in order to obtain transition probabilities in matrix *P* separately for each algorithm. Transition matrices representing the entire above single channel algorithms are detailed in [28]. However, to give the idea of reaching the transition matrix based on the system entities provided in Chapter 2 and section 3.2, we would rephrase the transition matrix bellow only for Single-IFT system consisting of transition components which produce transition matrix elements with respect to the given conditions:

$$p_{i,j} = P_r\{N^{(t+1)} = j \mid N^{(t)} = i\} = \qquad (4)$$

P_r [One arrival enters the system | No transmission out of i backlogged users]

+

P_r [More than one transmission out of i backlogged | No arrival to the $M-i$ thinking users] =

$$(M-i)\sigma(1-\sigma)^{M-i-1}(1-p_t)^i + [1\text{-}ip_t(1-p_t)^{i-1}](1-\sigma)^{M-i} \quad , \quad if\ j = i$$

P_r [One transmission out of i backlogged | No arrival to the $M-i$ thinking users] =

$$ip_t(1-p_t)^{i-1}(1-\sigma)^{M-i} \quad , \quad if\ j = i-1$$

P_r [One arrival enters the system | Not no transmission out of i backlogged users] =

$$(M-i)\sigma(1-\sigma)^{M-i-1}[1-(1-p_t)^i] \quad , \quad if\ j = i+1$$

P_r [$j-i$ arrivals enter the system | $M-i$ thinking users] =

$$\binom{M-i}{j-i}\sigma^{j-i}(1-\sigma)^{M-j} \qquad if\ j \geq i+2.$$

Obviously there is no possibility to have transition when $if\ j \leq i-2$. Thus, the transition probability in this case would be zero. Similarly, we could use the approach discussed here to obtain the transition matrix for Single-DFT-1 and Single-DFT-2 considering each system characteristics and attributes.

3.2.2. Single Channel Performance Metrics Analysis

To obtain the equation demonstrating the system performance metrics like average throughput or average access delay steady-state probability vector is essential. Following the approach described above we could reach the vector by means of transition matrix and system of linear equations (See Equation 3). Assuming the stable channel for transmission, the steady-state channel throughput and the instantaneous number of backlogged users can be obtained as delivered in [28]:

$$S_{out} = S_{out}(n,\sigma) \times \pi, \qquad (5)$$

$$N = n \cdot \pi, \qquad (6)$$

where n denotes the instantaneous number of backlogged users in the system. Equation 5 confirms that the steady-state throughput of the system depends on the arrival rate σ and n obtaining the instantaneous value of above metrics; we could end up with the average equations as follows:

$$\overline{S}_{out} = \sum_{i=0}^{U} S_{out}(i)\ \pi_i, \quad (7)$$

$$\overline{N} = \sum_{n=0}^{U} n \cdot \pi_n, \qquad (8)$$

where $S_{out}(i)$ denotes steady-state throughput being at state i obtained through equation 5. Average discrete throughput shown in equation 7 can be applied to any of transmission types discussed above. However, the steady-state throughput for each algorithm is dependent on the system behavior and characteristics. Instantaneous channel departure for Single-IFT, Single-DFT-1 and Single-DFT-2 is summarized in Table 1. To recap, formulating the throughput is mainly concentrated on considering the conditions and constraints leading us to make successful transmission. As an example, steady-state throughput for Single-IFT is described exclusively bellows:

$$S_{out} = \underbrace{(1-p_t)^n (M-n)\sigma(1-\sigma)^{M-n-1}}_{<1>} + \\ + \underbrace{np_t(1-p_t)^{n-1}(1-\sigma)^{M-n}}_{<2>}, \qquad (9)$$

<1>: one device out of *M-n* thinkers transmits while one of n backlogged devices transmits over the channel ,

<2>: one of n backlogged devices transmits over the channel and no packet generation among *M-n* thinking devices.

If we consider our system operation based on discussed algorithms, we could calibrate the average time that each device spends accessing the channel into a discrete-time queuing model. Connecting the system content and the customer delay as a trend in queuing theory, Little's Law offers a valid contribution for any arrival process, service process or scheduling discipline [30]. As such, we may define the average access delay for each aforementioned single channel case transmission algorithms as follows:

$$\overline{D} = \overline{N} \big/ S_{out} \quad . \qquad (10)$$

To sum up, we recapped the analytical approach utilized for single channel as detailed in [28]. Furthermore, we observed how to analyze desired performance metrics by means of Markov chain process characteristics. We will see from next subsection on, how we have captured this method as a mathematical baseline to extend this work to M2M transmission over a multi channel Aloha based channels.

Table 1. *Steady-State throughput expression for single channel analysis*

Transmission Algorithm	**Throughput expression**
Single-IFT	$(1-p_t)^n (M-n)\sigma(1-\sigma)^{M-n-1} +$ $np_t(1-p_t)^{n-1}(1-\sigma)^{M-n}$
Single-DFT-1	$\sum_{k=0}^{M-n} \binom{M-n}{k} \sigma^k (1-\sigma)^{M-n-k} (n+k) p_t (1-p_t)^{n-1+k}$
Single-DFT-2	$np_t(1-p_t)^{n-1}$

3.3. Multi Channel Markovian Analysis

This section explains the main analytical approach used in Thesis describing the Multi Channel Markovian process. As we mentioned in previous sections, before applying the method analyzing the desired performance metrics, an appropriate mathematical is required. Based on the system operation explained in Chapter 2 and the mathematical tool introduced in previous section for single channel case analysis, we would define the followings as the main stationary probability distribution characteristics:

- *N(t)* which represents the number of backlogged users is defined as the finite and memoryless discrete-time Markov state can be chosen at the end of slots.
- Since the time axis is slotted into equal slots, we would have a finite Markovian process in which *N(t)=i* where *t =0,1,2,...*
- Assuming that steady-state distribution exists, we could define conditional transition probability for all of the transmission types.

The transition matrix of such Markovian process is illustrated in Figure 13.

3.3.1. Multi Channel IFT Algorithm (Multi-IFT)

To obtain transition probability matrix, we observe the IFT system in the state *N(t)* in which effective arrivals may occur among *U-N(t)* devices. This effect could be measured as *(U-N(t))σ*. If we denote *a* new devices out of *U-i* idling devices become activated considering the transition from state *i* to the *j* then we obviously have $\binom{U-i}{a}\sigma^{a}(1-\sigma)^{U-i-a}$ as the corresponding probability. Along with new arrivals, we might have *n* retransmission(s) among *i* backlogged devices which decide to transmit with access probability p_t. As such, we have totally *n+a* users contending in the current slot.

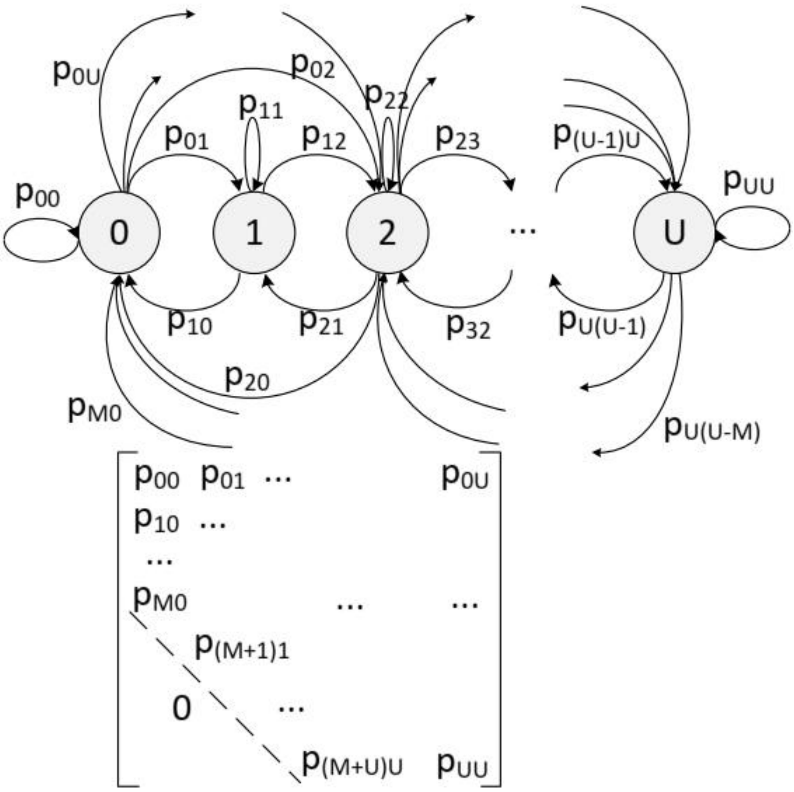

Figure 13. *State transmission diagram and transmission matrix of the Slotted ALOHA Multi Channel Markov chain*

Successful transmission through the contention between new arrivals and remaining backlogged devices should be formulized providing the capacity of measuring performance metrics analytically. We introduce the conditional probability S (c | *n*) which specifies the probability of *c* successful transmissions out of *n* contending devices as follows [31]:

$$S\{c \mid n\} = \frac{(-1)^c M!n!}{c!M^n} \sum_{k=c}^{\min(n,M)} \frac{(-1)^k (M-k)^{n-k}}{(k-c)!(M-k)!(n-k)!} \quad , \quad (11)$$

where $0 \le c \le \min(n,\mathrm{M})$, $0 \le n \le U$

This conditional probability as it can be seen specifically depends on the number of channels and number of contending devices. Eligible devices to transmit successfully or in the words decide to contend for the shared channel(s) speaking off different transmission type.

Figure 14 illustrates the considered Markov chain for IFT system containing all the important events. It can be seen that the slotted timeline is divided into embedded points to represent the Markov chain states. If there is *i* backlogged users at the embedded point *N(t)*, after the possible following events we will reach *j* backlogged users at *N(t+1)*:

- *a* out of *(U-i)* number of new activated devices transmit immediately over *M* available channels.
- *n* out of *i* backlogged devices decide to transmit
- *n+a* devices contend over *M* available channels
- *c* out of *n+a* contentions will be successfully transmitted

Hence, if we take $j = i + a - c,\ 0 \le c \le \min(M, n+a),\ n \le i$ as the specific relationships for Multi-IFT system, the transition matrix (See Figure 13) which produces all the transition probabilities can be derived as follows:

$$p_{i,j} = P_r\{N(t+1) = j \mid N(t) = i\} =$$

$$= \sum_{a=\max(0,j-i)}^{\min(M+j-i,U-i)} \sum_{n=\max(0,i-j)}^{i} \binom{U-i}{a} \sigma^a (1-\sigma)^{U-i-a} \times \binom{i}{n} p^n (1-p)^{i-n} S(i+a-j \mid n+a). \qquad (12)$$

It can be seen that Equation 2 contains all the events possibly happen described above between 2 embedded Markov chain points. In other words, we may define the IFT transition formula into three independent parts consists of *a* new generated packets, *n* packets including *a* new transmitted packets and *c* packets among which are successfully transmitted. $S(i+a-j \mid n+a)$ represents the probability of exactly *c* successful transmissions over *M* channels where *n+a* devices either among new arrivals or currently backlogged devices simultaneously attempt to transmit.

Deriving the Multi-IFT transition matrix along with assuming the existence of steady-state distribution, the throughput of being at state *i* can be delivered as follows [32]:

$$S_{IFT}(i)=\sum_{a=0}^{U-i}\sum_{n=0}^{i}\sum_{c=0}^{\min(n+a,M)}\binom{U-i}{a}\sigma^{a}(1-\sigma)^{U-i-a}\times\binom{i}{n}p^{n}(1-p)^{i-n}\cdot c\cdot\ S(c\mid n+a). \tag{13}$$

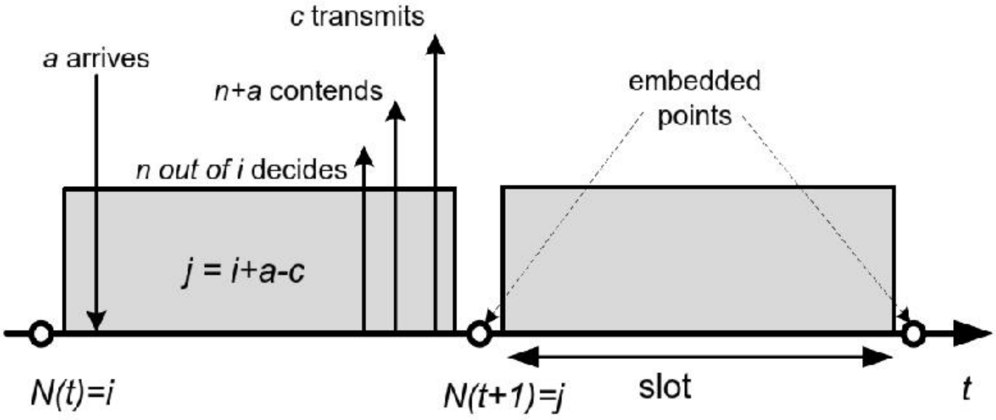

Figure 14.*Multi-IFT system embedded Markov chain*

Obviously, throughput at each state is achieved by multiplying successful transmissions to the transmission probability aimed at being in state *i*. Consequently; we are capable of analyzing the performance metrics like average number of users, average throughput or average access delay based on the proposed analytical modeling. We will discuss it in details in section 3.4.

3.3.2. Multi Channel DFT-1 Algorithm (Multi-DFT-1)

Multi Chanel Delayed First Transmission Type-1 analysis utilizes discrete-time Markov chain as the fundamental mathematical tool. Like Multi-IFT algorithm, the number of Machine-Type backlogged devices *N(t)* at the moment of *t* represents the memoryless state of the chain. Investigating the transition probability between the states $N(t)=i$ and $N(t+1)=j$, the state transition diagram will be similar to what is given in Figure 13.

Embedded points view of the Multi-DFT-1 Markov chain is given in Figure 15. In contrast with the Multi-IFT algorithm, *a* out of *U-i* idle devices activate and immediately join the current *i* backlogged devices first and then the contention begins among them with the channel access probability p_t. Therefore, following events may occur in the given order over the transition from $N(t)$ to $N(t+1)$:

- *a* out of *(U-i)* number of new activated devices join the current backlogged devices.
- *n* out of $i+a$ backlogged devices decide to transmit
- *n* devices contend over *M* available channels
- *c* out of *n* contentions will be successfully transmitted

For clarification, if we denote the new-activated devices as $a = j - i + c$ considering $0 \le c \le n, n \le i + a$ as the required variable boundaries in the summation. We may define the DFT-1 state transitions as follows:

$$p_{i,j} = P_r\{N(t+1) = j \mid N(t) = i\} =$$

$$\sum_{a=0}^{\min(U-i,M+j-i)} \sum_{n=\max(0,i-j+a)}^{i+a} \binom{U-i}{a} \sigma^a (1-\sigma)^{U-i-a} \times \binom{i+a}{n} p^n (1-p)^{(i+a-n)} S(i+a-j \mid n). \quad (14)$$

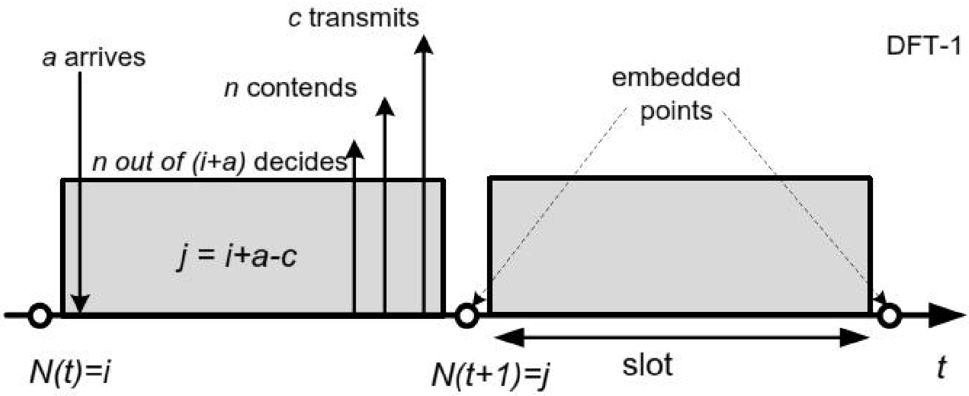

Figure 15.*Multi -DFT-1 system embedded Markov chain*

According to the Multi-DFT-1 system behavior, number of backlogged users involved transmitting over the channels with respect to the access probability p_t is different in contrast with IFT algorithm. Therefore, $S(i + a - j \mid n)$ applies on only n simultaneous transmissions over M channels current backlogged devices who would decide to transmit their data.

Utilizing the same approach explained for Multi -IFT algorithm, the throughput at state i for Multi -DFT-1 can be defined as follows [32]:

$$S_{DFT1}(i) = \sum_{a=0}^{U-i} \sum_{n=0}^{a+i} \sum_{c=0}^{\min(n,M)} \binom{U-i}{a} \sigma^a (1-\sigma)^{U-i-a} \times \binom{i+a}{n} p^n (1-p)^{i+a-n} \cdot c \cdot S(c \mid n). \quad (15)$$

Since there are totally n contentions attempt for transmission, state throughput would obtain among such deciders. It is obviously understandable that the non-immediate transmission mechanism used in this transmission type would impose some delays to the system considering the so called *pre-backoff* feature. However, we will explain in Chapter 4 how we could utilize this approach in the application and evaluate the performance metrics.

3.3.3. Multi Channel DFT-2 Algorithm (Multi-DFT-2)

There is another approach which characterizes mathematically the Multi-DFT algorithm. We may employ the same logic as when analyzing the Multi-DFT-1 system with the only difference in the order of retransmissions and arrivals. Therefore, in Multi -DFT-2 algorithm we assume the current backlogged devices attempt first their transmissions with the access probability p_t and then new arrival decisions are made among idling devices (See Figure 16).

As it can be seen in Figure 16, the event timeline begins with n contentions over M channels with respect to the channel access probability p_t. Afterwards, new arrivals to the system is considered. Therefore, in the given order the transition from $N(t)$ to $N(t+1)$ includes:

- n out of i backlogged devices decide to transmit
- n devices contend over M available channels
- c out of n contentions will be successfully transmitted
- a out of *(U-i)* number of new activated devices join the current backlogged devices.

Similarly to Multi-IFT and Multi-DFT-1 algorithm, the boundaries of involved variables $c = i + a - j, 0 \le c \le n, n \le i$ are essential to be taken into account in summation. The transition probability matrix for the Multi -DFT-2 is delivered as follows:

$$p_{i,j} = P_r\{N(t+1) = j \mid N(t) = i\} =$$

$$\sum_{a=\max(0,j-i)}^{\min(U-i,M+j-i,j)} \sum_{n=\max(0,i-j+a)}^{i} \binom{i}{n} p^a (1-p)^{i-n} \times \binom{U-i}{a} \sigma^a (1-\sigma)^{U-i-a} S(i+a-j \mid n). \quad (16)$$

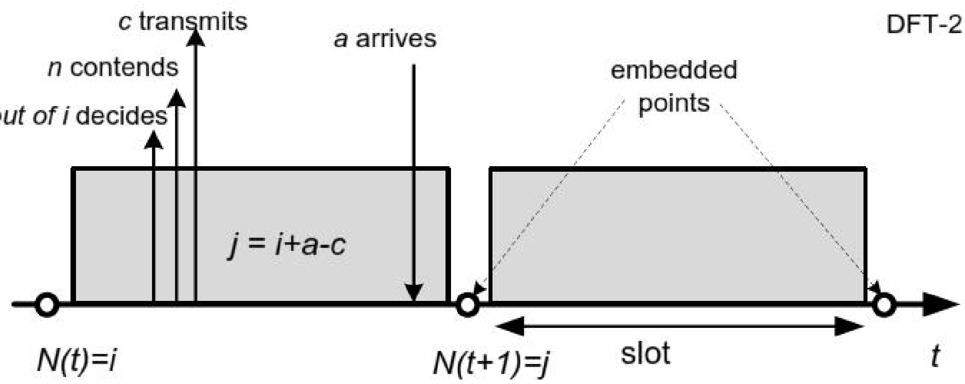

Figure 16.*Embedded Markov chain for Multi-DFT-2 System*

Successful transmission probability in Multi-DFT-2 analysis which denoted by *S(i+a-j|n)* is similar to what we presented for Multi-DFT-1 algorithm. Given that *n* attempt to transmit simultaneously, there will be exactly *c* successful transmissions.

Following the same approach as what we introduced for Multi-IFT and Multi-DFT-1, the throughput at state *i* can be calculated as [32]:

$$S_{DFT2}(i) = \sum_{n=0}^{i} \sum_{c=0}^{\min(n,M)} \sum_{a=0}^{U-i} \binom{U-i}{a} \sigma^{a} (1-\sigma)^{U-i-a} \times \binom{i}{n} p^{n} (1-p)^{i-n} \cdot c \cdot S(c \mid n). \quad (17)$$

Similarly to Multi-DFT-1 algorithm, throughput logic at state *i* is based on *n* deciders among which are currently backlogged even though the order of new arrivals and re-transmission attempts have been exchanged.

Considering the similarities of multi channel analysis between Multi-DFT-2 and Multi-DFT-1, we may have different outputs when it comes to evaluating the performance metrics of interests. We will observe this effect in Chapter 4 comprehensively.

3.4. Multi Channel Performance Metrics Analysis

As we mentioned through single channel analysis case in section 3.2, transition matrix *P* firstly is essential to analyze the performance metrics of interest. As the second step we obtain the steady-state probability vector π in which represents the probability of being at state *N(t)* when $t \to \infty$ (See Equation 1,2) utilizing the state transition matrix $P = \{\ p_{ij}\ \}_{i,j=0}^{U}$ and system of linear equations. Hence, the average backlogged devices for multi channel case can be derived:

$$E[N(t)] = \overline{n} = \sum_{n=0}^{U} n \cdot \pi_{n} \ , (18)$$

where π_n represents the stationary probability of being at state *n* calculated by Equation 3.3. Furthermore, average throughput of multi channel transmission regardless of transmission type can be delivered as:

$$S_{(.)} = \sum_{i=0}^{U} S_{(.)}(i) \cdot \pi_{i}, \qquad (19)$$

where $S_{(.)}(i)$ corresponds to the related discussed algorithms state throughput expressions (See equations (4),(6) respectively).

Consequently, the average medium access delay is achieved through applying the Little's law (similar to what compiled to single channel case) to the average system backlog $E[N(t)]$ as follows:

$$E[T] = \frac{E[N(t)]}{S_{(.)}} \text{ .} \quad (20)$$

To sum up, we introduced the main mathematical approach used in this Thesis to characterize system operation and entities. In other words, the proposed analysis provides the possibility of modeling system operation to characterize contention behavior on hand, and increase the reliability of the simulation-level results when it comes to evaluating performance metrics of interests. We will utilize the proposed analytical model in Chapter 4 and introduce the possible enhancements in application inspired by the framework analyzed in Chapter 3.

CHAPTER 4: MACHINE-TYPE CONTENTION BEHAVIOR OVER LTE PRACH

This chapter details the connectivity between the proposed analytical model and the current LTE specifications. In other words, in this chapter we bridge the indicated gap described in Chapter 1 through applying the mathematical characterization explained in previous on the current air interface cellular wireless technology and evaluate the numerical results. First, we take a look at the random access procedure in 3GPP LTE cellular networks. Afterwards, we will detail the scenarios where the proposed model for different transmission types could be utilized. Considering the assumptions taken in both simulation and analysis, we will finally discuss the performance analysis to obtain numerical results.

4.1. PRACH Operation Overview

Before offering the possibilities of using the mathematical framework in the application, we give the general coverage of random access procedure specifications. This overview is essential further to observe the connectivity between the described system explained above and the current technology.

Random access procedure over 3GPP LTE can be either *contention based* or *non-contention based* [33]. The contention based procedure occurs when the UE (User Equipment) attempts for a random access through one of the following events:

1) The initial network entry is performed over random resource control connection establishment.
2) Re-establishment occurrence after radio link failure.
3) Random request in case of intra-system handover.
4) Uplink or downlink data arrival to the “non-synchronized” UE which requires random access procedure.
5) System resources demand which is sent through the so-called scheduling request when there is no Physical Uplink Control Channel (PUCCH) allocated to the UE.

In brief, contention based Random Access (RA) procedure involves the following 4 steps (See Figure 17) [34]:

1) *Random Access Preamble:* the UE selects randomly a so-called *random access preamble* out of available sequences and transmits it over the random access channel.
2) *Random Access Response:* the eNodeB (E-UTRAN Node B) responses the UE with an access grant for uplink after detecting the preamble transmission.
3) *Random Access Message:* the UEs provide its identity to the eNodeB through the first scheduled uplink transmission when multiple UEs might select the same random access preamble.
4) *Random Access Contention Resolution:* UE identity is echoed back by the eNodeB as the resolution of possible contention. Therefore, random access procedure accomplishes by the UE confirmation.

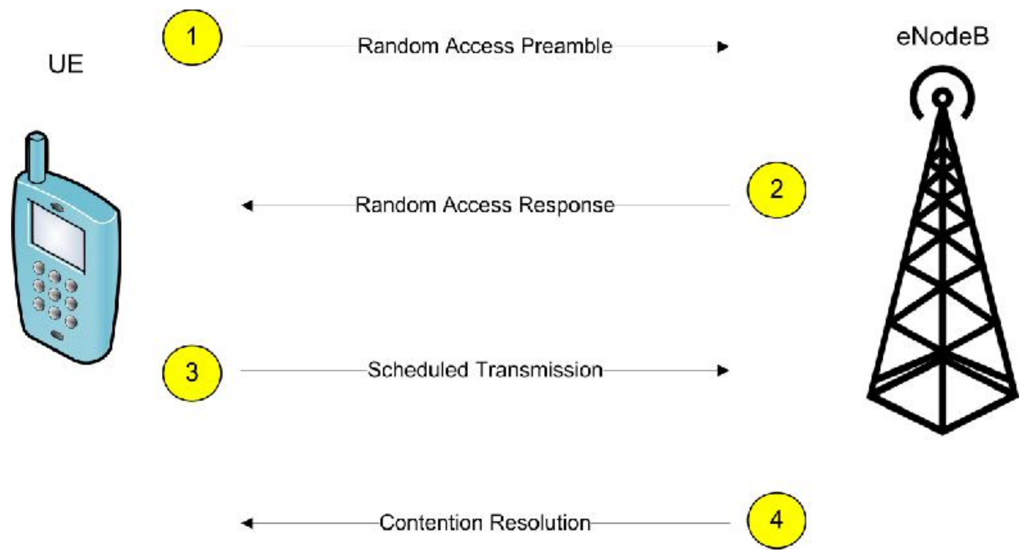

Figure 17. *Contention based Random Access Procedure in 3GPP LTE*

In contrast, non-contention based random access or literally *contention-free* random access involves no contention resolution where a temporary valid and scheduled preamble is dedicatedly assigned from the eNodeB to the UE which handover may affect (See Figure18). 3GPP LTE Contention free random access is applicable to only third and forth events among which mentioned above for the contention based case. We may consider the following steps for contention-free random access procedure [35]:

1) *Preamble Assignment*: the eNodeB assigns preamble code.
2) *Random Access Preamble*: the assigned preamble is transmitted by the UE.

3) *Random Access Response*: similar to contention based RA, the eNodeB transmits RA-preamble identifier and some other information possibly addressed in one response for one or more UE.

Relevant to the topic, in this Thesis we focus on contention based random access procedure particularly the case when the initial device entry or contention re-establishment is considered.

PRACH known as one of the uplink physical channels 3GPP LTE plays a significant role in random access procedure where it carries the so called random preambles transmitted from UE to eNodeB.

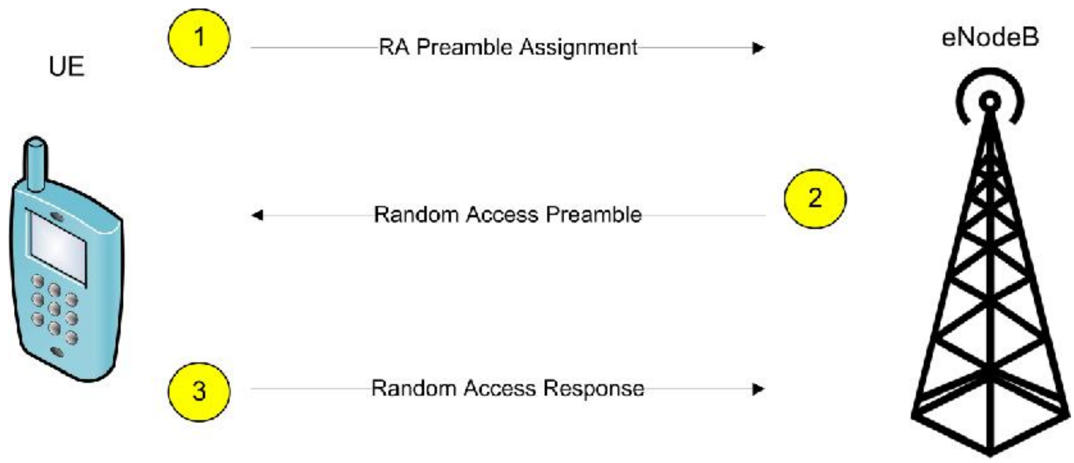

Figure 18. *Contention-free Random Access Procedure in 3GPP LTE*

When the random access preamble step begins in the contention based random access procedure, the UE selects a set of resources in terms of a preamble sequence for the PRACH to be transmitted in the next available PRACH subframe (See Figure 19). There are totally 64 possible preamble sequences which could be randomly selected during the contention based random access procedure. Each preamble sequence is required to distinguish multiple UEs using the same Resource Blocks. Delving into the concept, each sequence along with a cyclic prefix and a guard time forms a so-called *random access preamble structure*. Furthermore, selecting PRACH preamble format which specifies the type of transmission scheme Time Division Duplex (TDD) or Frequency Division Duplex (FDD) is required in advance. However, in this Thesis preamble sequence selection part is on focus.

After transmitting PRACH preamble (termed “message one”, Msg1), the UE waits for random access response (termed Mgs2) equal to the time defined by so-called Random response window. This window starts three subframes after transmitting preamble and its size can be signaled to the UE within Radio Resource Control (RRC) connection reconfiguration.

If a preamble transmitted successfully, the device sends its random access message (Msg3) in the contention-free manner after exploiting the indicated resource through Msg2. The entire procedure is accomplished successfully after the contention resolution is received by the UE.

Transmission of each aforementioned message may fail which results in unsuccessful for some defined probabilities [32]. As an example, preamble sequence transmission is failed when the Msg1 for some quite large L_1 times. Since the resulting losses do not remarkably affect the system operation, it would consider out of scope of this Thesis.

Contention based access opportunity is made available periodically during the PRACH procedure (e.g., once in 5ms) where the time frame is divided into 10 subframes with the length of 1ms each defined by the 3GPP LTE [33].

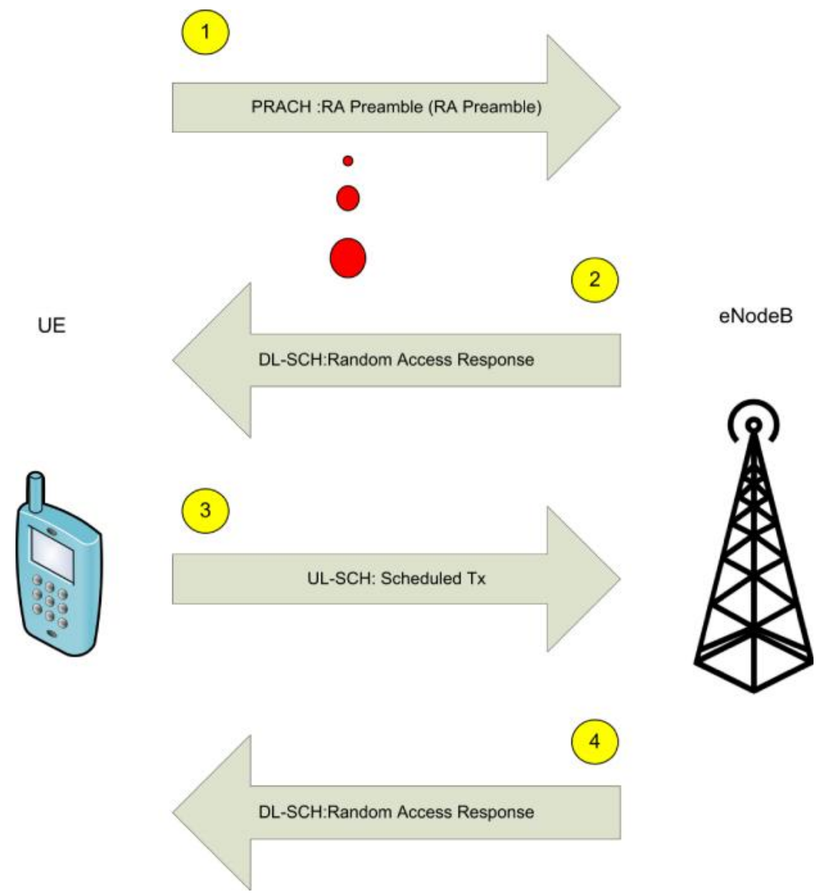

Figure 19. *Contention based Random Access Signaling*

Recapping the essential points of 3GPP LTE PRACH procedure for the contention based RA, we will detail the scenario in which the proposed multi channel mathematical model could be employed to improve the M2M contention behavior over the LTE.

4.2. Machine-Type Contention Based Transmission over 3GPP LTE PRACH

As we mentioned in this Thesis we concentrate on the case when initial device entry or contention re-establishment is considered. The reason behind this is actually due to studying Machine-Type nodes which are mainly characterized by their infrequent and small data transmission. Furthermore, featuring a large number of Machine-Type devices, PUCCH resources may rapidly become depleted. Therefore, PRACH would be appropriately employed for massive MTC deployments [32].

Having PRACH procedure in background, we detail a scenario in which RA procedure could be applied for Machine-Type transmission. If we consider an idle Machine-Type device which is activated for contending the shared channel, PRACH opportunities can be offered to start its RA procedure. Thus, each Machine-Type device takes the entire PRACH opportunity when it selects a pseudo-random preamble sequence (Msg1) chosen out of *M* available orthogonal sequences. We may consider each offered PRACH opportunity as one time slot in our proposed model. In this Thesis, we also interpret these *M* preamble sequences as the non-interfering channels similar to what we discussed in Chapter 2 where we introduced the system entities.

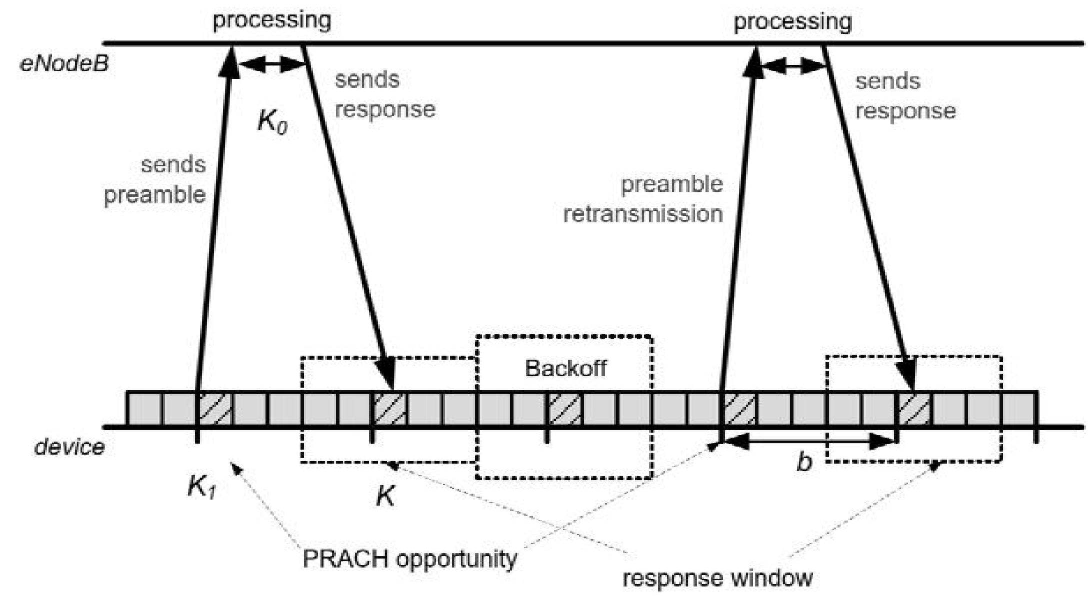

Figure 20. *3GPP LTE RA procedure for the proposed model*

When the preamble sequence is transmitted by a specific Machine-Type device through the given opportunity, it may collide with another preamble from one or more other devices which corresponds to what we had in our model as conventional collision on one of the *M* channels. Contrarily, if there is a case when different preambles are selected by contending devices then we will have a successful transmission as we described in Chapter 2 at a specific PRACH. Consequently, all the Msg1 transmissions will be decoded by the eNodeB individually.

Figure 20 illustrates the modeled RA procedure for the aforementioned scenario. We assume duration of *b* seconds between each consecutive PRACH opportunity. Additionally, PRACH duration is denoted by K_1 and eNodeB processing time dedicated for the received preambles occurred during K_0 subframes before responding to the transmitting devices over Physical Downlink Control Channel (PDCCH) sometime within the following *K* subframes named as *response window*. Although the response is forwarded over a separate channel, only the pointer to the actual feedback message is sent in order to save the PDCCH resources.

Machine-Type device considers the preamble transmission (Msg1) unsuccessful if it does not receive any feedback response during the response window (Msg2). Therefore, it repeats at a different PRACH opportunity after ω subframes of *uniform backoff* with another preamble. This backoff timing is selected randomly based on the uniform distribution over the interval [0,*W*-1]. *W* is named as *backoff indicator* (BI).

As we pointed out in the previous section, Machine-Type device after successfully transmitting preamble will send its contention-free connection request message (Msg3) via the PUCCH. eNodeB ends up the procedure by sending the *connection set-up message* (Msg4). Both Msg3 and Msg4 could be repeated up to L_3 and L_4 times respectively. However, these processes are out of scope of this Thesis and we only concentrate Msg1 and Msg2 timings throughout the RA procedure discussed in the following section.

4.3. Machine-Type Transmission Model and PRACH Timing Connection

As we mentioned, the proposed system model in Chapter 3 is based on the equally slotted ALOHA protocol. In order to connect this model with the LTE PRACH actual operation we require to somehow aggregating the system time through the transmission opportunities described above. We may translate the behavior of the uniform backoff into the corresponding channel access probability which can be derived as:

$$p = \min\left(\frac{b}{\left(\overline{\omega} + K_1 + K_0 + K\right)}, 1 \right). \qquad (21)$$

Where b subframes make one correspondent time slot as defined in the mathematical model. As such, we would have arrival rate equals to λb. $\overline{\omega}$ denotes the average interval comprising the backoff time encompassing the next PRACH waiting time which is detailed in [36] as:

$$\overline{\omega} = c_1^{\,2} + bc_1(K_0 - 1) + \frac{b^2 K_0(K_0+1)}{2} + \ldots + l_0(c_1 + K_0 b + b) \ , \qquad (22)$$

where

$$K_0 = \left\lceil \frac{W-2-c_1}{b} \right\rceil, l_0 = W - 1 - c_1 - b\left\lceil \frac{W-2-c_1}{b} \right\rceil, c_1 = \left\lceil \frac{K_0 + K_1 + K}{b} \right\rceil b - (K_0 + K_1 + K).$$

Consequently, the average access delay can be delivered in milliseconds as:

$$E[\tau] = b\frac{\overline{n}}{S_{(.)}} + (K_1 + K_0 + \frac{K+1}{2}) + b/2 - 1 \ , \qquad (23)$$

in which $(K_1 + K_0 + \frac{K+1}{2})$ is actually service time of a successful preamble with respect to eNodeB processing time, response window time and preamble transmission duration. Furthermore, $b/2$ is assumed as the average time between device activation and first PRACH opportunity. $\frac{\overline{n}}{S_{(.)}}$ as the output of (10) is multiplied by b to be translated in milliseconds. The parameters involved in the timing connection utilized in numerical results will be detailed in the following sections.

4.4. Multi Channel Mathematical Analysis & LTE RA Mechanism

Three mathematical ALOHA type algorithms were discussed in Chapter 3. Based on the given explanation, the Multi-IFT channel access algorithm translates the initial Msg1 transmission attempt occurs in the next PRACH available time slot. Besides that, uniform backoff procedure with a particular access probability (as described in 4.3) can be applied to the proposed algorithms depending on the BI.

According to some proposals given in [37], the pre-backoff may be essential in massive MTC deployments. Based on such proposals, channel access attempts surged by many Machine-Type devices might be de-correlated by invoking the backoff time at the beginning of every RA procedure as well as after any unsuccessful preamble transmission attempt. On the other hand, pre-backoff feature does not impose any significant modification of LTE specifications. This usage has been comprehensively captured by the Multi-DFT channel access algorithm in our model. Performance evaluation of such channel access algorithms in both analysis and simulation level is provided in the next section.

4.5. Performance Evaluation & Numerical Results

All the evaluations and performance examples are described in this section. For all the results given in bellow we contrast our mathematical analysis against the results of the protocol level simulation of RA procedure calibrated with the reliable 3GPP reference data reported in [10]. We employ artificial examples to evaluate performance metrics in our mathematical ALOHA-based analysis and window-based simulation utilizing non-LTE parameters. In order to compare analytical results with simulation, we also vary the overall arrival rate λ to make this comparison over a wide range of loads.

For the performance metrics evaluation we have taken totally 100 Machine-Type devices *(U=100)* transmitting over three different number of preamble channels *(M=1, 3, 10)* throughout the results given bellow.

Since the only difference between Multi-DFT-1 and Multi-DFT-2 is the order between new arrivals attempts and retransmission attempts, the results shown below are mainly focused on comparing Multi-IFT with Multi-DFT-2 except for the average number of backlog metric where we have provided numerical results for both Multi-DFT-1 and Multi-DFT-2.

Figure 21 illustrates the contrast between the analysis and our simulation results for both Multi-IFT and Multi-DFT-2 systems focusing on the average access delay transmission.

As discussed above, Multi-IFT system corresponds to the standard LTE PRACH behavior. Thus, it has been concentrated primarily to exemplify the obtained numerical results. Interestingly, both Multi-IFT and Multi-DFT-2 systems behave almost the same as the arrival rate grows slightly when only single channel case is taken into account. Whereas, when the higher number of available preambles (channels) is applied the average access delay drops remarkably in both systems. Although Multi-IFT system imposes lower delay due to the immediate transmission opportunity given to the users, the average delay difference between discussing systems becomes slighter as the higher number of preamble sequences are applied.

In order to ensure what is captured as the simulation results are reliable enough, we have utilized regenerative method to produce confidence interval of average access delay for all the iterations. In Figure 21 the confidence intervals are seen through the error bars captured at each calculated point versus the achieved values as the simulation result.

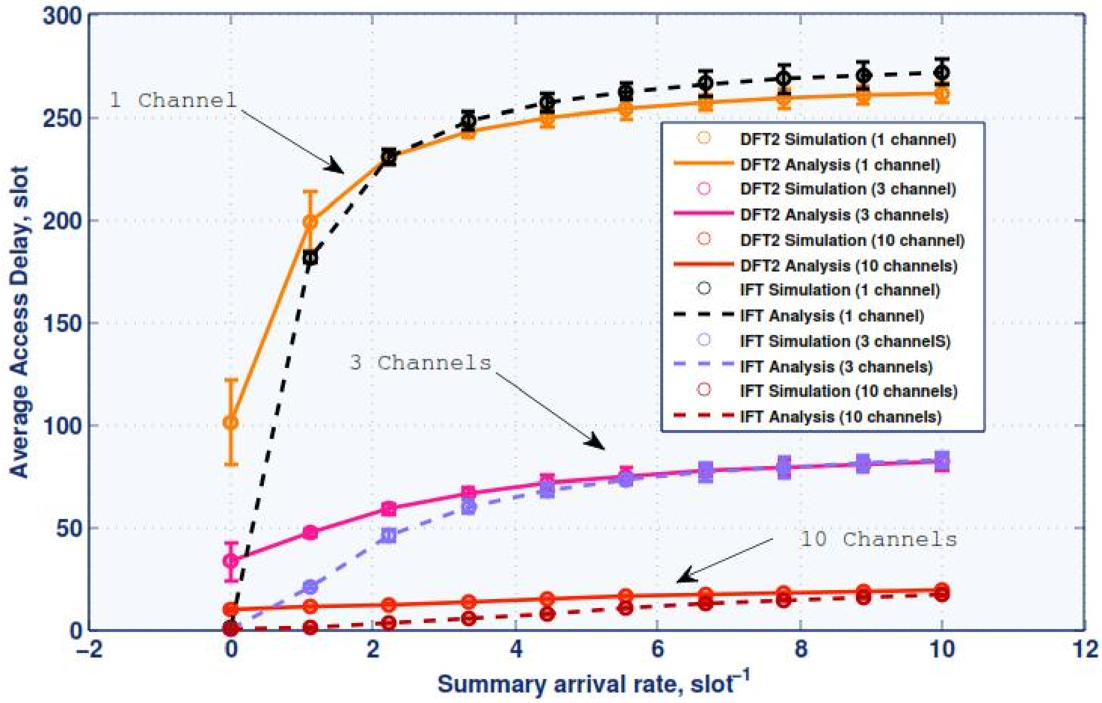

Figure 21. *Multi-IFT vs. Multi-DFT-2 average transmission delay analysis and simulation*

The other performance metric focused in this Thesis is the average throughput of our multi-channel system. Figure 22 represents the average throughput comparison between simulation and analysis for both Multi-IFT and Multi-DFT-2 systems per slot. Significantly, the achievable throughput of any finite number of Machine-Type devices tends to the asymptotic maximum stable throughput for infinite device population as given in [38].

Similarly to average access delay, delivering more channels gives us better performance. As it is seen, nearly 0.25 of transmissions per slot over the single channel for both Multi-IFT and Multi-DFT-2 systems are successful. By contrast, when 3 multi channel case is utilized the throughput performance tend to increase again for both Multi-IFT and Multi-DFT-2 systems as the throughput increases approximately by factor of four. The same behavior applies when 10 non-interfering preamble sequences are taken *(M=10)* where the successful transmissions increase dramatically while the more arrivals entered to the system. Eventually, when higher number of channels applies, Multi-IFT and Multi-DFT-2 average throughput become closed at the higher arrival rates consequently.

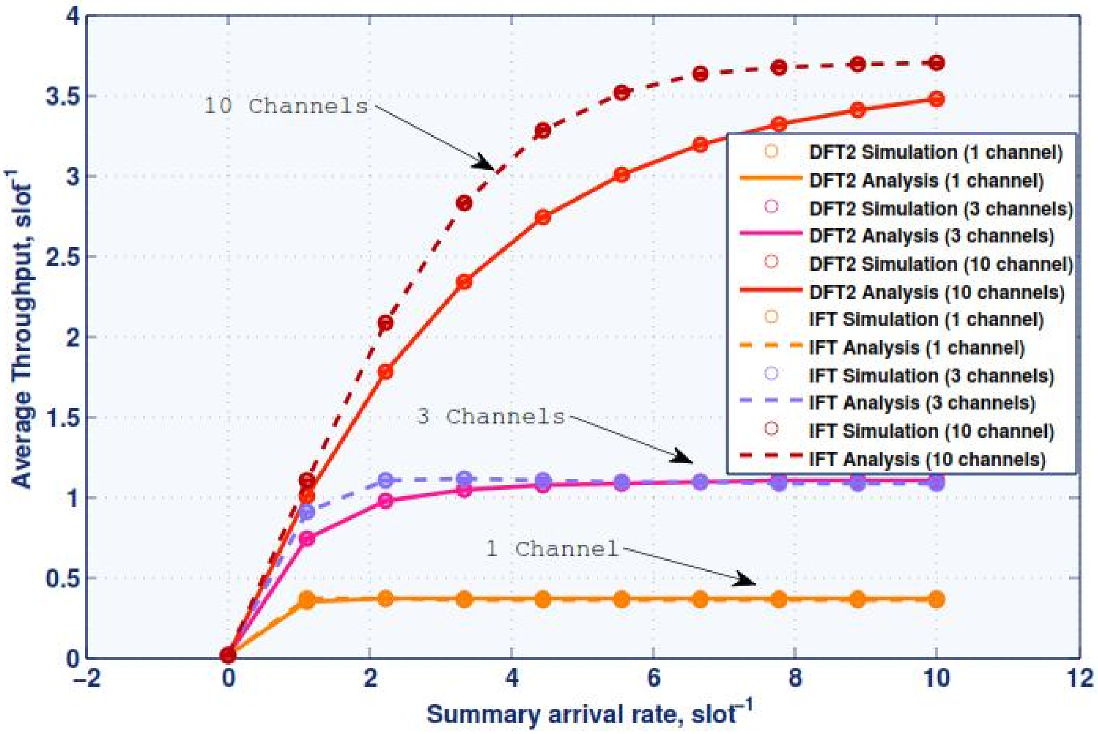

Figure 22. *Multi-IFT vs. Multi-DFT-2 average throughput analysis and simulation*

Figure 23 illustrates the comparison between IFT and DFT-2 for analysis and simulation when it comes to capturing the average number of backlog users in the system. Similarly, we have measured the average number of users in the system versus total arrival rate to the system. Interestingly, both IFT and DFT-2 behave the same when the single channel for MTC transmission is employed. However, it is clearly seen that as we utilize more number of channels IFT imposes lower number of backlog users to the system. Just to illustrate the slight difference between the DFT-1 and DFT-2 performance, Figure 24 depicts average backlog comparison when IFT and DFT-1 are employed in both simulation and analysis. It is seen that DFT-1 approaches IFT slightly faster than DFT-2 for arbitrary number of preambles. Therefore, if we consider new arrivals to the system first may result in better performance in average number of backlogged users.

Analytical behavior of the PRACH can be followed under taking different BI values from the current 3GPP LTE specifications [39], [10]. As Figure 25 represents, transmission delay for different backoff window in Multi-IFT and Multi-DFT-1 systems are considered. In other words, the connection between the proposed model and current standard specifications can be made through Equation (21) where we interpret access probability into milliseconds based on given parameters. Based on the system parameters provided in Table 2, different BI values have taken to measure the impact on average delay Multi-IFT and Multi-DFT-1 systems (See Figure 25). Although 3GPP LTE employs a total of 64 preamble sequences, there might be fewer preambles available for

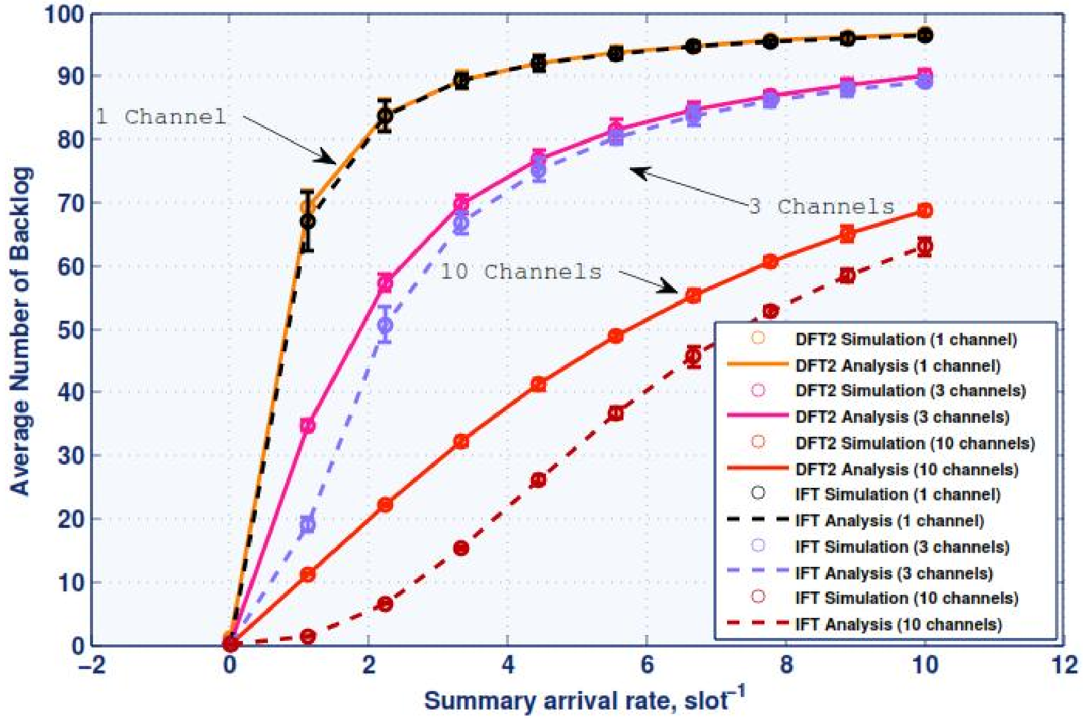

Figure 23. *Multi-IFT vs. Multi-DFT-2 average backlog simulation and analysis*

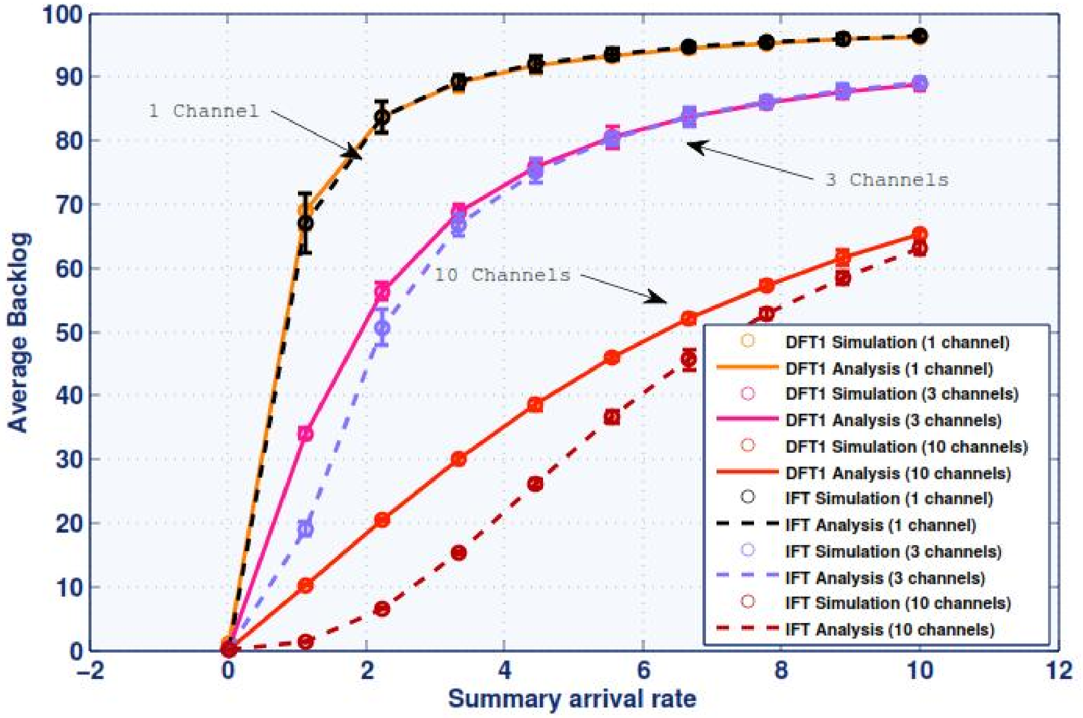

Figure 24. *Multi-IFT vs. Multi-DFT-1 average backlog simulation and analysis*

Machine-Type devices since conventional H2H communication have higher-priority. Having this assumption, we used 54 preambles for producing the result seen in Figure 25. Assuming relatively high number of Machine-Type devices *(U=100)*, it is seen that smaller BI values performs better only when the arrival rate is dramatically low. In contrast, for higher offered load the optimal BI value increases relatively. As such, only larger backoff may benefit the system. Simultaneously, reaching the saturation, high BI values performance gap becomes less significant. As such, we may optimize RA procedure through selecting BI values based on the total arrival rate to the system.

Table 2. *System Parameters*

Notation	Parameter description	Value
U	Number of M2M devices	100
M	Number of channels (preambles)	54
b	Periodicity of PRACH opportunities	5ms
K	PRACH response window	5ms
K_1	Preamble transmission duration	1ms
K_0	Preamble processing by eNodeB	2ms
W	PRACH backoff indicator	variable

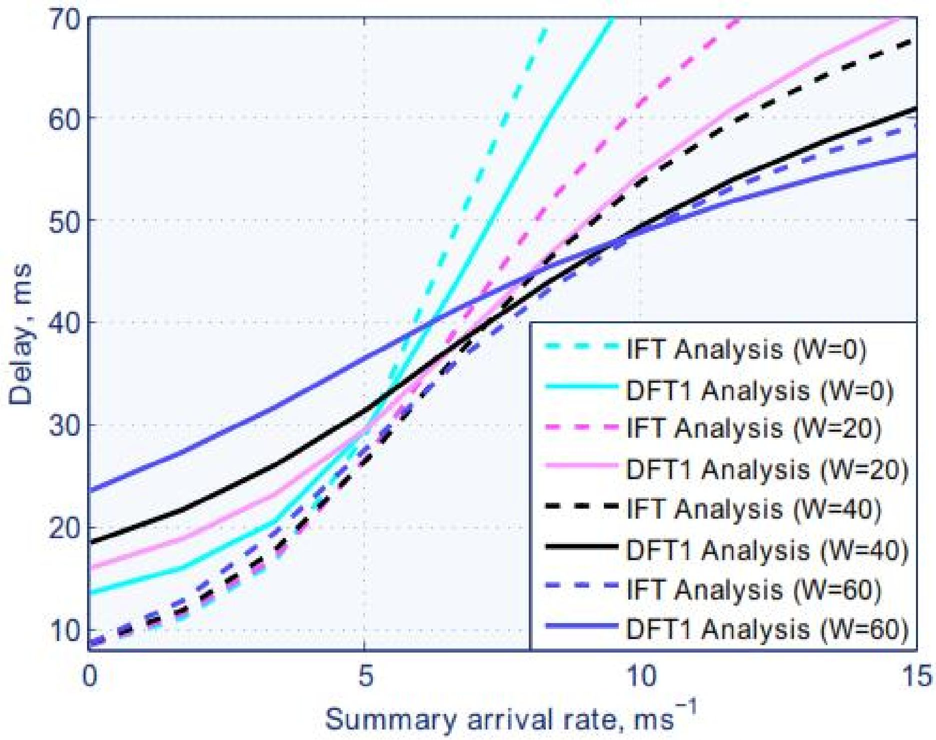

Figure 25. *Different Backoff indicators transmission delay comparison*

4.6. Conclusion and Future Work

In this Thesis we emphasized the lack of comprehensive and rigorous analytical model capturing Machine-Type contention behavior and tailoring it to MTC over-LTE use cases. Furthermore, previous results and works have taken limited attention to provide a unified analytical framework mainly focused on Machine-Type contention-based behavior due to the potential 3GPP LTE deterioration for higher M2M loads. As such, we have accounted for the analytical modeling of the recent LTE technology RA procedure attractiveness while calibrating our proposed mathematical model through protocol level simulation.

In Chapter 3, we utilized the existing analytical framework delivered in [28] as an appropriate baseline perfectly matched to our system operation and entities. On top of that, we have proposed a novel mathematical multi channel random access model to fill in the gap between previous works and the indicated missing part. Further, the dynamic Machine-Type contention behavior in the multi-channel environment across a range of access algorithms has depicted. This dynamic Machine-Type contention-based behavior have also accounted for characterizing performance metrics mathematically.

In-depth enhancements of the proposed mathematical framework dedicatedly used in 3GPP LTE PRACH RA procedure are discussed in Chapter 4. Concentrating on Msg1 and Msg3, we have shown how perfectly our proposed multi-channel model can be modified for such use taking into account the PRACH timing aspects and attributes. Our approach allows investigating the performance of Machine-Type devices in terms of conventional metrics such as average channel access delay, average throughput and average backlogged users in case of remarkable number of users.

Moreover, potential enhancements of LTE PRACH have highlighted featuring pre-backoff technique. Since such technique does not require any major change to the whole protocol, two delayed versions of accessing channels were introduced specifically and evaluated by the usage of different BI values as well calibrating the aforementioned performance metrics.

Research contributions on Machine-Type communication always welcome analytical instruments in order to verify the output of the protocol-level simulation. The analytical model presented in this Thesis, is sufficiently powerful and flexible where it was successfully applied and calibrated for different technology based scenarios.

Our numerical results of access delay and throughput has been found to be very helpful and accurate to work on it for further use considering the realistic characteristics of PRACH performance. Our analytical approach is also appropriate for studying other M2M LTE use cases enhancements such as MTC scheduling requests sending in joint with conventional H2H communication.

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APPENDIX A: MARKOVIAN PROCESS PROPERTIES

A stochastic process is a mathematical model that evolves over time in a probabilistic manner. *Markov Process* considers as a specific stochastic process characterizing an important class of finite memory random walks. The outcome of such experiment depends only on the outcome of previous experiment. Therefore, the next state of the system depends only on the present state, not on preceding states (only the current state of the process influence where it goes next). This means that if we know an initial condition for the process which is defined, we can likely demonstrate the outcomes of the process. *State space* and *transition matrix* are required for defining any particular Markov chain. Each entry of transition matrix denotes the probability of moving from state *i* to *j* in one step. Therefore, Markov property can define as follows:

$$P(X_n = x \mid X_0, \ldots\ldots, X_{n-1}) = P(X_n = x \mid X_{n-1}),$$

where X_n is a random variable at state *"n"*. If we exclusively consider the case where the process contains only a countable set of states, it is typically referred to as a *Markov chain*. Significantly, the memoryless property makes it possible to predict the behavior of a Markov chain by computing probabilities and expected values which simulate such behavior. Furthermore, what makes Markov chains quite vast and diverse is the simplicity of mathematical models this tool offers for random phenomenon on one hand, and its simple structure which makes it easy to deal about the behavior of the random processes. It would not be surprising to believe that the whole study of random processes can be considered as a generalization of theory of Markov chains analysis.

If we raise the transition matrix to the n^{th} power, obviously the element *(i,j),* is the probability of moving from state *i* to state *j* after exactly *n* steps. Equilibrium distributed Markov chain represents the long-term proportion of the time being at any state leading us to understand the outcome of the process as mentioned above. If the Markov chain is *irreducible* and *aperiodic* then it could converge to an equilibrium distribution as *n* gets large:

Definition A chain is irreducible if every state can be reached from any other one. That is $p_{i,j} > 0 \ \forall i, j$.

Definition An irreducible chain is aperiodic if the greatest common denominator of the path lengths is one when considering all possible paths from any state i back to it.

If the above pair of conditions exists, the Markov chain is called *Ergodic*. Ergodicity makes Markov chains useful from algorithmic perspective since a unique equilibrium distribution regardless of initial states can be reached through this property.

To sum up, the essential property of ergodic Markov chain supports useful algorithmic purposes where it quickly caused the finite Markov chain to get converged to its equilibrium distribution.