UNIVERSITI PUTRA MALAYSIA

RANDOM ACCESS CONTROL SCHEMES FOR MASSIVE MACHINE TYPE COMMUNICATIONS IN CELLULAR IOT NETWORKS

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By

ALTHUMALI, HUDA DAKHILALLAH A

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

June 2022

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DEDICATIONS

I would like to dedicate this thesis to my beloved motherland
"KINGDOM OF SAUDI ARABIA".

&

To my family and all whom I love.

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

RANDOM ACCESS CONTROL SCHEMES FOR MASSIVE MACHINE TYPE COMMUNICATIONS IN CELLULAR IOT NETWORKS

By

ALTHUMALI, HUDA DAKHILALLAH A

June 2022

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Machine Type Communications (MTC) refer to the autonomous interaction between connected devices without human intervention. The deployment of MTC on cellular networks provides ubiquitous services to Internet-of-Things (IoT) systems. Recently, the Third-Generation Partnership Project (3GPP) introduced the standard specifications of deploying MTC on cellular networks. The 3GPP recommends the recent cellular networks such as Long-Term Evolution (LTE), LTE-Advanced (LTE-A) and Fifth-Generation (5G) networks as an appropriate infrastructure for MTC due to wide coverage, scalability, low latency and spectral efficiency.

Indeed, with an increased number of devices connecting to the network everyday, massive numbers of machine devices are expected to simultaneously access the network resources especially during emergency scenarios. This massive access results in excessive congestion and collisions in the random access channel (RACH) which is considered the first step to access network resources. These massive collisions cause the devices to be blocked from accessing network resources which results in performance degradation for the overall MTC system. For this reason, it is important to improve random access (RA) control schemes to accommodate the increased number of machine devices connecting to the network. In this thesis, RA control schemes are classified according to targetted objectives into three categories: (1) massive access control schemes, (2) energy efficiency schemes and (3) performance improvement schemes. Each category is further divided into two subcategories, and the relevant RA schemes are presented for each category. Furthermore, an analytical comparison has been provided among the different schemes according to several performance parameters. This work mainly focuses on the massive access control schemes which are sub-divided into congestion control and collision resolution schemes.

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In order to increase the access success rate during massive access scenarios, this work proposes a new dynamic backoff collision resolution scheme (DBCR) for delay-tolerant devices. In this scheme, the RACH collisions are resolved using a backoff procedure which dynamically adjusts the backoff indicator (BI) based on the number of backlog devices and available resources. The proposed scheme is integrated with three well-known random access schemes. The mathematical analysis of the DBCR and derivation of the optimal value of BI is presented for the three different combinations. Thereafter, extensive simulations are performed to evaluate the proposed scheme. The analysis and simulation results demonstrate that the DBCR scheme achieves an access success rate of 99.9% with a slight increase in access delay which is reasonable for delay-tolerant applications during massive arrivals scenarios.

Further, this work introduces a dynamic tree splitting (DTS) scheme to resolve RACH collisions for delay-sensitive devices during burst arrival scenarios. The DTS scheme assigns a specific number of resources/preambles to the collided group of devices for their next access attempt with the aim of reducing access delay. The number of preambles assigned for each group is determined based on the mean number of collisions in each random access opportunity (RAO) in order to increase the utilisation of preambles. The mathematical analysis of the proposed scheme is presented and the access delay is derived. The analysis and simulation results show that the DTS reduces the access delay by approximately 12% compared to the recent benchmarks, with a very low drop rate, which indicates the efficiency and reliability of the proposed scheme.

Furthermore, a priority-based load-adaptive preambles separation (PLPS) RA scheme for quality-of-service (QoS)-differentiated applications in 5G networks is proposed. In this scheme, three classes of devices are considered. These are devices with enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC) and massive machine type communication (mMTC). The available number of preambles is divided into three groups, and the number of preambles is assigned for each group based on class priority and load intensity. The mathematical analysis of the proposed scheme is presented along with the derivations of several performance metrics. The analysis and simulation results show that the PLPS scheme succeeds in achieving the targetted QoS requirements for each class even for a large number of devices, which is very promising for the 5G heterogeneous services.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SKEMA KAWALAN CAPAIAN RAWAK YANG BAGI KOMUNIKASI JENIS MESIN BESAR DALAM RANGKAIAN SELULAR INTERNET BENDA

Oleh

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Komunikasi Jenis Mesin (MTC) adalah interaksi autonomi antara peranti yang berhubung tanpa campur tangan manusia. Penggunaan komunikasi MTC pada rangkaian selular membolehkan perkhidmatan sistem Internet Benda (IoT) digunakan di merata tempat. Baru-baru ini, Projek Perkongsian Generasi Ketiga (3GPP) memperkenalkan spesifikasi piawai penggunaan komunikasi MTC pada rangkaian selular. 3GPP mengesyorkan rangkaian selular terkini seperti rangkaian Evolusi Jangka Panjang (LTE), LTE Termaju (LTE-A) dan Generasi Kelima (5G) sebagai infrastruktur yang sesuai bagi komunikasi MTC kerana liputan yang luas, kebolehskalaan, kependaman yang rendah dan kecekapan spektrum.

Malah, peningkatan jumlah peranti yang berhubung ke rangkaian setiap hari bermaksud capaian kepada sumber rangkaian dijangka dilakukan secara serentak oleh sejumlah besar peranti mesin, terutamanya dalam situasi kecemasan. Capaian besar-besaran ini mengakibatkan kesesakan dan perlanggaran yang melampau dalam saluran capaian secara rawak (RACH) yang merupakan langkah pertama dalam mengakses sumber rangkaian. Perlanggaran besar-besaran ini pula menyebabkan peranti disekat daripada mengakses sumber rangkaian dan mengakibatkan prestasi keseluruhan sistem MTC merosot. Oleh itu, adalah penting bagi teknik kawalan akses secara rawak (RA) dipertingkatkan untuk menyesuaikan dengan peningkatan bilangan peranti mesin yang berhubung ke rangkaian. Dalam kajian ini, teknik kawalan capaian secara rawak dikelaskan kepada tiga kategori berdasarkan objektif yang disasarkan: (1) teknik kawalan capaian besar-besaran, (2) teknik kecekapan tenaga dan (3) teknik peningkatan prestasi. Setiap kategori dipecahkan lagi kepada dua subkategori dan teknik RA yang berkaitan dibentangkan untuk setiap kategori.

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Tambahan pula, perbandingan secara analitikal dibuat antara teknik-teknik yang berbeza berdasarkan beberapa parameter prestasi. Kajian ini tertumpu terutamanya pada teknik kawalan capaian besar-besaran yang dibahagikan kepada teknik kawalan kesesakan dan teknik penyelesaian perlanggaran. Bagi meningkatkan kadar kejayaan capaian semasa senario capaian besar-besaran, kajian ini mencadangkan skema penyelesaian backoff collision dinamik (DBCR) baharu untuk peranti tahan lengah. Dalam skema ini, perlanggaran RACH diselesaikan menggunakan prosedur backoff yang secara dinamik melaraskan penunjuk backoff (BI) berdasarkan bilangan peranti yang tertunggak dan sumber yang tersedia. Skema yang dicadangkan disepadukan dengan tiga skema capaian rawak yang terkenal.

Analisis matematik terhadap DBCR dan terbitan nilai optimum BI dipersembahkan untuk tiga kombinasi yang berbeza. Setelah itu, simulasi terperinci dibuat untuk menilai skema yang dicadangkan. Hasil analisis dan simulasi menunjukkan bahawa skema DBCR mencapai kadar kejayaan capaian sebanyak 99.9% dengan sedikit peningkatan dalam kelewatan capaian yang munasabah bagi aplikasi tahan kelewatan sewaktu senario ketibaan besar-besaran. Selanjutnya, kajian ini memperkenalkan algoritma pemisahan pokok dinamik (DTS) untuk menyelesaikan perlanggaran RACH bagi peranti sensitif lengah semasa senario letusan ketibaan. Algoritma DTS menetapkan bilangan sumber/pendahuluan yang khusus kepada kumpulan peranti yang berlanggar untuk percubaan capaian seterusnya dengan tujuan mengurangkan kelewatan capaian. Bilangan pendahuluan yang ditetapkan untuk setiap kumpulan ditentukan berdasarkan purata bilangan perlanggaran dalam setiap peluang capaian rawak (RAO) untuk meningkatkan penggunaan pendahuluan. Analisis matematik bagi algoritma yang dicadangkan dibentangkan dan kelewatan capaian diperoleh. Keputusan analisis dan simulasi menunjukkan bahawa DTS berjaya mengurangkan kelewatan capaian sebanyak hampir 12% berbanding penanda aras terkini. DTS menunjukkan kadar penurunan yang sangat rendah, yang menandakan kecekapan dan kebolehpercayaan algoritma yang dicadangkan.

Tambahan pula, skema RA pemisahan pendahuluan penyesuaian beban berasaskan keutamaan (PLPS) untuk aplikasi terbeza bagi kualiti perkhidmatan (QoS) dalam rangkaian 5G turut dicadangkan. Skema ini mempertimbangkan tiga kelas peranti; jalur lebar mudah alih tertingkat (eMBB), komunikasi kependaman rendah yang sangat boleh dipercayai (URLLC) dan peranti komunikasi jenis mesin besar (mMTC). Bilangan pendahuluan yang tersedia dibahagikan kepada tiga kumpulan, dan bilangan pendahuluan ditetapkan untuk setiap kumpulan berdasarkan keutamaan kelas dan keamatan beban. Analisis matematik bagi skema yang dicadangkan dibentangkan bersama dengan terbitan beberapa metrik prestasi. Keputusan analisis dan simulasi menunjukkan bahawa skema PLPS berjaya mencapai keperluan QoS yang disasarkan untuk setiap kelas, walaupun untuk sejumlah besar peranti. Keputusan ini adalah amat menggalakkan bagi perkhidmatan heterogen 5G.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision
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LIST OF ABBREVIATIONS

3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
ACB	Access Class Barring
BI	Backoff Indicator
BS	Base Station
CABC	Cooperative Access Class Barring
CABC-LB	Cooperative Access Class Barring with Load Balancing
CDF	Cumulative Distribution Function
CR	Connection Request
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DAB	Dynamic Access Class Barring
DBCR	Dynamic Backoff Collision Resolution
DDQL	Delay-Aware Double Deep Q-learning
DTS	Dynamic Tree-Splitting
EAB	Extended Access Class Barring
eMBB	Enhanced Mobile Broadband
eNB	Evolved Node B
GF	Grant-Free
gNB	Logical Node B
HARQ	Hybrid Automatic Repeat Request
HTC	Human Type Communication

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IoT	Internet of Things
IoT-GSI	Global Standards Initiative on Internet of Things
LC-MTC	Low Cost Machine Type Communication
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution-Advanced
M2M	Machine-to-Machine
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
mIoT	Massive Internet of Things
MME	Mobility Management Entity
mMTC	Massive Machine Type Communication
MTC	Machine Type Communication
NOMA	Non-Orthogonal Multiple Access
NSA	Non-Stand Alone
PACB	Priority-based Access Class Barring
PDCCH	Physical Downlink Control Channel
PDF	Probability Distribution Function
PLPS	Priority-based Load-adaptive Preamble Separation
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
RA	Random Access
RACH	Random Access Channel
RAN	Radio Access Network
RAO	Random Access Opportunity
RAR	Random Access Response

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RAUG	RA-Slot Based URLLC Grouping
RNTI	Radio Network Temporal Identifier
SA	Stand Alone
SBCR	Standard Backoff Collision Resolution
SFN	System Frame Number
S-GW	Serving Gateway
SIM	Subscriber Identity Module
SRA	Standard Random Access
TA	Timing Advance
TRA	Tree-Based Random Access
UE	User Equipment
URLLC	Ultra-Reliable Low Latency Communication

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CHAPTER 1

INTRODUCTION

1.1 Background

The Internet of Things (IoT) is a recent paradigm that has received much attention in the last decade due to the growing interest in the use of autonomous computing. According to the Global Standards Initiative on Internet of Things (IoT-GSI), the IoT can be defined as the infrastructure of the information society. In the IoT, physical objects are connected to the existing network infrastructure to be sensed and controlled remotely through the network. These objects are embedded with sensors, actuators and software that facilitate the sensing and controlling process, as well as the network connection which allows data to be exchanged among the connected objects [1]. Such connectivity results in smart city improvements where all systems such as transportation, lighting, power and water are managed intelligently [2]. These capabilities will give rise to incredible developments in system efficiency and reliability. To support the IoT, machine-to-machine (M2M) communications, or in other words, machine type communications (MTC) are required because billions of devices will be connected to the Internet in the near future [3]. MTC stands for the automated interaction between machine devices without human intervention. This technology provides significant services for several IoT applications such as e-healthcare, e-transportation, e-commerce and automated control systems.

Enabling MTC on cellular networks provides a promising future for IoT. The Third-Generation Partnership Project (3GPP) has introduced the standards for MTC on cellular networks [4]. Cellular networks such as Long-Term Evolution (LTE), LTE-Advanced (LTE-A) and fifth generation (5G) networks have been considered appropriate infrastructure for MTC due to widespread coverage, scalability, low latency, large capacity, spectral efficiency and Quality-of-Service (QoS) guarantees. However, LTE/LTE-A and 5G networks are optimised for human type communications (HTC) , which have different characteristics from MTC. Usually, MTC includes short data packets with more frequent transmissions compared to HTC. Therefore, the current cellular networks require some improvements to cope with the special characteristics of MTC.

1.1.1 Cellular IoT Networks

Cellular IoT Networks involve several MTC systems which connect to the internet through cellular networks. Cellular-based MTC systems are composed of three main domains: the device domain, the network domain and the application domain [5]. As shown in Figure 1.1, the device domain contains MTC devices which perform sensing, actuating and data gathering. These devices

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are connected to the core network through a radio access network (RAN) or an MTC gateway. The core network and the RAN formulate the network domain which is connected to the MTC cloud server in the application domain. The MTC cloud server communicates with the MTC application user that could be a human or another MTC device performing system monitoring and management [6].

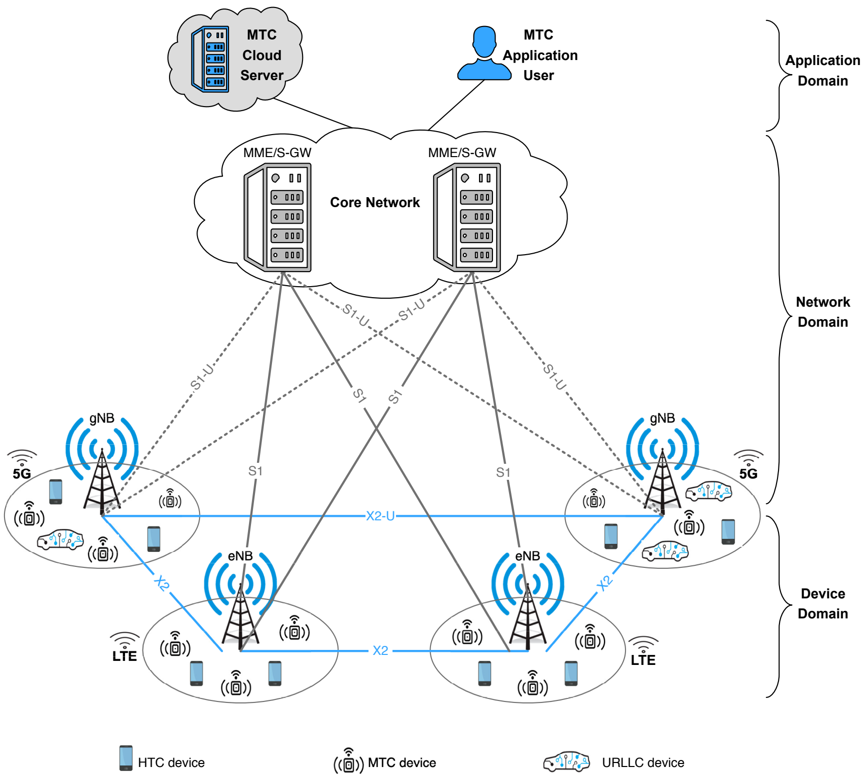

Figure 1.1: Cellular-based MTC System.

MTC devices are connected to the core network through either an LTE/LTE-A or 5G network. LTE is a recent cellular network paradigm that was developed by 3GPP under the fourth-generation (4G) standardization. Starting from Release 8, 3GPP has defined the specifications for LTE networks that provide high peak data rates and efficient management for radio resources [7]. LTE was recently developed to LTE-A which aims to provide higher data rates and spectral efficiency [8]. In LTE/LTE-A networks, the Evolved Node B (eNB) is the base station (BS) component which is responsible for providing physical and medium access control (MAC) layer services, such as radio resource management, access traffic control, packet scheduling, routing and handover. Multiple eNBs are connected using a high-speed X2 interface which facilitates communication among them. eNBs are connected to the core network through an S1 interface which allows the eNB to access the mobility management entity (MME) and the serving gateway (S-GW). The core network components facilitate the communication between the RAN and the Internet.

5G networks introduce the new radio (NR) interface to provide higher flexibility which is required to support several types of service [9]. The 5G RAN can be connected to a 5G core network in the stand alone (SA) architecture. Further, 5G RAN can be connected to an LTE/LTE-A core network in the non-stand alone (NSA) Architecture as adopted in Figure 1.1. The BS of the NR is called the logical node B (gNB). Multiple gNBs are connected together via an X2-U interface and connected to the LTE/LTE-A core network through an S1-U interface. 5G networks provide connectivity for several service classes including enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC) and massive Internet of things (mIoT). eMBB is designed to provide high data rates for large payload applications such as 4K video, live streaming and cloud gaming. URLLC aims to achieve fast and high reliable services for critical applications such as smart transport systems, remote medical assistance and industrial automation. Finally, mIoT is enabled through the massive MTC (mMTC) which provides connectivity for an extremely large number of devices with high energy efficiency for delay-tolerant applications such as sensing, metering, and monitoring in smart grid networks. The service requirements differ among the three classes according to connection and traffic density, reliability and latency constraints [10].

However, deploying MTC on recent cellular networks has many challenges. These challenges are as follows [11]:

- Cellular networks such as LTE/LTE-A provide a higher data rate at the downlink (50 Mbps) and a lower data rate at the uplink (25 Mbps) which is not suitable for MTC that requires an increased data rate at the uplink.

- Allowing MTC communication in cellular networks creates an overhead problem that may affect the performance of HTC communications.

- Although MTC involves small data transmissions, congestion may occur in the uplink due to the massive number of devices trying to access the network simultaneously.

- Cellular network transmission and reception consume more power which must be reduced for MTC to cope with limited-energy devices.

- Transmission protocols must be optimized to consume low power to extend the lifetime of batteries.

- Interferences may occur in the communications lines of cellular networks due to MTC [12].

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1.1.2 Standard Random Access Procedure

When the user equipment (UE) is turned on for the first time, the UE goes through a synchronization process by which it acquires the system information from a particular network operator to which the UE subscribes [13]. After synchronization, the UE must go through a random access (RA) procedure to inform the BS that the UE requires the connection. The RA procedure is carried out through the random access channel (RACH) which periodically provides RA opportunities (RAOs). Normally, the UE is required to perform the RA procedure for the following reasons [14]:

- To acquire the initial access to the network.
- To re-establish the connection after the failure of a radio link.
- To hand over from one eNB to another.
- To update the user equipment location.
- To make scheduling requests.

To support the previous situations, two forms of RA procedures are defined in cellular networks [15] [16]:

1. Contention-based RA: in this form, the access process is triggered by UEs that compete to access the RACH. This form is more suitable for delay-tolerant applications due to the probability of collisions.

2. Contention-free RA: in which the access process is initiated by the BS which allocates particular access resources to the UEs to allow them to transmit their access requests. This form is appropriate for delay-sensitive applications that require high success rates and involve fewer devices.

The standard RA (SRA) procedure in cellular networks is contention based, where the UEs are competing to acquire access to the BS [17]. The SRA procedure involves four message transmissions between the UE and the BS as shown in Figure 1.2. The four message transmissions of the SRA procedure can be summarised as follows [18]:

- Msg1: Preamble transmission. Whenever a UE requires network access, it randomly choses a preamble and transmits it to the BS in the nearest available RAO. This preamble must be unique among all the transmitted preambles in the same RAO, otherwise, a collision of Msg3 will occur.

- Msg2: Random access response (RAR). The BS transmits the RAR message to the successfully received preambles. This message contains information

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about the uplink resources to be used by the UE for the next message transmission. The RAR must be received by the UE within a specific time duration called RAR window size W_{RAR}. Otherwise, the UE should start a new RA attempt.

• Msg3: Connection request (CR). The UE transmits a CR message to the BS using the uplink resources determined in the RAR message. The CR message contains the UE temporary identifier and the connection purpose. If two or more UEs selected the same preamble in Msg1, they will receive the same RAR message and use the same uplink resource to transmit Msg3, therefore, a collision in Msg3 transmission will occur for both devices.

• Msg4: Connection response. The BS transmits this message as a response to the RC message sent to the UEs that succeeded in Msg3 informing them that they have successfully completed the RA procedure.

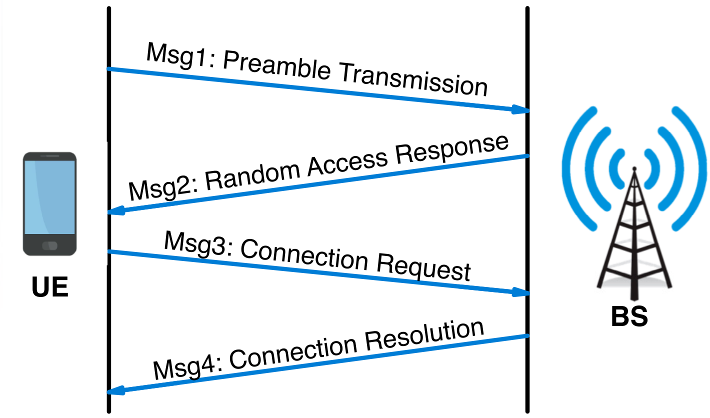

Figure 1.2: SRA Procedure in Cellular Networks.

After the successful completion of the RA procedure, the UEs immediately proceed to the data transmission phase. If a UE did not succeed in the RA procedure for any reason such as connection failure or Msg3 collision, the UE performs another access attempt after a specific backoff time T_{BO}. The UE is allowed to perform up to k_{max} transmission attempts, after which the UE request is dropped.

1.2 Research Motivation

Rapid improvements in IoT have led to MTC becoming a hot area for research. The increased number of MTC devices that are connecting to the network requires more improvements to communication protocols, especially for RA control protocols, which opens a space for researchers to keep improving these protocols. It is important for researchers to develop efficient RA control protocols that support MTC in recent wireless networks which are considered a promising infrastructure for IoT. Although that there is good work being done in this area, the latest RA control protocols are still insufficient, especially for massive, delay-sensitive and heterogeneous MTC systems.

1.3 Problem Statement

The accelerated increase in the number of MTC devices connected to the networks causes great numbers of MTC devices to access the network simultaneously in order react to some event. This massive synchronous access causes intensive congestion and collisions in the RACH due to the limited number of resources/preambles that are available for RA contention. These collisions cause serious degradations in RACH availability which leads to high drop rates, low access success probability and increased access delay. Although the 3GPP has introduced the standard backoff collision resolution (SBCR) scheme to resolve the RACH collisions during massive access scenarios, there is a need to optimize the SBCR scheme to increase the access success rate of MTC devices during massive access scenarios.

Furthermore, the delay-sensitive services, which have strict deadline requirements, should have special consideration during the development of the RA procedure. Although there are few solutions that have been proposed to solve the RACH collisions for delay-sensitive MTC devices, still there is a lack of RA collision resolution schemes that aim to reduce the access delay for delay-sensitive MTC devices.

5G networks are required to provide connectivity for eMBB, URLLC and mMTC services. Therefore, the heterogenous QoS requirements of 5G services is a major issue. This has to be considered during the improvement of the RA procedure for 5G networks. The problem becomes more complicated when the three service classes exist in the same RAN which causes congestion and collisions in the RACH and therefore failure to meet QoS requirements for different services. Although some solutions have been proposed for improving the RA in 5G networks, none of them have considered the three classes of services in the same RAN. Thus, it is challenging to develop customised RA schemes for 5G networks, especially when different service classes are sharing the same RAN.

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1.4 Research Questions

The research questions for this study are as follows:

1. How can the parameters of the backoff collision resolution scheme be optimized to maximize the access success rate of MTC devices during massive access scenarios?

2. How can the access delay be reduced for delay-sensitive devices during massive access scenarios?

3. How can the RA procedure be improved so that heterogeneous services sharing the same RAN meet their targetted QoS requirements?

1.5 Research Objectives

The main objective of this research is to improve the performance of the RACH of the recent cellular IoT network which involves massive MTC. In particular, this objective is divided into three sub-objectives as follows:

1. To propose a dynamic backoff collision resolution (DBCR) scheme that optimises the backoff parameter with the aim of increasing the access success rate of MTC devices during massive access scenarios.

2. To propose a dynamic tree-splitting (DTS) scheme that resolves RACH collisions to reduce the access delay for delay-sensitive MTC devices.

3. To propose a priority-based load-adaptive preamble separation (PLPS) RA control scheme aiming to deliver the required QoS requirements for 5G heterogenous services sharing the same RAN.

1.6 Research Scope

This research focuses on studying massive MTC in recent cellular IoT networks including LTE, LTE-A and 5G. Specifically, it concentrates on enhancing the performance of the RACH which is used by the MTC devices as a first step to access the network resources. The RACH is one of the uplink transport channels that are located in the MAC layer, which is one of the important layers in the cellular network protocol stack. Moreover, this research investigates massive burst arrivals of MTC devices which usually occur when a massive number of such devices try to access the BS simultaneously due to a specific event. In order to facilitate the work and to avoid extra costs, all the analysis and simulations in this thesis are implemented using Matlab which is free and open source software. The scope of this research is illustrated as a red rectangle in Figure 1.3.

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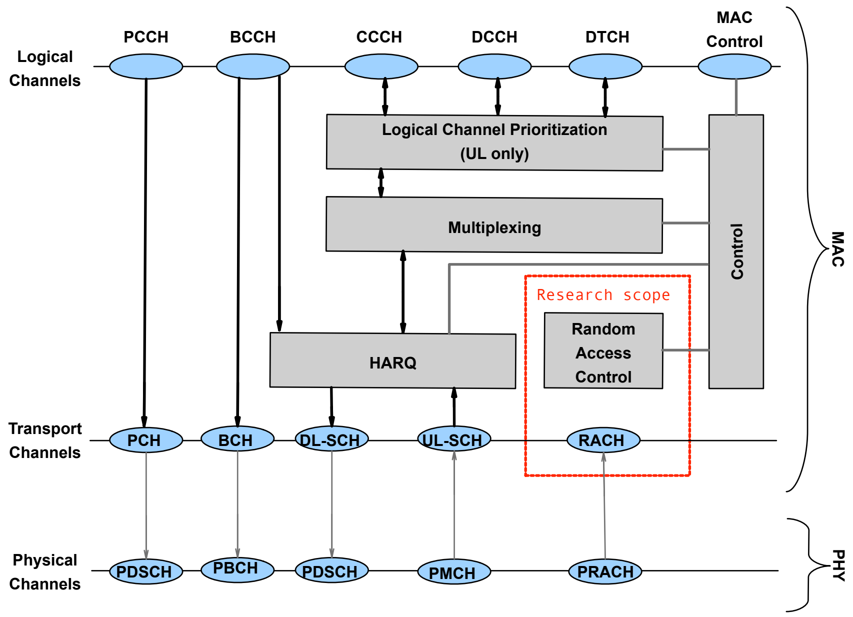

Figure 1.3: Research Scope Illustration.

1.7 Research Contributions

This thesis contributes to existing knowledge by improving the performance of the RACH in recent cellular networks that involve mMTC. The research contributions are summarized as follows:

- It proposes a DBCR scheme that optimizes the backoff parameter according to the number of contending devices and available resources. The optimal value of the backoff parameter that achieves the highest access success probability is mathematically derived and the access success probability of the proposed DBCR scheme is analyzed.

- It introduces a DTS scheme to resolve RACH collisions for delay-sensitive devices during burst arrival scenarios. A mathematical analysis of the proposed algorithm is presented as well as the derivations of throughput and access delay.

- It develops a PLPS RA scheme in which RACH resources are separated between the different devices classes according to the class priority and load estimation. The mathematical analysis and the performance indices are derived for the proposed scheme.

1.8 Thesis Organization

The rest of this thesis is organized as follows:

Chapter 2 – presents the literature review. It discusses related RA control schemes which have already been proposed for massive MTC in LTE/LTE-A and 5G networks. A comparative analysis among the reviewed scheme is provided.

Chapter 3 – describes the overall research methodology. It defines the notations related to this research. After that, the research framework, the simulation environment and the performance metrics are described in detail.

Chapter 4 – explains the proposed DBCR scheme and provides the mathematical analysis of the access success rate and the derivation of the optimal backoff parameter.

Chapter 5 – shows the design of the DTS algorithm which is proposed for delay-sensitive applications. After this, the mathematical analysis of the access delay and RACH throughput is presented.

Chapter 6 – explores the design and the evaluation of the PLPS scheme which is proposed for 5G heterogeneous services. The mathematical analysis along with the derivations of several performance metrics is also shown.

Chapter 7 – concludes the thesis and recommends some directions for future work.

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REFERENCES

[1] Qian Zhu, Ruicong Wang, Qi Chen, Yan Liu, and Weijun Qin. Iot gateway: Bridgingwireless sensor networks into internet of things. In *Embedded and Ubiquitous Computing (EUC), 2010 IEEE/IFIP 8th International Conference on*, pages 347–352. IEEE, 2010.

[2] Shanzhi Chen, Hui Xu, Dake Liu, Bo Hu, and Hucheng Wang. A vision of IoT: Applications, challenges, and opportunities with china perspective. *IEEE Internet of Things journal*, 1(4):349–359, 2014.

[3] Jayavardhana Gubbi, Rajkumar Buyya, Slaven Marusic, and Marimuthu Palaniswami. Internet of Things (IoT): A vision, architectural elements, and future directions. *Future generation computer systems*, 29(7):1645–1660, 2013.

[4] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on RAN Improvements for Machine-type Communications; (Release 11). *Technical Report*, TR 37.868(V11.0.0):1–28, 2011.

[5] Carles Anton-Haro and Mischa Dohler. *Machine-to-machine (M2M) communications: architecture, performance and applications*. Elsevier, 2014.

[6] Pawan Kumar Verma, Rajesh Verma, Arun Prakash, Ashish Agrawal, Kshirasagar Naik, Rajeev Tripathi, Maazen Alsabaan, Tarek Khalifa, Tamer Abdelkader, and Abdulhakim Abogharaf. Machine-to-Machine (M2M) communications: A survey. *Journal of Network and Computer Applications*, 66:83–105, 2016.

[7] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Core Network and Terminals; Mobile radio interface Layer 3 specification; Core network protocols; Stage 3 (Release 8). *Technical Specification*, TS 24.008(V8.12.0):1–593, 2010.

[8] 3GPP Jeanette Wannstrom. Lte-advanced. `http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced`, 2013.

[9] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Release 15 Description; Summary of Rel-15 Work Items (Release 15). *Technical Report*, TR 21.915(V15.0.0):1–118, 2019-09.

[10] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Service requirements for the 5G system; Stage 1 (Release 18). *Technical Specification*, TS 22.261(V18.4.0):1–107, 2021.

[11] Anum Ali, Ghalib A Shah, Muhammad Omer Farooq, and Usman Ghani. Technologies and challenges in developing machine-to-machine applications: A survey. *Journal of Network and Computer Applications*, 83:124–139, 2017.

© COPYRIGHT UPM

[12] Abdelmohsen Ali, Walaa Hamouda, and Murat Uysal. Next generation M2M cellular networks: challenges and practical considerations. *IEEE Communications Magazine*, 53(9):18–24, 2015.

[13] Monowar Hasan, Ekram Hossain, and Dusit Niyato. Random access for machine-to-machine communication in LTE-advanced networks: issues and approaches. *IEEE communications Magazine*, 51(6):86–93, 2013.

[14] Erfan Soltanmohammadi, Kamran Ghavami, and Mort Naraghi-Pour. A survey of traffic issues in machine-to-machine communications over LTE. *IEEE Internet of Things Journal*, 3(6):865–884, 2016.

[15] Andrés Ernesto Laya Romero, Luis Gonzaga Alonso Zárate, and Jesús Alonso-Zárate. Is the random access channel of LTE and LTE-A suitable for M2M communications? A survey of alternatives. *IEEE Communications Surveys & Tutorials*, 16(1):4–16, 2014.

[16] Raphael Rom and Moshe Sidi. *Multiple access protocols: performance and analysis*. Springer Science & Business Media, 2012.

[17] Mariyam Ouaissa, Mariam Benmoussa, Abdallah Rhattoy, Mohammed Lahmer, and Idriss Chana. Performance analysis of random access mechanisms for machine type communications in LTE networks. In *2016 International Conference on Advanced Communication Systems and Information Security (ACOSIS)*, pages 1–6. IEEE, 2016.

[18] ETSI 3GPP. 5G; NR; Medium Access Control (MAC) Protocol Specification (Release 15). *Technical Specification*, TS 38.321(V16.6.0):1–80, 2021.

[19] Ajinkya Rajandekar and Biplab Sikdar. A survey of MAC layer issues and protocols for machine-to-machine communications. *IEEE Internet of Things Journal*, 2(2):175–186, 2015.

[20] 3GPP. Merits of the slotted access methods for MTC, R2-112247 . `https://www.3gpp.org/ftp/tsg_ran/WG2_RL2/TSGR2_73bis/Docs`, 2011.

[21] Andrea Zanella, Michele Zorzi, André F dos Santos, Petar Popovski, Nuno Pratas, Cedomir Stefanovic, Armin Dekorsy, Carsten Bockelmann, Bryan Busropan, and Toon AHJ Norp. M2M massive wireless access: challenges, research issues, and ways forward. In *Globecom Workshops (GC Wkshps), 2013 IEEE*, pages 151–156. IEEE, 2013.

[22] Ming-Yuan Cheng, Guan-Yu Lin, Hung-Yu Wei, and Alex Chia-Chun Hsu. Overload control for machine-type-communications in LTE-advanced system. *IEEE Communications Magazine*, 50(6):38–45, 2012.

[23] Angel Sanchis-Cano, Luis Guijarro, Vicent Pla, and Jose R Vidal. Economic viability of HTC and MTC service provision on a common network infrastructure. In *Consumer Communications & Networking Conference (CCNC), 2017 14th IEEE Annual*, pages 1044–1050. IEEE, 2017.

[24] RONALD Rivest. Network control by Bayesian broadcast. *IEEE Transactions on Information Theory*, 33(3):323–328, 1987.

© COPYRIGHT UPM

[25] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Service accessibility (Release 14). *Technical Specification*, TS 22.011(V14.5.0):1–30, 2017.

[26] Hongliang He, Qinghe Du, Houbing Song, Wanyu Li, Yichen Wang, and Pinyi Ren. Traffic-aware ACB scheme for massive access in machine-to-machine networks. In *2015 IEEE international conference on communications (ICC)*, pages 617–622. IEEE, 2015.

[27] Shao-Yu Lien, Tzu-Huan Liau, Ching-Yueh Kao, and Kwang-Cheng Chen. Cooperative access class barring for machine-to-machine communications. *IEEE Transactions on Wireless Communications*, 11(1):27–32, 2012.

[28] Zehua Wang and Vincent WS Wong. Optimal access class barring for stationary machine type communication devices with timing advance information. *IEEE Transactions on Wireless communications*, 14(10):5374–5387, 2015.

[29] Ning Li, Chao Cao, and Cong Wang. Dynamic resource allocation and access class barring scheme for delay-sensitive devices in machine to machine (M2M) communications. *Sensors*, 17(6):1407, 2017.

[30] Jen-Po Cheng, Chia-han Lee, and Tzu-Ming Lin. Prioritized random access with dynamic access barring for RAN overload in 3GPP LTE-A networks. In *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, pages 368–372. IEEE, 2011.

[31] Zahra Alavikia and Abdorasoul Ghasemi. Overload control in the network domain of LTE/LTE-A based machine type communications. *Wireless Networks*, 24(1):1–16, 2018.

[32] Kuai Xu and Haojin Zhu. *Wireless Algorithms, Systems, and Applications: 10th International Conference, WASA 2015, Qufu, China, August 10-12, 2015, Proceedings*, volume 9204. Springer, 2015.

[33] Hu Jin, Waqas Tariq Toor, Bang Chul Jung, and Jun-Bae Seo. Recursive pseudo-bayesian access class barring for M2M communications in LTE systems. *IEEE Transactions on Vehicular Technology*, 66(9):8595–8599, 2017.

[34] Jianlong Liu, Lijun Song, et al. A Novel Congestion Reduction Scheme for Massive Machine-to-Machine Communication. *IEEE Access*, 5:18765–18777, 2017.

[35] Morteza Tavana, Vahid Shah-Mansouri, and Vincent WS Wong. Congestion control for bursty M2M traffic in LTE networks. In *2015 IEEE International Conference on Communications (ICC)*, pages 5815–5820. IEEE, 2015.

[36] Sami Gharbi and Nawel Zangar. Adaptive multiple access class barring factors for M2M communications in LTE-A networks. In *2015 12th Annual IEEE Consumer Communications and Networking Conference (CCNC)*, pages 605–606. IEEE, 2015.

© COPYRIGHT UPM

[37] Jihun Moon and Yujin Lim. Adaptive access class barring for machine-type communications in LTE-A. In *2016 Eighth International Conference on Ubiquitous and Future Networks (ICUFN)*, pages 398–402. IEEE, 2016.

[38] Suyang Duan, Vahid Shah-Mansouri, Zehua Wang, and Vincent WS Wong. D-ACB: Adaptive congestion control algorithm for bursty M2M traffic in LTE networks. *IEEE Transactions on Vehicular Technology*, 65(12):9847–9861, 2016.

[39] Luis Tello-Oquendo, José-Ramón Vidal, Vicent Pla, and Luis Guijarro. Dynamic access class barring parameter tuning in LTE-A networks with massive M2M traffic. In *2018 17th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net)*, pages 1–8. IEEE, 2018.

[40] Luis Tello-Oquendo, Diego Pacheco-Paramo, Vicent Pla, and Jorge Martinez-Bauset. Reinforcement learning-based ACB in LTE-A networks for handling massive M2M and H2H communications. In *2018 IEEE International Conference on Communications (ICC)*, pages 1–7. IEEE, 2018.

[41] Yujin Sim and Dong-Ho Cho. Performance Analysis of Priority-Based Access Class Barring Scheme for Massive MTC Random Access. *IEEE Systems Journal*, 14(4):5245–5252, 2020.

[42] Diego Pacheco-Paramo and Luis Tello-Oquendo. Delay-aware dynamic access control for mMTC in wireless networks using deep reinforcement learning. *Computer Networks*, 182:107493, 2020.

[43] Ali TURAN, Mehmet KOSEOGLU, and Ebru AKCAPINAR SEZER. Reinforcement Learning based Adaptive Access Class Barring for RAN Slicing. In *2021 IEEE International Conference on Communications Workshops (ICC Workshops)*, pages 1–6. IEEE, 2021.

[44] Mayukh Roy Chowdhury and Swades De. Delay-aware Priority Access Classification for Massive Machine-type Communication. *IEEE Transactions on Vehicular Technology*, Early Access:1–16, 2021.

[45] Israel Leyva-Mayorga, Luis Tello-Oquendo, Vicent Pla, Jorge Martinez-Bauset, and Vicente Casares-Giner. On the Accurate Performance Evaluation of the LTE-A Random Access Procedure and the Access Class Barring Scheme. *IEEE Transactions on Wireless Communications*, 16(12):7785–7799, 2017.

[46] Luis Tello-Oquendo, Israel Leyva-Mayorga, Vicent Pla, Jorge Martinez-Bauset, José-Ramón Vidal, Vicente Casares-Giner, and Luis Guijarro. Performance analysis and optimal access class barring parameter configuration in LTE-A networks with massive M2M traffic. *IEEE Transactions on Vehicular Technology*, 67(4):3505–3520, 2018.

[47] Vahid Shah-Mansouri, Seshadhri Srinivasan, and Valentina E Balas. Optimal Access Class Barring in Machine to Machine Systems with Random Activation Time. *Informatica*, 28(2):285–302, 2017.

© COPYRIGHT UPM

[48] Mikhail Vilgelm, Sebastian Schiessl, Hussein Al-Zubaidy, Wolfgang Kellerer, and James Gross. On the Reliability of LTE Random Access: Performance Bounds for Machine-to-Machine Burst Resolution Time. In *2018 IEEE International Conference on Communications (ICC)*, pages 1–7. IEEE, 2018.

[49] Wei Jiang, Xian Wang, and Tao Deng. Performance analysis of a pre-backoff based random access scheme for machine-type communications. In *2014 International Conference on Intelligent Green Building and Smart Grid (IGBSG)*, pages 1–4. IEEE, 2014.

[50] Ruki Harwahyu, Xian Wang, Riri Fitri Sari, and Ray-Guang Cheng. Analysis of group paging with pre-backoff. *EURASIP Journal on Wireless Communications and Networking*, 2015(1):1–9, 2015.

[51] Osama Arouk and Adlen Ksentini. Multi-channel slotted aloha optimization for machine-type-communication. In *Proceedings of the 17th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems*, pages 119–125. ACM, 2014.

[52] Kwang-Ryul Jung, Aesoon Park, and Sungwon Lee. Machine-type-communication (MTC) device grouping algorithm for congestion avoidance of MTC oriented LTE network. In *International Conference on Security-Enriched Urban Computing and Smart Grid*, pages 167–178. Springer, 2010.

[53] Shao-Yu Lien and Kwang-Cheng Chen. Massive access management for QoS guarantees in 3GPP machine-to-machine communications. *IEEE communications Letters*, 15(3):311–313, 2011.

[54] Yunyan Chang, Chan Zhou, and Oemer Bulakci. Coordinated random access management for network overload avoidance in cellular machine-to-machine communications. In *European Wireless 2014; 20th European Wireless Conference*, pages 1–6. VDE, 2014.

[55] Qinghe Du, Wanyu Li, Lingjia Liu, Pinyi Ren, Yichen Wang, and Li Sun. Dynamic RACH partition for massive access of differentiated M2M services. *Sensors*, 16(4):455, 2016.

[56] Chia-Wei Chang, Jyh-Cheng Chen, Chien Chen, and Rong-Hong Jan. Scattering random-access intensity in LTE machine-to-machine (M2M) communications. In *2013 IEEE Global Communications Conference (GLOBECOM)*, pages 4729–4734. IEEE, 2013.

[57] Germán Corrales Madueno, Nuno K Pratas, Čedomir Stefanović, and Petar Popovski. Massive M2M access with reliability guarantees in LTE systems. In *2015 IEEE International Conference on Communications (ICC)*, pages 2997–3002. IEEE, 2015.

[58] Nuno K Pratas, Henning Thomsen, Čedomir Stefanović, and Petar Popovski. Code-expanded random access for machine-type communications. In *2012 IEEE Globecom Workshops*, pages 1681–1686. IEEE, 2012.

© COPYRIGHT UPM

[59] Bahereh Hassanpour and Abdorasoul Ghasemi. Online load estimation for efficient random access of machine type communications in LTE networks. In *2016 24th Iranian Conference on Electrical Engineering (ICEE)*, pages 732–737. IEEE, 2016.

[60] Mukesh Kumar Giluka, Aiswarya Prasannakumar, Nitish Rajoria, and Bheemarjuna Reddy Tamma. Adaptive RACH congestion management to support M2M communication in 4G LTE networks. In *2013 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, pages 1–6. IEEE, 2013.

[61] Md Shipon Ali, Ekram Hossain, and Dong In Kim. LTE/LTE-A random access for massive machine-type communications in smart cities. *IEEE Communications Magazine*, 55(1):76–83, 2017.

[62] 3GPP. Separate backoff scheme for MTC, 3GPP TSG-RAN2, R2-103776. `https://portal.etsi.org/webapp/meetingDocuments/ViewDocumentList.asp?MTG_Id=28034`, 2010.

[63] Leonard Kleinrock and Fouad Tobagi. Packet switching in radio channels: Part I–Carrier sense multiple-access modes and their throughput-delay characteristics. *IEEE transactions on Communications*, 23(12):1400–1416, 1975.

[64] Ali MH Abbas, Jahan Ali, Md Arafatur Rahman, and Saiful Azad. Comparative investigation on CSMA/CA-based MAC protocols for scalable networks. In *2016 international conference on computer and communication engineering (ICCCE)*, pages 428–433. IEEE, 2016.

[65] German Corrales Madueno, Čedomir Stefanović, and Petar Popovski. Efficient LTE access with collision resolution for massive M2M communications. In *2014 IEEE Globecom Workshops (GC Wkshps)*, pages 1433–1438. IEEE, 2014.

[66] John Capetanakis. Tree algorithms for packet broadcast channels. *IEEE transactions on information theory*, 25(5):505–515, 1979.

[67] James L Massey. Collision-resolution algorithms and random-access communications. In *Multi-user communication systems*, pages 73–137. Springer, 1981.

[68] Michael Paterakis and Panayota Papantoni-Kazakos. A simple window random access algorithm with advantageous properties. *IEEE Transactions on Information Theory*, 35(5):1124–1130, 1989.

[69] Benny Van Houdt and Chris Blondia. Robustness of Q-ary collision resolution algorithms in random access systems. *Performance Evaluation*, 57(3):357–377, 2004.

[70] Changbae Yoon. Distributed queuing with preamble grouping for massive IoT devices in LTE random access. In *2016 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 103–105. IEEE, 2016.

© COPYRIGHT UPM

[71] Anh-Tuan H Bui, Chuyen T Nguyen, Truong C Thang, and Anh T Pham. Design and Performance Analysis of a Novel Distributed Queue Access Protocol for Cellular-Based Massive M2M Communications. *IEEE Access*, 6:3008–3019, 2018.

[72] Jiantao Yuan, Hangguan Shan, Aiping Huang, Tony QS Quek, and Yu-Dong Yao. Massive Machine-to-Machine Communications in Cellular Network: Distributed Queueing Random Access Meets MIMO. *IEEE Access*, 5:2981–2993, 2017.

[73] Ray-Guang Cheng, Zdenek Becvar, and Ping-Hsun Yang. Modeling of Distributed Queueing-Based Random Access for Machine Type Communications in Mobile Networks. *IEEE Communications Letters*, 22(1):129–132, 2018.

[74] Jun Suk Kim, Sungkil Lee, and Min Young Chung. Efficient Random-Access Scheme for Massive Connectivity in 3GPP Low-Cost Machine-Type Communications. *IEEE Transactions on Vehicular Technology*, 66(7):6280–6290, 2017.

[75] Jelena Mišić, Vojislav B Mišić, and Nargis Khan. Sharing it my way: Efficient M2M access in LTE/LTE-A networks. *IEEE Transactions on Vehicular Technology*, 66(1):696–709, 2017.

[76] Guan-Yu Lin and Hung-Yu Wei. Auction-based random access load control for time-dependent machine-to-machine communications. *IEEE Internet of Things Journal*, 3(5):658–672, 2015.

[77] H Murat Gürsu, Mikhail Vilgelm, Wolfgang Kellerer, and Martin Reisslein. Hybrid collision avoidance-tree resolution for M2M random access. *IEEE Transactions on Aerospace and Electronic Systems*, 53(4):1974–1987, 2017.

[78] José-Ramón Vidal, Luis Tello-Oquendo, Vicent Pla, and Luis Guijarro. Performance Study and Enhancement of Access Barring for Massive Machine-Type Communications. *IEEE Access*, 7:63745–63759, 2019.

[79] Leonidas Georgiadis and Panayota Papantoni-Kazakos. A collision resolution protocol for random access channels with energy detectors. *IEEE Transactions on Communications*, 30(11):2413–2420, 1982.

[80] Andres Laya, Luis Alonso, Periklis Chatzimisios, and Jesus Alonso-Zarate. Massive access in the random access channel of LTE for M2M communications: An energy perspective. In *2015 IEEE International Conference on Communication Workshop (ICCW)*, pages 1452–1457. IEEE, 2015.

[81] Julian Popp, Joerg Robert, and Albert Heuberger. Energy consumption of low data rate M2M communications in LTE. In *Smart SysTech 2015; European Conference on Smart Objects, Systems and Technologies*, pages 1–5. VDE, 2015.

[82] A Pourmoghadas and PG Poonacha. Performance analysis of a machine-to-machine friendly MAC algorithm in LTE-advanced. In *2014 International conference on advances in computing, communications and informatics (ICACCI)*, pages 99–105. IEEE, 2014.

© COPYRIGHT UPM

[83] David Aragao, Dario Vieira, Miguel Franklin de Castro, and Yacine Ghamri-Doudane. A dynamic backoff approach to control the congestion in M2M communication over LTE networks. In *2015 Global Information Infrastructure and Networking Symposium (GIIS)*, pages 1–6. IEEE, 2015.

[84] Amin Azari. Energy-efficient scheduling and grouping for machine-type communications over cellular networks. *Ad Hoc Networks*, 43:16–29, 2016.

[85] Anum Ali, Ghalib A Shah, and Junaid Arshad. Energy efficient techniques for M2M communication: A survey. *Journal of Network and Computer Applications*, 68:42–55, 2016.

[86] Andres Laya, Luis Alonso, Periklis Chatzimisios, and Jesus Alonso-Zarate. Reliable machine-to-machine multicast services with multi-radio cooperative retransmissions. *Mobile networks and applications*, 20(6):734–744, 2015.

[87] Derya Malak, Harpreet S Dhillon, and Jeffrey G Andrews. Optimizing data aggregation for uplink machine-to-machine communication networks. *IEEE Transactions on Communications*, 64(3):1274–1290, 2016.

[88] Shin-Yeh Tsai, Sok-Ian Sou, and Meng-Hsun Tsai. Reducing energy consumption by data aggregation in M2M networks. *Wireless Personal Communications*, 74(4):1231–1244, 2014.

[89] Yi Liu, Zuyuan Yang, Rong Yu, Yong Xiang, and Shengli Xie. An efficient MAC protocol with adaptive energy harvesting for machine-to-machine networks. *IEEE Access*, 3:358–367, 2015.

[90] Sai Huang, Zhiqing Wei, Xin Yuan, Zhiyong Feng, and Ping Zhang. Performance characterization of machine-to-machine networks with energy harvesting and social-aware relays. *IEEE Access*, 5:13297–13307, 2017.

[91] Yuya Toyoda and Hiroyuki Yomo. Improving random access efficiency with uniformly deployed relays and interference cancellation for energy-constrained M2M devices. In *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 1132–1136. IEEE, 2015.

[92] Mei-Ju Shih, Guan-Yu Lin, and Hung-Yu Wei. Two paradigms in cellular Internet-of-Things access for energy-harvesting machine-to-machine devices: push-based versus pull-based. *IET Wireless Sensor Systems*, 6(4):121–129, 2016.

[93] Xin Jian, Yuqin Liu, Yixiao Wei, Xiaoping Zeng, and Xiaoheng Tan. Random access delay distribution of multichannel slotted ALOHA with its applications for machine type communications. *IEEE Internet of Things Journal*, 4(1):21–28, 2017.

[94] Suyang Duan, Vahid Shah-Mansouri, and Vincent WS Wong. Dynamic access class barring for M2M communications in LTE networks. In *2013 IEEE Global Communications Conference (GLOBECOM)*, pages 4747–4752. IEEE, 2013.

© COPYRIGHT UPM

[95] Wanyu Li, Qinghe Du, Lingjia Liu, Pinyi Ren, Yichen Wang, and Li Sun. Dynamic allocation of RACH resource for clustered M2M communications in LTE networks. In *2015 International Conference on Identification, Information, and Knowledge in the Internet of Things (IIKI)*, pages 140–145. IEEE, 2015.

[96] Nuno K Pratas, Cedomir Stefanovic, Germán Corrales Madueño, and Petar Popovski. Random access for machine-type communication based on Bloom filtering. In *2016 IEEE Global Communications Conference (GLOBECOM)*, pages 1–7. IEEE, 2016.

[97] Ningbo Zhang. An improved random access procedure for M2M communications. In *2016 IEEE Wireless Communications and Networking Conference*, pages 1–5. IEEE, 2016.

[98] Manal El Tanab and Walaa Hamouda. Machine-to-Machine Communications with Massive Access: Congestion Control. *IEEE Internet of Things Journal*, 6(2):3545–3557, 2018.

[99] Dimas Tribudi Wiriaatmadja and Kae Won Choi. Hybrid random access and data transmission protocol for machine-to-machine communications in cellular networks. *IEEE Transactions on Wireless Communications*, 14(1):33–46, 2015.

[100] Ahasanun Nessa, Michel Kadoch, and Bo Rong. Fountain coded cooperative communications for LTE-A connected heterogeneous M2M network. *IEEE Access*, 4:5280–5292, 2016.

[101] Yi-Huai Hsu, Kuochen Wang, and Yu-Chee Tseng. Efficient cooperative access class barring with load balancing and traffic adaptive radio resource management for M2M communications over LTE-A. *Computer Networks*, 73:268–281, 2014.

[102] Guan-Yu Lin, Shi-Rong Chang, and Hung-Yu Wei. Estimation and adaptation for bursty LTE random access. *IEEE Transactions on Vehicular Technology*, 65(4):2560–2577, 2016.

[103] Lawal Mohammed Bello, Paul Mitchell, David Grace, and Tautvydas Mickus. Q-learning Based Random Access with Collision free RACH Interactions for Cellular M2M. In *2015 9th International Conference on Next Generation Mobile Applications, Services and Technologies*, pages 78–83. IEEE, 2015.

[104] Nasir A Shinkafi, Lawal M Bello, Dahiru S Shu'aibu, and Paul D Mitchell. Priority-based learning automata in Q-learning random access scheme for cellular M2M communications. *ETRI Journal*, 43(5):787–798, 2021.

[105] Seungyeob Chae, Sangjin Cho, Sujin Kim, and Minjoong Rim. Coded random access with multiple coverage classes for massive machine type communication. In *2016 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 882–886. IEEE, 2016.

[106] Cedomir Stefanovic and Petar Popovski. ALOHA random access that operates as a rateless code. *IEEE Transactions on Communications*, 61(11):4653–4662, 2013.

© COPYRIGHT UPM

[107] Jinho Choi. On the adaptive determination of the number of preambles in RACH for MTC. *IEEE Communications Letters*, 20(7):1385–1388, 2016.

[108] Zahra Alavikia and Abdorasoul Ghasemi. Collision-Aware Resource Access Scheme for LTE-Based Machine-to-Machine Communications. *IEEE Transactions on Vehicular Technology*, 67(5):4683–4688, 2018.

[109] Wen Zhan and Lin Dai. Massive Random Access of Machine-to-Machine Communications in LTE Networks: Modelling and Throughput Optimization. *IEEE Transactions on Wireless Communications*, 17(4):2771–2785, 2018.

[110] Bo Yang, Guangxi Zhu, Weimin Wu, and Youjun Gao. M2M access performance in LTE-A system. *Transactions on Emerging Telecommunications Technologies*, 25(1):3–10, 2014.

[111] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC) (Release 16). *Technical Report*, TR 38.824(V16.0.0):1–78, 2019.

[112] Thilina N Weerasinghe, Vicente Casares-Giner, Indika AM Balapuwaduge, and Frank Y Li. Priority enabled grant-free access with dynamic slot allocation for heterogeneous mMTC traffic in 5G NR networks. *IEEE Transactions on Communications*, 69(5):3192–3206, 2021.

[113] Amin Azari, Petar Popovski, Guowang Miao, and Cedomir Stefanovic. Grant-free radio access for short-packet communications over 5G networks. In *GLOBECOM 2017-2017 IEEE Global Communications Conference*, pages 1–7. IEEE, 2017.

[114] Yan Liu, Yansha Deng, Maged Elkashlan, Arumugam Nallanathan, and George K Karagiannidis. Analyzing grant-free access for URLLC service. *IEEE Journal on Selected Areas in Communications*, 39(3):741–755, 2020.

[115] Jinho Choi and Jie Ding. Network Coding for K-Repetition in Grant-free Random Access. *IEEE Wireless Communications Letters*, 10(11):2557 – 2561, 2021.

[116] Nurul Huda Mahmood, Renato Abreu, Ronald Böhnke, Martin Schubert, Gilberto Berardinelli, and Thomas H Jacobsen. Uplink grant-free access solutions for URLLC services in 5G new radio. In *2019 16th International Symposium on Wireless Communication Systems (ISWCS)*, pages 607–612. IEEE, 2019.

[117] Muhammad Basit Shahab, Rana Abbas, Mahyar Shirvanimoghaddam, and Sarah J Johnson. Grant-free non-orthogonal multiple access for IoT: A survey. *IEEE Communications Surveys & Tutorials*, 22(3):1805–1838, 2020.

[118] Jinho Choi, Jie Ding, Ngoc-Phuc Le, and Zhiguo Ding. Grant-free random access in machine-type communication: Approaches and challenges. *IEEE Wireless Communications*, Early Access:1–8, 2021.

© COPYRIGHT UPM

[119] Ameha Tsegaye Abebe and Chung G Kang. MIMO-Based Reliable Grant-Free Massive Access With QoS Differentiation for 5G and Beyond. *IEEE Journal on Selected Areas in Communications*, 39(3):773–787, 2020.

[120] Huimei Han, Ying Li, Wenchao Zhai, and Liping Qian. A Grant-Free Random Access Scheme for M2M Communication in Massive MIMO Systems. *IEEE Internet of Things Journal*, 7(4):3602–3613, 2020.

[121] Qi Zhang, Shi Jin, and Hongbo Zhu. A Hybrid-Grant Random Access Scheme in Massive MIMO Systems for IoT. *IEEE Access*, 8:88487–88497, 2020.

[122] 3GPP. Revised work item description, 2-step RACH for NR, (Release 16), RP-190711. `https://portal.3gpp.org/ngppapp/CreateTDoc.aspx?mode=view&contributionUid=RP-190711`, 2019.

[123] Jun-Bae Seo, Waqas Tariq Toor, and Hu Jin. Analysis of Two-Step Random Access Procedure for Cellular Ultra-Reliable Low Latency Communications. *IEEE Access*, 9:5972–5985, 2021.

[124] Jinho Choi. Performance Analysis of 2-Step Random Access With CDMA in Machine-Type Communication. *IEEE Transactions on Communications*, 69(4):2387–2397, 2021.

[125] Junseok Kim, Goodsol Lee, Seongwon Kim, Tarik Taleb, Sunghyun Choi, and Saewoong Bahk. Two-step random access for 5G system: Latest trends and challenges. *IEEE Network*, 35(1):273–279, 2020.

[126] Mamta Agiwal, Mukesh Kumar Maheshwari, and Waqas Tariq Toor. Two Step Random Access Latency Improvement in Congested beyond 5G Networks. *Electronics*, 9(11):1974, 2020.

[127] Huimei Han, Jun Zhao, Wenchao Zhai, Zehui Xiong, and Weidang Lu. Smart City Enabled by 5G/6G Networks: An Intelligent Hybrid Random Access Scheme. *arXiv preprint arXiv:2101.06421*, 2021.

[128] Yu-Jia Chen, Li-Yu Cheng, and Li-Chun Wang. Prioritized resource reservation for reducing random access delay in 5G URLLC. In *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 1–5. IEEE, 2017.

[129] Mikhail Vilgelm, H Murat Guersu, Wolfgang Kellerer, and Martin Reisslein. LATMAPA: Load-adaptive throughput-maximizing preamble allocation for prioritization in 5G random access. *IEEE Access*, 5:1103–1116, 2017.

[130] Jayashree Thota and Adnan Aijaz. On performance evaluation of random access enhancements for 5G uRLLC. In *2019 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1–7. IEEE, 2019.

[131] Thilina N Weerasinghe, Indika AM Balapuwaduge, and Frank Y Li. Priority-based initial access for URLLC traffic in massive IoT networks: Schemes and performance analysis. *Computer Networks*, 178:107360, 2020.

© COPYRIGHT UPM

[132] 3GPP. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (Release 14). *Technical Specification*, TS 36.211(V14.2.0):10–86, 2017.

[133] Osama Arouk and Adlen Ksentini. General model for RACH procedure performance analysis. *IEEE Communications Letters*, 20(2):372–375, 2015.

[134] Osama Arouk, Adlen Ksentini, and Tarik Taleb. How accurate is the RACH procedure model in LTE and LTE-A? In *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*, pages 61–66. IEEE, 2016.

[135] Chia-Hung Wei, Ray-Guang Cheng, and Shiao-Li Tsao. Modelling and estimation of one-shot random access for finite-user multichannel slotted ALOHA systems. *IEEE Communications Letters*, 16(8):1196–1199, 2012.

[136] Vicente Casares Giner, Víctor Miguel Sempere Paya, and David Todoli Ferrandis. Framed ALOHA protocol with FIFO-blocking and LIFO-push out discipline. *Network Protocols and Algorithms*, 6(3):82–102, 2014.

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