Medium Access Control Techniques for Massive Machine-Type Communications in Cellular Networks

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Abstract. *A key component of the Internet of things (IoT) ecosystem is wide-area network connectivity, for which cellular network technologies are a promising option through their support of massive machine-type communication (mMTC). However, numerous devices transmitting sporadically small data packets in a highly synchronized way can generate overload on the radio access network, leading to a shortage of resources, especially those associated with the random access procedure, such as orthogonal preambles and control and data resources. This paper summarizes the main contributions of the first author's doctoral dissertation supervised by the second author. The dissertation proposes medium access control (MAC) techniques for addressing problems related to the support of mMTC in cellular networks. Results show that the proposals support quality of service (QoS), decrease access latency, decrease the device energy consumption, and increase the probability of successful channel access and resource utilization under massive random access.*

1. Introduction

The Internet of things (IoT) is one of the major technological trends transforming our society by improving quality of life, increasing industry productivity, and creating new business opportunities [Al-Fuqaha et al. 2015]. It involves numerous devices equipped with sensing, computing, and communication capabilities, such as sensors, actuators, machines, and vehicles [Cheng et al. 2012]. Several industry sectors benefit from the information exchange in the IoT, such as transportation, health care, manufacturing, agriculture, smart cities, smart grid, and smart home.

The Third Generation Partnership Project (3GPP) cellular network technologies are gaining momentum in the Low Power Wide Area (LPWA) IoT connectivity landscape [Laya et al. 2016] due to their capacity to overcome issues of the unlicensed such as interference, reliability, and availability, coverage, ubiquity, and management. However, conventional human-type communication (HTC)-oriented technologies have several limitations when dealing with machine-type communication (MTC) traffic [3GPP 2011]. The 3GPP has made many efforts to improve the support of IoT applications in cellular networks, which resulted in the specification of the cellular IoT (CIoT) technologies, including enhancements for MTC support in existing cellular technologies, *e.g.*, LTE-MTC (LTE-M) and Narrowband IoT (NB-IoT) [GSMA 2018].

The fifth generation (5G) networks cover three broad use case families: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC) and ultra-reliable and low-latency communications (URLLC). To meet their stringent requirements, the 5G standard encompasses both the evolution of the Long Term Evolution (LTE) technology (*e.g.*, the LTE enhancements for MTC such as LTE-M and NB-IoT) and the addition of a new radio access technology known as new radio (NR) [Series 2021]. Since NB-IoT and LTE-M fulfill the 5G network requirements for mMTC services, they both were recognized as IMT-2020 5G standards and will evolve as part of the 5G specifications in the 3GPP [GSMA 2018].

The IoT is exponentially increasing the number of devices connected to the Internet as never seen before. However, this huge number of expected MTC devices transmitting sporadically small packets in a highly synchronized way puts very high pressure on the aforementioned cellular network technologies for mMTC. This traffic pattern leads to shortage of radio resources, especially those associated with the random access protocol, which is typically used by the IoT devices to request resources for sporadic uplink packet transmissions.

2. Issues and Approaches for Supporting Massive Machine-type Communication in the 3GPP Random Access Protocol

The *shortage of random access resources* rises naturally with massive random access attempts since many devices enter the random access procedure simultaneously, a situation quite common in massive IoT (MIoT) scenarios. It is the root cause of various problems introduced in cellular networks due to the support of mMTC services, such as *preamble collision*, *blocking of control messages*, and *data collision*. These problems are briefly described next.

2.1. Preamble Collision

The *preamble collision* occurs when two or more devices choose the same preamble in a given random access (RA) subframe. Despite the name of this problem, a preamble under collision is typically successfully detected by the base station [Jin et al. 2017]. Thus, the base station physical (PHY) entity passes the list of detected preambles including non-collided and collided preambles to its medium access control (MAC) entity for subsequent resource allocation [Jin et al. 2017]. This is due to the physical characteristic of the preamble signals and their detection technique, typically based on energy peak searching in the physical random access channel (PRACH) power delay profile (PDP) [Bertrand and Jiang 2011]. Although this problem can occur even with HTC traffic, its impact is much more notorious with mMTC traffic due to the high probability of several devices simultaneously transmitting random access preambles.

Several improvements to the random access procedure for supporting mMTC have been proposed, including contention avoidance, contention resolution, and random access channel (RACH) resource augmentation. For the preamble collision problem, this work focuses on the latter category, which addresses the *problem of preamble collision* by increasing the random access contention resources. Particularly, we focus on increasing the random access resources in the code domain by using the multipreamble approach known as code-expanded random access (CeRA) scheme [Vural et al. 2017].

However, the code-expanded random access is challenging because the *code ambiguity problem* [Vural et al. 2017] limits its performance, avoiding releasing all the potential of the approach. This problem happens because the network infer more valid codewords than those actually transmitted in a superframe. It highly impacts on uplink resource utilization and even on the RA success probability under resource constraints. A codeword that was not actually transmitted by any device, but that is still inferred as valid by the base station after the decoding process, is called a *phantom* codeword. Thus, the *code ambiguity problem* is an open problem that needs to be addressed to fully exploit the true potentiality of the code-expanded random access scheme in 5G and beyond networks.

2.2. Blocking of Control Messages

Since the amount of network resources is limited, the *blocking of control messages* can also occur in the random access procedure. This problem happens because resources available to respond to the successfully detected preambles (MSG1) within a random access response window and to successfully decoded data transmissions (MSG3) before the expiration of the contention resolution timer may not be enough. In such a situation, blocking of control messages due to resource limitations may cause that some devices with a successfully detected preamble or successfully received data message do not receive the random access response (RAR) message and the contention resolution (CR) message to continue/finish the random access procedure. In both cases, the device has to perform a new RACH trial after a backoff time, further increasing the RACH load. The number of RAR (equivalently, uplink grants) and CR messages that a base station can deliver in time is limited and depends on the available downlink control resources as well as on uplink data resources. Moreover, the problem can be still worst in networks with coexistence of MTC devices and HTC users. In such a scenario, devices with different quality of service (QoS) requirements and scheduling mechanisms (*e.g.*, dynamic scheduling, semi-persistent scheduling, and random access) compete for the shared network resources.

There are just a few proposals for scheduling of control messages at the base station, particularly for the packet downlink control channel (PDCCH) [Astudillo 2022]. However, almost all of them are data-plane oriented since they only deal with control messages to signaling user data allocations, neglecting other control messages involved in the PDCCH scheduling process, such as those for controlling the random access procedure. Moreover, no PDCCH scheduler deals with QoS provisioning in the allocation of PDCCH resources.

Therefore, a PDCCH resource management model and scheduling algorithms involving the interaction of random access control messages as well as user-plane data transmission signaling are missing in the literature. Moreover, existing studies do not allow the proper evaluation of the impact of massive number of MTC devices on cellular network performance in the mMTC scenarios proposed by 3GPP in [3GPP 2011]. Moreover, even though the some random access schemes can provide differentiation among preamble groups in the *signature transmission* phase, current algorithms for scheduling of control messages do not consider the random access priority associated to individual random access-related control messages of the subsequent phases of the random access procedure.

2.3. Data Collision

Once the base station allocates radio resources to detected preambles by means of a RAR messages including an uplink grant, all devices involved in a *preamble collision* receive the same allocation. Consequently, their data transmissions (MSG3) collide with high probability, generating a *data collision*. A *data collision* also involves *collision of data retransmission*s because the hybrid automatic repeat request (HARQ) protocol is employed in the random access procedure for protecting the data transmission from channel impairments.

However, in the random access procedure, the MSG3 message transmission from several devices can collide when they receive the same uplink grant in the RAR message to transmit their MSG3 message (intra-cell interference). This happens because more than one device selected the same preamble in the initial phase of the random access procedure.

Considering that cellular radio access technologies apply power control to the packet uplink shared channel (PUSCH) transmissions, capture effect in the MSG3 reception is difficult to be achieved due to the small differences in the Signal to Interference Ratio (SIR) of the involved interfering signals [Kim and Lee 2017]. Even if the capture effect could be exploited, it allows the decoding of a maximum of one device transmission per RAR message. Thus, there is a need for a HARQ protocol which can achieve a high number of MSG3 decoding per RAR message issued to improve the overall random access procedure performance.

3. Objectives and contributions

The dissertation has proposed and evaluated medium access control solutions for the support of massive machine-type communication in 3GPP cellular networks by exploring the interplay between random access and resource allocation. Particularly, it addresses the *shortage of random access resources* and the problems derived from it. First, this dissertation introduces resource allocation mechanisms to deal with the effects of the *blocking of control messages* on network performance. Then, random access solutions to address the problems of *collision of data retransmission*s and *preamble collision*s are proposed.

In the following, the main contributions of this dissertation are described and contextualized into the research questions posed at the beginning of the study. These contributions are applicable all the way from legacy fourth generation (4G) LTE to 5G NR radio access technologies. The extension of the contributions of this dissertation through this large range of technologies is possible because the main problems to support massive machine-type communication rely on their random access procedure, which is common to all cellular IoT networks.

Research question 1: ***What is the actual impact of machine-type communication traffic on the performance of cellular radio access technologies?***

A thorough assessment of the impact of machine-type communication over cellular networks was presented in [Astudillo 2022, Chapters 2 and 3], answering this research question. Chapter 2 provides the first study in the literature assessing the performance of the traditional cellular networks in a coexisting MTC/HTC scenario and jointly including: (*i*) the contention-based random access procedure; (*ii*) the scheduling of data transmissions and control messages; and (*iii*) realistic assumptions on the random access procedure and its related resource constraints. Chapter 3 complements Chapter 2 by adding to the performance evaluation the non-contention based random access procedure and the RACH resource separation scheme, as well as their related implications on access differentiation and QoS provisioning.

Chapter 2 evinced that the random access procedure plays an important role in cellular networks with support to machine-type communication, and the random access delays strongly impact on the QoS provisioning in mMTC scenarios, particularly for delay-sensitive users and applications. Chapter 3 evinced that random access schemes aiming at providing prioritization and QoS differentiation need to be complemented with proper resource allocation strategies to achieve their goals.

These two chapters showed the importance of considering all the aforementioned aspects on the assessment of MTC-oriented cellular networks, given that the *shortage of random access resources* is likely to occur in these networks due to massive number of devices accessing the network simultaneously.

To properly assessing the performance of IoT over cellular networks and achieving the aforementioned features, a simulator was incrementally developed in a series of publications, as related in Table 1.

Research question 2: ***How can a mobile network operator provide prioritization and quality of service in the 3GPP random access procedure with a massive number of MTC devices?***

This question was also answered in [Astudillo 2022, Chapters 2 and 3] by proposing and evaluating resource allocation mechanisms to deal with the *shortage of random access resources* and the *blocking of control messages*. To address this question, Chapter 2 proposes first a PDCCH resource management model that includes the random access control messages into the whole resource allocation process at the base station. Then, Chapters 2 and 3 employ this model to propose novel control scheduling policies to provide the network with the means to prioritize control messages for both random access and conventional user data transmissions. Control scheduling policies for random access prioritization and QoS provisioning were proposed.

On the one hand, Chapter 2 showed that prioritization of random access messages helps to improve the performance of MTC oriented networks, while the QoS-aware policies are able to improve the QoS provisioning in coexisting scenario. To achieve these, the control scheduling policies needs to be coupled with proper packet scheduling strategies depending on the mobile network operator (MNO) goals and business objectives. On the other hand, Chapter 3 showed that prioritization inside the random access control messages is also required for supporting differentiated random access under high RACH loads and radio resource constraints.

The proposals in those two chapters have proved to be fundamental in the analysis and support of MTC in current cellular networks, as recognized by the high number of citation received by the publications related to this contribution set. They provide the mobile network operator with the tools to support prioritization and random access differentiation in MTC scenarios.

Research question 3: ***How can one increase the efficiency of the data transmission phase of the 3GPP random access procedure?***

This question was answered in [Astudillo 2022, Chapter 4] by proposing a probabilistic retransmission scheme, especially designed for cellular IoT network technologies. To increase the efficiency of the data transmission phase of the random access procedure, the proposed scheme addresses the *problem of collision of data retransmission* by exploiting probability theory in the hybrid automatic repeat request mechanism. It includes a probabilistic retransmission protocol, a novel method to estimate the number of concurrent devices in a random access opportunity (RAO) at the device, and two retransmission policies based on this estimation.

Results in Chapter 4 showed that the proposed scheme effectively reduces the number of MSG3 collisions. Moreover, it saves energy, reduces the access delay, and yet reduces the PUSCH channel utilization when compared to the traditional random access scheme. Thus, the proposed protocol showed to be effective in its goal of increasing the efficiency of the data transmission phase. This protocol represents the first step in the literature to address the *problem of collision of data retransmission* employing currently available technologies.

Moreover, since it is based on the standardized random access procedure, random access schemes and control signaling to operate, the implementation of the protocol in commercial cellular networks is facilitated.

Research question 4: *How can one increase the network capacity for massive machine-type communication in current cellular network technologies*

This question was answered in Chapter 5 by proposing the OptCeRA scheme to alleviate the *shortage of random access resources*, which is the root cause of various other problems presented in the random access procedure for massive machine-type communications. OptCeRA focuses on decreasing the collision probability by introducing a game changing approach of using the available random access contention resources in existing radio access technologies. To do so, the optimal code-expanded random access (OptCeRA) scheme introduces a disruptive way of performing random access based on maximum average distance codes, which were proposed for the first time in this dissertation to deal with the *code ambiguity problem* in code-expanded random access schemes. This dissertation formulates the maximum average distance (MAD) code problem, characterizes these codes, derives an encoding procedure, and proposes efficient decoding algorithms. Moreover, a PHY/MAC cross-layer technique to remove *phantom* codewords from the set of valid codewords based on PHY-layer information was also proposed. In addition, this dissertation derives probabilistic analytical modela for the schemes. By taking advantage of the proposed models, an algorithm to maximize the random access success probability by adjusting the scheme parameters to the network load is introduced.

Results showed that the OptCeRA schemes effectively alleviates the *code ambiguity problem*, which was an *open problem for roughly a decade*. The proposed MAD code allows the base station to infer less valid codewords in a given superframe, greatly increasing the random access success probability as well as the efficiency in resource utilization. This scheme allows mobile network operators to increase the RACH capacity and the number of users supported simultaneously for MIoT scenarios with existing technologies.

The complete list of publication achieved with the research of the dissertation is described and related to the aforementioned contributions in Table 1.

4. Publications, Awards, and Grants

The research conducted in this dissertation has generated 16 publications (Table 1). The publications related to this dissertation's research topics are listed as follows. Four journal articles and eight conference papers have already been published, whereas three journal articles and a patent are under submission on topics covered by the content of this dissertation.

Beside the publications related to the main contributions of this dissertation, ten papers and two technical reports in diverse topics other than those directly related to this dissertation were written as a PhD student, which are listed in [Astudillo 2022, Section 1.9.2]. Those publications were the result of student mentoring, participation in research projects, and research collaborations during the doctorate period, being an essential component of the PhD training.

The dissertation received the second-place prize at the Latin American PhD Thesis Contest (CLTD) of the Latin American Informatics Conference (CLEI 2022) awarded by the Latin American Center for Informatics Studies (CLEI)[1].

[1]https://clei2022.uniquindio.edu.co/clei2022/publicaciones/1799/ganadores-concurso/

Table 1. List of publications with quality indicators, including venue, Qualis classification, impact factor, H5, and number of citations in Google Scholar (GS)

Cat.	Contri.	Title	Venue	Quality Indicators: *Qualis*	*IF (Percentil)*	*H5*	*Citations GS* total	*Citations GS* per year
Journal	4	Random access based on maximum average distance code for massive MTC in cellular IoT networks	IEEE WCL	A1	5.28 (89.63%)	76	1	0.7
	1, 2	The Random Access Procedure in Long Term Evolution Networks for the Internet of Things	IEEE CM	A1	9.03 (99%)	130	61	10.3
	1, 2	Allocation of control resources for machine-to-machine and human-to-human communications over LTE/LTE-A networks	IEEE IoTJ	A1	10.24 (98%)	144	58	8.7
	1	Transmission and reception alignment for user equipment energy efficiency in LTE networks	IEEE LNET	B2		15	1	0.31
Conference	3	Probabilistic retransmissions for the random access procedure in cellular IoT networks	IEEE ICC	A1		75	6	1.67
	1	PRACH power control mechanism for improving random-access energy efficiency in long term evolution	IEEE Latincom	B1		11	9	2.2
	1	Energy-efficient fragmentation-avoidance uplink packet scheduler for SC-FDMA-Based systems	IEEE ISCC	A2		26	2	0.47
	1, 2	Impact of preamble-priority-aware downlink control signaling scheduling on LTE/LTE-A network performance	IEEE VTC	A1		42	6	1.2
	1, 2	Allocation of control resources with preamble priority awareness for human and machine type communications in LTE-Advanced networks	IEEE ICC	A1		75	12	2.18
	1, 2	Impact of M2M traffic on human-type communication users on the LTE uplink channel	IEEE Latincom	B1		11	16	1.2
	1	Random access mechanism for RAN overload control in LTE/LTE-A networks	IEEE ICC	A1		75	19	2.56
	1	The impact of massive machine type communication devices on the access probability of human-to-human users in LTE networks	IEEE Latincom	B1		11	15	1.88
Unpublished	4	Code-expanded random access for massive Internet of things in cellular networks: A cross-layer approach						
	4	Scalable random access for massive IoT in cellular networks						
	2, 3	Medium access control techniques for massive machine-type communications in cellular IoT networks.	CLEIJ					
	4	Methods and apparatus for code-expanded random access						
		Total Number of Citations & Number of Citations per Year					206	33.37

This research received a grant from the Emerging Leaders in the American Program (ELAP) of the Canadian Government to conduct part of the project at the University of Manitoba, Canada. In addition, two student travel grant awards were received for attending the IEEE International Conference on Communications (ICC) in 2017[2] and 2019[3].

5. Conclusion

This article summarized the contributions of the dissertation entitled *"Medium Access Control Technique for Massive Machine-Type Communications in Cellular Networks"* [Astudillo 2022]. It proposes and evaluates medium access control solutions for the support of massive machine-type communication in 3GPP cellular networks by exploring the inter playing between random access and resource allocation. Particularly, the *shortage*

[2]https://icc2017.ieee-icc.org/authors/student-travel-grants.html

[3]https://icc2019.ieee-icc.org/program/student-travel-grants.html

of random access resources and the problems derived from it were addressed. First, this dissertation introduces resource allocation mechanisms to deal with the effects of the *blocking of control messages* on network performance. Then, random access solutions to address the problems of *collision of data retransmission*s and *preamble collision*s are proposed. In the way, a solution for the *code ambiguity problem* [Vural et al. 2017] was proposed, which was an open problem for several years in the area. In addition, this novel solution was achieved thanks to a new class of codes, also proposed in the dissertation, the MAD codes. These codes are likely to find innovative applications in diverse fields, such as telecommunications, machine learning, and biology. The solutions proposed showed their efficiency in addressing the posed problems. The publications generated by the work of the dissertation have received around 200 citations from articles indexed in Google Scholar as of February 2023, evincing their relevance to the field.

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