NON-ORTHOGONAL SCHEMES AND DIVERSITY TECHNIQUES FOR MASSIVE MACHINE-TYPE COMMUNICATIONS

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**Abstract**

This thesis performs a global overview of machine-type communications (MTC), which refer to automated data between devices, enabling a broad range of applications from mission-critical services to massive deployment of devices. The main MTC requirements and challenges toward 5G systems are also analysed, and several existing techniques to satisfy them are also studied. Different non-orthogonal multiple access (NOMA) technologies, able to accommodate a massive number of devices, are studied. In addition, a feedback-free network-assisted domain multiple access (FF-NDMA) system is analytically modelled and evaluated through simulation. This scheme is able to provide satisfactory performance in terms of throughput, delay and energy consumption, as well as a significant reduction of number of collisions with respect to previous protocols. Hence, FF-NDMA is a potential candidate to support MTC applications.
To my family, friends and loved ones.
Acknowledgements

I would like to thank my tutor Josep Vidal and my co-tutors Sandra Lagén and Adrián Agustín for their supervision, constant dedication and huge patience, without whom the completion of this thesis would not have been possible. I also wish them the very best of luck with the submission of the conference paper written after the derived results from this thesis.
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Glossary

3GPP: Third Generation Partnership Project
5G: 5th Generation
ACB: Access Class Barring
ADR: Adaptive Data Rate
BER: Bit-Error Ratio
BPSK: Binary Phase Shift Keying
BS: Base Station
CDMA: Code Division Multiple Access
CN: Core Network
CP: Contention Period
C-RNTI: Cell Radio Network Temporary Identity
CSS: Chirp Spread Spectrum
D2D: Device-To-Device
DSSS: Direct Sequence Spread Spectrum
EC-GSM: Extended-Coverage GSM
eDRX: Enhanced Discontinuous Reception
EPC: Evolved Packet Core
FDD: Frequency Division Duplex
FDMA: Frequency Division Multiple Access
FF-NDMA: Feedback-Free Network-assisted Diversity Multiple Access
FSA: Frame Slotted ALOHA
GSM: Global System for Mobile communications
H2H: Human-to-Human
IEEE: Institute of Electrical and Electronics Engineers
IoT: Internet of Things
ISM: Industrial Scientific Medical
KPI: Key Performance Indicators
LBT: Listen-Before-Talk
LDS: Low-Density Spreading
LoRa: Long Range Radio
LPWA: Low Power Wide Area
LPWAN: LPWA Network
LTE: Long Term Evolution
LTE-A: LTE-Advanced
LTE-M: LTE for MTC
M2M: Machine-To-Machine
MIMO: Multiple-Input Multiple-Output
MPA: Message-Passing Algorithm
MPR: MultiPacket Reception
MTC: Machine-Type Communications
MTC-A: Aggregation-point MTC
MTC-D: Direct-access MTC
MTC-M: Direct MTC
MUD: Multi-User Detection
MUSA: Multi-User Shared Access
NB: Narrow-Band
NB-IoT: Narrow-Band IoT
NB-LTE-M: Narrow-Band LTE for MTC
NDMA: Network-assisted Diversity Multiple Access
NFV: Network Function Virtualization
NOMA: Non-Orthogonal Multiple Access
OFDM: Orthogonal Frequency Division Multiplexing
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<th>Full Form</th>
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<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiplexing Access</td>
</tr>
<tr>
<td>OMA</td>
<td>Orthogonal Multiple Access</td>
</tr>
<tr>
<td>OSTBC</td>
<td>Orthogonal Space-Time Block Coding</td>
</tr>
<tr>
<td>PER</td>
<td>Packet Error Ratio</td>
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<tr>
<td>PSM</td>
<td>Power Saving Mode</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<td>QPSK</td>
<td>Quadrature Phase-Shift Keying</td>
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<td>Random Access Channel</td>
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<td>Random Access Network</td>
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<td>RF</td>
<td>Radio-Frequency</td>
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<td>R-FTDMA</td>
<td>Random Frequency-Time Division Multiplex</td>
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<td>RRC</td>
<td>Radio Resource Control</td>
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<td>SCMA</td>
<td>Sparse Code Multiple Access</td>
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<tr>
<td>SIC</td>
<td>Successive Interference Cancellation</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference Power Ratio</td>
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<tr>
<td>SISO</td>
<td>Single-Input Single-Output</td>
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<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
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<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UNB</td>
<td>Ultra Narrow Band</td>
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1. **Introduction**

The fifth generation of cellular networks (5G), set for availability around 2020, is expected to enable a fully mobile and connected society, characterised by a massive growth in connectivity and an increased density and volume of data traffic. Hence, a broad range of use cases and requirements arises, such as high scalability, rapid programmability, high levels of capacity, security, reliability, availability, low latencies and low impact on battery life [1].

All these requirements pave the way for machine-type communications (MTC), sometimes referred to as the ‘Internet of Things’ (IoT). Unlike human-to-human (H2H) communications, MTC devices will be able to communicate among them without being controlled and managed by people. MTC must be able to address different use cases that range from massive MTC, where the number of deployed devices is very high, to mission-critical MTC, where the real-time and high-reliability communication needs have to be satisfied.

Several alternatives have been studied to address these requirements. In this sense, a promising technology is the non-orthogonal multiple access (NOMA), which can accommodate much more users than orthogonal-based techniques via non-orthogonal resource allocation and in addition can notably enhance system throughput.

This thesis also studies the feedback-free Network-assisted Diversity Multiple Access (FF-NDMA) scheme for multiple-input multiple-output (MIMO) configurations. The FF-NDMA scheme consists on a signal-processing solution for resolving collisions over the random access channel of cellular systems by means of using the diversity gain attained thanks to the retransmission of packets, which can significantly improve the performance in terms of throughput, mean access delay and energy with respect to ALOHA-type random access schemes.

1.1. **Structure of the thesis**

This document starts with an introduction of MTC technologies and their perspective toward 5G systems in section 2. In the subsequent subsections, the different use cases and requirements are introduced (section 2.2); as well as a state of the art where the most representative technologies intended for MTC are described (section 2.3), making a distinction between proprietary Low Power Wide Area (LPWA) technologies and Third Generation Partnership Projects (3GPP) cellular systems. A brief state of the art of the non-orthogonal multiple access (NOMA) landscape is also performed, analysing both power domain and code domain multiplexing schemes (section 2.4).

Section 3 introduces the feedback-free Network-assisted Diversity Multiple Access (FF-NDMA) scheme. Section 3.1 describes the system model, including the basic operation of the system and the analysed scenarios. Section 3.2 introduces the multipacket reception (MPR) model that allows characterising the FF-NDMA scheme. Based on the MPR model, the expressions for the metrics of interest are derived (i.e. throughput, mean access delay and consumed energy). Sections 3.3 and 3.4 analyse the system stability, and backoff techniques (strategies that control the retransmission probabilities of wrongly-received packets such that the system performance is optimised), respectively.
In section 4, the simulation results of the FF-NDMA scheme are presented. Subsection 4.1 introduces the system parameters and simulation conditions. In subsection 4.2, the FF-NDMA is evaluated in a symmetric scenario: both for multi-antenna systems, with several antennas at the base station and with one-slot contention periods; and for a FF-NDMA multiple-input multiple-output (MIMO) approach (with different contention period lengths for a single-input single-output (SISO) scheme and for a 2x2 MIMO scheme). The metrics obtained with the FF-NDMA model are evaluated both as a function of the offered load and as a function of the signal-to-noise (SNR). The rest of the subsection analyses the scheme under the perspective of stability and of the backoff techniques. Then, subsection 4.3 studies the performance of FF-NDMA systems in asymmetric conditions (in non-sectorised and sectorised-based scenarios).

Finally, section 5 summarises the obtained conclusions from the results and how these can be exploited for MTC systems. Possible future work that could be carried out is also suggested.

1.2. Methods and procedures

This thesis continues the work initiated by UPC researchers Josep Vidal and Maribel Madueño on the FF-NDMA scheme. Their jointly-written papers, “Joint physical-MAC layer design of the broadcast protocol in ad-hoc networks” and “PHY-MAC performance of a MIMO network-assisted multiple access scheme” have served as a starting point for evaluating further capabilities of the FF-NDMA scheme. In this sense, the mathematical expressions derived on these papers were fundamental to model a parametrised FF-NDMA system in the MATLAB environment.

1.3. Work plan

In Table 1: Work plan of the thesis with Work Packages and their corresponding tasks and outputs the structure of the work plan is detailed in work packages (WP) and their subsequent tasks. Outputs are also summarised for different groups of tasks:
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*Table 1: Work plan of the thesis with Work Packages and their corresponding tasks and outputs*
Figure 1 shows the work plan in the form of a Gantt diagram, which gives a more visual representation of the development of the different tasks.

Figure 1: Gantt diagram of the thesis
1.4. Deviations from the initial plan

The initial plan on the thesis intended to perform a more detailed analysis on Random Access schemes (both contention-based and contention-free), developing several algorithms that could deal mainly with the problems of pilot signals collision. A deeper analysis of the MPR capabilities of several NOMA schemes was also planned. The outputs from both tasks would be used to build a system level simulation that would compare the performance of contention-based and contention-free schemes. However, the work was finally focused on the analysis of a single scheme (FF-NDMA), which could yield very good performances in terms of throughput, delay and energy by using specific MIMO configurations for different scenarios. The study of the aforementioned metrics was expanded by analysing system stability and different backoff strategies.

1.5. Contributions

By wisely combining an adequate MIMO configuration and the studied FF-NDMA scheme, the number of collisions can be potentially reduced with respect to ALOHA-type random access protocols. The feedback-free nature of the FF-NDMA dramatically improves the overhead present in other systems. In addition, very good performances in throughput, delay and energy can be reached. Hence, FF-NDMA satisfies many important requirements for MTC technologies and proves to be a highly potential solution for IoT systems.

1.6. Output and publications

The results derived from this thesis have allowed the submission of a conference paper, whose details are:

2. **State of the art of MTC technologies**

2.1. **Introduction**

Machine-type communications (MTC) or machine-to-machine communications (M2M) consist on automated data communications among electronic devices and the underlying data transport infrastructure. MTC devices might communicate with a server or with other MTC devices. The fields where MTC technology is used encompass both personal and professional spaces, including healthcare, smart power grids, industry automation, smart cities, etc. The utility of the mentioned applications has led to a scenario where the popularity of services based on MTC keeps on increasing, due in part to the continued fall in the prices of devices capable of actuating and sensing. That will fuel an increasing growth of the number of devices in the near future (about a 25% interannual growth rate according to [2] reaching 30 billion MTC connected devices by 2025 [3]).

Communication among MTC devices can be achieved through point-to-point and multi-hop wireless networks, which include ad hoc, sensor and mesh networks. These technologies enable the implementation of the Internet of Things (IoT). Mobile network operators see in the IoT applications a huge market potential; which pushes developing technologies such as IEEE 802.11ah, supporting low-power transmissions with extended coverage range in Wi-Fi networks [4].

The main drawbacks of these schemes are the lack of efficient backhaul, which limits network coverage and scalability; and the lack of reliability, due to their operation over unlicensed frequency bands. Cellular systems, such as Long Term Evolution (LTE), successfully bridge this gap by reducing costs and enhancing coverage due to their ubiquitous presence, as well as operating over regulated and interference-controlled links, which ensures a more reliable communication.

However, a service optimised for MTC is expected to be significantly different from that for H2H communications. H2H applications experience a higher traffic demand on the downlink, whereas MTC communications are characterised by a big amount of devices requiring a high volume of uplink traffic as a whole, but little traffic per device. This is true for smart metering applications, for which LTE systems should also implement effective techniques for overload control, mechanisms to lower power consumption and support efficient transmission with low-overhead packets [5]. These features should be supported in most MTC devices, along with limited computational and power resources. The Third Generation Partnership Project (3GPP) has specified the main requirements for MTC communication and identified remaining challenges and issues. Several standardization measures have been tackled to support MTC for future releases of LTE networks, known as LTE-Advanced (LTE-A) [4].

More recently, with a broader perspective toward the future, some methods, use cases and requirements for 5G systems have also been studied. 5G will consist on a radio access technology that must address high traffic growth and increasing demand for high-bandwidth connectivity beyond 2020. It will also support massive number of connected devices and meet the real-time, high-reliability requirements of mission critical applications. From a general point of view, the main objective of 5G is to provide ubiquitous connectivity for any connected device.

5G defines a new flexible air interface known as NX directed to extreme mobile broadband deployments. It will target scenarios requiring high traffic and bandwidth, as
well as supporting mission-critical and real-time communications with good latency and reliability terms. In addition, the development of Narrow-Band IoT (NB-IoT) in 3GPP is expected to support massive connectivity in wide area applications. This technology will most likely be deployed in frequencies below 2GHz, providing high capacity and coverage for a massive number of devices [6].

In order to achieve a gradual transition from LTE systems toward 5G technologies, 5G networks will incorporate LTE access (based on Orthogonal Frequency Division Multiplexing (OFDM)), as well as new other interfaces in a transparent fashion toward both the service layer and the users. It is important that by 2020, most operators with 4G networks transition all or part of their spectrum to newer wireless access technologies. On the other side, it is essential for LTE to evolve to a point where it is a member of the 5G family of air interfaces, in such a way that dual connectivity between LTE (operating within bands below 6 GHz) and the NX air interface (in bands from 6 to 100 GHz) is possible [6].

2.2. Use cases and requirements

MTC will constitute an important share of the amount of total devices in the near future. Since the number of MTC connected devices is expected to surpass by tenfold the H2H devices [7], 5G must be tailored according to the use cases and needs of MTC. MTC applications can be divided in two main categories: massive MTC and mission-critical MTC. Massive MTC aims at achieving connectivity for a high amount of low-cost and low-energy devices intended for the IoT, whereas mission-critical MTC pursues real-time control and automation of dynamic processes in diverse fields. These categories are described in more detail in the following subsections.

2.2.1. Massive MTC

This category of MTC is characterised by a massive deployment of MTC devices. Their requirements are low cost (small and simple devices), low energy consumption (10 years of battery life), capability of handling small bursts of data, high coverage spanning challenging locations (intended coverage of 99.9%), low protocol overhead (small data volume), and high scalability (supporting 10-100 times more devices [8]).

Massive MTC use cases include the following applications [9]:

- Utilities such as sensors and smart meters in the smart grid (i.e. distributed weather sensors).
- Smart buildings: home automation, alarm systems or smoke detectors.
- Smart cities: parking sensors, smart lightning or waste management.
- Healthcare: assisted living (blood pressure information, pulse…).
- Agriculture: sensors and actuators intended for irrigation, fertilization…
- Environment: flood monitoring alerts or environmental monitoring.
- Transport and management: fleet management or goods tracking.
- Industrial utilities: process monitoring and control, maintenance monitoring…

Depending on the specific application, requirements might vary: for instance, temperature status indicators only send a few messages per day, and industrial remote guidance may
need to transmit a video stream, so the difference in throughput requirements is huge. Other potential requirements for some of the use cases are two-way communication capability (to increase robustness in applications such as monitoring and control of devices), positioning (essential for tracking systems) and security (needed in building security applications where sensitive information could be eavesdropped) [9].

Three different radio access schemes are envisioned for massive MTC: direct access (MTC-D) to the access network; with accumulation/aggregation point (MTC-A), which accumulates the traffic locally and sends it to the access point; and direct MTC communication (MTC-M) between peer devices using D2D communication [10]. The main performance requirements are not low delays, but providing efficient access and optimised scheduling for this kind of devices.

Figure 2: Massive MTC and its three types: (a) direct network access (MTC-D), (b) access via an aggregation node (MTC-A) and (c) short-range D2D access for massive MTC devices (MTC-M) (extracted from [10]).

2.2.2. Mission-critical MTC

On the other hand, mission-critical MTC systems have to satisfy more demanding Quality of Service (QoS) requirements in terms of latency, scalability and reliability with respect to traditional cellular services. This translates into end-to-end delays around 1-10 ms (time delay between data being generated and being received), high reliability of successful transmission (around 99.999%), high availability of connectivity, and support for local communication solutions.

Service functions in this category include [9]:

- Smart grid distribution automation.
- Industrial application and control.
- Autonomous driving and traffic safety.
- Remote control of machines: with potential applications in fields like healthcare (remote surgery), remote manufacturing and training with operation in hazardous environments.

Whereas standardization work on massive MTC is being currently tackled, both in 3GPP and IEEE; mission-critical MTC is still in early development, with a lot of challenges to perform research [11]. Since current wireless communication systems such as 2G, 3G or 4G cannot satisfy the requirements of the aforementioned services; research for 5G MTC communication systems is mainly focused on latency and reliability. Use cases such as
automotive or smart grid systems require a maximum allowable end-to-end latency (including jitter) of 5 ms; as well as a high level of reliability, with packet loss rates below $10^{-9}$ or a 99.999% availability, especially important in remote control applications.

2.3. MTC in communication systems

Since the IoT is only expected to increase during the near future, the list of communication protocols that are necessary becomes higher and higher. Special attention must be given to the estimated growth of the number of connections; although most of them will consist of fixed and short-range communication, around 7 billion cellular and LPWA (Low Power Wide Area) -based connections are expected by 2025 [12].

Inside LPWA, two main categories can be differentiated. On one side we have 3GPP standardised cellular technologies (Cellular IoT) which operate in licensed spectrum; on the other, the proprietary LPWA technologies, such as LoRa and Sigfox, which operate over unlicensed frequency bands. Along this section, we will review both categories (including the available channel access methods for each system), which will allow us to draw conclusions between the different technologies.

2.3.1. Licensed-spectrum technologies

Starting the analysis with the licensed Cellular IoT technologies, different solutions are being standardised in 3GPP: EC (Extended Coverage)-GSM (Global System for Mobile communications), NB (Narrow Band)-IoT and LTE-M. In Release 13 a new option named NB LTE-M is introduced, whose 200-kHz frequency band is refarmed from GSM. In the following subsections we will review the LTE-M and NB LTE-M technologies, as well as the NB-IoT alternative.

2.3.1.1. LTE-M

LTE-M and NB LTE-M are two supplementary solutions addressing different use cases, offering higher capacity in the case of LTE-M, and higher coverage and lower cost on NB LTE-M. In addition, LTE can operate with FDD (Frequency Division Duplex) and with TDD (Time Division Duplex) using a short subframe structure of 1 ms, which allows minimizing delays.

One of the main particularities of LTE-M is that it aims at reducing the complexity of LTE caused by the focus on high performance, introducing new KPIs (Key Performance Indicators). Such complexity reductions provide significant cost reductions. In Table 2 we can see the evolution in complexity for LTE-based systems:
In 3GPP Release 12, a new device category (Cat-0) was introduced. These devices allow half duplex FDD operation, which eliminates the need of using filters. In addition, using less antennas and lowering the data rate requirements reduce complexity and cost in both power and memory. Release 13 supports lower bandwidths (1.4 MHz), which allows using simpler narrowband RF designs. This same release specifies as well the bandwidth for NB LTE-M (200 kHz) in both uplink and downlink.

As it was mentioned before, LTE-M and NB LTE-M are compatible with the legacy LTE network, which allows reusing the same infrastructure and sharing spectrum without coexistence issues. Thus, deploying LTE-M is as simple as a software upgrade to the radio interface to enable a full IoT network; besides, LTE-M can achieve better coverage than the LTE network.

This coverage enhancement can be obtained using techniques such as power boosting of data and reference signals, new coding and retransmissions or repetitions and relaxed performance requirements. In Release 13, some downlink LTE control channels are eliminated, which can increase coverage to reach a higher number of devices. Using lower bandwidths produces a boost in coverage, yielding 15 additional dB in the case of LTE-M (seven times better area coverage) and 20 dB for NB LTE-M (ten times better area coverage).

Release 12 introduced a power saving mode (PSM), which significantly improves battery lifetime. It consists on the devices requesting a timer that specifies for how long the device remains reachable. They start the active timer when moving from connected to idle mode, and when the timer expires, the device moves to power saving mode. The device remains in this unreachable mode until some uplink transaction requires it to perform any procedure towards the network. Release 13 specifies the ability of enhanced Discontinuous Reception (eDRX), which allows the devices to monitor the physical downlink channel in a discontinuous way, saving a significant amount of battery.

Further improvements are detailed in [4], where the evolution toward 5G systems is envisioned. In Figure 3 we can see these main enhancements illustrated:
The main parts of the architecture are the MTC device domain, the network domain and the MTC application domain. As it can be observed, the MTC devices (also called User Equipments (UEs)) can be connected to base stations (eNodeBs in the LTE context) either directly or through MTC gateways. Release 12 introduces an important enhancement known as device-to-device (D2D) communications. It consists on allowing a direct radio link between the devices without transiting through the network.

In 4G systems, the cellular network domain includes a radio access network (RAN) and a core network (CN). The random access network (RAN) connects the devices to the CN through air interfaces, and the CN manages the control of the MTC and data delivery. In the context of LTE, the CN is known as evolved packet core (EPC), and includes all the entities used for H2H and MTC communications. The other main improvement toward 5G that can be seen in the figure is the use of Network Function Virtualization (NFV), which allows performing the functions of entities inside the evolved packet core (EPC) on virtual machines, instead of using sophisticated and expensive infrastructures. Hence, moving higher layer functionalities to a network cloud can significantly reduce the equipment and operation cost of eNodeBs.

Traditionally, in LTE technology, UEs use the Random Access Channel (RACH) to perform initial network association, request transmission resources and establish a connection to the eNodeB. The RACH consists on a periodic sequence of allocated time-frequency resources, reserved in the uplink channel to transmit access requests [14].

LTE distinguishes among to types of random access: contention-based and contention-free access. In the contention-based mode, a four-message handshake between the UE and the eNodeB is carried out. This interchange is initiated when the UE selects at random one preamble sequence from the set of orthogonal preamble sequences reserved for contention-based access and transmits it. Since the number of available
preambles is finite, in a massive MTC scenario, collision probability of preambles will grow, resulting in serious performance degradation [15]. Several methods have been studied to mitigate this problem, such as Access Class Barring (ACB) [16], consisting on separating users into groups or classes. By blocking one or several classes the eNodeB is able to control the load. Other strategies include separating RACH resources for MTC into two groups (one for H2H traffic and one for MTC traffic) [15]; or UEs detecting channel congestion so that the eNodeB can adapt the number of offered resources for random access [17]. The process (pictured in Figure 4a) is continued with the Random Access Response, where the eNodeB answers the same preamble to the UE and assigns it a temporary C-RNTI (Cell Radio Network Temporary Identity), necessary for further communication. Then, the UE replies with a Radio Resource Control (RRC) request and a scheduling request, to which the eNodeB answers with the contention resolution message to end the RACH procedure [18].

![Figure 4: RACH procedure in contention-free and contention-based systems [18]](image)

On the other hand, contention-free access (Figure 4b) involves the eNodeB allocating access resources for requests that require high probability of success, such as handover. The handshake is initiated by the eNodeB, which assigns a 6-bit preamble to a given UE, which sends it back to the eNodeB. Finally, the eNodeB replies with the Random Access Response (also used in the contention-based procedure) [18].

Both random access schemes are based on multi-channel Frame Slotted ALOHA (FSA) medium access [14], a variant of Slotted ALOHA where slots are grouped into frames. Although successive releases of LTE for MTC reduce the capabilities (maximum peak rates, bandwidth, complexity, cost and power requirements) of the devices to make them more suitable for the IoT, all LTE-M upgrades still use the same FSA scheme.

### 2.3.1.2. NB-IoT

Narrow Band IoT (NB-IoT) is a 3GPP radio-access technology intended to meet the connectivity requirements for MTC applications. Unlike NB LTE-M, which consists on an overlay of the existing LTE structure, NB-IoT is not based on LTE and thus not fully backwards compatible with such technologies [14]. However, it is designed to achieve a good coexistence level with legacy GSM or LTE systems. In this sense, NB-IoT is expected to operate either in-band of LTE resources, exploiting the guard bands between...
channels, or using dedicated frequency resources [19]. This technology will operate in Half-Duplex mode, with UE bandwidths of 200 kHz and maximum uplink and downlink data rates of 200 kbps. Complexity is significantly reduced with respect to Cat-1 LTE devices in Release 8, and link budget is improved increasing the coverage area.

NB-IoT systems take into account the received signal strength information for an efficient management of RACH resources. Depending on the coverage conditions for each UE, several coverage classes can be defined and the random access procedure parameters can be modified for different classes. NB-IoT makes use of overlaid Code Division Multiple Access (CDMA) to handle collision on the RACH, where orthogonal codes allow separating users within a certain coverage class [14].

2.3.2. Unlicensed-spectrum technologies

Several LPWAN (LPWA Network) technologies are gaining attention as suitable IoT alternatives (LoRa, Sigfox, Weightless…) whose main particularity is their use of unlicensed spectrum, which might make QoS requirements difficult to ensure, as opposed to 3GPP standards. However, the use of dedicated devices can help achieve higher power and cost efficiency than 3GPP technologies. In the following subsections, we review two of the most widely-deployed solutions: LoRa and Sigfox.

2.3.2.1. LoRa

LoRa (Long Range Radio) or LoRaWAN is a wireless technology targeted for MTC and IoT systems intended for operation in regional, national or global networks. It consists on a bidirectional solution that complements M2M cellular or WiFi technologies, and provides a low-cost way to connect mobile or battery-operated devices to the network infrastructure or to end points. The LoRa Alliance is an open non-profit association that was formed by different companies to standardise LPWAN for MTC and IoT. Although LoRa was developed by Semtech, standardizing the technology will enable a much larger growth of the market.

The architecture of the LoRa network consists on a star-based topology where gateways act as a transparent unit relaying messages between devices and a central network server. The network server manages the network, acts to eliminate duplicate packets, schedules acknowledgement, and adapts data rates. Gateways are connected to the network server via standard IP connections. On the other side, devices use single-hop communication to one or several gateways in such a way that end-to-end communication is generally bidirectional.
LoRa operates on unlicensed frequency bands. In Europe the 868 MHz ISM (Industrial Scientific Medical) band is used, which enables much better coverage than 2.4 or 5.8 GHz ISM bands. Inside this region, communication between devices and gateways is spread on different frequency channels and data rates. The use of spread spectrum techniques allows avoiding interference and increases gateway capacity. In addition, in order to optimise battery life of the devices, the LoRa network server individually controls the data rate and RF output for every device using an adaptive data rate (ADR) scheme.

Several key features of the LoRa network are its long range, as it can reach up to 15-20 km; its high capacity, since one LoRa gateway is in charge of thousands of nodes; and its long battery life, which can last over ten years.

The PHY layer of LoRa is based on Chirp Spread Spectrum (CSS) techniques, a subcategory of Direct Sequence Spread Spectrum (DSSS) which uses controlled frequency diversity to recover data from weak signals. Spectrum spreading is achieved by means of a chirp signal that varies in frequency and lowers the receiver design complexity [14].

LoRa defines three different classes of end-point devices (Class-A, B and C) [20], each one with different medium access approaches. Class-A devices are meant for communications initiated by the end devices and use pure-ALOHA combined with Listen-Before-Talk (LBT) -which requires synchronization between devices and gateways- whenever they have data to transmit [14]. This scheme is highly susceptible to collisions and yields low throughputs, but it is used in devices with low-energy constraints. Class-B devices also initiate transmission, but using a beacon-enabled time-slotted scheme along with LBT that allows scheduled message reception windows. On the other side class-C devices always listen to the channel waiting for an incoming signal from the gateways, which results in lower latencies at the cost of higher energy consumption on the end-device side [14].
2.3.2.2. Sigfox

Sigfox is a wireless cellular network that connects devices using Ultra Narrow Band (UNB) technology. It is aimed at massive low rate data applications, which makes it suitable for IoT and MTC systems. Sigfox has expanded over several cities in the United States, as well as over various countries in Europe, including Spain, where together with Securitas Direct and Telefónica it has provided a quintuple play service, including security, broadband, telephone, mobile and TV.

The Sigfox technology allows up to 140 messages per device in a day, the payload size for each message is 12 bytes, and the throughput is limited to 100 bits/second (using Binary Phase Shift Keying, BPSK).

The use of UNB allows very low transmitter power levels while maintaining a robust data connection. Like LoRa, Sigfox operates over unlicensed ISM bands (868 MHz in Europe). Choosing bands below GHz frequencies enable a wider range, which can reach up to 30-50 km in rural areas, and 3-10 km in urban scenarios.

The Sigfox network topology consists on a star-based cell infrastructure, designed to provide a scalable high-capacity network with very low energy consumption. Hence, battery life can last up to 20 years (unlike GSM batteries, which last up to 2 years).

Sigfox does not use any collision avoidance mechanisms for medium access, but a Random Frequency-Time Division Multiplex (R-FTDMA) scheme. Each device transmits on a randomly-chosen frequency in the continuous available frequency band, in an ALOHA-based procedure without previous channel sensing, which allows increasing energy efficiency; and with no need for channel synchronization, which reduces complexity. However this system is prone to high interference and collision probability, which can be mitigated by means of software-defined radio techniques at the receiver side [14].

2.3.3. Comparison between the reviewed technologies

In order to grasp a better view of the global picture of the studied MTC alternatives, a comparison among all of them will help us to draw conclusions. Table 3 summarises the key features of the different technologies. Since a 5G solution is expected to be part of the new 5G framework by 2020 [12], it is also included on the table:
### Table 3: Connectivity overview of the different technologies (excerpt from [12])

<table>
<thead>
<tr>
<th></th>
<th>Unlicensed frequency bands</th>
<th>Licensed frequency bands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sigfox</td>
<td>LoRa</td>
</tr>
<tr>
<td>Range (outdoor)</td>
<td>&lt;13 km (160 dB)</td>
<td>&lt;11 km (157 dB)</td>
</tr>
<tr>
<td>Spectrum bandwidth</td>
<td>100 Hz</td>
<td>&lt;500 kHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>&lt;100 bps</td>
<td>&lt;10 kbps</td>
</tr>
<tr>
<td>Battery life</td>
<td>&gt;10 years</td>
<td>&gt;10 years</td>
</tr>
<tr>
<td>Availability</td>
<td>2016</td>
<td>2016</td>
</tr>
</tbody>
</table>

The different medium access techniques for each technology have also been discussed, so it might be interesting to be able to compare all schemes at a glance in Table 4:

### Table 4: Channel access methods for the different technologies (excerpt from [14])

<table>
<thead>
<tr>
<th></th>
<th>Sigfox</th>
<th>LoRa</th>
<th>LTE-M</th>
<th>NB-IoT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contention-based</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure ALOHA</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slotted ALOHA</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Contention-free</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDMA</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>CDMA</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Time slot reservation</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spread spectrum techniques</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As previously stated, depending on whether the specific technology operates on licensed or unlicensed frequency bands, the set of advantages and drawbacks will noticeably vary. LPWAN systems (Sigfox, LoRa…) use dedicated devices, which allows reaching low cost and power values. However, due to the use of an unlicensed part of the spectrum, QoS requirements might not be satisfied.

On the other hand, standardised cellular technologies offer significant advantages over unlicensed ones, such as global reach, a higher QoS level, better scalability, diversity and security. 3GPP’s ongoing standardization work for GSM, LTE and NB-IoT facilitates the ability to satisfy the requirements for MTC systems.

#### 2.4. Non-Orthogonal Multiple Access techniques

The fast growth of mobile Internet together with the rapid expansion of the IoT will require huge improvements such as high spectral efficiency and massive connectivity for 5G systems. To address these requirements, several novel technologies have been analysed, such as massive MIMO (Multiple-Input Multiple-Output), millimetre-wave communication and non-orthogonal multiple access (NOMA).

NOMA’s principle of operation is based on accommodating a large number of users via non-orthogonal resource allocation. Traditionally, in wireless communications only orthogonal multiple access (OMA) techniques were used: frequency-division multiple access (FDMA) for 1G, time-division multiple access (TDMA) for 2G, code-division
multiple access (CDMA) for 3G and orthogonal frequency-division multiple access (OFDMA) for 4G [21].

NOMA is able to accommodate multiple users that share time and frequency in the same layer by means of power domain and code domain multiplexing schemes. Let us briefly review some of these schemes in order to gain general insights of the global NOMA landscape.

2.4.1. NOMA via power domain multiplexing

As in [21], let us discuss some power domain multiplexing techniques only for downlink NOMA. Such techniques are based on allocating different power levels to different users according to their channel conditions so that the maximum gain in system performance is obtained.

2.4.1.1. NOMA with a SIC basic receiver

This NOMA scheme, which can be also applied in the uplink, consists on linearly adding up the signals for different users at the base station (or eNodeB in the LTE context). This addition is performed taking into account the restrictions in the transmitted power, by weighting each signal by a specific coefficient. Then, Successive Interference Cancellation (SIC) is employed at the receiver device (or UE in the LTE context). For simplicity’s sake, let us consider only 2 devices in this example. Since the channel conditions may be very different among users, SIC is performed at users with high signal-to-interference power ratio (SINR) following a descending SINR order, as pictured in Figure 7. By exploiting the SINR difference among users (caused by the near-far effect or by non-uniform power allocation at the base station), multi-user detection (MUD) can be successfully achieved [23].
2.4.1.2. NOMA in Massive MIMO systems

NOMA can be used in MIMO systems such that spectral efficiency is improved. At a base station, having several antennas allows implementing beamforming. Each beam simply combines the different signals. At the receiver, the possible inter-beam interference is suppressed by spatial filtering, and then, the previously discussed SIC method is used to separate the desired signal [21].

2.4.2. NOMA via code domain multiplexing

Code domain multiplexing techniques consist on assigning different codes to different users, and then they are multiplexed over the same time-frequency resources. These schemes can achieve higher spreading and shaping gain than power domain multiplexing schemes; however, the required signal bandwidth is higher [21]. In the following subsection some of the most popular techniques are described.

2.4.2.1. Low-Density Spreading CDMA

In classical CDMA systems in the downlink, the transmitted symbol of a given user is generated by mapping a sequence of independent information bits to a constellation alphabet. Then the modulation symbol is mapped to a unique spreading sequence and finally, all the users’ symbols are combined for transmission. In conventional CDMA systems, spreading sequences are not sparse, they contain many non-zero elements. The principle of operation of low-density spreading (LDS) CDMA is to use sparse spreading sequences, which allows efficiently decreasing interference between users and achieving overloading [24].

At the receiver, MUD can be performed by means of a message-passing algorithm (MPA), which consists on a sequence detector. It can be modelled by a factor graph (depicted in Figure 8) where a variable node represents the transmitted symbol and a factor node corresponds to the received signal at each chip (pulse of DSSS code). MPA is often followed by a channel decoder, since LDS has limited error-correction capability.
A variant of LDS-CDMA is LDS-OFDM, where chips are replaced by OFDM subcarriers to combat the multipath fading. The transmitted symbols are mapped to LDS sequences and transmitted on different OFDM subcarriers. Overloading is also allowed, the number of symbols can be larger than the number of subscribers, which enhances spectral efficiency. As with LDS-CDMA, a MPA can also be used at the receiver [24].

2.4.2.2. Sparse Code Multiple Access

Sparse Code Multiple Access (SCMA) consists on an enhanced version of LDS-CDMA. Its principle of operation is based on directly mapping bit streams to different sparse codewords. In Figure 9 we can see how each one of the six users has a codebook. Each codebook contains zeros in the same two dimensions, which vary among users to avoid collisions between them. Codewords for all users are multiplexed over four shared orthogonal resources, for example OFDM subcarriers.

An advantage of SCMA over LDS is that by designing a multi-dimensional constellation to generate codebooks, a shaping gain can be achieved. This is due to the fact that SCMA enjoys additional degrees of freedom in the constellations design [25]. The shaping gain, is the gain in the average symbol energy when the shape of the constellation is changed, which can increase up to a maximum of 1.53 dB [21].
SCMA offers the multi-access benefits of LDS in terms of overloading, moderate complexity or interference whitening, while avoiding the poor link performance of LDS. Hence, SCMA can present a good performance in both uplink and downlink multiple access scenarios of 5G networks [25].

2.4.2.3. Multi-User Shared Access

Multi-user shared access (MUSA) is another code-domain multiplexing technique that is based on spreading each user’s symbols by a spreading sequence. In the uplink, this sequence is randomly chosen from a set of spreading sequences. Then each user’s spread symbols are transmitted on the same radio resource by means of “shared access”, a superposition process. At the base station, codeword-level SIC is employed to separate data from different users. This process is illustrated in Figure 10:

![Figure 10: Uplink MUSA system with four resources shared by multiple users (extracted from [24])](image)

In downlink MUSA, users are separated into groups. In each group, different users’ symbols are mapped to different constellations in a way that can ensure Gray mapping in the combined constellation of superposed signals. Gray mapping of the combined constellation reduces the dependency on advanced receivers, so receiver complexity can be reduced. In addition, orthogonal sequences can be used to spread the superposed symbols to get time or frequency diversity gain [21].
3. Feedback-Free Network Diversity Multiple Access

The use of ALOHA-type random access protocols predominates in today's bursty communications due to their straightforward implementation for devices in a shared communication channel. For example, the principle of operation of the Random Access Channel (RACH) in LTE is based on slotted ALOHA (as seen in Table 4). These protocols are becoming increasingly considered in some use cases for future 5G networks (e.g. MTC), since they prove to be suitable for scenarios with a massive number of low-powered devices generating bursty traffic with low latency requirements [4].

The operation of basic ALOHA-type protocols is based on the collision model: a packet is correctly received only in the case where a single user transmits. Thus, the medium access control (MAC) and the physical layer (PHY) are fully decoupled, and the analysis of the protocol is simplified. A groundbreaking approach in the collision model was made in [26] by Guez et al. by introducing the multipacket reception (MPR) model: when there are simultaneous transmissions, reception is described by conditional probabilities (instead of associating collisions to deterministic failures). Thus, by means of a closer interaction between PHY and MAC layers, signal processing techniques can resolve collisions. MPR can be realised through different techniques, such as multiple-input multiple-output (MIMO) systems, code division multiple access (CDMA) schemes, or advanced receivers. A complete survey is presented in [27], where the available techniques are classified from three different perspectives: transmitter, trans-receiver and receiver.

A promising trans-receiver approach called Network-assisted Diversity Multiple Access (NDMA) was introduced in [28]. It consists on storing in memory the received signals after a collision and combining them with future repetitions to recover all collided packets. In the single-antenna case and under the assumption of perfect reception, NDMA only requires the number of repetitions to be equal to the number of collided packets. Hence, NDMA significantly enhances the throughput and delay performance as compared to ALOHA-type protocols. On the other hand, the required overhead to identify collisions and specify the number of repetitions grows exponentially with the number of devices in the system.

In [29] a feedback-free NDMA (FF-NDMA) scheme is proposed, where the number of slots reserved for repetitions (contention period (CP)) is fixed for all devices ($R$ slots), significantly reducing the necessary feedback. Although this scheme is labelled as feedback-free, a minimum feedback is still necessary: the base station transmits a bit per CP over a downlink broadcast control channel that determines whether the packets in the CP have been correctly received or not, without making distinction among specific devices. However, the feedback-free denomination arises due to the fact that the feedback is much lower to that of the NDMA scheme, where a feedback bit per time slot is required [28]. Devices are only allowed to start transmission at the beginning of the contention period. Thus, collisions of up to $R$ devices can be resolved in the single antenna case. The joint PHY-MAC performance analysis of the FF-NDMA scheme is studied in [30] for the general case of MIMO systems with orthogonal space-time block coding (OSTBC), but assuming that whenever a packet is received in error it is lost.

In this thesis we analyse the FF-NDMA scheme from a cellular perspective by considering a finite-user slotted random access system where packets are not discarded. In this sense, we use the MPR model and characterise the system as a Markov chain to
evaluate performance in terms of throughput, mean access delay and energy in different scenarios. These metrics will also be analysed in terms of different backoff policies. Moreover, we will study the stability of the network under two criteria. The results are shown for a variable number of slots \( R \) and single and multi-antenna configurations, which allows gaining insights on the different trade-offs between metrics.

3.1. System model

Suppose a wireless cellular system composed of a base station with \( N \) receive antennas and multiple devices. Consider that the coverage area of the base station is partitioned into ring-shaped regions.

![Figure 11: User grouping based on ring-shaped regions for random access](image)

In this thesis different scenarios based upon this ring-shaped scheme have been analysed for the FF-NDMA model. Distinction among scenarios can be done according to the SNR (depending on the path loss) characteristics in each region and the number of regions taken into account:

- **Symmetric scenario**: the whole area is divided into ring-shaped regions such that the received SNR from every device within each region is similar.
- **Asymmetric non-sectorised scenario**: the coverage area is treated as a whole and the SNR value is different for every device.
- **Asymmetric sectorised scenario**: the coverage area is partitioned into two ring-shaped regions. Within each sector the devices SNR is not the same.

Let us focus for the moment on the symmetric scenario where only a specific ring-shaped region is taken into account. Within this region there are \( K \) devices with \( M \) transmit antennas and a single packet buffer each.

The structure of the time-slot-based MAC frame is shown in Figure 12. Time slots are grouped into contention periods (CPs) of \( R \) time slots. Each device is slot and CP synchronised with the base station. All packets have the same size and duration: one time slot.
Orthogonal resources are reserved for devices placed in different regions, so they transmit whenever they have a packet at the start of a given CP. During each CP repetitions are performed and devices transmit their packets \( R \) times, as in [30]. Devices become aware of whether all \( R \) packets have been correctly sent or not through the feedback bit of each CP. Collisions might occur, and every device can be in one of two different states at a given time: **thinking** and **backlogged**. In the thinking state, devices do not have a packet in their buffer and do not participate in any scheduling activity. In this state, packets are generated during a certain CP with probability \( \sigma \), and their transmission is attempted at the beginning of the next CP and repeated during \( R \) slots. If the transmission succeeds, the device remains in the thinking state and the described process restarts. On the other hand, if the transmission is not successful, the device moves into the backlogged state and retransmits the packet with a probability \( \upsilon \). While in the backlogged state, the device cannot generate any new packets. When reception at the base station is finally successful, the device moves back to the thinking state and the process starts again. Figure 13 gives a visual approach of the described process:

![State diagram of the packet transmission process](image)

Each device transmits through an OSTBC (orthogonal space-time block code) with \( Q \) complex symbols spread in time and space over \( T \) channel uses and the \( M \) transmit antennas, as in [30]. The transmitted symbols are QPSK, the noise is assumed white and Gaussian in time and space, and the average SNR of each device within the region is \( \gamma \).

If a decorrelating receiver is used at reception, the bit-error ratio (BER) for user \( k \) given that \( \tilde{k} \) users are transmitting can be written as:

\[
\text{BER}_{\tilde{k}k} = Q\left(\sqrt{\frac{X_k \gamma}{2RM}}\right), \quad \forall k \leq \tilde{k}, \quad \forall \tilde{k} \leq K
\]  \hspace{1cm} (1)

With \( X_k \) being a chi-square-distributed random variable with \( D = 2(RNM - Q \tilde{k} + Q) \) degrees of freedom for any orthogonal space-time block code with \( M = T \).

A packet is in error if the BER is above a certain threshold level \( \omega \). An upper bound can be established for the PER of user \( k \) given that \( \tilde{k} \) devices are transmitting as:
\[ \text{PER}_{k} \leq \Pr \left( \sqrt{Z_k} \leq Q^{-1}(\omega) \sqrt{\frac{2RM}{\gamma}} \right) = 1 - F_1(\sqrt{Rx}) \]  

(2)

where \( F_1 \) is the cumulative function of the chi distribution and \( I = \frac{D}{2} - 1 \):

\[ F_1(\sqrt{Rx}) = e^{-\left(\sqrt{Rx}\right)^2 / 2} \sum_{i=0}^{I} \left(\frac{(\sqrt{Rx})^2}{2}\right)^i \frac{1}{i!} \],

(3)

and where \( x \) is defined as following:

\[ x = Q^{-1}(\omega) \sqrt{\frac{2M}{\gamma}} \]  

(4)

3.2. MPR model for FF-NDMA

In this section we characterise the MPR matrix for the FF-NDMA scheme, analyse it using a Markov chain to obtain the system state probabilities, and then derive throughput, delay and energy.

3.2.1. MPR matrix

The channel can be described by a matrix of conditional probabilities introduced in [26]. The structure of the matrix \( C \in \mathbb{R}^{k(R+1)} \) with \( R = NR \) (\( R \) denotes the maximum number of packets that can be decoded at the base station with FF-NDMA) is the following:

\[ C = \begin{pmatrix}
C_{10} & C_{11} & 0 & \ldots & 0 \\
C_{20} & C_{21} & C_{22} & 0 & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
C_{k0} & C_{k1} & C_{k2} & \ldots & C_{kk}
\end{pmatrix}, \]  

(5)

where the elements are defined as:

\[ C_{xy} = \Pr(\text{y decoded packets} \mid x \text{ transmitted packets}); \ 1 \leq x \leq \tilde{R}, \ 0 \leq y \leq x, \]  

(6)

that is, the probability that given \( x \) transmitting devices, \( y \) out of \( x \) transmissions are successful. The element \( C_{xy} \) contains the product of PERs corresponding to the combinations of \( x \) devices for which \( y \) transmissions are successful and \( x-y \) are not. For instance, \( C_{21} \) is given by:

\[ C_{21} = \text{PER}_{21}(1 - \text{PER}_{22}) + \text{PER}_{22}(1 - \text{PER}_{21}). \]  

(7)

It can be noted that the conventional slotted ALOHA random access protocol, where the receiver can only demodulate one packet at a given time, can be modelled by this matrix, which has the following structure:
At this point it is interesting to describe the derivation of the MPR matrix depending on the scenario characteristics.

**Symmetric scenarios:** In the symmetric scenario, \( \gamma \) is assumed equal for all \( K \) devices within a given ring-shaped region, so distinction among specific devices is not necessary. Thus, in the symmetric case the following condition is fulfilled:

\[
\text{PER}_{jk} = \text{PER}_{\bar{j}k}, \quad \forall j, k.
\]

By denoting the PER elements as simply \( \text{PER}_x \), we can write:

\[
C_{xy} = \binom{x}{y} \text{PER}_x^{x-y} (1 - \text{PER}_x)^y.
\]

**Asymmetric scenarios:** On the other hand, in the asymmetric scenarios the MPR matrix computation is not strictly analytic. Distinction among devices must be considered as each one has different SNR values. Since the \( \bar{k} \) active devices in a given CP are randomly chosen, it might turn out that all of them present very good or very bad SNR characteristics, which is unusual (especially as \( \bar{k} \) increases) and might yield inaccurate results. The values of the \( \bar{k} \)th row of the MPR matrix will be approximated by the average value obtained over multiple random situations, where the subset of active terminals (placed in different positions) changes. Hence, for \( U \) random deployments, the MPR matrix can be computed as:

\[
C = \frac{1}{U} \sum_{u=1}^{U} C_u,
\]

where \( C_u \) is the MPR matrix obtained in the \( u \)th deployment.

### 3.2.2. Markov chain and system state

Let us consider the random variable \( B(s) \), which defines the number of backlogged devices at the beginning of the \( s \)th CP. This variable denotes the state of the system, which depends on the previous state \( (B(s-1)) \) and the number of devices whose state changed during the CP. Hence, the process can be modelled by a finite Markov chain as in [31], where \( B(s) \leq K \).

The steady-state probability of the system being in state \( i \) \( (\pi_i) \) denotes the steady-state probability of the system being in state \( i \):

\[
\pi_i = \lim_{s \to \infty} \text{Prob}(B(s) = i)
\]

The transition probability from state \( i \) to state \( j \) \( (p_{ij}, 0 \leq i, j \leq K) \) is defined by:
\[ p_{i,j} = \lim_{s \to \infty} \text{Prob}[B(s) = j \mid B(s-1) = i] \] (13)

Figure 14 shows the aspect of the Markov chain for a simplified scenario with \( K = 3 \). Under conventional slotted ALOHA, downward transitions are only possible from state \( i \) to state \( j = i - 1 \), since a single packet can be decoded at a time; \( p_{0,1} = 0 \), as when the backlog is empty and only a packet is generated, it will surely be decoded. However, under FF-NDMA \( p_{0,1} \) is no longer zero; and downward transitions are possible from state \( i \) to state \( j \leq i - \tilde{R} \), as long as \( j \geq 0 \). For simplicity’s sake, in Figure 14 all downward transitions are shown, although only those from state \( i \) to state \( j \leq i - \tilde{R} \) are possible (such that \( p_{i,j} \neq 0 \)):

![Markov chain](image)

Figure 14: Markov chain modelling the number of backlogged devices in FF-NDMA scheme for \( K = 3 \)

The transition probabilities \( p_{i,j} \) can be obtained after the MPR matrix \( C \) in (5), the generation probability (\( \sigma \)) and the retransmission probability (\( \nu \)). Let us define \( \phi_{mn}^{i} \) as the probability that \( m \) backlogged devices transmit and \( n \) new packets are generated by thinking devices given that the backlog state is \( i \) (i.e. there are \( i \) backlogged devices). Since packet generation and packet retransmission are independent events, \( \phi_{mn}^{i} \) can be written as:

\[
\phi_{mn}^{i} = \binom{m}{i} \nu^{m-i} (1-\nu)^{i-m} \left( \frac{K-i}{n} \right) \sigma^{n} (1-\sigma)^{K-i-n}; \quad 0 \leq r+c \leq \tilde{R} \] (14)

In a similar fashion we can define \( \phi_{mn}^{l} \) as the probability that more than \( m \) backlogged devices transmit and \( n \) new packets are generated by thinking devices given that the system state is \( i \):

\[
\phi_{mn}^{l} = \left( 1 - \sum_{i=0}^{m} \binom{m}{i} \nu^{i} (1-\nu)^{m-i} \right) \binom{K-i}{n} \sigma^{n} (1-\sigma)^{K-i-n}; \quad m+n = \tilde{R} \] (15)

With these probabilities, the transition probabilities \( p_{i,j} \) in (13) for \( i - \tilde{R} \leq j \leq i + \tilde{R} \) can be found with the following expression:
Note that the left-hand-side vector includes all transition probabilities between state $i$ to states between $i - R$ and $i + R$. For illustrative purposes, let us explain how, for instance, $p_{i,i}$ is computed. By taking each row of the MPR matrix, we consider all the possible cases where from 1 to $R$ packets are sent. The first right-hand-side matrix product takes into account the case where 1 packet is sent. In this case two events can happen: a backlogged packet is transmitted but it is not successfully decoded, or a packet is generated and it is successfully decoded. In both situations the state of the backlog does not change. This procedure is repeated for 2, 3, ..., $R$ transmitted packets in the following right-hand-side matrices. In this particular case where state $i$ remains unchanged, the probability of not transmitting any packet is also considered (through $\phi_i^{00}$); as well as the case where more than $R$ backlogged packets are transmitted (i.e. $\phi_i^{R0}$).

The remaining transition probabilities $p_{i,j}$ where $j < i - R, j > i + R$ are obtained as following:

$$p_{i,j} = \begin{cases} 0, & j < i - R. \\ \binom{K-i}{j-i} \sigma_i^j(1-\sigma)^{K-j}, & j > i + R. \end{cases}$$

(17)

It can be seen that downwards transitions from state $i$ towards states $j < i - R$ are impossible because at maximum $R$ packets can be successfully decoded, and upwards transitions from state $i$ towards states $j > i + R$ happen when $j-i$ thinking devices generate packets that collide (the activity of the backlogged devices is immaterial in this case since collision is always caused by thinking devices).

The steady-state probabilities $\pi_i$ defined in (12) can be obtained after the transition probabilities $p_{i,j}$. By arranging all the transition probabilities $p_{i,j}$ into a matrix $P \in \mathbb{R}^{(K+1)\times(K+1)}$ and all the steady-state probabilities $\pi_i$ into a vector $\pi \in \mathbb{R}^{(K+1)}$. The steady-state vector must satisfy [32]:

$$\pi = P\pi \rightarrow (I - P)\pi = 0$$

(18)

and $\sum \pi_i = 1$. Therefore, $\pi$ can be obtained as the normalised single eigenvector of the kernel of matrix $(I-P)$.

### 3.2.3. Throughput

The throughput ($S$), measured in packets/slot, is given by the product of the steady-state probabilities and the associated throughput, i.e.:
Notice the $1/R$ penalty, which arises because devices transmit the same packet $R$ times within the CP. $S_i$ denotes the throughput obtained in state $i$ and takes into account the different cases where successful decoding takes place (i.e. the elements of the MPR matrix $C_{xy}$ such that $1 \leq x \leq \hat{R}$, $1 \leq y \leq x$, each with its associated throughput of $y$ successfully decoded packets:

$$S_i = \sum_{x=1}^{\hat{R}} \sum_{y=1}^{x} yC_{xy} \sum_{m+n=x} \phi_i^{mn}.$$  

For instance, with $\hat{R} = 2$, the throughput associated to each state $i$ would be:

$$S_i = C_{11}(\phi_i^{01} + \phi_i^{10}) + C_{21}(\phi_i^{02} + \phi_i^{11} + \phi_i^{02}) + 2C_{22}(\phi_i^{20} + \phi_i^{11} + \phi_i^{02}).$$  

### 3.2.4. Mean access delay

In order to calculate the mean delay of the system (the average number of required slots since a packet is generated until it is successfully transmitted), we need to determine the mean backlog delay. Let us define $\bar{B}$ as the mean number of devices in the backlog, which can be obtained by considering the average between all the states times the probability of being in each state:

$$\bar{B} = \sum_{i=0}^{K} i\pi_i.$$  

If devices join the backlog at a rate $b$, by using Little’s formula [33], the mean time spent in the backlog is $\bar{B}/b$. Considering this, since a fraction $(S-b)/S$ of the packets are never backlogged (which have a $(3R-1)/2$ mean delay, corresponding to the delay of a packet transmission ($R$ slots), plus the mean waiting time until the CP starts $(R-1)/2)$; the packets whose fraction is $b/S$ will experience the mean backlog delay plus the $(3R-1)/2$ delay. Thus, the average delay, measured in slots, can be written as:

$$D = \frac{S-b}{S} \frac{(3R-1)}{2} + b\left(\frac{\bar{B}}{b} + \frac{(3R-1)}{2}\right) = \frac{(3R-1)}{2} + \frac{\bar{B}}{S}.$$  

Notice that the rate at which devices join the backlog ($b$) is used to derive the mean access delay $D$, but it is not needed to compute $D$, so its value does not need to be obtained.

### 3.2.5. Energy

Energy consumption can also be studied; let us follow a similar approach to that used in [5], where three different possible power states are defined (each one with a different power consumption level):

- **idle state ($P_i$)**: there is no data to transmit,
• waiting state ($P_1$): there is a packet to transmit but there is no transmission opportunity; and
• transmitting state ($P_2$): the device is transmitting.

The mean times that a device spends on each state are:

$$T_0 = 1/ \sigma, \quad T_1 = D - RN_{TX}, \quad T_2 = RN_{TX},$$

(24)

$T_0$ depends on the inverse of the packet generation probability, $T_1$ on the number of transmissions required for a successful transmission ($N_{TX}$) and the repetition of each packet $R$ times during each transmission, and $T_2$ on the average delay minus the transmission time $T_1$, such that it considers the waiting time in the backlog and the waiting time for the CP to start. $N_{TX}$ can be defined as:

$$N_{TX} = \sum_{n=1}^{\infty} n P_{suc|tx} (1 - P_{suc|tx})^{n-1} = \frac{1}{P_{suc|tx}},$$

(25)

$P_{suc|tx}$ specifies the probability of a successful transmission given that a specific packet has been transmitted. It can be computed after the average between all the states and the probability of success given that a packet is transmitted on each of the different states (i.e. $P_{suc|tx}$):

$$P_{suc|tx} = \sum_{i=0}^{K} \pi_i P_{suc|tx}^i,$$

(26)

and $P_{suc|tx}^i$ is obtained by taking into account all the cases where successful transmission can occur ($k = 1, \ldots, R$) with the success probability times the probability that $k - 1$ devices transmit:

$$P_{suc|tx}^i = \sum_{k=1}^{R} (1 - PE_{R}) \sum_{m+n=k-1} \phi_{i}^{m+n},$$

(27)

with $PE_{R} = \frac{1}{k} \sum_{k \leq k} \frac{PE_{R}}{k^{j}}$.

The mean consumed energy $E$ (Watts x slot) can be obtained after the product of the time that devices spend on each state by the power spent on each state:

$$E = T_0 P_0 + T_1 P_1 + T_2 \frac{P_2}{R}.$$

(28)

Notice the dividing factor $R$ in the term corresponding to the energy consumed on the transmitting state. This is due to the fact that consumed energy per CP is fixed for every device and does not increase as more slots are used.

3.3. Stability criteria

In literature, stability is often analysed for infinite-user random access [26] or for finite-user infinite-buffer random access [34]. In the former case, the system becomes unstable when the number of backlogged devices grows to infinity; and in the latter, when the
buffer size grows to infinity. Let us develop other criteria to analyse stability for our finite-user with single-packet buffer system.

We will consider two different criteria whose main rationale is driven by avoiding undesired states (i.e. that all users are in the backlog, which would of course cause instability of the system):

- Stability based on the probability of the last state: the system is supposed stable if the probability of being in state \( K \) is below a certain threshold:
  \[ \pi_K \leq \alpha . \] (29)

- Stability based on the number of devices in the backlog: the system is supposed stable if the mean number of devices in the backlog is below a certain threshold:
  \[ \bar{B} \leq \beta . \] (30)

3.4. Backoff techniques

Besides the number of slots per CP \( (R) \) and the antenna configuration \( (N, M) \), the other parameter that can be tuned in order to achieve good results is the packet retransmission probability \( \nu \). Hence, five different backoff techniques are analysed and will be compared in terms of throughput, delay and energy:

- Variable retransmission rate: \( \nu = \sigma \).
- Fixed retransmission rate: \( \nu = 1 / K \).
- Retransmission rate to maximise throughput: \( \nu^* \) such that \( S \) is maximum.
- Retransmission rate to minimise probability of the last state: \( \nu^* \) such that \( \pi_K \) is minimum.
- Retransmission rate to minimise mean number of backlogged devices: \( \nu^* \) such that \( \bar{B} \) is minimum.
4. **Results evaluation**

In this section we evaluate the FF-NDMA scheme in terms of throughput, delay and energy for the symmetric scenario, as a function of the offered load \( G = K \sigma \) for two different backoff schemes \( \nu = \sigma \) and \( \nu = 1/K \) and as a function of the SNR. In this scenario, the multi-antenna model (setting \( R = 1 \) and varying the number of antennas at the base station) will also be studied, as well as the conventional slotted ALOHA scheme. In addition, the metrics will be analysed as a function of the retransmission probability \( \nu \) such that stability conditions are fulfilled; and as a function of the offered load for the five aforementioned backoff techniques.

The asymmetric scenario will also be evaluated, both in the non-sectorised and sectorised cases. In the former, all metrics (throughput, delay and energy) will be analysed; but only throughput (with two different methods to combine throughputs from both sectors) will be studied for the latter due to the higher complexity in delay and energy derivation for specific coverage areas.

4.1. **System parameters**

For the symmetric scenario an equal average SNR of 20 dB \( (\gamma = 100) \) for all devices is considered. The BER threshold is set to \( \omega = 0.001 \). \( K = 100 \) devices are considered. The multi-antenna scheme is studied for 1x1 SISO \( (M = N = T = Q = 1) \) and 1x2, 1x4 and 1x8 MISO \( (M = T = Q = 1, N = 2, 4, 8) \) schemes. For the FF-NDMA scheme two different antenna configurations are evaluated: 1x1 SISO \( (M = N = T = Q = 1) \) and 2x2 MIMO with Alamouti OSTBC (i.e. 2 antennas at every device and base station \( (M = N = T = Q = 2) \). Results are shown for different CP lengths \( (R = 1, 2, 3, 4) \). The power consumption levels are extracted from [5] (i.e. \( P_0 = 0.01 \) mW, \( P_1 = 10 \) mW and \( P_2 = 300 \) mW).

For the asymmetric scenario, devices are uniformly spread over a circular area of radius \( w = 10 \). The MPR matrix is computed considering \( U = 30 \) repetitions, following the procedure described in (11). SNR conditions are expressed in path loss terms, which can be written as a function of the distance from each device to the base station:

\[
L(dB) = 10\alpha \log_{10}(d) \tag{31}
\]

Where \( d \) is the distance to the base station, and \( \alpha \) the path loss exponent, that according to [35] has values from 2 to 5 in most cases. For our analysis we will suppose \( \alpha = 2 \), corresponding to a free-space with Line-Of-Sight scenario.

![Path loss as a function of distance](image)

*Figure 15: path loss variation vs. distance for different path loss exponents*
For the sectorised scenario, the coverage area is divided into two ring-shaped regions. The threshold separating both areas will be found after analysing the results in the symmetric scenario as a function of the SNR. Either a different behaviour in throughput, delay or energy after a certain SNR value is reached will serve us to derive thresholds, different for SISO and MIMO configurations.

4.2. **Evaluation of different MPR strategies in symmetric scenarios**

4.2.1. **Multi-antenna systems (R = 1)**

4.2.1.1. **Metrics analysis as a function of the load**

Since we are considering a symmetric scenario, the transmitted power and the path loss are the same for every user. Let us recall that the different MIMO scenarios that we will study are a particular case of the FF-NDMA scheme with \( R = 1 \). Besides, it will be interesting to compare these results to the ones obtained with the conventional slotted ALOHA configuration (where the MPR matrix defined in (8) is used).

In the following plots, we can see throughput, delay and energy as a function of the load for the variable \( \nu \) (left column) and for the fixed \( \nu \) (right column) policies. The variable \( \nu \) policy will also be compared to conventional slotted ALOHA.

It is noticeable that by using spatial diversity at the receiver, dramatically better results can be obtained for all metrics (higher throughput and lower delay and energy consumption). Since good SNR conditions are considered, the value of \( C_{11} \) in the MPR matrix (5) is almost one in the SISO case. Slotted ALOHA assumes perfect decoding when a single packet is sent, so \( C_{11} = 1 \); hence, in all metrics slotted ALOHA yields slightly better results than the SISO case. However, as spatial diversity is introduced, results improve significantly.

Figure 16.(a),(b) show throughput (in packets/slot) vs. the offered load for the variable and fixed backoff policies, respectively. In the former (\( \nu = \sigma \)), throughput increases with load until a point above which throughput begins to decay; whereas in the latter (\( \nu = 1/K \)), after reaching the maximum throughput, it is approximately maintained when shifting towards higher load due to the capture effect for finite-user random access with \( \sigma \gg \nu \) [31].

Figure 16.(c),(d) displays delay (in slots) as a function of the load for both backoff policies, and Figure 16.(e),(f) energy (in mWxslot) vs. load for the same policies. Both metrics exhibit a similar behaviour: for the \( \nu = \sigma \) policy, both delay and energy grow rapidly with load (as more antennas are used at the base station, both metrics are reduced, but the growth is still fast). Thus, at high loads it is impractical to adopt this policy, since throughput becomes null and instability is reached. On the other hand, for the \( \nu = 1/K \) policy, delay and energy grow fast at low loads, but at medium-high loads they remain nearly constant. Introducing spatial diversity helps reducing these values.
Figure 16: Metrics as a function of load for multi-antenna systems
4.2.1.2. Metrics analysis as a function of the SNR

It is interesting to see how the different metrics vary as a function of the SNR, which might give important information about the best configuration to adopt depending on whether the SNR conditions are good or bad. This analysis will be done for fixed values of $\nu$ and $\sigma$, so we will consider two main different situations: low load values ($\sigma = 1/K = 0.01$ packets/slot) and higher ones ($\sigma = 5/K = 0.05$ packets/slot). In both cases, we will use the $\nu = 1/K$ policy; however, in the high load case we will also analyze the effects of increasing the retransmission rate to the value of the arrival one. Thus, both $\nu$ and $\sigma$ will be equal to $5/K$.

The following plots show the variation of the metrics along the SNR for the three described situations.

- **Throughput vs. SNR**

![Throughput vs. SNR](image)

(a): $\nu = \sigma = 1/K$
(b): $\nu = 1/K$, $\sigma = 5/K$
(c): $\nu = \sigma = 5/K$

*Figure 17: Throughput vs. SNR*
Figure 17.(a), (b) and (c) show throughput (packets/slot) as a function of the SNR. In all figures it can be seen that at low SNR values, using more antennas improves the throughput values. Note that in Figure 17.(a), and (c), \( \nu = \sigma \), and the maximum achievable throughput values are determined by Figure 16.(a): at low loads, using spatial diversity increases throughput, but not as quite as at medium-high loads, where the improvement is significant (since \( \nu = \sigma = 5/K \) corresponds to the throughput peak in Figure 16.(a) for \( N = 8 \), whereas at \( \nu = \sigma = 1/K \) throughput is still growing for that same configuration, and does not yield important benefits at high SNRs with respect to lower schemes). On the other hand, lower antenna configurations have already started their decay vs. load at \( \nu = \sigma = 5/K \), so the maximum achievable throughput is reduced.

- **Delay vs. SNR**

![Delay versus SNR (K=100 users)\( (\nu=1/K, \sigma=1/K) \)](image)

![Delay versus SNR (K=100 users)\( (\nu=1/K, \sigma=5/K) \)](image)

![Delay versus SNR (K=100 users)\( (\nu=5/K, \sigma=5/K) \)](image)

*Figure 18: Delay vs. SNR*
• Energy vs. SNR

Figure 18 and Figure 19 depict delay and energy vs. SNR, respectively. Both behave similarly in the sense that as SNR increases, they diminish down to a constant level. Using spatial diversity helps reducing this level (the reduction is significant at higher schemes like $N = 8$). However, we can anticipate from Figure 16.(d) and (f) that as load increases while keeping the retransmission probability constant ($\nu = 1/K$), both delay and energy will slightly grow (Figure 18.(a), (b) and Figure 19.(a), (b)). Figure 18.(c), and Figure 19.(c) show that as both generation and retransmission probabilities increase ($\nu = \sigma = 5/K$), results in terms of delay and energy become dramatically worse (except for $N = 8$, which presents its peak in throughput and good delay and energy values at this specific load).
4.2.2. Feedback-free NDMA MIMO systems

4.2.2.1. Metrics analysis as a function of the load

In this section the FF-NDMA model in terms of throughput, delay and energy is evaluated for the previously described configurations (SISO and MIMO 2x2) for different CP lengths \( R = 1, 2, 3, 4 \) and for two different backoff schemes \( \nu = \sigma \) and \( \nu = 1/K \). In the following plots, we can see throughput, delay and energy as a function of the load for the variable \( \nu \) (left column) and for the fixed \( \nu \) (right column) policies.

Figure 20.(a) and (b) depict throughput as a function of the offered load for both backoff policies \( \nu = \sigma \) and \( \nu = 1/K \), respectively. It can be seen that using MIMO schemes over SISO ones yields much better throughput values for both policies. Figure 20.(a) shows that throughput grows at low loads until a peak, above which it starts decaying. Using a larger \( R \) helps increasing the maximum achievable throughput as well as delaying its decay with load, enlarging the stability region. Figure 20.(b) displays throughput for the fixed backoff policy. At low loads throughput grows until a maximum level is reached; then, it remains constant. This growth is slower for high \( R \), but on the other hand, higher throughput values can be reached. Therefore, switching points exist such that at low loads it is wiser to use several slots per CP even with the \( \nu = 1/K \) criterion.

Figure 20.(c) and (d) depict delay for \( \nu = \sigma \) and \( \nu = 1/K \), respectively; and Figure 20.(e) and (f) do the same with energy. For the \( \nu = \sigma \) policy, both delay and energy grow rapidly to infinity with load. Using MIMO schemes over SISO schemes and high \( R \) values, delay and energy are reduced but their growth is still very fast. Hence, at high loads it might be more practical to use the \( \nu = 1/K \) policy, since a maximum level both in delay and energy can be reached, which can be lowered by using MIMO schemes and longer CPs.
Figure 20: Metrics as a function of load for FF-NDMA MIMO systems
4.2.2.2. Metrics analysis as a function of the SNR

It is interesting to see in the FF-NDMA model too how the different metrics vary as a function of the SNR, which might give important information about the best configuration to adopt depending on whether the SNR conditions are good or bad. This analysis will be done for fixed values of $\nu$ and $\sigma$, so we will consider two main different situations: low load values ($\sigma = 1/K = 0.01$ packets/slot) and higher ones ($\sigma = 5/K = 0.05$ packets/slot). In both cases, we will use the $\nu = 1/K$ policy; however, in the high load case we will also analyze the effects of increasing the retransmission rate to the value of the arrival one. Thus, both $\nu$ and $\sigma$ will be equal to $5/K$.

The following plots show the variation of the metrics along the SNR for the three described situations:

- **Throughput vs. SNR**

![Throughput vs. SNR plots](image)

(a): $\nu = \sigma = 1/K$

(b): $\nu = 1/K$, $\sigma = 5/K$

(c): $\nu = \sigma = 5/K$

*Figure 21: Throughput vs. SNR*
Figure 21.(a), (b) and (c) show throughput (packets/slot) as a function of the SNR. In Figure 21.(a) and (c), \( \nu = \sigma \), so these values are reflected in Figure 20.(a): since higher MIMO schemes and larger CP configurations grow slower with load, at \( \sigma = 1/K \) (Figure 21.(a)) the configuration with one slot per CP (especially for the MIMO case) reaches its maximum throughput. However, the MIMO \( R = 4 \) configuration does not improve the SISO case at high SNR values, since throughput has not reached its peak as a function of load yet. On the other hand, in Figure 21.(c) the value of the load is higher, which approximately corresponds to the peak of the \( R = 4 \) MIMO scheme, which overpasses the other 2x2 MIMO schemes at high SNR values. At this load value, it is especially notorious the decay of the \( R = 1 \) MIMO configuration, which presents worse values than the \( R = 4 \) SISO one. Figure 21.(b) shows that better throughput values can be obtained by keeping \( \nu \) fixed (according to Figure 20.(b)). At high SNR values it is wiser to use several slots per CP, but it can be observed that at low SNR it is better to use few slots, so a switching point exists where a specific CP configuration might be better than others.
This behaviour is also found in delay (Figure 22) and energy (Figure 23). Switching points exist above which it is better to use several slots per CP, and below which a one-slot CP is desirable. MIMO schemes help reducing the minimum attainable values in both delay and energy; in addition, they shift the switching point to a lower SNR value with respect to the SISO one. It can be seen as well that by moving toward higher loads, the minimum reachable delay and energy values grow, especially if the retransmission probability grows too, as the increase in traffic is notable.

- **Energy vs. SNR**

![Energy versus SNR (K=100 users)\(\sigma = 1/K, \nu = 1/K\) (a): \(\nu = \sigma = 1/K\)](image)

![Energy versus SNR (K=100 users)\(\sigma = 5/K, \nu = 1/K\) (b): \(\nu = 1/K, \sigma = 5/K\)](image)

![Energy versus SNR (K=100 users)\(\sigma = 5/K, \nu = 5/K\) (c): \(\nu = \sigma = 5/K\)](image)

*Figure 23: Energy vs. SNR*

### 4.2.2.3. Stability analysis

In this section the two described stability policies in section 3.3 are evaluated, i.e. stability based on the probability of the state \(K (\pi_k)\) and stability based on the mean number of devices in the backlog \(\bar{B}\). Figure 24 shows the variation of \(\pi_k\) along \(\nu\) and \(\sigma\).
Figure 24: probability of having all users backlogged for SISO and MIMO schemes with different values of $R$ for $K=100$ users (SNR = 20 dB)
It can be observed that by increasing the CP length or by using higher antenna configurations, lower $\pi_K$ values are obtained and the stability region is thus expanded. For instance, if for a fixed value of $\sigma$ the stability condition is $\pi_K < 0.1$ then larger values of $\nu$ are available to meet the stability condition by using several slots or larger MIMO schemes.

Let us now analyse the results by setting the aforementioned threshold on $\pi_K < 0.1$. Figure 25 shows the metrics as a function of $\nu$ such that the stability condition is fulfilled:

Figure 25: Metrics versus $\nu$ such that the stability condition on probability of all devices being backlogged is met for $\sigma = 0.1$ and $K = 100$ devices

Figure 25.(a), (b) and (c) show throughput, delay and energy as a function of $\nu$. All plots show that by using more slots and more antennas, higher $\nu$ can be used as the stability region is enlarged. Anyway, better results in terms of all three metrics are obtained when choosing low retransmission probabilities (around $\nu < 0.02$).

Figure 26 displays the variation of $\bar{B}$ along $\nu$ and $\sigma$ for different antenna configurations with different CP lengths.
Figure 26: mean number of backlogged users for SISO and MIMO schemes with different values of $R$ for $K=100$ users (R=1,SISO), SNR = 20 dB.
It can be seen that using a larger amount of slots per CP or using more antennas, lower values of $B$ are obtained and thus the stability region is enlarged. It is noticeable that as $\sigma$ increases, the system saturates rapidly in terms of number of backlogged devices (this condition is more restrictive than keeping the probability of all devices being backlogged under a certain level).

Let us now analyse the results by setting the threshold on $B < 80$. Figure 27 shows the metrics as a function of $\nu$ for $\sigma = 0.1$ such that the stability condition is fulfilled.

![Throughput](image1)
![Delay](image2)
![Energy](image3)

(a): Throughput  
(b): Delay  
(c): Energy

Figure 27: Metrics versus $\nu$ such that the stability condition on mean number backlogged devices is met for $\sigma = 0.1$ and $K = 100$ devices

Figure 27.(a), (b) and (c) show throughput, delay and energy as a function of $\nu$. The most remarkable result is that configurations regarding number of antennas and CP length that do not meet the stability condition for any $\nu$ are not displayed. For $\sigma = 0.1$, the condition such that $B < 80$ is only met for MIMO schemes with $R \geq 3$ (and is not satisfied for any SISO configuration with $R \leq 4$).

Let us now analyse the results by setting the threshold on $B < 80$ but with $\sigma = 0.05$. Figure 28 shows the metrics as a function of $\nu$ such that the stability condition is fulfilled.
Figure 28: Metrics versus $\nu$ such that the stability condition on mean number backlogged devices is met for $\sigma = 0.05$ and $K = 100$ devices

Figure 28.(a), (b) and (c) show that for a lower traffic rate, the stability region is enlarged (and thus more values of $\nu$ can be chosen) with respect to the previous case and more configurations are available. For $\sigma = 0.05$, $B < 80$ is met for SISO schemes with $R \geq 3$ and for MIMO schemes with $R \geq 2$. Note that for both values of $\sigma$, choosing low retransmission probabilities yields better results.

4.2.2.4. Backoff techniques

In this section we will analyse the five different backoff techniques described in section 3.4 for the symmetric FF-NDMA scheme with SISO and MIMO 2x2 configurations and $R = 1, 2, 3, 4$. We will compare all policies in terms of the previously defined metrics and conclude which one might be best for our purposes.
• Throughput comparison

Figure 29 shows the obtained throughputs for each of one of the policies.

(a): $\nu = \sigma$ policy

(b): $\nu = 1/K$ policy

(c): maximum S policy

(d): minimum $\pi(K)$ policy

(e): minimum B policy

Figure 29: Throughput vs. offered load for different backoff policies
It can be seen (as in Figure 20.(a)) that by using a variable $\nu$ equal to $\sigma$ (not making distinction between generated and backlogged packets), a maximum level at low loads is achieved but as the load increases, the throughput diminishes (Figure 29.(a)). Using more slots per CP increases the value of the maximum achievable throughput, and its decay is slower; hence, if $\sigma$ takes high values, it might be wiser to use several slots per CP. By adopting MIMO configurations, the throughput can noticeably increase.

Using a fixed $\nu$ equal to the inverse of the total number of users (which according to stability results in section 4.2.2.3 can provide good results), after reaching the maximum throughput, it is approximately maintained when shifting towards higher loads (Figure 29.(b)). The rest of policies (Figure 29.(c), (d) and (e)) do not use a fixed $\nu$, but its variation is not as significant as in the first policy, so the behaviour of reaching and keeping the maximum level is repeated. It is interesting to note that the maximum throughput policy (Figure 29.(c)) manages to increase throughput along with load above that level.

- **Delay comparison**

Figure 30 depicts the obtained delays for each of one of the policies.

It can be seen from Figure 30.(a) that for the variable $\nu$ policy, delay grows rapidly to infinity as loads increase. By using more slots delay can be reduced, but the growth is still too fast. Thus, at high loads it will be impractical to adopt this policy (as throughput is null, the instability region is reached).

The fixed $\nu$ (Figure 30.(b)) and optimum policies (Figure 30.(c), (d) and (e)) present similar behaviours: delays grow fast at low loads, but at medium-high values of the load a maximum level is reached above which it remains constant or varies very little. When using more slots per CP, delays are reduced. Hence, it might be interesting to use several slots per CP; in addition, MIMO schemes notably reduce delays respect to SISO ones.

The optimum throughput policy (Figure 30.(c)) also shows a slight delay diminishment at very high loads, as throughput was quite high at such loads.

- **Energy comparison**

Figure 31 shows the obtained energy for each of one of the policies.

As it occurred with the delay (Figure 30.(a)), for the $\nu = \sigma$ policy (Figure 31.(a)), energy grows rapidly to infinity with load. Increasing the number of slots per CP and using MIMO schemes reduces the energy consumption, but it still results impractical for scenarios with medium-high loads.

The other policies (Figure 30.(b), (c), (d) and (e)) have similar behaviours between them: energy rapidly grows until a load level after which it remains constant. Using longer CPs or MIMO configurations instead of SISO ones can help reducing the energy consumption with respect to SISO schemes.
\( \nu = \sigma \) policy

\( \nu = \frac{1}{K} \) policy

maximum \( S \) policy

minimum \( \pi(K) \) policy

minimum \( B \) policy

Figure 30: Delay vs. offered load for different backoff policies
Figure 31: Energy vs. offered load for different backoff policies

(a): $u = \sigma$ policy

(b): $u = 1/K$ policy

(c): maximum $S$ policy

(d): minimum $\pi(K)$ policy

(e): minimum $B$ policy
4.3. **Evaluation of different MPR strategies in asymmetric scenarios**

4.3.1. **Non-sectorised scenario**

4.3.1.1. **FF-NDMA MIMO scheme: metrics analysis as a function of the load**

In this scenario the user terminals are uniformly spread over the coverage area, which we suppose of radius $W$ (that we will set equal to 10, as specified in section 4.1). Figure 32 shows the distribution of devices in the area:

![Distribution of the user devices](image)

*Figure 32: Spatial distribution of devices in the asymmetric scenario*

Figure 33 displays throughput, delay and energy as a function of the load for the $\nu = \sigma$ (left column) and for the fixed $\nu = 1/K$ (right column) policies.

We can see how overall SNR conditions are worse, so the results are not as good as in the symmetric scenario, where we assumed a good value of the SNR (20 dB). May the mean SNR value (of all devices) serve as a reference taking into account every user: around 7.4 dB. Even considering repetitions (11) that account for good and bad conditions, in some cases the majority of devices have good SNR values and in other cases they have poor SNR values. This phenomenon explains the randomness of the obtained results (e.g. MIMO scheme with $R = 3,4$), since for each curve the active users are different.
Throughput versus offered load (100 users) ($\alpha = \sigma$)

Throughput versus offered load (100 users) ($\alpha = 1/K$)

Delay versus offered load (100 users) ($\alpha = \sigma$)

Delay versus offered load (100 users) ($\alpha = 1/K$)

Energy versus offered load (100 users) ($\alpha = \sigma$)

Energy versus offered load (100 users) ($\alpha = 1/K$)

Figure 33: Metrics as a function of load for a MIMO FF-NDMA asymmetric system
4.3.2. Sectorised scenario

4.3.2.1. FF-NDMA MIMO scheme

As we previously introduced in the description of the different scenarios, in the sectorised strategy we will only analyze throughput. That is due to the fact that both sectors are studied separately and later, both throughput values are combined using two different schemes that do not straightforwardly apply for the analysis of delay and energy consumption.

Let us first derive the thresholds that will separate both regions. For our analysis, we will choose them considering the metrics analysis as a function of the SNR. Let us take into account for our study the case where the generation probability is higher than the retransmission probability \( \nu = 1/K \) and \( \sigma = 5/K \). Note from Figure 21(b), Figure 22(b) and Figure 23(b) (throughput, delay and energy) that up to a certain SNR level, it is convenient to use as few slots as possible per CP; but above that level, using many slots per CP yields better results for all metrics. Note as well that for MIMO cases the SNR threshold appears at a lower SNR level than for SISO ones.

Although these SNR thresholds are slightly different in the throughput, delay and energy plots, let us approximate them as 5 dB for MIMO and 8.5 dB for SISO. Losses for both SISO and MIMO cases can be obtained subtracting the SNR levels to the average SNR (20 dB). Then, such losses can easily be translated into distance with expression (31). The resulting distances are 3.76 m in the SISO case (straight line in Figure 34) and 5.62 m in the MIMO case (dotted line in Figure 34), both from the base station.

It is interesting to notice that by increasing the number of antennas, the threshold SNR levels are lowered; that is, that the range of SNR values where it is more convenient to use several slots per CP will become larger.

![Figure 34: Spatial distribution of devices in the asymmetric sectorised scenario](image)

After having computed the throughput for each sector in a separate way, several ways of combining them can be studied. Some of them might try to find a fair sharing between users of both sectors, and others focus into achieving a better global throughput. The idea of combining consists on controlling the amount of time reserved for each sector to transmit. Based upon this concept, we can study two main approaches:
• **‘½’ scheme**

If we write as $T_1$ and $T_2$ (such that $T_1 + T_2 = 1$) the time destined for users in regions 1 and 2, respectively; the **‘1/2’ method** states that the same amount of time is dedicated for both sectors, which makes the total throughput equal to the arithmetic mean between both throughputs.

$$S_{total(1/2)} = \frac{S_1 + S_2}{2}$$  \hspace{1cm} (32)

A more general expression can be derived for the case where the coverage area is divided into $Z$ sectors:

$$S_{total(1/Z)} = \frac{\sum_{z=1}^{Z} S_z}{Z}$$  \hspace{1cm} (33)

• **‘Fair’ scheme**

On the other hand, the **‘fair’ scheme** will compensate users in the second sector (located further away from the base station) by allowing them more time to transmit than users in the first region. To achieve balanced fairness, the following must hold:

$$S_1T_1 = S_2T_2.$$  \hspace{1cm} (34)

The resulting overall throughput is the following:

$$S_{total(fair)} = \frac{S_1T_1 + S_2T_2}{T_1 + T_2} \rightarrow \frac{2S_1S_2}{S_1 + S_2}.$$  \hspace{1cm} (35)

This scheme can be generalised too for the $Z$ -sector case. The condition that must be satisfied is:

$$S_1T_1 = S_2T_2 = \cdots = S_ZT_Z,$$  \hspace{1cm} (36)

yielding the following expression:

$$S_{total(fair)} = \frac{Z}{\sum_{z=1}^{Z} S_z}.$$  \hspace{1cm} (37)

4.3.2.1.1. **Throughput analysis as a function of the load**

The throughput analysis is performed for the cases where each CP has 1 and 2 slots, for both SISO and 2×2 MIMO configurations. Figure 35 depicts both combining techniques in terms of throughput.
For a $\phi = 1/K$ value, as the load increases, throughput attains a nearly constant level. In the first sector (the closest one to the base station), the SNR conditions are good, and when the number of slots per CP is increased, the maximum achievable levels are slightly increased, both in the SISO and the MIMO case. However, in the second sector (the farthest one) the SNR conditions are much worse. According to Figure 21(b), increasing the number of slots per CP will yield significantly lower throughput values.

Thus, when adopting the combining strategies, configurations with higher $R$ values will be degraded by the throughput values from the farthest sector, which severely decreases throughput as the number of slots per CP increases. The $1/2$ scheme begins to show this behaviour for $R = 2$ in both antenna configurations, and the throughput is worsened by the values from the second sector. The ‘fair’ scheme yields even lower throughputs, since the second-sector devices are given much more time to transmit than first-sector devices. It can be also seen, that using several slots per CP returns lower throughput values than the $R = 1$ cases (the penalty in throughput is more severe), when comparing it to the $1/2$ scheme. However, by using higher antenna schemes, those throughput penalties can be mitigated, and using several slots per CP might prove more convenient.
5. **Conclusions and future development**

This thesis evaluates the potential benefits of the feedback-free NDMA scheme in different cellular scenarios in terms of throughput, mean access delay and energy. The principle of operation of the FF-NDMA scheme is to resolve collisions by means of packet repetitions during a contention period (CP). It has been analysed that, by using one-slot CPs, FF-NDMA can also model the slotted ALOHA scheme. Different antenna configurations have been evaluated for the one-slot case, showing that increasing the number of receive antennas can significantly improve the results in terms of all three metrics.

On the other hand, increasing the CP length helps increasing throughput and reducing delay and energy when the SNR conditions are good. In bad channel conditions, the metrics can additionally be improved by adopting higher MIMO schemes (the configuration studied in this document is the 2x2 MIMO Alamouti scheme) with multiple slots per CP. Stability criteria also shows that using larger CPs along with higher MIMO configurations can enhance the stability region, allowing a wider range of generation and retransmission probabilities.

Different backoff strategies have also been evaluated in terms of all three metrics. The obtained results show that little-varying retransmission probabilities help maintaining good results as the offered load increases. In particular, the maximising-throughput policy delivered excellent results at higher loads. The results of the metrics in terms of stability are also useful to confirm that using low retransmission probabilities (around $\nu = 1 / K$) the obtained metrics reach optimum values.

The FF-NDMA scheme has also been analysed in terms of all three metrics as a function of the SNR. The most interesting result is that shifting points in SNR exist below which it is better to use short CP lengths, and above which it is better to use as many slots per CP as possible. By adopting higher MIMO schemes, those shifting points can be lowered such that even in bad SNR conditions, it might be beneficial to use several slots per CP.

This analysis has been made for a symmetric scenario (all devices have similar SNR values), but an asymmetric cellular scenario with two subcases (non-sectorised and sectorised) has also been studied. The SNR analysis has been useful to derive distance thresholds in the sectorised scenario considering the aforementioned SNR shifting points.

In the sectorised scenario, where only two ring-shaped regions were considered, two different strategies have been reviewed to combine resulting throughputs from each area: the $\frac{1}{2}$ scheme and the ‘fair’ one. In the $\frac{1}{2}$ scheme, devices from each area are given the same amount of time to transmit, so the final throughput is the average of the sectors throughput. In the ‘fair’ scheme, the more distant devices (and with worse SNR conditions) are given more time to transmit than closer devices to the base station, which results in a worse global throughput but improves system fairness. However, adopting higher antenna schemes can enhance the maximum achievable levels in throughput, and in addition, lower the SNR shifting point. In these configurations, even when the SNR conditions are bad, using larger CP lengths will yield better results in terms of all metrics.

Future work on this thesis could be continued, especially in the asymmetric sectorised scenario, where only throughput has been studied. Delay and energy calculation proved to be more complex, since the time assigned to each sector to transmit has to be taken into account as well.
In conclusion, FF-NDMA provides a promising solution for MTC systems, since by reducing the number of collisions, performance in terms of throughput, delay and energy is significantly improved. In addition, its feedback-free nature provides a reduction of the overhead, which can successfully address bursty traffic. Potential massive MTC traffic can be effectively served by using several antennas at the base station; such MIMO schemes would also yield an important enhancement in coverage.
Bibliography


