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An Agent-Based Communication Architecture to Hybrid NOMA-OMA Decisions

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Dedication

This dissertation is dedicated to my family and girlfriend, for all the support and belief that I was capable to achieve the goals needed to conclude the Master degree in Computer Science. This dissertation is also dedicated to my advisors who contributed greatly through all the research. In memory of my beloved godfather and uncle, Jose Henrique.

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Resumo

O avanço das tecnologias relacionadas a Internet das Coisas, Industria 4.0 e as novas formas de consumo de dados móveis intenisficaram problemas já existentes em redes de comunicação móvel e criaram novos desafios para que redes futuras possam operar e prover qualidade aos usuários no serviço prestado. Os problemas enfrentados pelas redes móveis são derivados do aumento do número de dispositivos que se conectam a rede, principalmente quanto a densificação das conexões em pequenos espaços, como fábricas, praças públicas, estádios, entre outros, resultando em uma falta de recursos espectrais disponíveis para atender todos os dispositivos. O espectro é um recurso finito e com um custo elevado que deve ser utilizado de maneira eficiente, contudo, as técnicas de comunicação empregadas atualmente estão atingindo o seu limite de capacidade, sendo necessário a busca por novas formas de transmissão que utilizem os recursos espectrais de forma mais eficiente.

Para atender os requisitos de redes 6G e as novas demandas de consumo de dados móveis, uma nova técnica de transmissão, com o potencial de atender novas demandas, conhecida como Acesso Múltiplo Não Ortogonal, é estudada e aprimorada para a sua utilização em redes de comunicação móvel. A técnica utiliza a multiplexação de usuários no domínio do tempo e da frequência, assim como as técnicas atuais, que são baseadas no Acesso Múltiplo Ortogonal, além disso, um novo domínio é adicionado a multiplexação de usuários, aumentando a capacidade e eficiência da rede. O Acesso Multiplo Não Ortogonal permite que usuários compartilhem o mesmo recurso de tempo e frequência sendo diferenciados pela potência que é destinada a cada usuário que compartilha o recurso.

Devido a quantidade limitada de recursos de tempo e frequencia para a transmissão de dados, a multiplexação de usuários pela potência permite um aumento da capacidade da rede e uma utilização mais eficiente dos recursos em troca da adição de interferência entre os usuários que compartilham os mesmos recursos. Em contraste, as técnicas baseadas no Acesso Múltiplo Ortogonal visam utilizar os recursos de forma exclusiva para cada usuário, minimizando a interferência entre usuários, por outro lado, os recursos não são utilizados com a máxima eficiência e a capacidade se limita a quantidade de espectro disponível.

As duas técnicas citadas apresentam problemas que não podem ser evitados e a utilização individual de uma das técnicas pode não ser suficiente para atender os requisitos. Para o Acesso Multiplo Não Ortogonal, a adição de interferência, se não for controlada, pode inviabilizar a transmissão de dados. Para o Acesso Multiplo Ortogonal, a capacidade limitada pode não atender o aumento da densidade de conexões em redes 6G. Para evitar problemas individuais inerentes as duas técnicas, a utilização conjunta de ambas em uma única rede, pode trazer os benefícios do aumento da capacidade pelo Acesso Multiplo Não Ortogonal e quando necessária, uma comunicação livre de interferência para os dispositivos.

Esse trabalho propõe o desenvolvimento de uma nova arquitetura de comunicação, baseada em Sistemas Multi Agentes para a operação e gerenciamento de uma rede móvel em relação aos recursos espectrais e decisões entre técnicas de transmissão com o objetivo de aumentar a Eficiência Espectral da rede. Chamada de *Adaptive Hybrid Non Orthogonal Multiple Access (AH-NOMA)*, a arquitetura foi desenvolvida para ser implementada na unidade de processamento de uma antena. A arquitetura proposta, implementa dois tipos de agentes que executam suas funções diferentes granularidades de tempo. Essas granularidades são da ordem de segundos, para um gerenciamento de pares e alocação de potência, e milissegundos para a tomada de decisões entre utilizar o Acesso Multiplo Não Ortogonal para o compartilhamento de espectro entre os usuários e o escalonamento de usuários em recursos ortogonais.

Os agentes implementados pela aequitetura são responsáveis pela decisão de qual técnica de transmissão deve ser utilizada para cada usuário presente na rede. Caso dois usuários possam compartilhar o mesmo recurso em uma transmissão não ortogonal, os agentes são responsáveis por realizar o pareamento de usuários e definir a potência necessária para cada usuário que compartilha o recurso. A decisão de compartilhar o mesmo recurso é baseada na demanda de cada usuário, ou seja, se os usuários puderem ter suas demandas satisfeitas compartilhando um mesmo recurso, sem que a comunicação sofra algum tipo de prejuízo, então utiliza-se o Acesso Multiplo Não Ortogonal. Caso os usuários possuam demandas que não possam ser atendidas através do compartilhamento de recursos, os usuários são alocados em recursos de forma ortogonal, consequentemente provendo uma comunicação livre de interferência.

A existência de uma relação inversa entre as duas técnicas, a adição de interferência reduzindo a qualidade do sinal transmitidos e a limitação de capacidade de atender usuários pela utilização individual de recursos, permite o desenvolvimento de uma otimização para maximizar a eficiência utilizando as duas técnicas para um conjunto de usuários. A otimização é utilizada pelos agentes para parear usuários e definir o modo de transmissão, alem de definir a potência necessária para cada usuário pareado. O funcionamento da arquitetura é baseada no *Contract Net Protocol*, um protocolo de comunicação entre agentes. O agente que opera na ordem de segundos colhe informações dos usuários a respeito da qualidade de canal e demandas de taxa de dados que devem ser cumpridas. Essas informações são armazenadas e utilizadas como variáveis na otimização. O agente então escolhe aqueles usuários mais adequados a compartilharem recursos espectrais e repassa ao agente que opera na ordem de milissegundos. Por vez, sua função é definir se os usuários pareados pelo outro agente podem ser alocados nos recursos não ortogonais ou devem ser escalonados para recursos ortogonais. Os agentes visam reduzir a complexidade do pareamento, alocação de recursos e as decisões tomadas a respeito da técnia de transmissão utilizada.

Diversas simulações foram realizadas para o estudo da relação entre os dois modos de transmissão e para a operação da arquitetura proposta. Os resultados foram comparados com outras abordagens propostas na literatura, a arquitetura se mostrou capaz de aumentar o número de usuários pareados para transmissões não ortogonais, reduzindo o número de recursos utilizados e aumentando a eficiência espectral da rede. Em termos numéricos, a arquitetura é capaz de parear mais de 60% dos usuários para recursos não ortogonais aumentando a eficiência espectral em mais de 20% quando comparado a abordagens que utilizam o Acesso Multiplo Não Ortogonal e aumentando em mais de 50% a eficiência espectral quando comparado com uma abordagem que apenas utiliza o Acesso Multiplo Ortgonal. Um aumento na quantidade de usuários pareados significa prover o serviço demandado por cada usuário, utilizando uma quantidade menor de recurso se comparado com a utilização ortogonal destes recursos. Dessa forma a relação entre a quantidade de usuários que podem compartilhar o mesmo recurso e a eficiência espectral da rede é diretamente proporcional.

A arquitetura ainda pode ser utilizada com diferentes objetivos além de buscar maximizar a eficiência espectral da rede como apresentado neste trabalho. Por exemplo, a utilização de métricas de eficiência energética, que buscam maximizar a quantidade de informação transmitida por unidade de energia consumida, ou objetivos como maximizar a justiça entre os serviços providos a cada usuário na rede, onde o pareamento e a alocação de potência para cada usuário busca padronizar o serviço que cada usuário recebe, assim a rede consegue fornecer um serviço mínimo comum a todos os usuários independente da qualidade de canal que cada usuário possui na rede. Além da flexibilidade na utilização de diferentes métricas, que também podem ser exploradas de forma adaptativa e dinâmica devido as características de agentes inteligentes que são implementados em cada antena. Existe ainda, a possibilidade de extensão da arquitetura para a utilização de outras tecnologias complementares as tecnologias de Acesso Múltiplo como ondas milimétricas, Múltiplas Entradas e Múltiplas Saídas (MIMO) e Superfícies refletoras inteligentes (IRS). A cooperação entre diversas arquiteturas implementadas também pode ser desenvolvida futuramente de forma a tornar o autônomo e eficiente, o gerenciamento e operação de um cenário composto por diversas estações de transmissão.

Palavras-chave: Non Orthogonal Multiple Access (NOMA), Multi Agent, Beyond 5G (B5G)

Abstract

The emerging of Internet of Things (IoT) and Industry 4.0, will massively increase the demand for connectivity and raise Quality of Service (QoS) requirements. New demands on data rates, latency, reliability, and other requirements push the limits of current mobile communication systems, making the spectrum scarcity problem even deeper. To overcome these limits, new techniques can be explored to provide an enhanced Spectral Efficiency (SE) and improve the capacity of users in the network. The current transmission techniques are based on the Orthogonal Multiple Access (OMA) schemes, which minimize the interference between users by allocating each user individually in one resource. This leads to underutilized resources and a limited capacity of users since the spectrum resources are limited. To overcome these drawbacks Non Orthogonal Multiple Access (NOMA) adds a new degree of freedom to multiplex users by different power allocation while sharing the same resource. The sharing of resources between users can enhance the capacity and reduce the number of underutilized resources, but it comes with a price to pay regarding the inter-user interference between devices sharing the same resources. Although both techniques are often considered in concurrent networks by the literature, both NOMA and OMA technologies present individual benefits and drawbacks. The interchange between both techniques can compensate the individual drawbacks, creating communication opportunities to enhance SE and improve capacity. To turn feasible such an interchanging technique, this work models a spectrum sharing problem and proposes a Multi Agent-Based Communication Architecture to make decisions in order to take advantage of the trade-off between a limited connectivity provided by OMA and the inter-user interference that is inherited from NOMA. Through our simulations, our results highlight opportunities to interchange NOMA and OMA meeting QoS requirements with enhanced SE. Named as AH-NOMA, the proposed architecture is based on the Contract Net protocol to dynamically allocates power and users. AH-NOMA is able to effectively improve the number of paired users and enhance the total spectral efficiency by more than 20% when compared to conventional NOMA scheme and over 50% comparing with OMA scheme.

The architecture can still be used for different purposes in addition to seeking the spectral efficiency of the network in this work. Maximize the use of energy efficiency services, in order to enhance the transmitted information for each unit of energy. The use of fairness services to provide a minimum common service to all users regardless of the quality of the channel that each user has on the network is also a different approach to AH-NOMA. In addition to the flexibility in the use of differentiated metrics, which can also be explored adaptively and due to the characteristics of intelligent agents that are implemented in each antenna. There is also the possibility of extending the architecture to the use of other complementary technologies such as milimeter Waves (mmWaves), Multiple Input Multiple Output (MIMO) and Intelligent Reflecting Surfaces (IRS). The operation between several architectures can also be developed in the future in order to become autonomous and more efficient in scenarios composed by small cells and numerous antennas.

Keywords: NOMA, Multi Agent, B5G

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Chapter 1

Introduction

As the world experiences the first Fifth Generation of Mobile Communication (5G) deployments, new use cases and technologies start to be developed for the Sixth Generation of Mobile Communication (6G). Advances in IoT and future generations of mobile applications bring an increasing demand for bandwidth and connected devices that leads to a spectrum scarcity problem [1]. The scarcity of spectrum is mainly related to the physical degrees of freedom to transmit information and due to the densification of connectivity in small areas, such as industrial plants, malls, sport stadiums and others [2]. Historically, the transmission of data in mobile networks started with the Frequency Division Multiple Access (FDMA) schemes, evolving approximately every 10 years to the Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) and the Orthogonal Frequency Division Multiple Access (OFDMA). These mentioned techniques belong to a set of orthogonal transmission techniques. Each technique allocates users on a specific resource, FDMA uses frequency bands, TDMA uses time slots, CDMA maps users to different orthogonal spreading sequences and OFDMA merges the FDMA and TDMA schemes. Due to the restricted degrees of freedom to transmit data *i.e.,* time, code and frequency, the massive connection of devices is hampered by the amount of resources available at each antenna and the frequency reuse capacity, that is not sufficient to support a large number of devices [3].

To cope with emerging 6G requirements and to provide more resources and distinct degrees of freedom to transmit information, Next Generation Multiple Access (NGMA) techniques may have to explore new and different forms to transmit data. Non Orthogonal Multiple Access (NOMA) is an emerging technique that exploits a new degree of freedom to transmit information, the power domain, with the potential to meet 6G requirements, such as the massive machine type communication and diverse data rate requirements [4][5]. NOMA still multiplex users in the frequency and time domain as Orthogonal Multiple Access (OMA) does, but it adds the user differentiation also in the power domain.

The current Multiple Access (MA) technique employed on mobile networks, OMA, is based on the orthogonal allocation of resources and provides connectivity minimizing the inter-user interference, that is, each user is allocated individually at one resource without any kind of resource sharing; thus, the capacity of users is limited by the number of available radio resources [2]. Even the employment of MIMO, with the addition of the spatial degree of freedom may not be sufficient to handle NGMA massive connectivity [6].

While OMA struggles to provide an enhanced SE and support a massive number of connected users due to interference mitigation and limited number of available resources [7], NOMA is capable of sharing the same time/frequency/code resource simultaneously between users under the occurrence of inter-users interference [8]. NOMA provides an improved SE with users sharing the same bandwidth, in contrast to OMA schemes that resources can be underutilized by users channel conditions and data rate requirements. NOMA enhance fairness between users and provide higher cell edge throughput [9]. Besides many other features it is important to state that NOMA can achieve the channel capacity limit while OMA schemes generally presents a sub-optimal performance [10].

While NOMA can outperform OMA, reliance on match conditions between users such as channel gain diversity, proper power allocation to users, and data rate demands may not be sufficient to justify NOMA as a dominant or exclusive MA technique in a network [11]. The literature often treats NOMA and OMA as simultaneous techniques of MA and compared both, individually, in studies that present individual advantages and disadvantages that can potentiate or harm 6G deployments.

Instead of view both NOMA and OMA as concurrent MA techniques, combining them can leverage individual features of each, and it can settle the drawbacks that are inherited from both [12]. Combining the techniques leads to what has been called in the literature as Hybrid-NOMA (H-NOMA), which is the combination of techniques with NOMA schemes [1]. As an enabler for such H-NOMA scheme, Cognitive Radio (CR) becomes another vital technology that is rethought for 6G networks. From CR, two main characteristics may be exploited together with NOMA and OMA with a huge potential to provide better SE and greater capacity [13]: (*i*) sharing and selection of unused portions of the spectrum, and (*ii*) CR inherent re-configurable capability to use various frequencies while using different MA technologies. Focusing on the later, 6G networks will be able to interchange MA techniques enabling the deployments of NGMA techniques, such as H-NOMA.

In this work, we propose a Multi Agent-based architecture, AH-NOMA, exploiting CR concepts and Multi-agent Systems (MAS) features such as agents' adaptability and autonomy to enhance SE. AH-NOMA is a MAS that is capable to handle the operation and network management in terms of resource sharing and allocation, user pairing and transmission mode selection. Agents that are the core of the proposed solution can act in different time granularities having their particular attributes aiming for specific predefined goals [14],[15]. Taking advantage of these properties, we place NOMA users pairing process in an agent that acts in the granularity of seconds, collecting information about the devices on the network and deciding the user pairing and proper power allocation.

On a much finer time granularity of fewer milliseconds, we create another agent that decides the user scheduling regarding their MA technique to communicate. Both agents work to reduce the complexity of MA decisions and user pairing and power allocation. This architecture enables AH-NOMA to enhance the network's performance, bringing more flexibility and efficiency than conventional NOMA and OMA schemes. Therefore, AH-NOMA increases the number of paired users, with more than 60% of the users paired to non-orthogonal resources and enhance the total SE by more than 20% when compared to Marcano *et al.* [16] scheme and over 50% comparing with OMA[17] scheme. AH-NOMA is designed to be employed in the processing unit of an antenna, acting as an autonomous controller to handle spectrum sharing decisions and the MA transmission mode for each time/frequency resource available at the antenna. The main contributions of this work are:

- a spectrum sharing scheme to NGMA networks focusing on satisfying the user's data rate requirements with non-orthogonal transmissions;
- an adaptive hybrid spectrum management scheme between OMA and NOMA to maximize the overall SE of the network, sharing resources when possible and providing at least the same performance as OMA scheme;
- an agent-based approach to hybrid NOMA networks dividing the pairing and power allocation of users and MA decision in different time granularities;
- A communication architecture capable of implementing the spectrum sharing with non-orthogonal transmissions, the adaptive hybrid spectrum management and the agents in different time granularities.

The rest of this manuscript is structured as: Chapter 2 presents a literature review of NOMA, a taxonomy is presented to a better understanding of NOMA approaches and the placement of AH-NOMA as a novel architecture, also is presented a review of the employment of MAS combined with NOMA schemes. Chapter 3 presents the System Model that AH-NOMA uses to optimize its performance, the power allocation and user pairing schemes defined as a spectrum sharing problem and all the variables that describe the problems that AH-NOMA solves. Chapter 4 brings a deeper look inside the AH-NOMA architecture, presenting the motivations to adopt a MAS as a network management architectures, the agents development and workflow interaction with the devices. Chapter 5 presents simulations, numerical results and comparisons of AH-NOMA with other NOMA approaches, with an OMA and also with an optimal baseline power allocation scheme. Finally, 6 presents the final remarks of the research and AH-NOMA.

Chapter 2

Related Work

In this chapter, a review of relevant work that surround NOMA and Hybrid NOMA schemes. First, a summary of reviewed surveys is shown in a table presenting an overview of the most researched topics and trends. In the following is presented a taxonomy dividing NOMA into three dominant domains and their variants. For each domain, we characterize different techniques for NOMA schemes highlighting their benefits and drawbacks organized according to Figure 2.1. At the end of this chapter, a literature review of the employment of MAS with NOMA is presented.

2.1 Broadview of Non-Orthogonal Multiple Access

In the literature, surveys cover a wide range of topics, challenges, issues, the state of the art, and future trends around Power Domain NOMA (PD-NOMA) and also Code Domain NOMA (CD-NOMA). The surveys were used to explore new trends and challenges to NOMA that later delimited the problems and the architecture presented in this work.

As Table 2.1 summarizes, surveys approach different NOMA techniques with a variety of goals, including some applications in different networks, emerging radio frequencies, and some topics on the standardization of NOMA.

It is worth mentioning the work of Budhiraja *et al.* [18] that presents a comprehensive review on the PD-NOMA and CD-NOMA to study the various challenges associated with them. The survey is a complete guide to NOMA schemes and the applications in device-to-device (D2D) communication, cooperative communication, cognitive-communication, Machine to Machine (M2M) communication, Simultaneous Wireless Information and Power Transfer (SWIPT), MIMO, massive Multiple Input Multiple Output (mMIMO), Software Defined Network (SDN), Mobile Edge Computing (MEC), Unmanned Aerial Vehicles (UAVs), Visible Light Communication (VLC), mmWave, Heterogeneous Network, and Vehicle-to-everything (V2X). A comparative analysis of NOMA variants is presented based on different transmission scenarios, throughput, sum rate, and other metrics. The presented work also discusses the CD-NOMA variants and a great variety of open issues and challenges of NOMA.

Authors	**Year**	**Title**	**Venue**	**Goals**	**MA Technique**
Ding *et al.* [19]	2017	Non-Orthogonal Multiple Access for 5G Networks: Research Challenges	IEEE Journal on Selected Areas in Communications	Overview of NOMA research results and innovations.	PD-NOMA, SCMA, LDS and PDMA
Makki *et al.* [20]	2020	A Survey of NOMA: Current Status and Open Research Challenges	IEEE Open Journal of the Communications Society	Mainly concentrate on the 3GPP discussions on NOMA.	WSMA-based NOMA
Zhang *et al.* [21]	2017	A Survey of Advanced Techniques for Spectrum Sharing in 5G Networks	IEEE Wireless Communications	Survey of recent techniques for spectrum sharing, summarizing five techniques: CR, D2D , IBFD , NOMA, and LTE-U	PD-NOMA
Zhou *et al.* [22]	2018	State of the Art, Taxonomy, and Open Issues on Cognitive Radio Networks with NOMA	IEEE Wireless Communications	Investigate, categorize, and review the state-of-the-art research efforts made in the domain of CR with NOMA	Cognitive Radio NOMA
Anwar *et al.* [23]	2019	A survey on application of non-orthogonal multiple access to different wireless networks	Electronics (Switzerland)	Exhaustively review the prior arts on NOMA from the perspective of its application to Cellular Networks, D2D and WSNs	PD-NOMA
Maraqa *et al.* [9]	2020	A Survey of Rate-optimal Power Domain NOMA with Enabling Technologies of Future Wireless Networks	IEEE Communications SurveysTutorials	A comprehensive review on the integration of PD-NOMA with advanced antenna architectures,in sub 6 GHz, mmWave and THz, COMP, Cognitive Radio and the other emerging communications	PD-NOMA
Aldababsa *et al.* [24]	2018	A Tutorial on Nonorthogonal Multiple Accessfor 5G and Beyond	Wireless Communications and Mobile Computing	Practicle implementation aspects, overview about the standardisation of NOMA in 3GPP LTE and application in the 5G scenarios.	PD-NOMA
Dai *et al.* [3]	2018	A Survey of Non-Orthogonal Multiple Accessfor 5G	IEEE Communications Surveys & Tutorials	Basic principles and discussion of pros and cons of NOMA.	PD and CD NOMA
Shah *et al.* [25]	2021	Survey and Performance Evaluation of Multiple Access Schemes for Next-Generation Wireless Communication Systems	IEEE Access	General comparisons of 1G to 6G and the different types of OMA and NOMA schemes.	OMA, PD and CD NOMA
Hassan *et al.* [26]	2021	Survey on NOMA and Spectrum Sharing Techniques in 5G	2021 IEEE International Conference on Smart Information Systems and Technologies (SIST)	Basic principles of NOMA and CR, the spectrum sharing way, and the advantages and challenges of NOMA and CR spectrum sharing.	PD-NOMA and CR
Vaezi *et al.* [27]	2019	Interplay between NOMA and other emerging technologies: A survey	IEEE Transactions On Cognitive Communications And Networking	Study on the combination and benefits with NOMA and different existing technologies.	PD-NOMA
Akbar *et al.* [28]	2021	NOMA and 5G emerging technologies: A survey on issues and solution techniques	Computer Networks	Systematically categorize and analyze issues of resource allocation, security and signal processing related challenges.	PD-NOMA

Table 2.1: Summary of surveys

2.2 Non-Orthogonal Multiple Access Taxonomy

Although surveys can provide wide coverage of NOMA, different problems, challenges, and open issues need a deeper investigation. As mentioned before, NOMA can be classified into three categories. As follows, we proposed the taxonomy in Figure 2.1 to describe the existing multiplexing domains, focusing on different Power Allocation (PA) techniques for NOMA schemes.

Fixed Power Allocation

Fixed Power Allocation (FPA) is one of the first power allocation algorithms to NOMA schemes. It is defined by fixing values for the power allocation coefficients, *i.e.,* no matter what is the user data rate demand, channel condition, resource availability and other conditions, the Base Station (BS) will always allocate a fixed coefficient to one user and, in the case of a two user NOMA scenario, allocate the remaining power to the other user. The Fixed Power approach is rigid, and occasionally cannot satisfy the users demand, since it is highly dependant on the user's channel conditions. It also struggles to serve users with low channel gain diversity, since the best case scenario for FPA would be to serve users with high channel gain diversity. To summarize, the major drawback of FPA is related to the fluctuations of the user's channel gain and the incapacity of the scheme to adapt the power coefficients [29].

The work done in [30] proposed two association algorithms, one providing a low complexity sub-optimal solution and the other with a globally optimal solution. Simulations presented that the low complexity algorithm with FPA can achieve the near-optimal solutions with much lower complexity compared with the proposed global optimal algorithm and that outperforms OMA in sum rate and outage probability. With the aid of game theory, the main objective was to achieve all user's target data rates in a multi-cell NOMA network. It is interesting to see in this work that if a user with good channel conditions, near a BS, cannot have the QoS requirements satisfied by that BS, this user is allocated to a farther BS where it will be allocated more power to satisfy its requirements.

Aiming to maximize the aggregate throughput, the work [31] proposed a packet-level scheduling scheme for the BS to decide using either NOMA or OMA. The authors considered dynamic packet arrivals, possible transmission failure, and a limited Channel State Information (CSI) to formulate a joint user pairing and PA problem under the constraint of FPA. Simulations show that the proposed scheme can achieve higher throughput, maintain stable backlogs, and achieved a lower transmission failure probability compared to the distance-based PA and the CSI based PA.

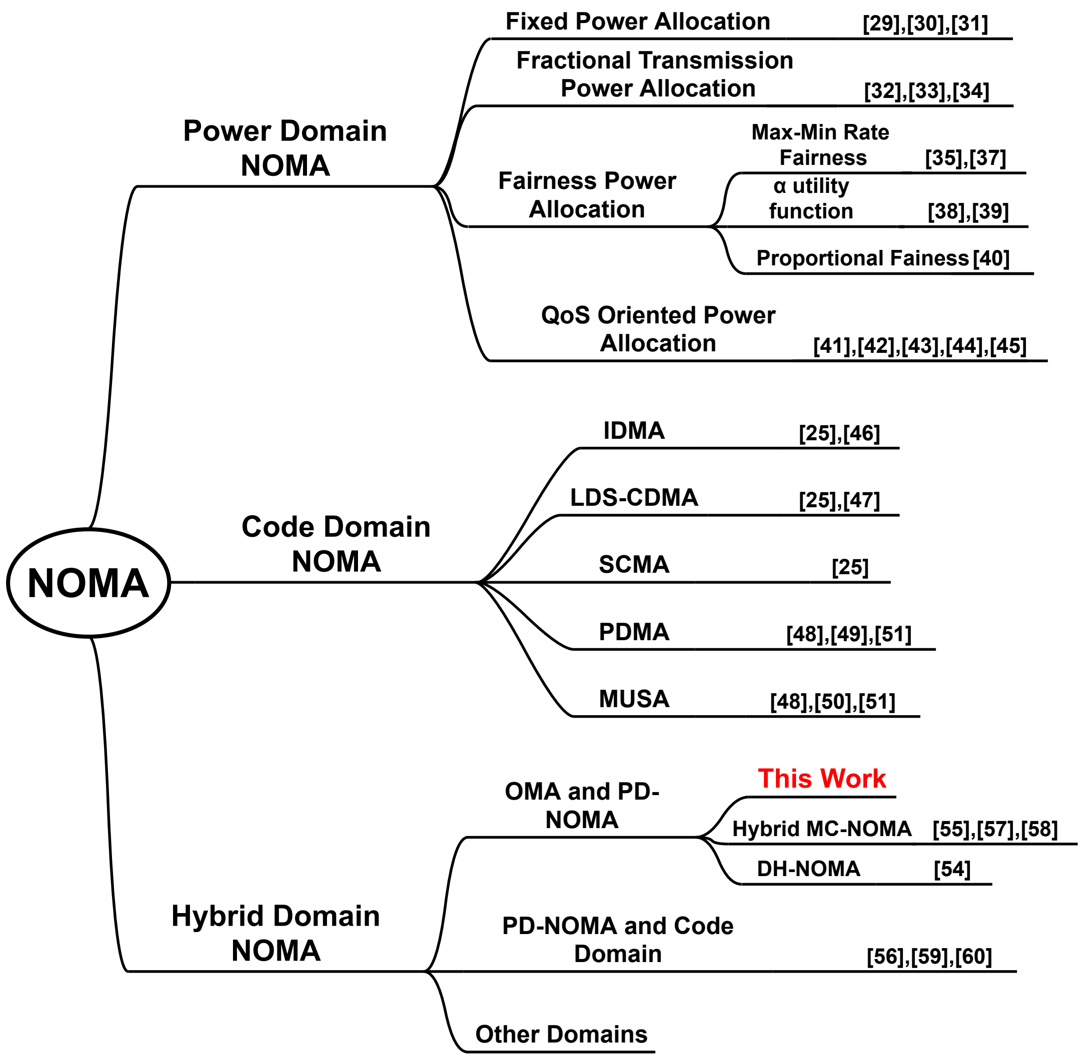

Figure 2.1: NOMA taxonomy

Fractional Transmission Power Allocation

The Fractional Transmission Power Allocation (FTPA) algorithm is defined by allocating power to the user's regarding the channel condition of the paired users. Note that the complexity of the algorithm is increased related to the FPA scheme. For the FTPA scheme, different combination of users, may result in different power allocation coefficients and hence different performance, it may overcome or not other techniques. One more time, the channel condition of each user affects dramatically the power allocation and it also benefits from the user channel gain diversity. Summarizing, the FTPA allocates more power to the user with poorer channel condition [32]. It is worth to remind that the FTPA tries to solve the major problem of the FPA scheme, but it does not solve all the problems, like the QoS user demand and minimum rate requirements [29].

In [33], the authors proposed a PA method based on the outage probability of the users in a NOMA single channel network. The analytical model for the outage probability with 2 users is described and simulated to find the optimal PA. It is shown that the outage probability decreases until the PA for the near user reaches 30% of the total power available, otherwise, the outage probability increases exponentially. The authors also compared their method with FPA method and FTPA in NOMA and OMA. The results showed that OMA has a lower system outage probability compared to NOMA.

In [34], the authors proposed a FTPA with a subchannel assignment aiming to maximize the Energy Efficiency (EE) of the network. The work uses an approach of the difference of two convex functions to obtain the power proportional factor. Therefore, a sub-optimal PA across subchannels was obtained, through extensive simulations, the performance of the proposed algorithms was compared with the OMA system and that the total sum rate and EE of the NOMA system are much higher. The approach also outperforms standard FTPA NOMA, allocating different power between subchannels instead of equal power achieving a higher EE of the system. Besides the results, the work considered a perfect CSI knowledge at the BS and only considered a two-user case per subchannel.

Fairness Power Allocation

The fairness in NOMA networks was first addressed in the work of Timotheou et al. [35]. Taking into account the instantaneous and average CSI at the transmitter it was proposed a Max-Min fairness low complexity PA. The main results of this work show that the network can ensure high fairness requirements through appropriate PA. The minimum rate and outage probability were compared with FPA NOMA and OMA. As the number of users increases, the advantage of NOMA over OMA increases almost linearly in terms of rate performance.

The fairness can be addressed in different ways, such as, the overall fairness index between all users and the fairness inside a pair of users allocated to the same resource. Maximizing the overall fairness means that all the users in the network will have an approximate experience, users in the cell edge achieve data rates closer to the cell center users. Taking account the fairness inside a cluster of user means that user's paired together will experience closer data rates, but it does not mean that all the users in the network will have closer data rates. Cell edge user may be paired with low data rate users and the fairness index can achieve higher values [36].

In [37] was proposed a joint cell association and PA scheme based on the max-min EE of Small Cells in a Heterogeneous Network considering an imperfect knowledge of the CSI. The main objective of the work is to maximize the minimum EE of all Small Cells regarding the QoS constraint of each user and the maximum transmit power constraint at the BS. Based on the worst-case approach, a mixed integer programming problem with infinite inequality constraints was converted into the convex which was solved by Lagrange dual method. The simulation results showed the effectiveness of the proposed algorithm in terms of EE and robustness in terms of the received interference power of the macro cell user.

Employing the α utility function for fairness, the work in [38] formulates a multi-objective optimization problem to investigate the trade-off between EE and SE with fairness considered for downlink NOMA networks. Varying the value of α it is shown that greater fairness levels in NOMA are harmful to the SE. The results also shown that the more users are multiplexed greater is the EE and the SE.

At [39], the authors investigated α-fairness based PA schemes for sum throughput and ergodic rate maximization problems in a downlink NOMA system with statistical and perfect CSI at the transmitter. For statistical CSI, a fixed target data rate is predefined for all users and the outage probability of each user is analyzed, therefore a PA optimizations framework is formulated for sum throughput maximization with α-fairness. For perfect CSI, the PA problem is formulated to maximize the instantaneous sum rate with α-fairness, where user rates are adapted according to instantaneous CSI. The results showed a higher Ergodic sum rate for NOMA with lower fairness. The results were compared with OMA system and a FPA NOMA scheme and different values of α. As the authors adopted a single antenna NOMA it is proposed an extension for MIMO NOMA with fairness.

With a Proportional Fairness (PF) approach to the work in [40], a low complexity spectrum resource, and PA with adaptive proportional fair user pairing algorithm is proposed with three different PA schemes. The first scheme directly allocates the total power of the sub-channel with proportional rate constraints. Under the constraint that the SIC is correctly executed, scheme 2 allocates the remaining power to the user with high channel gain as much as possible. The third scheme first satisfies the minimum data rate and then allocates the remaining power with a proportional rate constraint. The work also proposes a power discretization to reduce the complexity of the algorithm achieving a suboptimal PA.

QoS Oriented Power Allocation

The QoS oriented Power Allocation relies on the individual user data rate requirements, *i.e.,* the user's power coefficient is defined by allocating power that satisfies the data rate requirement. The technique desensitizes the dependency of channel gain difference between paired users, having a cluster with good channel conditions of both users can enhance the overall cluster data rate [41]. Also QoS oriented power allocation reduces the inefficient use of the available resources since devices neglect extra received power [42].

Employing a QoS oriented PA the work presented in [43] proposed two PA algorithms, one based on CSI and the other based on QoS where the CSI based allocates power inversely proportional to channel gain. The QoS based allocates power necessary to achieve a pre-defined QoS to the high priority user, the rest of the power is allocated to the other user. The CSI approach achieved an increase near 30% in the overall system throughput compared to OMA. The results of QoS based shown that can successfully provide high priority NOMA with higher rates than provided in OMA.

Another work done employing a QoS oriented PA is presented in [44], the authors investigated the subchannel and PA considering EE, quality of service (QoS) requirements, power limits, and queue stability using using Lyapunov optimization. The results show a great increase in the average EE performance for different values of the control parameter V, which represents the emphasis on utility maximization compared to queue stability.

In [45], a QoS approach was employed to optimize the PA to maximize the sum-rate under the total power constraint and individual minimum rate requirements. The approach consists on allocate additional power to the user with the best channel gain, while other users are allocated with minimum power to maintain their minimum rate requirements. The simulation results were compared to fairness PA NOMA and OMA. The proposed algorithm outperforms the fairness algorithm in terms of sum rate especially when the minimum rate requirement is small. The authors obtained the optimal PA in closed form for the sum-rate maximization problem proposed.

Code Domain NOMA

Moving on to the Code Domain, the technique uses specific sequences with sparse and different density properties for each user. There are several transmission schemes that are related to Code Domain NOMA. Since the focus of the work is the usage of PD-NOMA with a hybrid architecture, the Code Domain NOMA techniques will be summarized in the following:

1. **Interleave Division Multiple Access (IDMA):** The scheme is closely related to the CDMA technique, although it uses the entire available bandwidth for forwarding the error correction code, reducing the code rate that can be provided to the users. Specific interleavers are used to multiplex user's on the transmission frame [25]. The IDMA prevails as a promising NOMA scheme since it can be adapted to the current standards wit a low implementation complexity [46].

2. **Low Density Spreading CDMA (LDS-CDMA):** The technique consists on the application of a low density spreadig sequence that enables a multi-user decoding through a Message Passing Algorithm (MPA) [47]. Recently, it has gain a lot of attention although the efficiency of the multi-user detection and decoding needs improvements to LDS-CDMA employs NGMA networks [25].

3. **Sparce Code Multiple Access (SCMA):** The SCMA is one of the most studied and well-known technique for Code Domain NOMA. It uses a unique and complex codebook for each user that enables the multi-user decoding. The bits are mapped into codewords and each user is differentiated by the codewords, achieving the multiple access [25].

4. **Pattern Division Multiple Access (PDMA):** The PDMA technique is a codebook based NOMA which differentiate users by a specific pattern of that maps modulated symbols to Resource Blocks (RBs) for each user. The decoding is usually based on iterative Successive Interference Cancellation (SIC) or MPA[48]. PDMA is more flexible than SCMA enabling a synchronous usage of time, frequency and space domains [49].

5. **Multi User Shared Access (MUSA):** The MUSA technique is a short sequence based NOMA scheme. The user-specific codes are transmitted in the same RB and, the detection of users is based on the SIC procedure [48]. Unlike SCMA, MUSA is classified as a grant free access scheme, *i.e.,* the users randomly selects the sequences without any communication with the BS and other users. The grant free access may generate collisions between users with bad cross-correlation sequences [50].

To summarize the applications of the Code Domain NOMA schemes presented, the SCMA uses a well defined structure of codes with a low complexity decoding schemes and it is well suited for highly overloaded scenarios meeting the requirements for a the massive Machine Type Communication (mMTC). MUSA is usually employed in uplink and downlink scenarios with a multi domain code and decoding structure. Although it has a much more complex code structure, MUSA offers a lower access time and simpler system implementation, reducing the energy consumption and greater capacity when compared to OMA schemes [51]. PDMA increase the SE by enhancing the spectrum utilization in the downlink and also in the uplink, since the decode is based on iterative SIC it has more complexity than SCMA and MUSA. PDMA is still facing some challenges regarding the design of simpler receivers, sequence patterns and the combination with technologies such as MIMO[51]. The IDMA technique is closely related to the well known CDMA schemes however it can provide a higher overloading factor, *i.e.,* serve more users within the same RB with a lower receiver complexity than SCMA schemes but it is highly dependant on the knowledge of the users channel condition to outperform PD-NOMA schemes [52].

Both PD-NOMA and Code Domain NOMA may encounter scenarios that detract from overall network performance. The employment of a hybrid network that combines different MA techniques can benefit from scenarios that are difficult for specific MA techniques. In the following, the concept of Hybrid Domain NOMA is shown.

Hybrid Domain NOMA

Finally, moving on to the Hybrid Domain. The Hybrid Domain is defined by the combination of different NOMA schemes into one system to build a hybrid network [53]. The work of Yang et al. [54] proposes a new dynamic power scheme based on hybrid NOMA (DH-NOMA). The presented work makes decisions on using OMA or NOMA when the strong user's channel gain is worse than a threshold determined by the weak user's fixed target rate. That is, in the opposite way of the system model presented in the next chapter where the target rate is fixed for the strongest user.

At [55], the authors investigate the resource allocation problem for spectral efficiency and energy efficiency tradeoff with users' minimum rate requirements in the hybrid system which incorporate both NOMA and OMA into one unified framework. The presented simulations show that the users' minimum rate requirements impose a significant impact on the selection of MA modes when NOMA and OMA coexist in the system. It is also stated that the performance gain brought by four or more users sharing the same subcarrier is very small suggesting that the maximum number of users sharing the same resource is three.

As NOMA can be integrated with different technologies, the work of Haider *et al.* [56] focused on a comparative analysis among three different hybrid NOMA schemes. The study presented analysis on bit error probability, EE, SE and SIC occurrence for MIMO-NOMA, NOMA-Generalized Space Shift Keying (GSSK) and Space Time Block Coding (STBC)-NOMA. The main goals of the authors were to provide intuitive insights to recommend suitable hybrid NOMA schemes to achieve 5G and Beyond requirements. The work presents analysis of different hybrid NOMA schemes, but the presented schemes do not avoid some limitations of NOMA, regarding the scenarios where OMA schemes can achieve and satisfy user's data rate demand without inter-user interference.

The work of Shi *et al.* [57] studied the usage of a hybrid NOMA scheme with limited power consumption constraints. The authors provided a heuristic resource allocation algorithm and compared to different methods such as the joint power and resource allocation using FPA, FTPA and an optimal solution. The case that the BS can use the full power consumption is also compared. Although the proposed heuristic method presents sub-optimal results compared to the optimal solution, the authors do not present any results regarding the pairing of users and how it is affected by the limited power consumption scenario and the full power consumption scenario.

Presenting a hybrid Multi-Carrier NOMA (MC-NOMA) system, the work of Song *et al.* [58] formulated a multi objective optimization problem with a minimum data rate requirement. A joint resource allocation algorithm for hybrid MC-NOMA is proposed and used to a general case where one sub-carrier is be allocated to an arbitrary number of users. The work presents an analysis of the Ratio of sub-carriers applying NOMA mode for each user. In contrast to the work of Shi *et al.* [57], it is given and intuition of how the pairing of users is affected by the minimum data rate requirement. Unfortunately, the work presents a limited scenario with a maximum of 4 users in a network which does not represent the number of users served by a BS for a 5G and Beyond network.

Combining Code-domain and Power-domain NOMA the authors in [59] proposed a novel SCMA based system that supports more users by adding low data rates users with PD-NOMA on top of SCMA users. The proposed method demonstrates a higher overall achievable sum rate than the baseline SCMA system.

The work in [60] brings a new approach called power domain sparse code multiple access (PSMA) where power domain and code domain are used to transmit multiple users' signals over a subcarrier simultaneously. The authors concluded that the PSMA technique significantly outperforms other NOMA techniques while imposing a reasonable increase in complexity on the system.

There are many more combinations that utilize NOMA and other Multiple Access schemes that can be included in the taxonomy such as Spatial Division Multiple Access

(SDMA), Signature-Based NOMA, Compressive Sensing (CS)-Based NOMA, Bit Division Multiplexing (BDM), and so on, but it is out of the scope of this work and would lead to an extensive and deep literature review.

2.3 Multi-agent Systems and Non Orthogonal Multiple Access

The study of MAS and NOMA is important for the design and development of the proposed solution presented in this work. The work of Garro *et al.* [61] presents a straightforward explanation to Multi-agent Systems and guidelines and perspectives to the development of new applications. Besides different possible agent-based applications, the authors claim the benefits of agents in constrained and complex scenarios with the reactive, autonomous, adaptive, flexible and collaborative characteristics of agents.

The work of Kumar *et al.* [62] presents a survey approaching CR and different MA schemes. The authors defines that a spectrum management system should include spectrum decision and spectrum sharing capabilities to meet QoS requirements. It is stated in the work that Multi-agent based schemes can be the great future of the management of spectrum. The agents features of coordinate and cooperate can achieve the optimum utilization of the spectrum. The authors also show that the spectrum management can be based on auction schemes, abstracting the free channels as objects to sell and the users as bidders. The integration of NOMA and OMA is also discussed to improve the network and it is concluded that an intelligent self-organizing MA scheme can work properly and effectively for mobile networks although it is still required extensive research.

The usage of MAS and NOMA is also exploited with Reinforcement Learning (RL) techniques. Although, in this case the agents are not employed to manage the spectrum and allocate resources, agents are used to simulate and train neural networks that allocate resources. The agents abstract the devices in a network and more realistic scenarios are simulated. This kind of approach can be found in the references [63],[64] and [65].

From the literature review presented in this work, it is clear that NGMA networks need new strategies to transmit data. NOMA is a potential MA scheme to enhance the spectral efficiency and capacity of networks although it still needs research to solve open issues. To work properly, NOMA has to match different conditions to enable users to share the same resource, these conditions are related to the channel conditions, data rate requirements, transmission power availability and others. NOMA by itself may not be the best alternative for NGMA network, however a hybrid network that can utilize NOMA and OMA schemes can bring diverse benefits and avoiding scenarios that are challenging for each MA scheme, *i.e.,* supporting massive connectivity for OMA schemes and matching conditions for NOMA schemes. To the best of the author's knowledge, there is a lack in the literature regarding the employment of a hybrid network and an architecture that enables the network to make spectrum decisions and management. Motivated by the MAS capabilities and the benefits of a hybrid network, this work proposes an agent based architecture named AH-NOMA that enables NOMA and OMA schemes to achieve a higher SE. The next chapter will present the system model and problem definition that drives the architecture.

Chapter 3

System Model

The system presented in this section describe the transmission modes, the achievable data rates for each user in each transmission mode, the variables and the spectrum sharing optimization problem that is the main operational function of the proposed MAS.

The system model consider a BS that can serve users in a downlink channel using NOMA with perfect SIC or one user at a time slot in an OMA transmission. Considering the main objective of this work as proposing an Architecture to provide enhanced SE through user and power allocation, spectrum sharing and transmission mode selection, propagation of errors and detection is not part of the scope of the work.

Our problem is formulated to decide which transmission mode is used, *i.e.,* if users can share one transmission time\frequency slot with NOMA or have to be scheduled to an OMA transmission scheme at individual time\frequency slots. In the proposed scenario, the users device can decode either NOMA superposed signal through SIC process or decode OMA transmissions. Also, we assume that interchanging between NOMA and OMA is feasible and can be done without any decrease of performance to the system. Figure 3.1 presents how users are allocated over time and frequency. On the left side of Figure 3.1, the BS is transmitting in OMA and the time slot cannot be shared by users, and, thus, only one user is allocated per time slot. Whereas on the right side, the BS can share the same frequency and time slot with different users in NOMA by superposing their communication with different power allocation.

The variables and equations that defines the spectrum sharing problem are defined as follows: A number n of users u_n, with $\{u_n \in \mathcal{U} \mid n = \{1, 2, ..., U\}\}$, where U is the number of users u_n that are randomly deployed in the coverage area of the BS. Each user channel gain, $|h_{u_n}|$, is modeled as an independent random Gaussian variable with zero mean and standard deviation σ^2, *i.e.,* $\mathcal{N}(0, \sigma^2)$. When transmitting in NOMA users are paired and differentiated by the channel conditions experienced at the receiver, Near User (NU) is represented by index i, where $\{u_i \in \mathcal{U} \mid i = \{1, 2, ..., U\}\}$ and is the one with

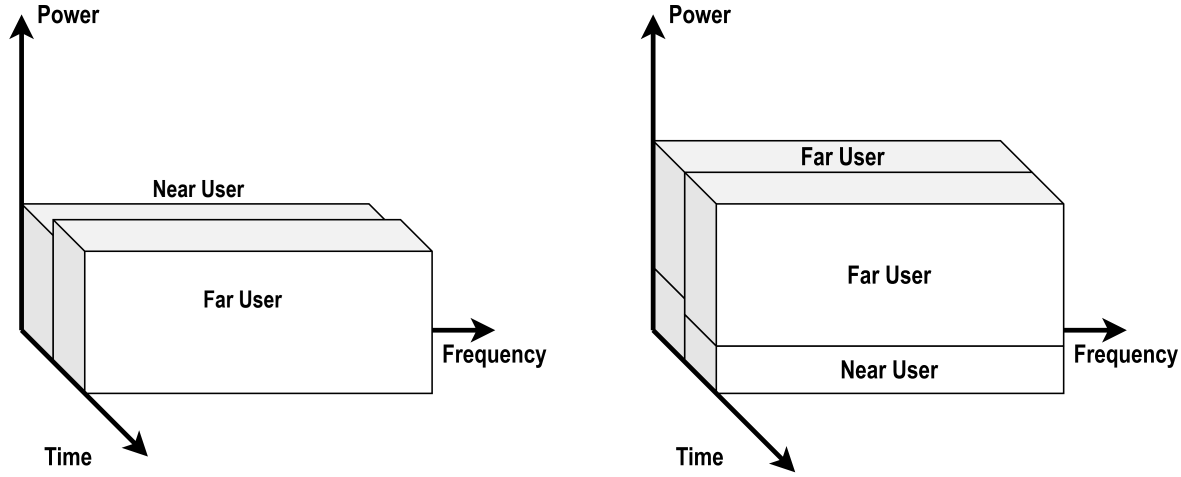

Figure 3.1: One time slot shared by two users considering NOMA and dedicated time slots for OMA.

better channel conditions than the other paired user *i.e.,* Far User (FU), represented by j, where $\{u_j \in \mathcal{U} \mid j = \{1, 2, ..., U\}\}$. The relationship $\{|h_\mathrm{j}|^2 \leq |h_\mathrm{i}|^2\}$ always hold. Therefore, based on Shannon's capacity, the achievable rate for the NU R_i when sharing spectrum resources using NOMA is defined by Equation (3.1):

$$R_\mathrm{i} = \log_2\left(1 + \frac{|h_\mathrm{i}|^2 P\alpha}{N_o}\right), \tag{3.1}$$

where, P is the total transmission power available at the BS and α is the power allocation factor for the near user, *i.e.,* the portion of transmission power allocated to each user in the shared resource. For the NU, since the Successive Interference Cancellation (SIC) process is carried out without errors, there is no remaining interference from the FU signal. As the FU decodes its message with the interference from the NU signal, its achievable rate R_j is defined as:

$$R_\mathrm{j} = \log_2\left(1 + \frac{|h_\mathrm{j}|^2 P(1-\alpha)}{(|h_\mathrm{j}|^2 P\alpha) + N_o}\right), \tag{3.2}$$

The system is modelled in such a way that both users entirely use P, the total energy is shared between both NU and FU, the portion of the FU is represented by $1-\alpha$ being the complement power left from the NU. Also, the interference occurring from the NU to the communication of the FU is part of the the divider term summed with the noise figure N_o. The hybrid MA scheme that is employed by the proposed communication architecture enables the users to exploit OMA for communication. The scheduling of a user to orthogonal resources, means that, the interuser interference is minimized and, thus, the achievable rate of a user using this scheme can be equated as:

$$R_{\text{u}} = \log_2\left(1 + \frac{|h_u|^2 P}{No}\right), \tag{3.3}$$

where R_u can either be related to NU or FU depending on what user is scheduled to use exclusively a time slot. Then the BS transmits data simultaneously to a pair of users the sum of SE provided to both users is defined by (3.4)

$$SR_{i,j} = R_{\text{i}} + R_{\text{j}} \tag{3.4}$$

Considering the equations presented in this chapter, it is possible to formulate a table $T_{i,j}$ that contains the sum of spectral efficiency provided for each pair of user and also the spectral efficiency that can be provided to each user receiving an OMA. The diagonal of table $T_{i,j}$, where $i = j$, represents the SE provided to the user i as an OMA transmission. The other values represented by $T_{i,j}$, with $i \neq j$, represents (3.4) as NU given by user i and FU represented by user j.

$$T_{i,j} = \begin{bmatrix} OMA_1 & SR_{12} & \dots & SR_{1U} \\ SR_{21} & OMA_2 & \dots & SR_{2U} \\ \vdots & \vdots & \ddots & \vdots \\ SR_{U1} & SR_{U2} & \dots & OMA_U \end{bmatrix}$$

After defining how transmissions occur in each and the variables that are inherent from each MA scheme, in the following, the transmission mode decision-making is presented and defined as a spectrum sharing optimization problem aiming to achieve maximum SE that can be provided to users.

3.1 Transmission mode selection problem

As NGMA requires enhanced data rate demands and bandwidth to provide service to users, maximize the total SE can ease the spectrum scarcity problem. A scheduler is required to determine the achievable rate of each pair of NU and FU when deciding to use OMA or NOMA. Users receiving OMA transmissions can have their rate calculated in (3.3). However, for NOMA communications, the same cannot be done, a trade-off between increasing or decreasing each user's data rate in favor of the other is found in (3.2). To exploit this trade-off and achieve the optimal network performance we formulate an optimization problem to maximize the total SE provided by a BS that can allocate users in different MA transmissions schemes. Considering the The optimal solution can be obtained through the power allocation and user pairing and it is defined as a baseline in (3.5a):

$$\underset{\alpha}{\text{maximize}} \quad \sum_{i}^{n}\sum_{j}^{n} T_{i,j} \cdot a_{i,j} \tag{3.5a}$$

subject to

$$\sum_{i}^{n}(a_{i,j} + a_{j,i}) = 2, \qquad \forall j \in \{1, 2, \ldots, n\} \tag{3.5b}$$

The problem is modelled by the decision variable $a_{i,j} \in \{0, 1, 2\}$ and the indexes i and j represents the NU and FU, respectively , where $a_{i,j} = 2$ for NOMA, $a_{i,j} = 1$ for OMA and $a_{i,j} = 0$ for user not allocated.

The decision variable $a_{i,j}$ must assume the values aforementioned so that each user can only be paired once in OMA transmissions or it can only be part of one pair in NOMA transmissions in (3.5b). The matrix $T_{i,j}$ represents the sum of SE that is provided to a pair of user (i, j) in NOMA transmission if $i \neq j$, with i representing the NU and j the FU, or the user demand that can be satisfied by OMA transmission to the user i, if $i = j$. Considering that there are n users deployed in the network waiting for a resource allocation and the power coefficient α as a continuous variable, the matrix $T_{i,j}$ may present uncountable versions, making the processing of pair allocation unfeasible in small granularities of time due to the number of users and complexity to find the optimal power allocation considering all the possible pairs permutation.

To solve the power allocation problem and reduce the number of possible pairs we formulate a spectrum sharing problem aiming to maximize the FU achievable rate by first satisfying the NU requirements. Our reasoning is based on the fact that QoS requirements of the NU tend to be achieved by consuming a smaller portion of the available transmission power due to the better channel quality. Thus, it remains a larger transmission power budget that can be allocated to the FU. The literature [12]-[16], on the other hand, prioritize to maximize the NU achievable rate which can provide more data rate to near users, far users in such schemes, may suffer from the worst channel condition and less available power to achieve NGMA requirements.

3.2 Spectrum Sharing Problem Definition

To decide whether to use OMA or NOMA, a scheduler is required to determine what are the achievable rate of each pair of NU and FU to make this decision. Users using OMA can have their rate calculated by using Equation (3.3). However, for NOMA communications, the same cannot be done since there is a trade-off between increasing or decreasing each user's data rate in favor of the other regarding the interference found in the FU achievable rate. To exploit this trade-off, we formulate a spectrum sharing problem aiming to maximize the FU achievable rate by first meeting the NU requirements. We start to model our spectrum sharing problem by defining $\{R_{fu}, R_{nu} \in \mathbb{R}^{+}\}$ as decision variables. Also, we introduce a QoS parameter QoS_{nu} to determine the bit rate required by the NU. Considering this definition, we aim to maximize R_{fu} subject to the following constraints.

3.2.1 Constraints

- **Power Coefficient α is equal to NU and FU data rates:**

  Since in NOMA transmissions, the BS uses all the transmission power available, it means that the power allocation between two users is complementary reusing the same α. Therefore, α can be isolated and matched in Equations (3.1) and Equation (3.2). Matching α leads to the constraint:

$$\frac{(2^{R_{fu}} * No) * (2^{R_{nu}} - 1)}{(|h_{nu}|^2 * P)} = \frac{(|h_{fu}|^2 * P) - (2^{R_{fu}} * No) + No}{(|h_{fu}|^2 * P)}$$

$$2^{R_{nu}} * No * |h_{fu}|^2 * \left((2^{R_{nu}} - 1) + \frac{|h_{nu}|^2}{|h_{fu}|^2}\right) + |h_{nu}|^2 * (No - P_t * |h_{fu}|^2) = 0 \tag{3.6}$$

- **NU data rate needs to be greater than the QoS demand:** The second constraint prevents the scheduler from allocating a power coefficient α that provides the NU data rate lower than its QoS demand.

$$R_{nu} \geq QoS_{nu} \tag{3.7}$$

- **FU data rate needs to be nonnegative :** This constraint is present in the problem to avoid the scheduler providing a negative data rate to the FU.

$$R_{fu} \geq 0 \tag{3.8}$$

- **Power Coefficient α boundaries:** In order to transmit to the NU, the power coefficient α needs to be greater than 0 and to make the SIC feasible and it needs to be smaller than 0.5 otherwise the decoding would fail. By isolating alpha in

Equation (3.1), we calculate the following upper and lower bound:

$$0 < \frac{(2^{R_{nu}} - 1) * No}{P_t * |h_{nu}|^2} < 0.5 \tag{3.9}$$

Considering the decision variables and constraints, the objective function of the spectrum sharing can be defined as a maximization of the R_{fu}, as defined in the objective of the optimization in Equation (3.10).

3.2.2 Spectrum sharing problem optimization

$$
\begin{aligned}
\underset{R_{nu}}{\text{maximize}} \quad & R_{fu} && (3.10a)\\
\text{subject to} \quad & 2^{R_{nu}} No|h_{fu}|^2 \left((2^{R_{nu}} - 1) + \frac{|h_{nu}|^2}{|h_{fu}|^2} \right) + |h_{nu}|^2 (No - P_t|h_{fu}|^2) = 0, && (3.10b)\\
& R_{nu} \geq QoS_{nu}, && (3.10c)\\
& R_{fu} \geq 0, && (3.10d)\\
& 0 < \frac{(2^{R_{nu}} - 1)No}{P_t|h_{nu}|^2} < 0.5 && (3.10e)
\end{aligned}
$$

After solving the optimization problem in Equation (3.10), a scheduler is capable of providing the achievable data rate that users could receive if the transmission mode is set to OMA, through Equation (3.3), or NOMA, through the presented problem. However, due to constraints defined by Equation (3.6) and Equation (3.9) the problem becomes non-linear. To turn this problem linear we introduce auxiliary variables being $A = (|h_{nu}|^2 * P)$, $B = (|h_{fu}|^2 * P)$, $X = (2^{R_{nu}} - 1)$, $Y = (2^{R_{fu}} * No)$, and $Y' = \frac{1}{Y}$. With this notation, the decision variable becomes X and Y' and maximizing R_{fu} has the same effect of minimizing Y', since it is the inverse anti-log of R_{fu}. By applying the auxiliary variables and performing some analytical procedures to the optimization, we have:

$$
\begin{aligned}
&\underset{X}{\text{minimize}} \quad Y' && (3.11a)\\
&\text{subject to} && \\
&X - AY' + \frac{A}{B} - \frac{A * No * Y'}{B} = 0, && (3.11b)\\
&X \geq 2^{QoS_{nu}} - 1 \qquad , && (3.11c)\\
&Y' \leq \frac{1}{No} \qquad , && (3.11d)\\
&0 < \frac{X * No}{A} < 0.5 && (3.11e)
\end{aligned}
$$

Considering the remodeled optimization using Y' and X as the decision variables make the constraints become linear, where the constraint (3.11b) is the linearized version of the constraint in (3.6) and (3.11e) is the linear version of Equation (3.9). The other constraint are also adapted to support the new variables definition. Now, this problem can be solved by any linear programming solver, such as OR-Tools [66]. By solving the spectrum sharing problem above, a scheduler still needs to determine whether to use NOMA or OMA. Therefore, we propose an Agent-Based architecture to handle the decision-making problem between transmitting with OMA or NOMA next. The architecture uses the optimization problem solution to pair users given the QoS demand and finally deciding whether to use one of the MA techniques or another.

Chapter 4

Adaptive Hybrid NOMA Architecture

In this chapter, we introduce an agent-based architecture, AH-NOMA, capable of sharing spectrum for a hybrid NOMA network. AH-NOMA exploits the trade-off between OMA and NOMA and leverage benefits from each MA technique implementing concepts inspired by CR. The CR concepts of sharing and selection of spectrum portions and the inherent re-configurable capability to use various frequencies while transmitting with different MA technologies are embedded into AH-NOMA, enabling an adaptive and dynamic operation, *i.e.,* AH-NOMA allocates users on non-orthogonal or orthogonal resources depending on the requirements and channel capabilities of each user.

4.1 Motivation to adopt a Multi-agent Systems (MAS) architecture

In the past few years MAS gained attention in research regarding diverse areas of science and the capability of describing different physical systems, models and behaviours [67]. The employment of agents was mainly motivated by the uncountable features that MAS can bring to the management of a network. Some important MAS features that can be highlighted [14]:

- *Adaptability*: agents can learn and improve based on previous experience.
- *Autonomy*: each agent takes actions on its own for achieving predefined goals.
- *Collaboration*: agents can work together to achieve a common goal.
- *Interactivity:* agents can interact with their surrounding environment.

Another important motivation to adopt a MAS architecture is the Contract Net Protocol. The protocol was introduced by Smith [68] and it is an interaction protocol for intelligent physical agents which nowadays is specified by Foundation for Intelligent Physical Agents (FIPA). The specifications of FIPA enables the agents to follow the standards of agents communication and thus agents can communicate and interact following the standards adopted by the community. The collaboration with other architectures can be implemented over the standards, contributing to an open network operation and cooperation. Considering some NGMA scenarios with Small Cells deployed in a small area, each antenna can be embedded with an AH-NOMA that can communicate with other AH-NOMA architectures and exchange information about users, perform handover operations and even work together to enhance an edge mobile user throughput.

The Contract Net Protocol is a task coordination protocol that specifies the interaction between agents enabling a competitive negotiation between a manager agent, named the initiator and the bidders agent, named as participants [68]. The Contract Net is adapted in AH-NOMA for users to provide information of data rate requirements and CSI, In possession of each user's information, the agents of AH-NOMA decides what transmission mode use, and how each user user is allocated, that is, if they are paired in NOMA transmissions or scheduled to OMA transmissions.

Although the employment of MAS in Mobile Communications is not usual, its capabilities and features are fundamental to the main hypotheses formulated in this research, *i.e.,* A MAS can be employed to manage a mobile communication network. The agents that constitute the architecture implement the spectrum sharing problem stated in Section 3, and through the collaboration and interactivity features, they work aiming a common goal of enhancing the SE. Although agents may be implemented with different goals and each individual agent may change its objectives over time to adapt the operation network for a better performance, or to achieve different goals, such as enhance fairness or EE. In the following it will be presented how the proposed MAS, AH-NOMA, is capable of manage the spectrum resources and user allocation.

4.2 AH-NOMA

The architecture of AH-NOMA is presented in Figure 4.1. The architectural elements deal with the new requirements of SE of 6G networks, taking into account that devices can decode either NOMA and OMA transmissions and can interchange between the two techniques.

The architecture is designed to be the core of the processing unit of an antenna and it is constituted by two agents: the Service Agent (SA) and the Transmission Agent (TA).

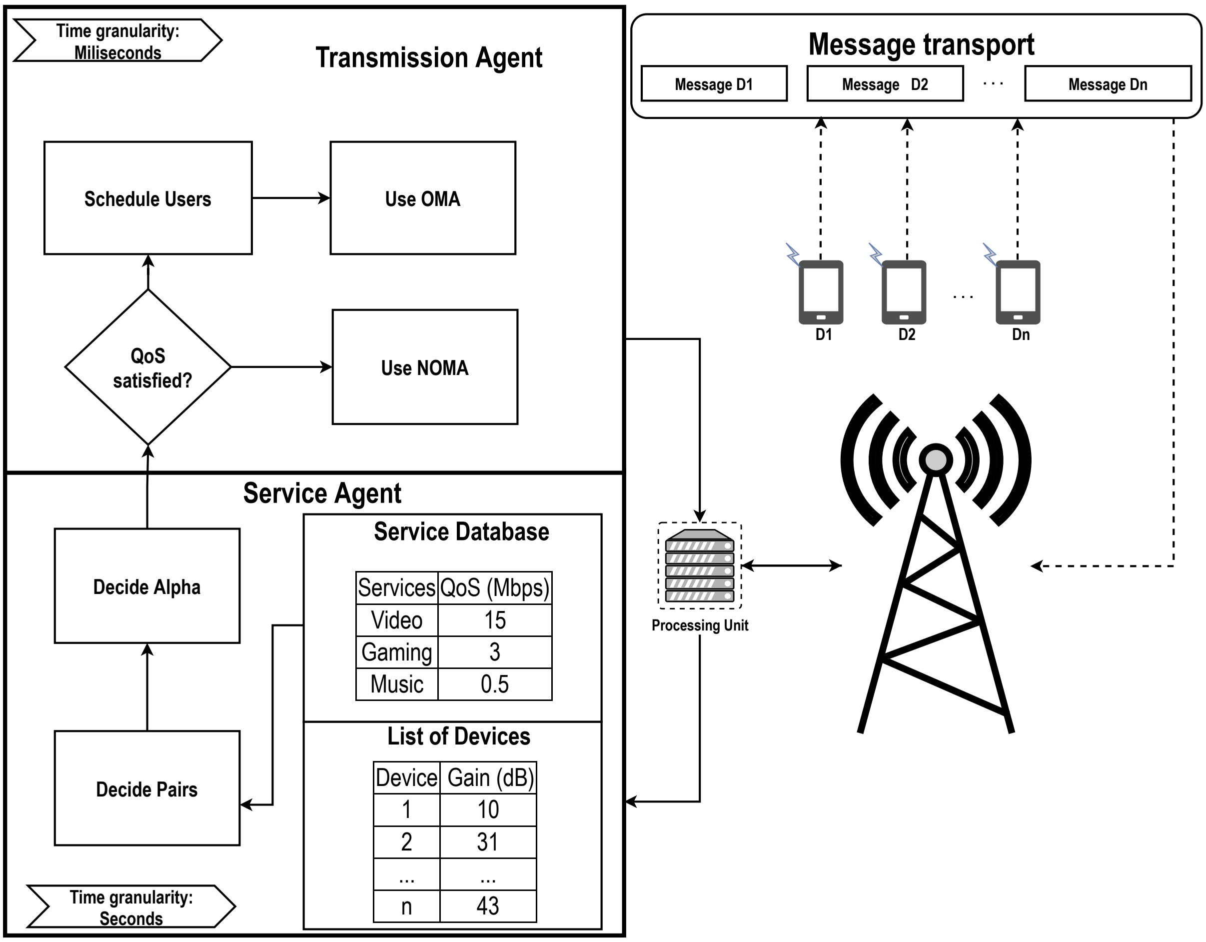

Figure 4.1: The AH-NOMA architecture.

The SA is responsible for collecting information about devices, sensing the spectrum and manage a preliminary user and power allocation in the coverage area by the architecture operating in the granularity of seconds. The information collected is related to the data rate requirements and channel gains that each device experiences and it is stored in the Service Database and List of Devices, respectively. These two databases are used by the SA to rank users, provide possible pairs, and calculate the coefficient of power allocation α that satisfies the NU data rate requirements. Afterward, the TA can query the SA for pairs and the power allocation coefficient to decide between transmitting in NOMA or OMA scheduling time slots and spectrum resources per-pair or individually in the time granularity of milliseconds or even less.

The architecture is implemented within three phases, as depicted in Figure 4.2. The first phase, named Update Information and Storage, is related to the work done by the SA perceiving the overall network scenario and retrieving information about the users located in the coverage area of the BS. Inspired by the Contract Net Protocol [68], the SA acts as a bid manager sending a Call For Proposal (CFP) to all devices. The devices located in the coverage area act as bidders. When receiving the CFP, users' respond to the SA with the channel gain and data rate requirements, the SA updates his databases in the first phase and proceed with the work process.

The second phase is named as Processing Pairs and Heuristics. As the Contract Net Protocol declares, "The manager may receive several bids and select one or more bids for the task using a task-specific bid evaluation procedure" [69]. This corresponds to the SA evaluation of all the devices channel gains and data rate requirements to inform the TA the pairs of users that may be allocated in non-orthogonal resources. The SA decides candidate pairs searching through all possible user pairs, selecting the most fitted to become candidates to use NOMA by solving the optimization problem for each users pair. After solving the pairwise problem, the SA computes potential values of α informing the TA from time to time. At this phase, the SA process can benefit by using heuristics to rank users or drop unfitted pairs of users and quicken the processing. Different heuristics can be implemented and developed to enhance the network performance and achieve diverse objectives.

The third phase of the architecture is related to the activities done by the TA as a scheduler and the employment of the CR concepts into the architecture. The TA decisions are based on instantaneous channel quality indicators to verify if the calculated set of α by the SA is still updated and valid at the time of transmission, determining whether a user switches from OMA to NOMA and vice-versa across the spectrum and over time, implementing the CR capability to use various frequencies while using different MA technologies. This decision is based on a particular heuristic. For instance, the TA may

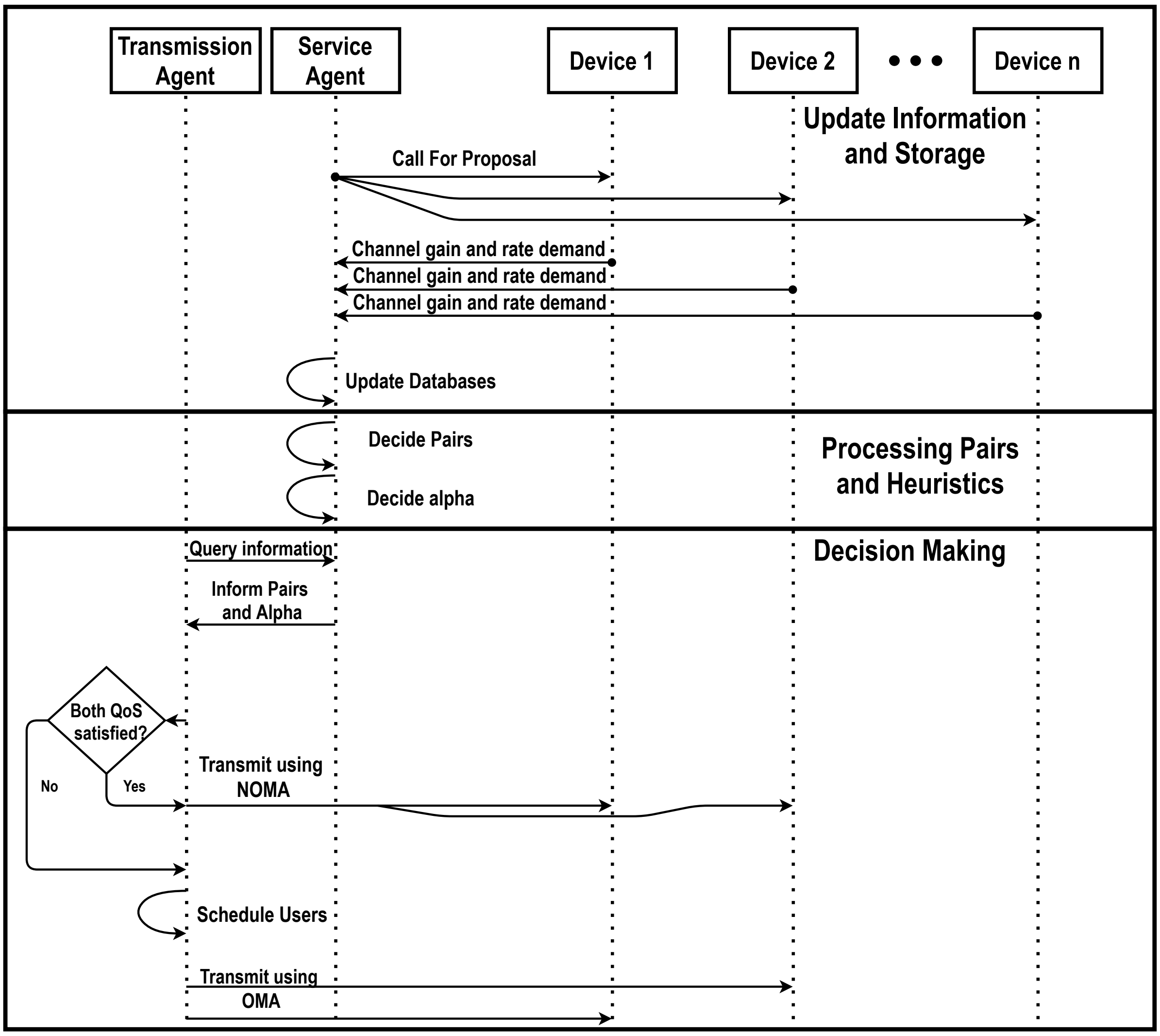

Figure 4.2: The AH-NOMA agents' interaction workflow.

decide the MA scheme for the users considering the one that increases the overall spectrum efficiency. Another option is to select NOMA only when both users' data rate requirements are satisfied. We consider this second option more interesting to be exploited. Therefore, in our work, the TA verifies if both data rate demands are satisfied according to an achievable rate of the users as presented in Equations 3.1 and 3.2, considering the already calculated α from the SA for NOMA and Equation 3.3 for OMA. Since AH-NOMA is designed to be flexible and adaptive architecture, different heuristics for the TA can be developed, aiming different objectives, and further enhancing the performance or making the network more robust to a variety of challenging scenarios that NGMA will face.

The AH-NOMA is designed based on the Python Agent DEvelopment (PADE) framework for python, developed by [70]. PADE is a framework for developing, executing, and managing multi-agent systems in distributed computing environments and is also free software and licensed in terms of MIT license. The Contract Net Protocol [68] is also implemented in python and the optimization problem solved by the agents was designed in OR-TOOLS [66]. Next, we evaluate AH-NOMA against an OMA baseline and the work of [16] to test the benefits and drawbacks of our proposal.

Chapter 5

Results

To evaluate the potential benefits brought by AH-NOMA, we performed different performance analyses considering the metrics:(i) Trade off and coverage, (ii) outage probability, (iii) overall bit rate, and the average number of formed pairs. The trade-off and coverage analysis gives the intuition on NOMA coverage capability and how it compares to OMA, presenting the points of interest that the proposed architecture can interchange its transmission mode enhacing the overall network performance.

For the outage probability, since we are interested in capturing the importance of pairing different users, we evaluate the capability of AH-NOMA to provide the best SE considering a single pair of users varying their distances to the BS and the individual QoS demand for the NU. The outage probability is also compared with a FPA approach. Afterward, we evaluate the average overall bit rate delivered by AH-NOMA in different scenarios containing 10, 20, 30, 40 and 50 users. The overall bit rate evaluation shows that AH-NOMA can operate and provide a suboptimal performance compared with other approaches. Finally, we evaluate the capability of AH-NOMA to associate users increasing the number of NOMA transmissions over the number of users allocated to orthogonal resources while meeting individual QoS requirements. For each experiment, we evaluated AH-NOMA against a typical OMA system [17] and the literature considering the work of [16], [71] and an optimal approach under different QoS requirements.

To perform our analyses, the AH-NOMA architecture was implemented using the PADE framework for Python language developed by [70]. The AH-NOMA implementation allowed different scenarios to be simulated. The objective of the simulations was to analyze the use of an adaptive hybrid NOMA and OMA MA communication techniques interchangeably. The Fixed NOMA [16], in turn, was implemented using a fixed value of $\alpha = 0.25$ that is used to pair users that when the NU is unable to receive data, it fallback to OMA transmissions, this implementation will henceforth be referred to as Fixed NOMA. The different scenario simulations and analysis to verify the AH-NOMA operation were carried out with the parameters presented in Table 5.1.

Table 5.1: Simulation Parameters

Transmission power (dBm)	44
Path Loss (dB)	$13.54 + 39.081 \log(d) + 20 \log(f)$ [72]
Noise Figure (dB)	9
Thermal Noise Density (dBm/Hz)	-174
Shadowing deviation (dB)	5.2 [16]
Channel fading	Rayleigh Fading [72]
Carrier Frequency (MHz)	2000
Near User maximum distance (m)	45
Far User maximum distance (m)	100
α-Fixed NOMA [16]	0.25
Maximum number of users	1 first scenario and 30 second scenario

5.1 Trade off and Coverage

This work proposes to maximize the achievable rate of the FU setting a minimum QoS demand to the NU. The potential benefits of exploiting NOMA and OMA in a hybrid architecture are given by the power allocation trade off between paired users and their individuals QoS demand. Therefore, results regarding chosen pairs of NU and FU are closely related to the coverage distance and the QoS demand as depicted in the following Figures. In Figures 5.1, 5.2, 5.3, and 5.4, the trade-off of a pair of NU and FU using NOMA are presented. In these figures, the distance between the NU and the BS is presented in the horizontal axis. In contrast, the vertical axis depicts the distance from the FU to the BS. Finally, the SE was measured in bps/Hz for the FU and it is presented through a heat map considering a gradient of colors where hot colors represent large values, *i.e.,* red color 30 bps/Hz, and cold colors represent the opposite, *i.e.,* dark blue 0 bps/Hz. It is worth to remind that the distance which is shown in the following figures is an abstraction of the channel condition, since the fading effect is closely related to the distance from the BS to the user.

Figure 5.1 shows the maximum achievable data rate of the FU for a low QoS requirement of the NU, *i.e.,* $QoS_{nu} = 1bps/Hz$. As can be observed, the QoS demand of the NU is low, and thus, it needs only a small part of the transmission power to satisfy its requirements. As a consequence, the remaining power is completely allocated to the FU achieving more than $4bps/Hz$ until 150 meters from the BS and more than $15bps/Hz$ in distances below 50 meters. It is worth mentioning that the distance of the FU is always bigger than the distance of the NU; otherwise, the roles of each user would have to be

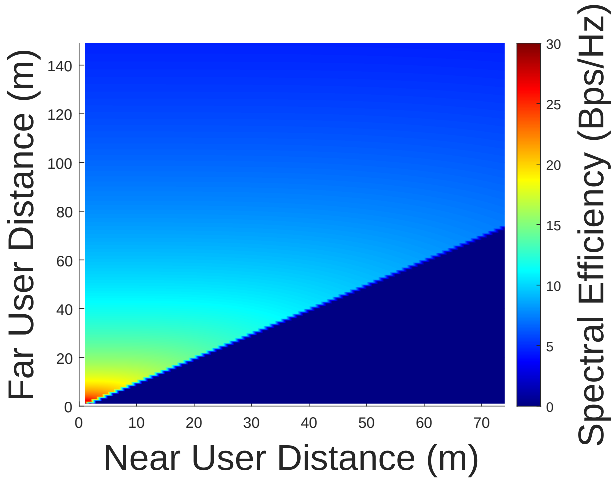

Figure 5.1: QoS_{nu}=$1bps/Hz$.

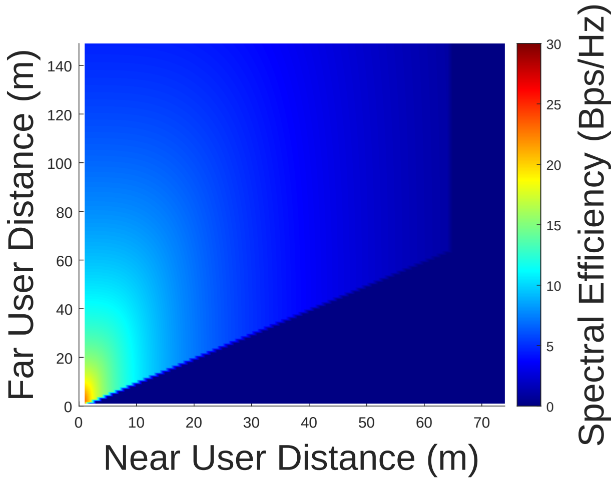

Figure 5.2: QoS_{nu}=$8bps/Hz$.

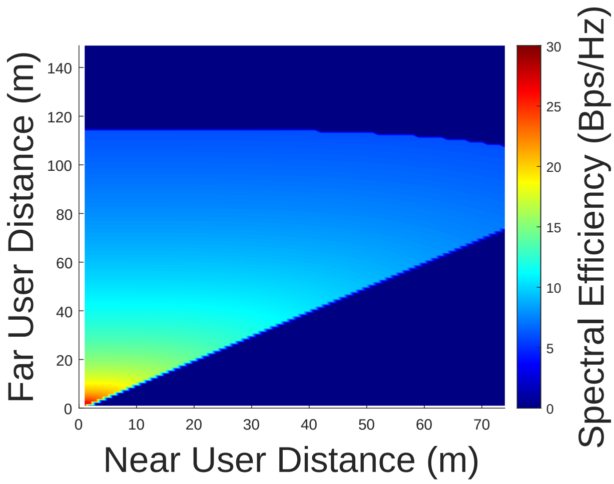

Figure 5.3: QoS_{nu}=$1bps/HzQoS_{fu} = 6bps/Hz$.

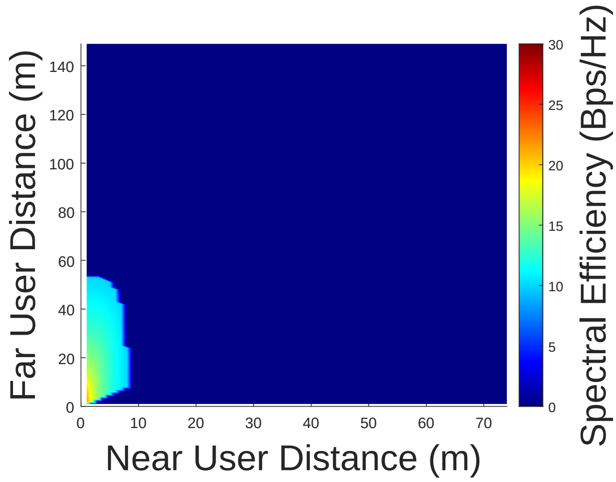

Figure 5.4: QoS_{nu}=$10bps/HzQoS_{fu} = 10bps/Hz$.

changed. For this situation, there is no service provision, as shown by the dark blue area in all figures.

The NU QoS demand can be increased impacting directly in the SE provided to the FU using NOMA. In Figure 5.2, the FU SE is drastically reduced for a $QoS_{nu} = 8bps/Hz$ compared to Figure 5.1, reducing the SE to $10bps/Hz$ for distances below 50 meters and $2bps/Hz$ for distances superior than 150 meters reducing the coverage area of NOMA. To evaluate how the coverage area changes, we introduce a new QoS requirement for the FU QoS_{fu}, *i.e.,* we paint in dark blue the areas that both QoS requirements QoS_{fu} and QoS_{nu} cannot be met in Figures 5.3 and 5.4.

Considering both QoS requirements, the proposed architecture would only be able to transmit using NOMA within a more restricted area, although it is guarantee that the QoS is met within the coverage area. In Figure 5.3, where the NU QoS demand is set to $QoS_{nu} = 1bps/Hz$ and the minimum FU QoS demand is set to $QoS_{fu} = 6bps/Hz$, the coverage area of a NOMA scheme would arrive at best at 116m. Whereas, in Figure 5.4, a very challenging scenario where both users paired by the architecture demands high data rates, such as $10bps/Hz$ for both, the coverage area is reduced to fewer meters, below 53 meters. In scenarios similar to Figure 5.4, the most likely decision of the architecture is to allocate users in an OMA so that each user can have its QoS demand satisfied without sharing resources. The study on the coverage area for NOMA shows that exists situations that NOMA transmission can be used and provide a high SE for the FU that can also be located far from the BS while meeting the FU SE requirements. The trade-off between NOMA and OMA rises from the situations where NOMA cannot provide enough SE to the users and thus it is better to satisfy the users demand allocating them in orthogonal resources while meeting each individual QoS requirement. The trade-off of switching NOMA and OMA, is explained in the following and present by Figure 5.5.

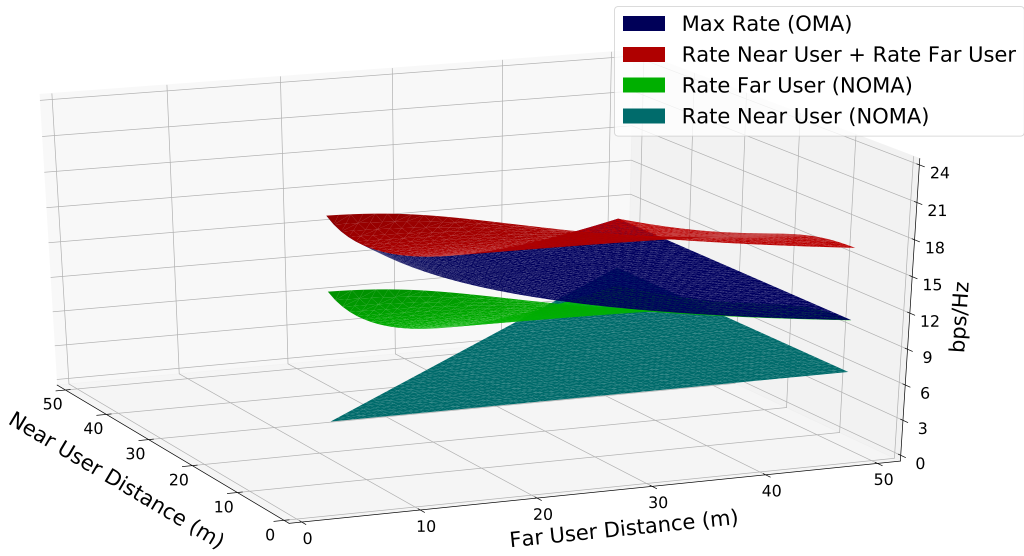

Figure 5.5: Trade-off of OMA and NOMA with a $QoS_{nu} = 6bps/Hz$

As can be seen in Figure 5.5, in the horizontal axes, the distance between the BS to both NU and FU can be seen. In the y-axis, the SE achieve by the users are presented. The cyan plane depicts the NU SE using NOMA and the green plane stands for the FU SE. Also, when both cyan and green planes are summed, the total SE that is achieved using NOMA is presented by the red plane. The dark blue plane represents the OMA SE achieved by the FU. As can be noticed, for a $QoS_{nu} = 6bps/Hz$ the FU using NOMA can almost be served with the same SE in bps/Hz of using the OMA scheme. This trade-off is held for distances until 50 meters. This is an evidence that for small cell scenarios, NOMA presents a great opportunity to share spectrum resources. At same place, OMA always exceeds in SE when compared to a single user's SE using NOMA, thus being more beneficial for high QoS requirements. In the following, an outage probability analysis is presented comparing different approaches to AH-NOMA. The NOMA-OMA trade off is detailed, presenting the scenarios that leverages the usage of NOMA and the scenarios that OMA may have benefits over NOMA.

5.2 Outage probability evaluation

We start to evaluate AH-NOMA calculating the outage probability for a single pair of users scenario for AH-NOMA, OMA and Fixed NOMA approach, presented in Marcano *et al.* [16]. As shown in Figures 5.6 to 5.10, each figure depicts different pair of distances of the NU and the FU from the base station: {x,y}, {w,z}, ... {a,b} meters for the figures from 5.6 to 5.10, respectively. In these figures, the x-axis represents the Far user Spectral Efficiency achieved. Whereas, in the y-axis, the outage probability is depicted. There are four different spectral efficiency demands of the NU $QoS_{\mathrm{nu}} \in \{2, 4, 8, 16\}$ bps/Hz represented by the solid curves in Blue, Orange, Green, and Red, respectively. The dashed purple curve represents the outage probability of the FU if it were allocated in an OMA transmission. Finally, the dotted brown line represents the outage probability of the Fixed NOMA scheme from [16] by applying a fixed power allocation policy of $\alpha = 0.25$.

Recalling that AH-NOMA always satisfies the NU QoS demand first ergo it will not experience any outage in the system, thus it is not considered in the following presented results. As the QoS demand of the NU changes, the remaining power that can be allocated to the FU gets reduced and it may experience some outage. As the AH-NOMA requires to satisfy the NU SE requirements, the outage of the service provided to the FU is influenced by a series of chained events starting at the NU QoS demand, the NU channel condition and the amount of power available, after satisfying the NU demand the FU achievable rate is determined by the remaining power left and its channel condition if its possible to also satisfy the FU requirement, both users are allocated to the same transmission. If one of the events makes pairing impossible than the FU gets an outage of the service.

In Figure 5.6, since both users are located near the BS, 15 and 20 meters for the NU and FU respectively, it is expected that both users experience similar channel conditions. In this case, the trade-off between satisfying different QoS demands of the NU and the maximum achievable SE to the FU is shown. Comparing with the outage probability of the FU allocated in orthogonal resources, satisfying high QoS demands for the NU dramatically affects the outage probability of the FU, since more power is allocated to the NU generating high interference due to their closeness. The interference effect can be captured, when satisfying a low QoS demand for the NU requiring less power and thus the interference that the FU experiences from the NU is also lowered.

Reducing the interference enables the FU to have similar achievable rate and outage probabilities of an OMA transmission. Allocating NU with lower data rate requirements can bring great benefits to the overall network performance, enabling NOMA to save spectral resources. Comparing to a fixed NOMA power allocation policy, it can be seen that the maximum achievable SE for the FU is $2bps/Hz$ due to an elevated interference caused by the NU and it provides more than $20bps/Hz$ to the NU. With fixed power allocation, there is no guarantee for the NU demand, it may be sufficient or not to achieve the user demand.

Typically, placing the FU farther from the BS means that it will experience a worst channel condition. Disruptively, Figure 5.7 shows how NOMA benefits from the diversity of channel gains between the NU and FU achieving the same performance of an OMA

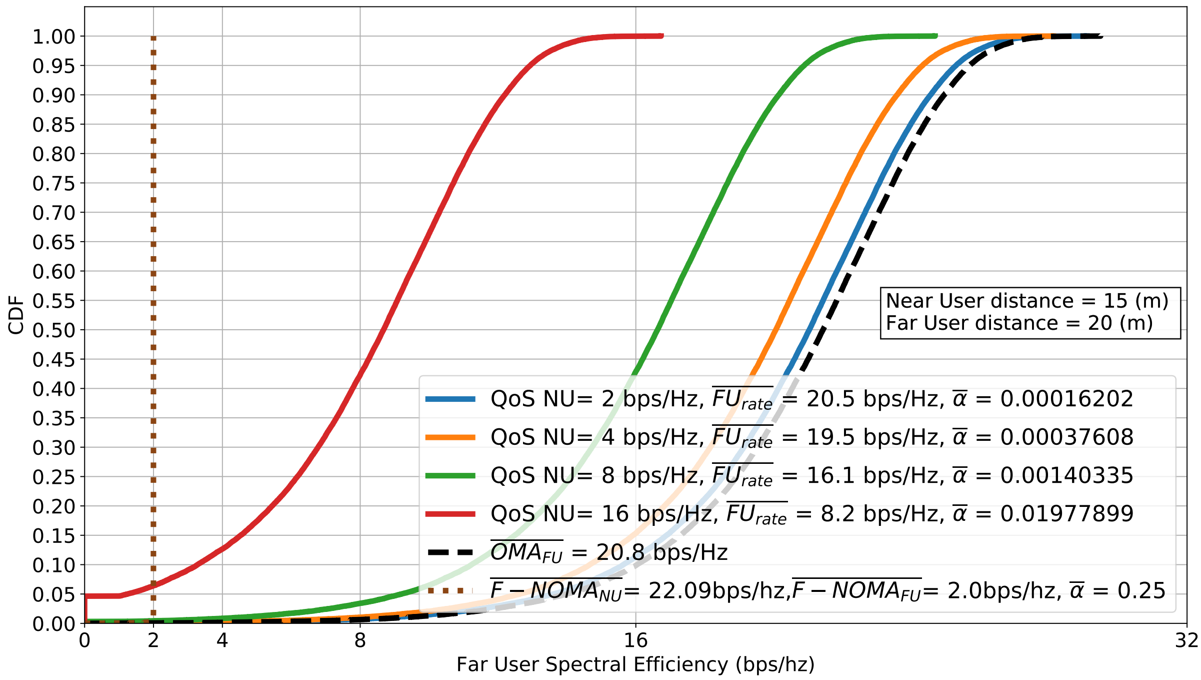

Figure 5.6: Outage probability

system despite that the NU is also being served for most of the cases. The outage probability and maximum achievable SE of the FU in an OMA transmission is lowered due to the channel conditions and starts to overlap with the achievable SE for NOMA while satisfying $2bps/Hz$, $4bps/Hz$ and $8bps/Hz$ to the NU. Figure 5.7 depicts the case where the interference caused by the NU to the FU is insignificant when compared to the path-loss, shadowing, fading, and noise.

By analyzing Figure 5.7, we highlight the importance of making a proper user pairing to enhance the total SE of the network. There will be cases where it is possible to share the same resources serving the NU without harming the transmission and achievable SE provided to the FU as it was allocated in an OMA transmission. Providing power to NU with higher QoS demands remains as the main reason for having a low SE and higher outage probability for the FU. For Fixed NOMA power allocation the interference still limits the maximum SE of the FU in $2bps/Hz$ and since the user is located farther from the BS comparing with Figure 5.6 it experiences a higher outage probability for SE below $2bps/Hz$.

Looking for more challenging scenarios to evaluate the distances impact on the pairing of different users, this time we modified the location of the NU to 40 meters away from the BS. From this position, more power is needed to satisfy the same NU QoS requirements. As Figure 5.8 depicts, the achievable SE of the FU is reduced and it is more likely to the FU experiences an outage when compared to an OMA transmission.

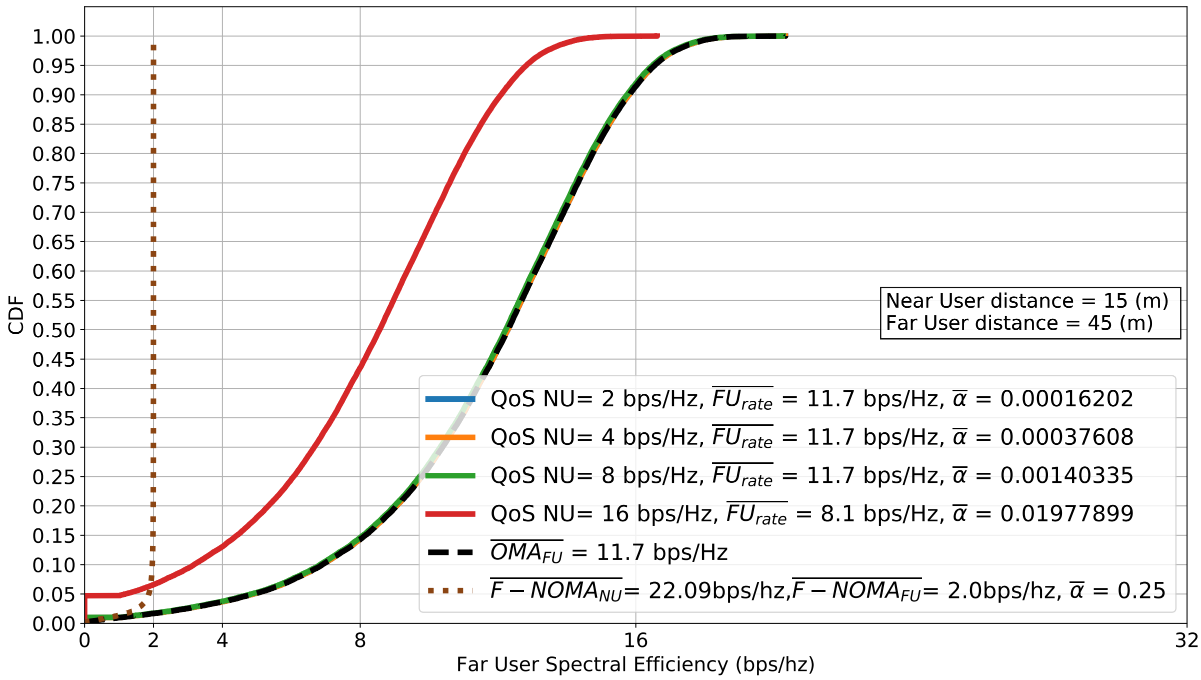

Figure 5.7: Outage probability

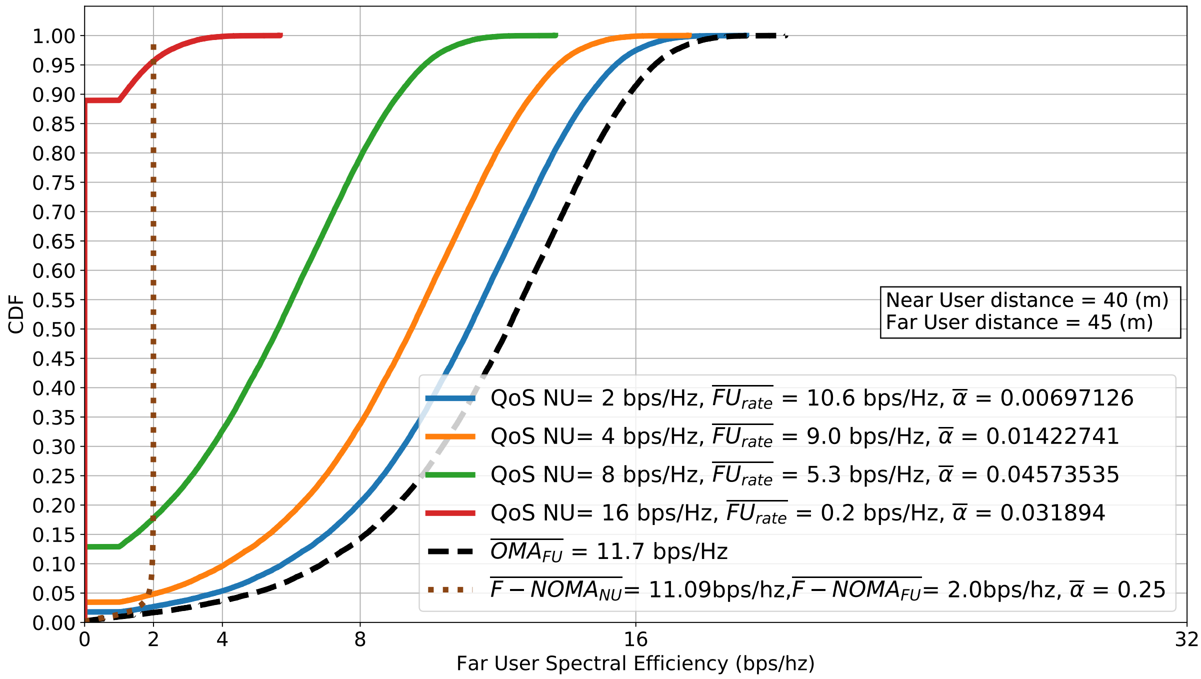

Figure 5.8: Outage probability

In this scenario, allocating a NU with a $16bps/Hz$ demand makes NOMA infeasible since the outage probability is near 90% for providing $1bps/Hz$, providing worst performance than a fixed NOMA power allocation policy.

Figure 5.9 presents a scenario where the NU is located at the middle between the cell

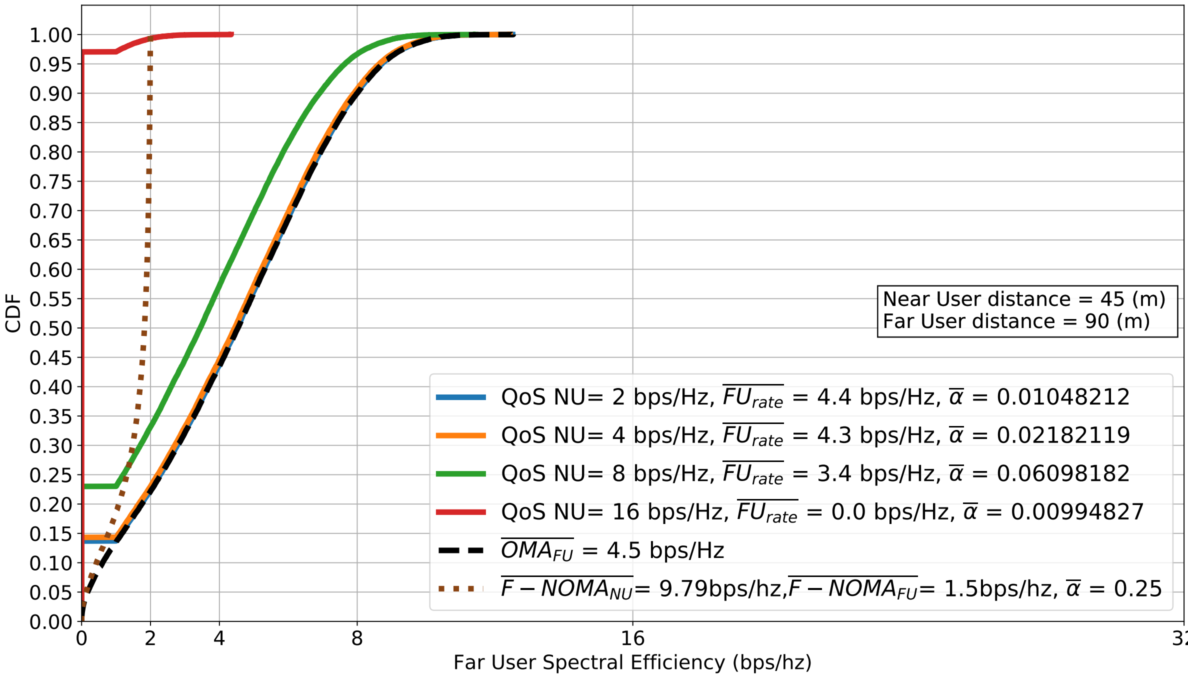

Figure 5.9: Outage probability

edge and the BS, while the FU is located in the cell edge. Similar to Figure 5.7, NOMA benefits from the channel gain diversity from the users and it is capable of providing a service resembling the OMA transmission, although the outage probability is higher due to the worst channel conditions that the FU experiences. As the NU gets farther from the BS it is possible to infer that AH-NOMA will not be able to pair users since the FU outage gets higher even though the NU has a low QoS demand.

The last case analyzed is the case where the NU is located at 15 meters from the BS and the FU is located at 90 meters away from the BS. This represents the maximum channel diversity between a NU and a FU. This time, it makes no difference the NU QoS demand, if there is a FU for which QoS demand can be satisfied by OMA, it can also be satisfied by NOMA.

Having analyzed all the presented cases, for the majority of the cases the SE provided to the FU depends on the user pairing and the NU demand, that is, the selection of the NU causes great impacts on the FU. The AH-NOMA decision process takes into account what users can be paired to satisfy the NU, in this way, AH-NOMA aims to minimize the outage probability of the FU since it has more headroom in power splitting.

Next, we present results regarding the achievable SE and the capacity of pairing users. A comparison with an optimal solution is presented, showing that AH-NOMA has a sub optimal performance and it enhances the overall SE when compared to the orthogonal and the Marcano *et al.* [16] approaches.

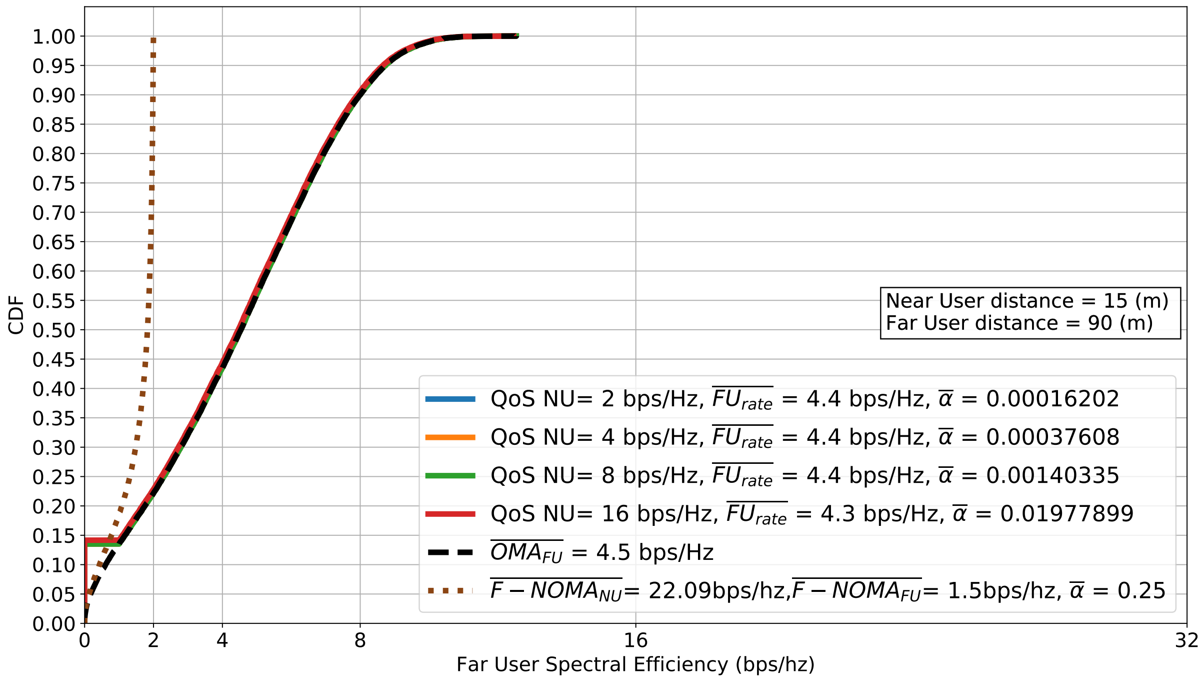

Figure 5.10: Outage probability

5.3 Overall bit rate evaluation

AH-NOMA is concerned about the trade-off and how it can dramatically affect the overall achievable SE of the network. In Figure 5.11, AH-NOMA is compared with allocating users in OMA transmissions, Marcano *et al.* [16], a fairness hybrid NOMA approach, proposed by Maeng *et al.* [71], and the baseline which is the optimal pairing that maximizes the total SE without concerning about satisfying users demand. AH-NOMA is capable of providing a higher total sum rate than OMA and Marcano *et al.* [16] to different scenarios while varying the number of users in the network. Also, AH-NOMA provides comparable SE to the baseline, reaching, at least, 97% of the baseline total SE.

When comparing to other approaches, AH-NOMA is capable of provide SE more than 20% over Marcano *et al.* [16] and 50% over the OMA approach. The main reason for AH-NOMA provides a higher SE is the capability of pairing users, as can be seen in Figure 5.12.

Since AH-NOMA objective is to satisfy the NU data rate demand, there is more power headroom to serve the FU. Thus, there are more candidates to be paired when compared to a Marcano *et al.* [16] approach. Figure 5.12 shows the number of pairs formed to transmit using NOMA by AH-NOMA, the Marcano *et al.* [16], and the optimal baseline. This result shows that AH-NOMA is more flexible and it can take advantage of the trade-off explained earlier to achieve almost optimal pairing results. Pairing more users means that the network is using less spectral resources since paired users share the same resource,

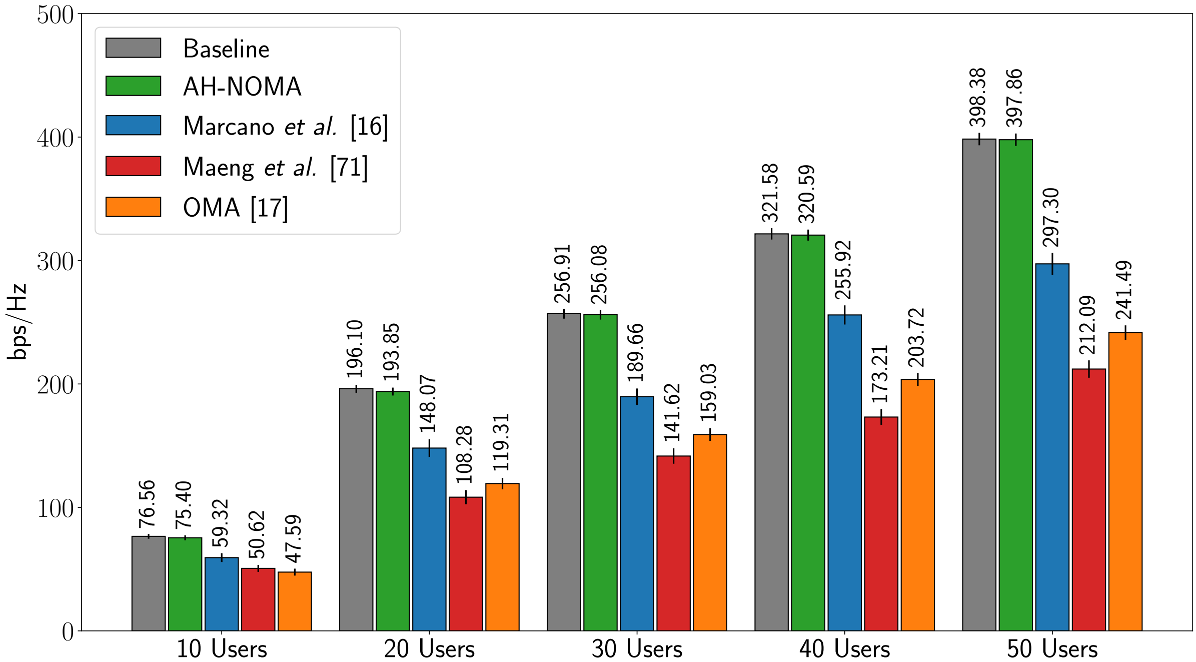

Figure 5.11: Total SE.

Users	AHNOMA	Marcano *et al.* [16]	Maeng *et al.* [71]	OMA [17]
10	98,48%	77,48%	66,12%	62,16%
20	98,85%	75,51%	55,22%	60,84%
30	99,68%	73,82%	55,12%	61,90%
40	99,69%	79,58%	53,86%	63,35%
50	99,87%	74,63%	53,24%	60,62%

Table 5.2: Performance comparison with the optimal Baseline approach.

and also have their demand satisfied.

The presented results shows that AH-NOMA can enhance the overall network performance, providing a greater SE than OMA and conventional NOMA approaches. AH-NOMA is capable of pairing more users due to the power allocation method, which focus on satisfying the NU demand. Table 5.2 shows the relative performance of the schemes compared with the optimal baseline approach. The AH-NOMA has a suboptimal performance and it is capable of overcome the other schemes in all simulated scenarios.

The performance gain of AH-NOMA over the Marcano *et al.* [16], Maeng *et al.* [71] and OMA is shown in Table 5.3. The worst scenario for AH-NOMA is the scenario with few users on the network, the amount of pairs for AH-NOMA gets limited and even though it was capable to provide a higher SE than Marcano *et al.* [16], Maeng *et al.* [71] and OMA. Table 5.3 also presents a performance gain of 57% over OMA which is the standard scheme used in mobile networks.

With all the presented results in this section, AH-NOMA certainly can be employed on

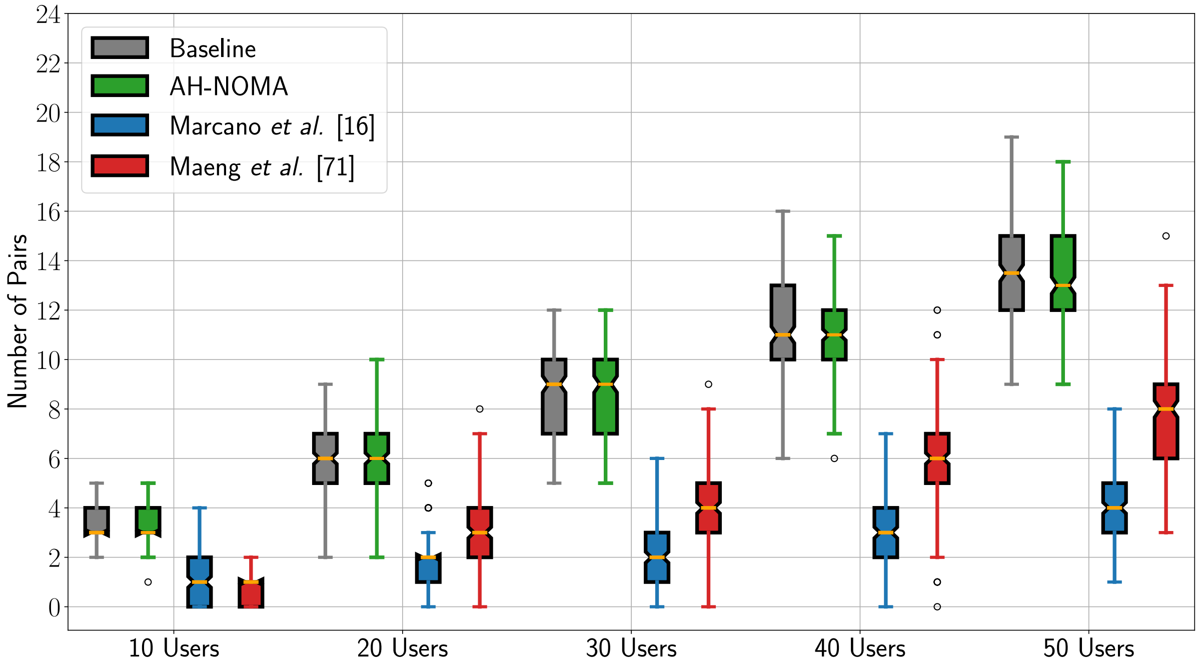

Figure 5.12: Number of paired users.

Users	Marcano *et al.* [16]	Maeng *et al.* [71]	OMA [17]
10	27,11%	48,95%	58,44%
20	30,92%	79,03%	62,48%
30	35,02%	80,82%	61,03%
40	25,27%	85,09%	57,37%
50	33,82%	87,59%	64,75%

Table 5.3: Performance gain comparison of AH-NOMA.

NGMA, enhancing the overall SE of the network and providing the flexibility needed to the achieve the new requirements that are expected for future networks. In the following, the conclusions of this work will be presented.

Chapter 6

Conclusion

The need for more spectrum to fulfill 6G communication demands, claims for higher spectral efficiency and capacity of users in NGMA, as shown in Section 1 the scarcity of spectrum is achieving an even deeper stage as the networks are getting more dense in terms of connected devices. In Section 2, the concepts related to NOMA were reviewed and classified in a Taxonomy, placing this work as a Hybrid NOMA domain, combining OMA and Power Domain NOMA.

This work uses concepts of Cognitive Radio and the employment of agents to introduce a novel communication architecture based on a Multi-agent System capable of share spectrum in an adaptive hybrid NOMA-OMA network. Relying on the premise that transmitters and receivers can either transmit or decode NOMA and OMA without compromising the overall operation. The AH-NOMA architecture aims to satisfy the users' data rate demands and enhance the overall SE of the network by transmitting using NOMA when possible and transmit using OMA when NOMA transmission is severely harmed by interference and/or users data rate demand.

The Multi-agent architecture splits the user pairing, power allocation and transmission mode selection into two different time granularities. Since user demands and channel state information may not change for a fewer seconds, the Service Agent is responsible to keep track of these information and pair the users according to the optimization problem presented in Section 3. Although, the channel state information may become outdated for the users and the pairing made by the Service Agent may not be valid at the moment of the transmission, thus, the Transmission Agent act as scheduler to avoid transmit using NOMA when not possible, allocating the pair formed in a previous moment to orthogonal transmissions.

The results presented in this work reinforce the advantages of applying a hybrid system to a communication network. Providing higher SE than conventional OMA is not the only benefit of AH-NOMA. The capability of meeting different users' data rate demand

and a greater capacity of pairing users when compared to conventional NOMA schemes makes the proposed solution much more robust for future networks and requirements. Also, it was shown the importance of a proper user pairing and the outage probability of users. The presented scenarios do not justify the employment of orthogonal transmissions while non-orthogonal transmissions can achieve the same performance sharing the resource between users with chance of enhanced SE. AH-NOMA was designed to enhance and bring flexibility to the network's operation with decisions regarding spectrum sharing and different MA techniques.

6.1 Future Work

As future works, it is expected to develop new features to the AH-NOMA architecture. The cooperation between various AH-NOMAs in small cell scenarios can enhance the coordination, handover process and interference mitigation between BS. The integration may include the creation of new agents to handle cooperation and a central management agent to coordinate the small cells from a global perspective and based on a much higher time granularity when compared to the implemented agents in this work. As defined by the work of Almeida *et al.* [73], agents can be implemented in different time granularities to work as one Multi-agent architecture and enhance the management, operation and efficiency of the network.

Approximating the proposed architecture to the massive connectivity scenario, new forms to reduce power consumption and the integration with existing technologies like MIMO and mmWave can further enhance the performance of AH-NOMA and extend its operation to new use cases. Technologies such as Augmented Reality (AR) and Virtual Reality (VR) demands larger portions of bandwidth and the densification of networks poses new challenges to these use cases. The need for a higher SE is important to mobile communication continues to evolve and provide new innovation to society as it has been providing since its first deployments.

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