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Mehdi Bennis

SPECTRUM SHARING FOR FUTURE MOBILE CELLULAR SYSTEMS

FACULTY OF TECHNOLOGY,
DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING,
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SPECTRUM SHARING FOR FUTURE MOBILE CELLULAR SYSTEMS

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Abstract

Spectrum sharing has become a high priority research area over the past few years. The motivation behind this lies in the fact that the limited spectrum is currently inefficiently utilized. As recognized by the World radio communication conference (WRC)-07, the amount of identified spectrum is not large enough to support large bandwidths for a substantial number of operators. Therefore, it is paramount for future mobile cellular systems to share the frequency spectrum and coexist in a more efficient manner.

The present dissertation deals with the problem of spectrum scarcity by examining spectrum sharing paradigms where a migration from fixed to flexible resource allocation is investigated. First, a radio resource management (RRM) architecture is proposed where advanced spectrum functionalities accounting for the short-term variations of the spectrum are examined. The achievable gains are shown in a multi-cell, multi-network environment with realistic traffic patterns from a European operator, enhancing thereby spectrum utilization. Second, inter-operator resource sharing in a broadband network is considered where a packet-based cellular network is developed. It is shown that the obtained gains in terms of quality-of-service (QoS), number of operators and different data rates requirements improve the overall efficiency of the network. Besides and in order to cope with the stringent data rate requirements, direct terminal-to-terminal (T2T) communication is examined in which a realistic algorithm is proposed advocating resource reuse in a cellular system with simultaneous communications between mobiles. Numerical results confirm the advantages of resource reuse in terms of throughput, average frame delays and power consumption.

In this thesis, a proposal is made as how to enhance spectrum sharing. The concept of hierarchy is proposed in which wireless competitive operators share the same spectrum band. The decentralized hierarchical approach is shown to bridge the gap between the selfish and centralized approach.

Interference avoidance is studied for point-to-point communication in a selforganized network where different optimal power allocation strategies are examined along with the impact of frequency reuse on the ergodic capacity of the network.

Keywords: cognitive radio, dynamic spectrum access, game theory, interference avoidance, opportunistic communication, radio resource management

Dedicated to my family

Preface

The research for this doctoral thesis has been carried out in the Centre for Wireless Communications (CWC), Department of Electrical and Information Engineering, University of Oulu, Oulu, Finland, during the years 2006-2009.

First of all, I would like to express my gratitude to Dr. Ian Oppermann, former director of CWC for providing me an opportunity to pursue my PhD at CWC.

I am very grateful to my supervisor Professor Matti Latva-aho for guiding me throughout the course of my research, his encouraging attitude, support and valuable recommendations. I will never forget our lunch conversation where you laid out my graduation plan. I would also like to thank Dr. Jorma Lilleberg for introducing me to the topic of spectrum sharing, his invaluable scientific support and numerous recommendations. It is a great honor to be your PhD student.

Many thanks go to Professor Merouane Debbah and Samson Lasaulce for giving me the opportunity to visit the Alcatel-Lucent chair in flexible radio, at SUPELEC Paris. This research visit would not have been possible without the support of both CWC and Nokia.

The financial support for this work was provided by the Finnish Funding Agency for Technology and Innovation (TEKES), Nokia, Nokia Siemens Networks and Elektrobit, through the Packet Access Networks with Flexible Spectrum Use (PANU) project and the FP7 European wireless world initiative new radio (WINNER) project. In addition to the project funding by CWC, the following Finnish foundations have granted personal scholarship for the doctoral studies: Nokia Oyj:n säätiö, Tauno Tönningin, Riitta and Jorma J. Takasen säätiö as well as Infotech Oulu Graduate School, which are hereby gratefully acknowledged.

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I thank all past and present colleagues at the CWC for the joyful and pleasant working environment. In particular, I would like to express my thanks to Dr. Attaphongse Taparugssanagorn, Dr. Antti Tölli, Dr. Kenta Umebayashi, Ikram Ashraf, Isameldin Suliman, Dr. Janne Lehtomaki, Dr. Kari Hooli, Lic. Tech. Mariella Säréstöniemi, Kaveh Ghaboosi, Dr. Pekka Pirinen, Professor Carlos Pomalaza-Ráez, Professor Tadashi Matsumoto, Juha Karjalainen, Dr. Shinsuke Ibi, Dr. Jouko Leinonen, Dr. Alberto Rabbachin, Professor Behnaam Aazhang, Gareth Middleton and many many others. The administrative support of Hanna Saarela, Elina Komminaho, Sari Luukkonen, Mari Lehminkangas, Kirsi Ojutkangas, Tero Suutari, Timo Aikas, Antero Kangas and Jari Sillanpää is gratefully acknowledged.

Besides work, sports have been an essential part of my life in Oulu. I had the honor and pleasure to be part of the *Jalapeños* football team with which I have won a number of tournaments. A shout-out to my basketball friends and to my international "family" for all those special moments spent together. I would like also to thank Dr. Abdenour Hadid for all his advices and support.

Lastly and most importantly, I would like to thank my parents Zohra and Mohammed, my brother Othman and Alicia for the invaluable love and support they have given me throughout my life. To them I dedicate this thesis.

Oulu, October 29, 2009 Mehdi Bennis

Abbreviations

x	*number of cells considered for negotiations*
n	*number of total cells*
P	*probability of interference of a simultaneously allocated chunk*
k	*ratio between allocated and total number of chunks*
$P_{threshold}$	*threshold probability of interference level*
d_{loc}	*expected distance between users within the same cluster*
d_{min}	*minimum distance between clusters*
r	*normalized cell radius*
β	*minimum required signal-to-interference-plus-noise ratio*
α	*path-loss exponent*
$C(i,j)$	*ergodic capacity for the transmitter receiver pair* (i,j)
N_0	*noise variance*
h_{ij}	*channel from transmitter i to receiver* j
r_{ij}	*radius of pair (i,j)*
$\mathbb{E}(\ )$	*ergodic expectation*
$f_p r_{jk}(\ )$	*probability distribution function of the distance between mobile i and its kth closest mobile.*
$f_1^a(r)$	*probability distribution function of the distance between mobile i and its kth closest mobile in the close talker case.*
C_0^a	*ergodic capacity for the close talker case with a range of a.*
R_i	*Shannon rate of operator i*
p_i^n	*power allocation of player i on carrier n*
$\overline{P}_i$	*maximum transmit power for player i*
Γ^{NCG}	*non-cooperative game*
Γ^{SG}	*Stackelberg game*
Γ^{RG}	*repeated game*
$\mathcal{K}$	*space of players*
t_0	*cut-off value*
f_{ru}	*frequency reuse*
λ	*stopping probability of the repeated game* $\mathcal{G}^{RG}$

AWGN	*additive white Gaussian noise*
BB	*busy burst*
BCH	*broadcast channel*
CDMA	*code division multiple access*
CEPT	*European conference on postal and telecommunications*
CR	*cognitive radio*
CIR	*carrier to interference ratio*
CSI	*channel state information*
DCA	*dynamic channel allocation*
DFS	*dynamic frequency selection*
DSA	*dynamic spectrum access - allocation*
DSTC	*distributed space-time coding*
FCC	*federal communications commission*
FDD	*frequency division duplex*
FDMA	*frequency division multiple access*
FMC	*fixed microwave communication*
FSU	*flexible spectrum use*
FSS	*fixed satellite services*
GW	*gateway*
GSM	*global system for mobile communications*
GT	*game theory*
HSA	*hierarchical spectrum access*
HWC	*horizontal sharing with coordination*
HWOC	*horizontal sharing without coordination*
IEEE	*institute of electrical and electronics engineers*
ITU	*international telecommunication union*
IFC	*interference channel*
ISM	*industrial, scientific and medical*
LA	*local area*
LTE	*long term evolution*
KKT	*Karush-Kuhn-Tucker*
MA	*metropolitan area*
MAC	*multiple access channel*
MIMO	*multiple input multiple output*
MS	*mobile station*

OSA	*open spectrum access*
NBS	*Nash bargaining solution*
NE	*Nash equilibrium*
OFDMA	*orthogonal frequency division multiple access*
QOS	*quality of service*
RAN	*radio access network*
RAT	*radio access technology*
RR	*round robin*
RS	*relay station*
SAO	*spectrum access opportunities*
SDR	*software defined radio*
SDMA	*spatial division multiple access*
SE	*Stackelberg equilibrium*
SNR	*signal-to-noise-ratio*
SINR	*signal-to-interference-plus-noise ratio*
SSC	*spectrum sharing and coexistence*
TDD	*time division duplex*
TDMA	*time division multiple access*
UMTS	*universal mobile telecommunications system*
VS	*vertical sharing*
VCG	*Vickrey Clark Groves*
WA	*wide area*
WF	*waterfilling*
WiMAX	*worldwide interoperability for microwave access*
WINNER	*wireless world initiative new radio*
WLAN	*wireless local area network*

List of original articles

This thesis is based on the following articles, which are referred to in the text by their Roman numerals (I–VIII):

I Bennis M, Kermoal JP, Ojanen P, Lara J, Abedi S, Pintenet R, Thilakawardana S & Tafazolli R (2009) Advanced spectrum functionalities for future radio networks. Wireless Personal Communication Journal 48: 175-191, DOI 10.1007/s11277-007-9423-8.

II Bennis M, Wijting C, Abedi S, Thilakawardana S & Tafazolli R (2008) Performance evaluation of advanced spectrum functionalities for future radio networks. Wiley Communication and Mobile Computing Journal, special issue on cognitive radio and advanced spectrum management. DOI: 10.1002/wcm.712.

III Bennis M & Lilleberg J (2007) Inter base station resource sharing and improving the overall efficiency of B3G systems. Proc of IEEE Vehicular Technology Conference, Baltimore, USA, September 30-October 3: 1494-1498.

IV Bennis M & Lilleberg J (2007) Inter-network resource sharing and improving the efficiency of beyond 3G systems. Proc. of IEEE Conference for Information Sciences and Systems, Baltimore, USA, March 14-16: 357-362.

V Bennis M, Middleton G & Lilleberg J (2008) Efficient resource allocation and paving the way towards highly efficient IMT-Advanced systems. Wireless Personal Communication Journal 45: 465-478. DOI: 10.1007/s11277-008-9483-4.

VI Bennis M, Lasaulce S & Debbah M (2009) Inter-operator spectrum sharing from a game theoretical perspective. EURASIP Journal on Advances in Signal Processing, special issue on dynamic spectrum access. DOI :10.1155/2009/295739.

VII Bennis M, Lasaulce S & Debbah M (2009) A Hierarchical game approach to inter-operator spectrum sharing. Proc of IEEE Global Telecommunication Communications, Hawaii, USA, November 30-December 4.

VIII Bennis M, Lilleberg J & Debbah M (2008) Opportunistic power allocation for point-to-point communication in self-organized networks. Proc of IEEE Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, USA, October 26-29: 480-484.

Contents

1 Introduction

1.1 The spectrum debate

Spectrum is a commodity owned by national regulatory bodies established by the governments of different countries. The national regulatory bodies cooperate with each other through the international organizations which make sure that national spectrum regulations provide the means for interoperability and that harmful interference between different countries is avoided. Currently, the radio regulations unit under the international telecommunications union (ITU) is in charge of the spectrum management decisions on an international level. Its European counterpart, the European conference on postal and telecommunications (CEPT) helps carry out studies and other preparatory activities to harmonize the use of the radio spectrum while the Finnish communications regulatory authority (FICORA) plans and administers its use in Finland.

In the last world radio communication conference (WRC'07), less than 600 MHz of bandwidth has been allocated to mobile communication systems. Further bandwidth allocation exclusively to mobile communication systems is not likely because spectrum below 5 GHz is already congested. This is in conflict with the estimated bandwidth requirement between 1200 MHz and 1700 MHz in 2020 (38). Figure 1 (4) gives an illustration of the candidate bands of the current spectrum situation ranging from 400 MHz to 5 7 GHz. Some of the bands are identified globally such as 450 – 470 MHz and 2 3 – 2 4 GHz while others are identified by regions or continents. The final allocation of these candidate bands will be addressed during the upcoming world radio conference.

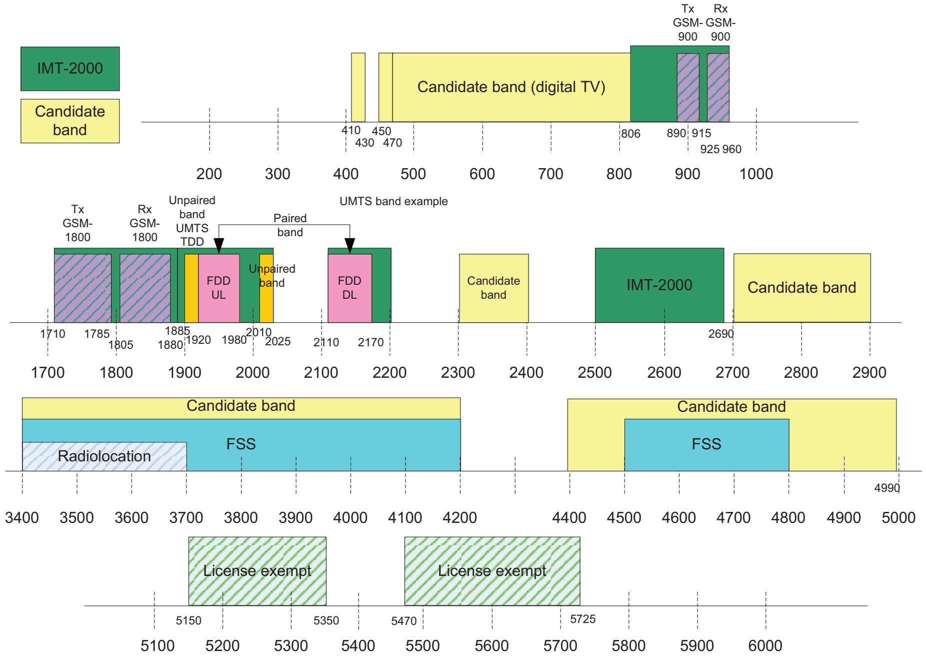


Fig 1. Illustration of the candidate band in the current spectrum situation ranging from 400 **MHz to** 5 7 **GHz based on the international telecommunication union.**

Up to now, spectrum resource allocation has been based on the classic *property rights* mode or *command and control* in which operators are granted licenses. This in turn allows them to exclusively use a certain frequency band in a given area. The government, being the entity responsible for allocating the spectrum and specifying the terms of usage for every spectrum chunk, specifies the types of services that could be provided over any spectrum chunk. This approach has been shaped by the needs of the telecommunications industry wherein the provided solutions have been made based on the communication technologies employed at the time of decision making. The main motivation at that time was to avoid unwanted interference between transmitters, which requires having transmitters operating on non-overlapping spectrum bands. These spectrum allocations are static in nature in the sense that they are valid for long time intervals and over large geographical areas. More recently, between 200 MHz and 1 GHz of spectrum is likely to be freed up in the switch-over from analogue to digital terrestrial television (136). This spectrum band offers an excellent balance between transmission capacity and distance coverage. Moreover, it is particularly suitable for the delivery of high-bandwidth services and indoor coverage thanks to its good signal propagation characteristics. As a result, considerable portions of spectrum will be available.

While the command and control approach has led to the immense success of cellular systems, recent results have shown, however, that this model often leads to inefficient spectrum usage in terms of spectral efficiency. A study conducted in the city of New York (1) has shown that only 13% of the spectrum opportunities was utilized on average. This is due to two main reasons: firstly, the spectrum remains non-utilized during the time that the licensed (primary) systems are idle. Secondly, the spectrum can be congested in one area while being non-utilized in another due to a low spatial density of radio devices. Likewise, a spectrum occupancy measurement campaign carried out in the city of Chicago (2) corroborates the fact that there is a significant non-utilized spectrum band (i.e., white spectral band). As a result, over the course of the last decade and motivated by the ever increasing demands for higher data rates and recent proliferation of networks operating on unlicensed bands such as IEEE 802 11 (i.e., WLAN) a migration from static to flexible and dynamic spectrum allocation has emerged as a new paradigm for more efficient resource allocations. Consequently, several bodies stemming from politicians, regulators, academicians and industrial partners have been looking at the issue of dynamic spectrum access where two proposals have been made: *spectrum property rights* and *spectrum commons*.

The spectrum property rights approach is motivated by the work in (8), in which it is suggested that spectrum holders would have an exclusive usage right, operating in an interference-free environment. Moreover, unused spectrum chunks can be traded in a secondary market in a way that makes spectrum more flexible and efficiently utilized. On the other hand, in the spectrum commons approach, encouraged by the proliferation of unlicensed spectrum band such as the industrial, scientific, and medical (ISM) bands (at 900 MHz, 2 4 GHz, and 5 8 GHz), and the advent of cognitive radios (10), (97) and software defined radio (SDR), it is argued that the overall efficiency of the network can be enhanced because of their potential for reusing the assigned spectrum where cognitive (secondary) radio systems try to locally utilize white spaces in the spectrum in the absence of the primary system. In this approach, the cognitive terminals will efficiently share the spectrum through spectrum etiquettes and self-organization mechanisms.

There is a lively debate between spectrum property and spectrum commons advocates where the former is criticized for deliberately asking for huge amounts of money for spectrum lease whereas the latter is criticized for its vulnerability to the tragedy of the commons (151) leading to an eventual depletion of the resources and no quality of service (QoS) guarantees. It is also argued in (9) that while allowing innovators to use spectrum in unexpected ways, spectrum policies should be enabled to support the growth of the more stringent applications. Finally, in (12) the authors adopt a different stance towards the spectrum debate by arguing that both models are not polar opposites and there may be governance regimes supporting both the exclusivity of property rights and the dynamic nature of shared managed access to a spectrum commons.

Figure 2 illustrates a classification/taxonomy for the problem of spectrum management. Dynamic spectrum access is divided into spectrum sharing and coexistence (SSC), and spectrum assignment (SA). The former deals with the case when different IMT-Advanced systems share and coexist in the same frequency band. SSC is further divided into horizontal sharing with (HWC) and without coordination (HWOC) according to the priority of accessing the spectrum. SA on the other hand deals with assigning spectrum within the same IMT-Advanced system and is divided into long-term (LT) and short-term (ST) spectrum assignment. Moreover, open spectrum access (resp. hierarchical spectrum access) are equivalent to horizontal sharing (resp. vertical sharing). It is to be noted that the proposed taxonomy serves as a baseline for addressing the spectrum sharing problem.

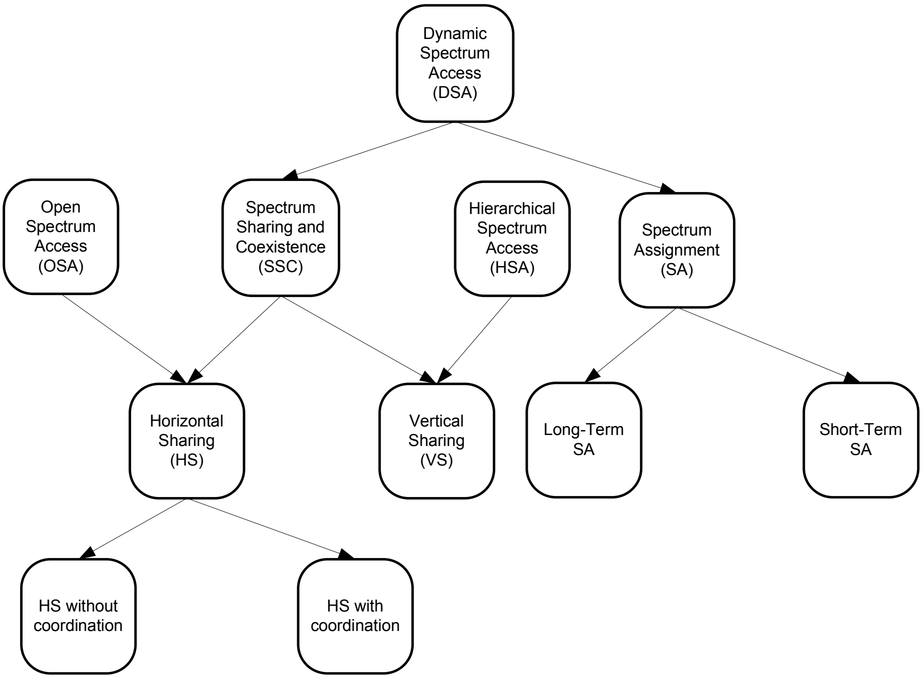


Fig 2. **Classification/taxonomy of dynamic spectrum access.**

1.2 Motivation for this thesis

The scarcity of spectrum resources and proliferation of networks operating on both licensed and unlicensed bands have sparked a lot of research in which there is a great deal of work in the literature. Presently, spectrum sharing and flexible spectrum use are planned to be used in current and upcoming emerging telecommunication standards such as worldwide interoperability for microwave access (WiMAX) (3), (7) and long term evolution (LTE) (5), (6). Clearly, efficient radio resource allocation remains an open problem in which interference is detrimental and this precisely constitutes the main motivation laying out the scope of this thesis.

For this purpose, we examine in this thesis different aspects of spectrum sharing. Firstly, an architecture capturing different aspects of spectrum sharing is defined accounting for the "dynamicity" of the spectrum where short-term spectrum assignment is proposed. Moreover, system level simulations are provided in a cellular setting where operators share different resources (spectrum, base stations, time-slots, etc). Different sharing gains are obtained for different service classes corresponding to different data rates requirements. Secondly, in a cellular context, the problem of direct terminal to terminal (T2T) communication is investigated where locally distributed terminals communicate without the need for base station, in which resources (time-slots) are reused and the spatial distribution of users in clusters is accounted for.

We then study the problem of spectrum sharing from a game theoretic perspective in which the competitive interaction of operators is studied. First, the inter-operator spectrum sharing is modeled as a non-cooperative game where operators act selfishly while accessing the spectrum. A hierarchical game is next proposed providing incentives for operators to improve their respective payoffs. In addition, when the game is no longer static, repeated games are proposed to further improve the payoffs of different operators, thereby sustaining cooperation.

Finally, in a self-organized setting, point-to-point communication is examined where different power allocation strategies are given.

1.3 Author's contribution

The thesis is in part based on eight original publications, including four journal papers [I, II, V, VI] and four conference papers [III, IV, VII, VIII].

In [I], the work was developed within the scope of the European project FP7 WINNER in which the author has had the main responsibility of developing the original idea related to the radio resource management architecture, namely the flexible spectrum use. Moreover, the author had developed the new concept of short-term spectrum assignment as a new mean for more efficient spectrum usage. The author has in addition written all the paper. The rest of the authors provided constructive criticism as well as editorial comments.

In [II], the work was developed within the scope of the European project FP7 WINNER in which the author has had the main responsibility of developing the idea of short-term (ST) spectrum assignment mechanisms as a novel radio resource management entity in addition to writing the software to perform the system-level simulations. The author has also made a proposal for a new protocol for base station to base station communication to enable short-term spectrum assignment. The second, third and fourth authors contributed with the concept of multi-band scheduler as well as providing valuable comments.

In [III], the author has had the main responsibility of writing all the paper. The part dedicated to terminal-to-terminal communication was done in cooperation with the second author. Finally, the third author introduced the concept of terminal-to-terminal communications and provided guidance and supervision.

In [IV, V], the author has had the main responsibility of developing the original idea, analysis as well as writing all the paper. Finally, the second author introduced the first author to the problem of spectrum sharing and provided guidance and supervision.

In [VI, VII], the author has had the main responsibility of developing the original idea, analysis as well as writing all of the paper. The second and third authors provided valuable guidance and supervision.

In [VIII], the author has had the main responsibility of developing the original idea, analysis as well as writing all the paper. The second and third authors provided guidance and supervision.

1.4 Outline of the thesis

The thesis is organized as follows. Chapter 2 gives an overview of spectrum sharing literature along with game theoretic spectrum studies. Chapter 3 concentrates on the author's own research and therefore, a summary of the original papers is presented which collectively map into the proposed taxonomy. Finally, conclusions of the main results of the thesis are given in Chapter 4, where also some possible directions for further research are presented.

2 Literature review

This chapter provides relevant background information and parallel work within the scope of the thesis.

From a radio resource management point of view, several channel allocation schemes have been proposed in the literature. In fixed channel allocation (FCA), channels are permanently allocated to each cell according to a given reuse pattern. FCA is very simple where interference between channels is easy to control. In cellular systems, the performance suffers from poor flexibility because FCA does not adapt to changing traffic conditions. A situation could occur where resources are running short in one cell, while adjacent cells have a lot of extra capacity. Due to the variable nature of traffic in cellular systems, more flexible strategies than FCA have been developed. In dynamic channel allocation (DCA), there is no fixed relationship between cells and channels. Basically, all channels are placed in a common pool, and when a new call arrives the channel is assigned from the pool if the carrier to interference ratio (CIR) constraint is satisfied. To overcome the weak efficiency of DCA schemes under high load conditions as well as the low flexibility of FCA, hybrid channel allocation (HCA) is proposed in (78) as a mixture of FCA and DCA. In HCA, the total number of available channels is divided into fixed and dynamic sets where the fixed set contains a number of nominal channels assigned to cells as in the FCA, and another set of channels is shared between all the users in the system to achieve flexibility.

Over the course of the last two decades, many approaches have been proposed to address the issue of dynamic spectrum allocation. In the mid-to-late 1990s, some of the initial foundational work on spectrum sharing was done in (26), (27), (28). It was shown that from a queueing theory perspective, independent networks could achieve an overall better capacity through cooperation. Examining the FCC-proposed *listen-before-talk* approach, they showed such greedy algorithms could lead to very poor spectrum utilization, and hence developed a system that imposed artificial penalties on greedy algorithms to keep them constrained. In his PhD dissertation in 2000, Mitola proposed the concept of cognitive radio (CR) (98) which is essentially a SDR (145) with artificial intelligence, capable of sensing and reacting to its environment. Later on, some work was conducted as a part of the Dynamic Radio for IP-Services in Vehicular Environments (DRiVE) and Spectrum Efficient Unicast and Multicast Services over

Dynamic multi-Radio Networks in Vehicular Environments (OverDRiVE) projects aiming at providing video content delivery to vehicles (70), (71), (72). The OverDRiVE architecture involves partitioning the spectrum in space, frequency and time where each radio access network (RAN) would be allocated certain blocks by a central authority in response to their predicted capacity needs. The CORVUS project used similar ideas (85) where they created a channelized spectrum pool from unused licensed spectrum proposing algorithms to allocate it efficiently. A dynamic intelligent management of spectrum for ubiquitous mobile access network (DIMSUMNet) architecture was proposed in (19) providing opportunistic access to large parts of under-utilized spectrum. A simpler pragmatic approach offering coordinated, spatially aggregated spectrum access via a regional spectrum broker is argued to be more attractive in the immediate future. These architectures are centralized requiring therefore *someone* to decide who should use which spectral resources at what time, while guaranteeing minimal interference to licensed devices. While achieving good results, current politics involved in frequency licensing would make adopting these approaches unlikely because the need for a central authority hampers feasible deployment. As a result, more recent research has mainly focused on distributed techniques for dynamic spectrum allocation, where no central spectrum authority is required.

A survey on distributed spectrum management functionalities is given in (97) with spectrum sensing, sharing, decision and mobility as key components. A common control channel is introduced to enable a distributed coordination between cognitive radio users. Due to the challenging design, complexity and imprecision of intelligent devices, fuzzy logic is proposed in (88), in the context of cognitive radios. In (90), the authors study the problem of multi-hop networking problem for cognitive radios aiming for efficient spectrum allocation, scheduling, interference avoidance and multi-path routing. A lower bound is given to estimate the objective function of the formulated problem which proves to be near-optimal. In (74) and (137) spectrum pooling is proposed as an innovative strategy to enhance spectrum efficiency, by overlaying a new mobile radio system on an existing one without requiring any changes to the actual licensed system. In (132), a distributed coordination approach for spectrum sharing is developed showing results outperforming the traditional dedicated channel approach by 25% – 35% in throughput and 50% reduction in delay. In (44)-(45), dynamic spectrum sharing for future mobile communication systems is studied where a busy-burst (BB) signaling is proposed to tackle interference coming from adjacent cells, in a distributed fashion.

From a system-level perspective, several works have been carried out on resource sharing between operators, commonly referred to as *channel borrowing* (78). When channels are borrowed between cells, networks have more flexibility improving thereby performances compared to traditional channel assignment schemes as well as preventing congestions in some cells. In (86), simulations related to channel borrowing schemes are examined depicting the achievable gains in terms of blocking probability. In (50), the performance of spectrum sharing is investigated for the universal mobile telecommunications system (UMTS) frequency division duplex (FDD) downlink. The obtained capacity gain is due to the increased trunking efficiency when both sub-networks share radio resources. It is seen that the lower the number of nominal channel is, the higher the trunking gain obtained. This study is further extended in (51) showing that spectrum sharing offers capacity gains under restricted and cooperative conditions, thanks to the trunking gain where resources are pooled. Moreover, the cooperation in terms of inter-operator signaling to maintain grouped base stations orthogonality is shown to be necessary to ensure the full benefit obtained from resource pooling.

There exist two scenarios of practical interest for the study of dynamic spectrum access (DSA) (13): hierarchical spectrum access (HSA) and open spectrum access (OSA). In HSA, cognitive radios coexist with legacy systems if and only if the additional interference overcome by the pre-existing systems is below a specific threshold. These thresholds can be predefined by network operators, manufacturers or regulators to ensure certain quality of service (QoS) for primary systems. Moreover, cognitive radios only transmit using radio resources left unused by the primary systems, hence CRs are often called *opportunistic* or secondary radio devices. Such unused radio resources are called spectrum access opportunities (SAO) or available channels. Typically, an available channel consists of non-occupied time-slots in time division multiple access (TDMA), frequency bands in frequency division multiple access (FDMA), spatial directions in spatial division multiple access (SDMA), tones in orthogonal frequency division multiple access (OFDMA), or spreading codes in code division multiple access (CDMA).

It is worth noting that interference management is done differently in CDMA-based system (i.e., IS-95 (11)) in which the simultaneous transmissions, intra-cell and inter-cell, cause interference due to universal frequency reuse. Nevertheless, in OFDMA-based systems, since a user's information is spread by hopping in the time-frequency grid, the transmissions within a cell can be kept orthogonal but adjacent cells share the same bandwidth and inter-cell interference still exists. Hence, interference management is more challenging in this case and as a result remains an open issue. Finally, OFDMA system has the advantage of the full frequency reuse of CDMA while retaining the benefits of narrow band system with no intra-cell interference.

In HSA, once the SAOs have been identified each cognitive radio decides whether or not to transmit based on their own performance criterion. Furthermore, the HSA model considers two different spectrum sharing scenarios, the underlay and the overlay approaches (13), (18). With underlay, opportunistic devices have to meet a certain power constraint in order to keep the interference level they generate on the primary systems always below their noise floor. This is the case of ultra wide-band (UWB) or interference alignment systems for example in (18), (69), (75). Here, opportunistic and primary transmitters can simultaneously transmit without generating harmful interference to the primary receivers. On the other hand, the overlay approach, which targets the spectral white spaces, does not impose any limit on the transmit power. It only requires opportunistic radio devices to identify radio resources left unused by the primary network and exploit them subject to the constraint that those resources can be required by the primary system at any time. In this approach, the opportunistic and primary players do not transmit simultaneously.

Within the framework of hierarchical spectrum access, a primary-prioritized Markov model is proposed in (113) modeling the interactions between primary and secondary users as continuous-time Markov chains, where a good trade-off can be achieved between spectrum efficiency and fairness. Optimal access probabilities are given for the secondary users, by which the spectrum access of secondary users is optimally coordinated, and spectrum dynamics are captured. In (116), the rate adaptation problem for secondary users is formulated as a zero-sum dynamic Markovian game with a delay constraint. The Nash equilibrium of the resulting game is computed as a randomized mixture of pure threshold policies, estimated by a stochastic approximation algorithm that adaptively estimates and tracks Nash equilibrium policies for non-stationary problems with time-varying channels. It has also been shown in (110), (111) that, interestingly enough, when unlicensed devices coexist with licensed devices in the same frequency and time simultaneously, the capacity achieved by unlicensed devices with reduced power is very low, while causing harmful interference to the licensed users.

In open spectrum access, the notion of primary and secondary systems does not exist. In this scenario, each terminal has the same rights to access the spectrum at any time. OSA typically includes the case of unlicensed bands. Radio devices operating in these bands include cordless telephones, wireless sensors, and devices operating under the standards of Wi-Fi (IEEE 802.11), Zig-Bee (IEEE 802.15.4), and Bluetooth

(IEEE 802.15.1). Here, each technology implements different coding and modulation schemes, so there exists neither a common multiple access technique nor a signaling system to harmonize the use of these bands. Different governmental agencies, such as the European radio communications office (ERO) in Europe and the federal communications commission (FCC) in the USA, have defined a set of rules either in terms of power spectral density masks or in terms of time duty cycles, depending on the application [6]. The power spectral density mask defines the limits on the peak-to-average power ratio (PAPR) as a function of the frequency offset around the central frequency. The time duty cycle defines the longest cumulative period a specific device is allowed to transmit within a time unit.

2.1 Spectrum sharing: architecture and concepts

As previously mentioned, cognitive radio systems and opportunistic communications have drawn a lot of attention in the research community because of their potential for reusing the assigned spectrum where cognitive (secondary) radio systems locally utilize *white spaces* in the spectrum in the absence of the primary system. Moreover, owing to the high envisaged data rate requirements, current cellular network topologies may fail to deliver universal coverage at affordable cost for network infrastructure and maintenance. The bandwidth requirements and the need to resort to frequencies above 3 GHz, will lead to significantly reduced cell size. As a consequence, new network topologies such as ad hoc and multihop networks have been investigated (48), (90), (148). Additionally, major efforts have been spent on the development of next generation wireless communication systems such as LTE (6) and WiMAX (3), (7). These evolved systems are considering terminal-to-terminal communication (T2T) (46), (47), (144) as underlay and/or overlay to the existing cellular network to further increase the spectral efficiency of the system.

Terminal to terminal communication shares the same resources with the cellular communication while staying under the control of the cellular network, which increases the spectrum utilization. It is paramount that the T2T communication must not generate harmful interference to the primary service, i.e., the cellular network. One simple method of sharing a licensed band is through spreading the signal energy radiated by each secondary transmitter over the whole band using spread sharing techniques (100), suppressing thereby the power spectrum density of the resultant interference to the primary receivers. This is much easier than detecting *white spaces* because the interference from the T2T communication can be controlled by the cellular network. Under this setting, the under-utilized spectrum, as the available radio resource which can be utilized by the secondary service, varies over time. Given an acceptable level of accuracy in the spectrum sensing, the temporal variations can then be exploited subject to the primary system interference threshold. Therefore, the maximum achievable capacity is directly affected by the temporal variations in the available radio resources. It is shown in (29) and (30) that obtaining the maximum achievable capacity for an additive white Gaussian noise (AWGN) channel in different transmission scenarios with interference threshold is an instance of the water-filling problem (22). Under various fading conditions, the achievable capacity is studied in (32) where it is shown that employing OSA results in a significant increase in the achievable capacity in comparison with the OSA in an equivalent AWGN channel. T2T communication has also been investigated under the term *hybrid* wireless network protocols in (33) where both advantages of BS oriented and ad hoc wireless networks are combined.

On the other hand, some few theoretical results exist on the network capacity trade-off between networks sharing spectrum despite this being a basic question. In (125), the transmission capacities of a two-tier network are analyzed, which consists of a cellular network and a network of femtocell hot-spots. In (129), the transport capacities of two coexisting multi-hop ad hoc networks are shown to follow the optimum scaling laws for an asymptotically large number of network nodes. In (152), the transmission-capacity trade-off between the coexisting cellular and ad hoc networks is analyzed for different spectrum sharing methods, and bounds on outage probabilities for both networks are derived for spectrum overlay and underlay, with and without successive interference cancellation (SIC). These results provide a theoretical basis for adapting the node density of the ad hoc network to the dynamic of the traffic in the cellular uplink under the outage constraint for both networks. The trade-off relationship suggests that transmission capacities of coexisting networks can be increased by adjusting various parameters such as decreasing the distances between intended ad hoc transmitters and receivers, increasing the base station density and link diversity gains, or by employing SIC. In (89), the design of a multiuser decentralized network is addressed, where for a given total system bandwidth and fixed data rate constraint for each transmission, the authors investigate how many frequency slots N the band should be partitioned into in order to maximize the number of simultaneous links in the network. It turns out that the bandwidth partitioning results in a trade-off where a large N allows for more parallel, non-interfering communications to take place in the same area at the expense of increasing

SINR requirements. Additionally, the impact of dynamic spectrum sharing techniques on legacy radio systems is investigated in (121), where a framework is developed to evaluate the interference profile at a legacy receiver under different system scenarios including the hidden-node and imperfect-sensing problems. Therein, two OSA scenarios are considered where the access time for the secondary system is considered in the first case, and the interference level in the receiver of the primary user is the main constraint for the secondary transmitter, in the second case. In the former scenario, the channel availability is based on an ON/OFF Markov model alternating between a busy and idle state (34) and (35). As expected, the maximum achievable capacity is significantly increased through decreasing the primary network activity factor. Similar conclusions hold for the latter scenario. Moreover, in (46), the performance of device to device (D2D) underlay communication is studied in a single cell environment where results show that the SINR statistics of D2D users is comparable to that of the cellular user in most of the cell area. In addition, it is observed that the uplink resource sharing is more beneficial for the system when the D2D pair is farther away from the base station.

2.2 Game theory for spectrum sharing

The imbalance between the increasing demands of wireless spectra and limited radio resources poses an imminent challenge in efficient spectrum sharing. In this context, an efficient dynamic spectrum sharing faces several difficulties: a) users' mobility and network topology is of a dynamic nature, b) various network infrastructures are likely to be interacting in the future, c) users may have different behaviors upon accessing the spectrum (cooperative, selfish, and even malicious) and finally d) the optimization of spectrum usage in a centralized approach is in general a multi-objective optimization problem, which is very difficult to analyze and solve. Therefore, game theory (GT) (14) is seen as a natural paradigm to study a network where terminals compete with each other for a common resource, namely the spectrum. Game theory is a mathematical tool that analyzes the strategic interactions among rational decision makers. The simplest representation of a game is the *normal form* defined as follow:

Definition 1 *(**Normal Form Game**(14)) A game in normal form is denoted by* $\{\mathcal{K}, \mathcal{S}, \{u_k\}_{\forall k \in \mathcal{K}}\}$ *and is composed of three elements:*

– *a set of players:* $\mathcal{K} = \{1, \quad ,K\}$,

– *a set of strategy profiles:* $\mathcal{S} = \mathcal{S}_1 \times \quad \times \mathcal{S}_K$*, where* $\mathcal{S}_k$ *is the strategy set of the* k^{th}

player,

- *a set of utility functions: The k^{th} player's utility function is $u_k : \mathcal{S} \rightarrow \mathbb{R}_+$ and is denoted by $u_k(s_k, \boldsymbol{s}_{-k})$ where $s_k \in \mathcal{S}_k$ and $\boldsymbol{s}_{-k} = (s_1, \quad , s_{k-1}, s_{k+1}, \quad , s_K) \in \mathcal{S}_1 \times \quad \times \mathcal{S}_{k-1} \times \mathcal{S}_{k+1} \times \quad \times \mathcal{S}_K$.*

The set of players is a finite set $\mathcal{K} \subset \mathbb{N}$ of which each element represents a player. The strategy set $\mathcal{S}_k$ contains the set of actions player k might take in the game. The utility function $u_k(s_k, \mathbf{s}_{-k})$ allows a player to evaluate the convenience of its strategy s_k with respect to the other players' strategies $\mathbf{s}_{-k}$.

The importance of studying dynamic spectrum sharing from a game theoretical perspective is multi-fold. First, by modeling dynamic spectrum sharing among network users (primary and secondary users) as games, the network users' behaviors and actions can be analyzed in a formalized game structure, by which the theoretical achievements in game theory can be fully utilized. Second, game theory equips us with various optimality criteria for the spectrum sharing problem. These criteria such as price of anarchy and price of stability (14) are of high concern in the case of multiplicity of equilibria. Third, the application of game theory to dynamic spectrum access enables us to derive efficient distributed approaches for dynamic spectrum access using local information. This aspect is useful when centralized control is no longer available and flexible self-organized approaches are deemed necessary. An overview of game theoretic dynamic spectrum sharing is found in (80).

It is worth noting that various types of games exist depending on the considered scenario along with its underlying assumptions. In a non-cooperative game, each player is selfish and unconcerned about all the other players' performance. In contrast, in a cooperative approach, each player maximizes a common benefit for the set of players assuming that all the other players have adopted the same cooperative behavior.

2.2.1 Non-cooperative games

In non-cooperative games, the network is totally decentralized and players selfishly optimize their individual performance criteria, leading to an equilibrium of the network, called Nash equilibrium (NE). A Nash equilibrium corresponds to a profile of strategies $s^* = (s_1^*, \quad s_K^*)$ for which each player's strategy s_k^*, $\forall k \in \mathcal{K}$ is the optimal response to all the other players' strategies s_{-k}^*.

Definition 2 *(**Nash equilibrium** (14)) In the game* $\{\mathcal{K}, \mathcal{S}, (u_k)_{\forall k \in \mathcal{K}}\}$ *a strategy profile* $s^* = (s_1^*, \quad , s_K^*) \in \mathcal{S}$ *is an NE if it satisfies,*

$$\forall k \in \mathcal{K} \quad \textit{and} \quad \forall s_k \in \mathcal{S}_k, \quad u_k(s_k^*, s_{-k}^*) \geq u_k(s_k, s_{-k}^*) \tag{1}$$

The existence and uniqueness of an equilibrium is an attractive feature of a decentralized network since the system owner(s) can predict the performance of the users and hence guarantee for instance a minimum QoS requirement.

One type of non-cooperative games called Potential games (107) have the desirable convergence property when players adopt a better-response or best-response strategy. The basic idea is to find the potential function such that the incentive of all players are mapped into one global function, and the set of pure Nash equilibria can be found by simply locating the local optima of the potential function. In (55), a unified framework based on potential games is proposed with an application to power control in CDMA in which sufficient conditions are given for the existence and uniqueness of the Nash equilibrium. Moreover, different distributed algorithms are provided along with their convergence properties. Cooperative potential games were considered in (56) for power control for UWB where the proposed algorithm outperforms the traditional scheme in terms of convergence, fairness and power consumption. In (58), Potential games were studied for base station selection and sharing in self-configuring networks. It is shown that depending on the number of transmitters, BS selection might perform better than BS sharing. This results in a Braess paradox (134) where increasing the strategy space of each player leads to a degeneration of the global network spectral efficiency. On the other hand, spectrum sharing was studied using congestion games (154), (155) modeling the competition for resources among multiple selfish players. Similar to the Potential games approach when a player unilaterally switches her strategy, the change in her own payoff is the same as the change in a global objective, known as the potential function.

In (79), the spectrum sharing problem in an unlicensed band is studied where a non-cooperative game is shown to yield inefficient (105) outcomes. In (52)-(54), the authors study the problem of maximizing mutual information subject to spectrum mask constraints and transmit power, for both simultaneous and asynchronous cases. The existence of the Nash equilibrium is proven and sufficient conditions are given for the uniqueness along with distributed iterative algorithms to reach the Nash equilibria. In (146)-(149), the authors examine the conditions and behavior of several common convergence dynamics from game theory and show how they influence the structure of networks of cognitive radios. Moreover, in (57), the benefits of bandwidth limiting in decentralized vector multiple access channels is examined. First, the authors study the case when transmitters use non-intersecting sets of bands, whereas in the second case all available frequency bands are freely exploited using successive interference cancelation. A closed-form expression is given for the optimal number of accessible bands in the former case, while bandwidth limiting does not bring any significant improvement to the network spectral efficiency in the latter. In (60), a game theoretic approach for distributed resource allocation is adopted, where a power-control game at the user level, and a throughput game at the system level are studied. The proposed games are shown to converge to near-optimal solutions. In (61), the authors propose a non-cooperative game approach for distributed sub-channel assignment, adaptive modulation, and power control for multi-cell OFDM networks where each user water-fills (81) its power on different sub-channels, regarding other users' powers as interference. An 80% reduction in transmission power is obtained compared with the fixed assignment algorithm.

In order to study the optimality of a non-cooperative game, the *price of anarchy* (14) is an important measure defined as the ratio between the worst possible Nash equilibrium and a social optimum that can be achieved only if a central authority is available. In (23), the price of anarchy is studied for non-cooperative spectrum sharing games, in which channel assignment for access points is studied for Wi-Fi networks. An interesting finding is that the price of anarchy is unbounded unless certain constraints such as the distribution of the users, are applied . Moreover, the price of anarchy is studied for the problem of spectrum assignment in local bargaining scenarios in (87) in which the proposed bargaining approach provides a complexity decrease of 50%.

Since the static game formulation leads to inefficient Nash equilibrium outcomes due to users' selfishness, repeated games (150) are considered allowing the possibility of building reputations and applying punishments. This way, a larger set of achievable rates is attained which supports an efficient NE. In (112), the authors investigated whether spectrum efficiency and fairness can be obtained by modeling the spectrum sharing as a self-learning repeated game. With the proposed framework, the inefficiency due to users' selfish behavior can be highly improved, and the secondary users can distributedly obtain their optimal access probabilities with only local observations. In (114) and (115), game-theoretical design methods were studied to suppress cheating and collusion between selfish users. With the Bayesian mechanism design, selfish users have no incentive to cheat and can achieve cooperative unlicensed spectrum sharing under the threat of punishment. With collusion-resistant dynamic spectrum pricing, licensed spectrum resources are efficiently distributed among multiple primary and secondary users, and user collusion is effectively suppressed by setting up the optimal reserve price in the auction. In (63), the authors formulate the problem of how two independent wireless networks share the spectrum without direct coordination and information exchange as a repeated game. Analysis and simulation results indicate that cooperation is an achievable equilibrium that often improves the overall spectrum efficiency.

Compared to Nash games where all players take their moves simultaneously, Stackelberg games (14), (15) model the scenario when a hierarchy exists between players. The players of a Stackelberg game include a leader and a follower/followers in which a leader commits to a strategy first, and then a follower selfishly optimizes his own reward considering the strategy selected by the leader. The game leader perfectly knows the set of strategies and the utilities of the followers. Similarly, it is guaranteed that the followers can observe the actions of their leader(s).

Definition 3 ***(Stackelberg Equilibrium (SE)*** *(14)) A strategy profile* (p_1^{SE}, p_2^{SE}) *is called a (pure) Stackelberg equilibrium if* p_1^{SE} *maximizes the single-variable utility of the leader and* $p_2^{SE} \in BR_2(p_1)$*, where the notation* $BR_j(p_i)$ *stands for best response of player* j *to player* $i \neq j$*. By denoting* (p_1^{SE}, p_2^{SE}) *the power profile at the SE, this definition translates mathematically as:*

$$p_1^{SE} = \arg\max_{p_1} u_1(p_1, p_2(p_1)), \tag{2}$$

with for all p_1*,*

$$BR_2(p_1) = \arg\max_{p_2} u_2(p_1, p_2), \tag{3}$$

and $p_2^{SE} = BR_2(p_1^{SE})$*.*

The framework of Stackelberg games is readily applied to the problem of dynamic spectrum access in which primary and secondary systems interact. Here, two different types of players (primary and secondary systems) exist whose priority is different upon accessing the radio resources. This concept naturally arises in multiple practical situations: a) when primary and secondary systems share the spectrum, b) when users have access to the medium in an asynchronous manner, c) when operators deploy their networks at different times and d) when some nodes have more power than others such as the base station. In a two-level Stackelberg game, the game leader moves first and the other players follow and play simultaneously. In the recent literature, an application of Stackelberg games in dynamic spectrum access was presented in (82) where the design of a multi-antenna access point using a non-cooperative Stackelberg game model is investigated. A primary system might offer a set of channels to the opportunistic terminals in exchange of cooperation in the form of distributed space-time coding (DSTC). It is shown that spectrum leasing based on trading secondary spectrum access for cooperation is a promising framework for cognitive radio. Moreover, in (142), the authors analyze the effect of hierarchy in energy-efficient power control games for multiple access channel for both the individual user and overall network performance. It is shown that both the leader and followers benefit from hierarchy and following is more energy-efficient than leading. In (108), a Stackelberg formulation is applied to power control and channel allocation in the context of cognitive radio networks where a Stackelberg leader (licensee) charges a virtual price for using the licensed frequency band that impacts player's utilities. Two price update algorithms were proposed where simulations show that the total utility of the network increases when this virtual pricing is played compared with the traditional Stackelberg game. Stackelberg games are also studied in (120) for distributed relay selection and power control for multi-user cooperative networks. The proposed system not only helps the source smartly choose relays at better locations but also help the competing relays ask a reasonable price to maximize their utilities. In (101), hierarchy is proposed for satellite systems rate allocation, in which both the efficiency of the network and users' satisfaction are improved. In (40), inter-cell interference management in OFDMA-based WiMAX/3GPP-LTE systems is investigated where the interactions between base stations are modeled using a Stackelberg game where they can make intelligent and rational decisions to reduce interference with minimum optimization cost. When the optimization cost is too high, the best choice for base stations is to avoid optimizing and the dominating Nash equilibrium is the outcome when BSs just randomly allocate sub-carriers. A survey of hierarchical power allocation games is given in (20).

2.2.2 Cooperative games

Unlike the non-cooperative setting, the global performance of the network becomes the main target in the cooperative game approach. Introducing cooperation in a game can be done by repeating the game, forming coalitions or by introducing a certain degree of hierarchy. Under this scenario, each player aims at maximizing a common benefit for the set of players, assuming that all the other players adopt the same cooperative behavior. A common benefit could be interpreted for instance, as the sum of individual benefits (social welfare problem).

In the case of cooperation, users form coalitions where coordination requires signaling among users, which is not always practically appealing. In (66)-(67), the DSA problem is modeled as a coalitional game where receivers belonging to the same coalition jointly decode their received signals and perform interference cancelation (92). This configuration corresponds to a set of single input multiple output - multiple access channels (SIMO-MAC). Similarly, transmitters can also form coalitions leading to virtual MISO systems and if both transmitters and receivers form coalitions, the network is equivalent to a set of virtual MIMO channels. In (102), coalitional game theory is studied allowing the dynamic formation of coalitions among wireless nodes. A simple and distributed merge and split algorithm for coalition formation is proposed through which transmitters are able to self-organize and form a structured network composed of disjoint stable coalitions. Simulation results show an improvement of the average user payoff by 26 44% and an efficient handling of user's mobility. In (103), a fair scheme to allocate subcarrier, rate and power for multi-user OFDMA systems is studied using Nash bargaining solutions (NBS) and coalitions. In (68), spectrum pooling was studied using coalitional game theory. By pooling their infrastructure and allowing the possibility of subscribers being served by any of the cooperating operators, an overall better user satisfaction and increased operator revenues are achieved. A generalization to multi-hop network is proposed in (104) allowing channel qualities and customer locations to change in time. Finally, a comprehensive tutorial on coalitional game theory can be found in (141).

In order to achieve efficient and fair dynamic spectrum sharing, NBS is important for optimality analysis in different spectrum sharing scenarios, albeit requiring full channel state information (CSI). In (139), the issue of distributed spectrum sharing is investigated using tools from cooperative game theory where NBS achieve a good compromise between fairness and efficiency. An extension of this work is provided in (140) with an analysis of different bargaining solutions and how they are affected by a non-convex utility space. Moreover, the proposed approach provides a reasonable compromise between efficiency and fairness, achieving thereby allocations with minima close to the egalitarian solution and efficiency close to the *MaxSum*. In (87), local bargaining is proposed where users affected by the mobility pattern self-organize into bargaining groups, and adapt their spectrum assignment to approximate a new optimal assignment. In (73), due to the very hard problem of lack of uniqueness of the NE points in the water-filling (WF) game, NBS solutions were considered for a simple 2×2 interference channel. From their simulation results, the cooperative solution NBS is shown to significantly outperform the competitive Nash equilibrium.

In non-cooperative games, each user aims to achieve as much utility as possible regardless of the impact on the other users. The pricing approaches therefore attempt to mitigate this by assigning a cost, or price, for accessing a resource. This approach is similar to cooperative approaches in that it attempts to proportionally divide access to a resource. However, a pricing approach can be more flexible, allowing users to be assigned different priorities, based on the users' willingness to pay. In (84), the authors propose a belief-assisted pricing approach for multiple primary and secondary users to efficiently share spectrum resources. The belief metrics are proposed to predict other users' future possible strategies according to the game histories and assist each user's decision making. Moreover, by using the proposed belief function, each user is able to make the optimal decision for the next bid with only local information. A distributed algorithm is then developed through the belief-based bidding process that can not only approach the optimal competitive equilibrium, but also substantially decrease the overhead of bid information compared to traditional continuous double auction mechanisms. Moreover, in (130) a power control solution is proposed for wireless data in which pricing of transmit powers was introduced to improve user utilities that reflected the QoS a wireless terminal received. Moreover, in (131) and according to an explicit set of rules, primary users (auctioneers) who attempt to sell unused channels to secondary users (bidders), determine resource allocation and prices on the basis of bids from the secondary users. In addition, multiple sellers and buyers may coexist, which indicates the double auction scenario where not only secondary but also primary users need to compete with each other to make beneficial transactions possible. In (87), the authors propose a local bargaining approach to achieve distributed conflict-free spectrum assignment adapted to network topology changes. Two bargaining strategies are proposed: one-to-one bargaining and one-buyer-multiple-seller. By using the proposed local bargaining, the optimal spectrum assignment does not need to be computed after each topology change, significantly decreasing the computation and communication overhead. In (95), an auction-based spectrum sharing approach is proposed where several secondary users purchase channels from one primary user or spectrum broker (manager) through a Vickrey-Clark-Groves (VCG) auction (131) to achieve a social optimal solution. Because of the required information from the users and the computational burden on the manager, two auction mechanisms, SINR and power-based, are proposed to allocate the received power as a function of bids submitted by the users and the price announced by the manager. It turns out that the power auction generates more revenues than the SINR auction, although the difference in revenue collected by the two auctions vanishes as the number of users increases. In (147), distributed power control algorithms for both single channel and multi-channel wireless networks are studied. Therein, users announce their prices to reflect their sensitivities to current interference levels and then adjust their power to maximize their surplus. The convergence of these algorithms can be characterized in certain cases achieving an optimal power allocation as well as requiring limited knowledge of channel gains by each user and quick convergence.

2.2.3 Bayesian games

When channel state information is no longer perfect, Bayesian games (135) have been proposed. In this setting, at least one player does not know the utility function of one or more of its opponents, hence each player plays the game based on a probabilistic approach. In (123), the dynamic spectrum access problem is investigated in the interference channel setup where each user selfishly maximizes its own rate. The underlying scenario is that radio devices do not know any of the parameters to play the game (CSI is not available neither at the transmitter nor the receivers). Rather, it is assumed that all the channel realizations are drawn from a known probability distribution function. It is found that under the assumption of incomplete information, a unique Nash equilibrium exists. In (117), the authors investigate the problem of decentralized DSA for cognitive radio where an adaptive regret based learning procedure is applied which tracks the set of correlated equilibria of the game. In (118), the authors deal with decentralized dynamic spectrum access using the theory of multivariate global games (119) where cognitive radios obtain noisy measurements of the quality of several logical channels and need to decide which channel to access. Each CR determines which channel to access based on its expected throughput and Bayesian estimate of the intention of other CRs. A simple characterization of the competitive optimal behavior of the system is obtained as a function of the prior probability distribution of spectrum hole occupancy, channel quality and observation noise.

3 Summary of published papers

3.1 General

The contents of the eight original articles can be divided into two categories. The first part consists of listed papers (Articles I, II, III, IV, V, VI and VII) investigating the spectrum functionality architecture (Article I) with a system-level performance evaluation of the short-term spectrum assignment (Article II). Inter-operator spectrum sharing for different service classes is studied in Articles III and IV. Article V studies direct terminal-to-terminal communication in a cellular network using resource reuse and simultaneous communications between mobiles. Articles VI and VII investigate means of enhancing spectrum sharing by introducing hierarchy.

The second part of the thesis deals with the interference avoidance issue being a key component for making spectrum sharing a reality. Different power allocation strategies are investigated for multiple transmit and receive pairs. Moreover, dynamic frequency reuse for point-to-point communication is studied (Article VIII).

3.2 Spectrum sharing

3.2.1 Advanced spectrum functionalities for future radio networks

Motivated by the increasing demand for a flexible use of the spectrum, Article I proposes a 4G radio network concept illustrated in Figure 3 covering the full range of operability scenarios from wide area (WA) over metropolitan area (MA) to local area (LA). The proposed architecture captures some of the key components provided in the proposed taxonomy (Figure 2). First, several scenarios are illustrated with envisagable technical solutions. Second, an advanced spectrum functionality architecture is proposed accounting for the foreseen interactions between the proposed system concept and other IMT-advanced systems. The proposed architecture is based upon the need for flexible spectrum use (FSU) and spectrum sharing and coexistence (SSC) capabilities. Within FSU, RANs can negotiate and exchange spectrum resources with one another (spectrum trading) whereas spectrum enabling technologies allow spectrum sharing with other IMT-advanced systems. FSU will lead, on both fast and slow basis, to a better utilization of the spectrum through multi-operator solutions, increasing thereby spectrum availability and utilization. On the other hand, SSC (for instance with fixed satellite services (FSS)) will enable network's deployment and lead to a better spectrum utilization in a multi-system environment. In other words, SSC corresponds to opportunistic use of spectrum.

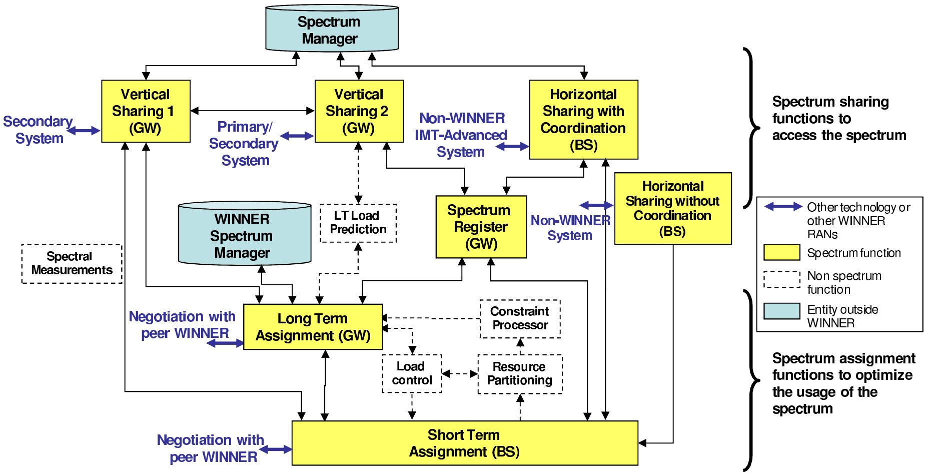


Fig 3. Illustration of the interactivity between the spectrum sharing and spectrum assignment functions ((156) published by permission of SPRINGER).

The concept of vertical sharing is proposed where WINNER system is the primary system which may assist a secondary system by sharing its primary spectrum resources. This is done through signaling via its broadcast channel (BCH). In contrast, horizontal sharing takes place when the involved systems (WINNER and other IMT-Advanced system) have equal access rights to the spectrum. In this case, the systems might choose either to coordinate their access to the spectrum in the case of HWC or not to do so in the case of HWOC.

The spectrum manager is responsible for the overall usage of the spectrum in coexistence with other non-WINNER radio access technologies (RATs). It is a policy and rules maker so that peer-to-peer negotiations between WINNER and non-WINNER RANs follow the same rules. The peer negotiating entities (VS_1, VS_2 and HWC) recognize the spectrum policies and comply with them. Likewise, the WINNER spectrum manager is a policy and rule maker but only for WINNER RANs.

Article I also discusses the network architecture in which both centralized and distributed approaches are considered. In the WA and MA deployment case, when WINNER is a primary system willing to share its band with secondary systems, an overall centralized coordination between VS_1 and LT assignment is expected. However, when WINNER is a secondary system sharing the spectrum with FSS, VS_2 resorts to a centralized approach in which a necessary compilation of measurements is performed in a cell cluster manner. Instead, for LA deployment case, a more autonomous and faster execution of the local vertical sharing VS_1 or HWC takes place where LT spectrum assignment plays a passive role and a closer interaction is established with local ST spectrum assignment.

Long term (LT) spectrum assignment is distributed to all radio access networks to prevent excessive signaling keeping the operation of the RANs independent from each other and further preventing cumbersome centralized architecture. Peer LT assignment entities connections are needed and the only central unit over the multiple RANs is the WINNER spectrum manager.

3.2.2 Performance evaluation of short-term (ST) spectrum assignment

Performance evaluation of spectral resource management with a main emphasis on short-term spectrum assignment is presented in Article II. The goal is to efficiently exchange spectrum resources between different RANs of the *same* technology on a fast basis, while managing the interference inflicted to neighboring cells. Sharing the spectrum on fast basis will be feasible only if efficient communications means are enabled between BSs. To this end, a protocol proposal is made where different solutions (over-the-air, through the IP backbone, wired and shared BSs) are presented with their pros and cons. Finally, the results of ST spectrum assignments are obtained in a system-level simulator consisting of a cellular topology of 16 cells following WINNER system concept (21) parameters.

The LT spectrum assignment is based on longer time-scales dealing with average or expected spectrum resources. In LT assignment these average spectrum resources taken from traffic demand curves are used to assign spectrum resources at the cell level. However, the actual (instantaneous) spectrum resources or the spectrum resources demand varies from the average value depending on the "dynamicity" of spectrum usage in each

RAN. Therefore, to efficiently allocate these spectrum resources during the ST assignment period, spectrum resources are allocated based on the actual spectrum resources rather than the average values. The difference between the actual usage of spectrum resources and the average allocation of spectrum resources results in additional or insufficient usage of resources at each cell resulting in spectrum boundary changes in both RANs.

The trend of the demand curves are based on average values of real traffic patterns. The average number of spectrum resources per day is calculated considering the mean demand over a weekly period. 50% of the data usage and 50% of voice usage are considered in resource requests. Due to operational limitations, it is assumed that only 80% of spectrum resources are utilized during the maximum demand, for example during the busy hour period, from the available 230 frequency chunks. Although the average number of requested chunks can be drawn from the traffic pattern curve, there is an instantaneous variation in actual requested number of chunks during each ST assignment during which the actual number of requested chunks is a random number drawn from a normal distribution $\mathcal{N}(\mu,\sigma)$, where μ is the average value from the traffic demand curves for each RAN and σ is the standard deviation.

Furthermore and for each RAN, both *greedy* and *generous* cells are defined depending on additional or insufficient resources. N_a is the number of resources allocated to each cell during LT assignment and N_d is the actual number of resources needed from the traffic demand curves. When $N_a > N_d$, these cells are categorized as generous where extra resources are available for negotiation, whereas if $N_a < N_d$ these cells are greedy as they are starving for more resources. During the ST assignment period, only generous and greedy cells negotiate with each other. Finally, to avoid conflicts between more than one cell pair entering ST negotiation, the number of cell pairs negotiation is *one*. Figure 4 depicts an illustration of the ST spectrum assignment between two RANs in which cells c_1 and c_{11} exchange spectrum.

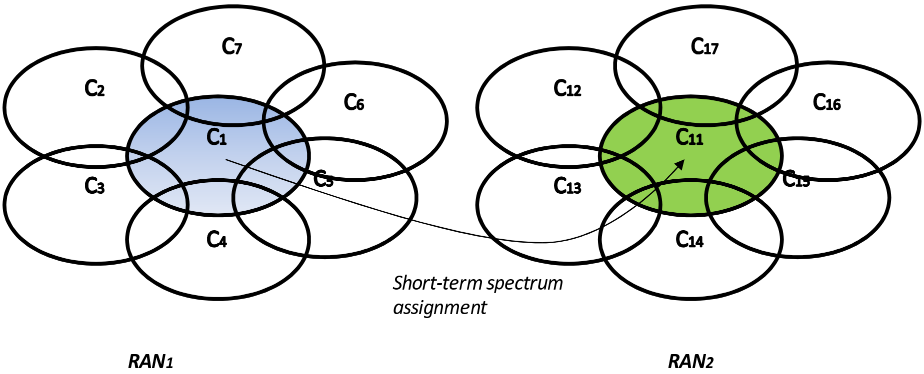


Fig 4. Short-term spectrum assignment between two RANs where cells c_1 and c_{11} exchange spectrum ((157) published by permission of WILEY).

The resource allocation in each cell is based on Costas arrays (127), (128). During ST assignment, cells of different RANs with extra spectrum resources can enter negotiations. Prior to that, the impact of interference between RANs needs to be measured where some chunks allocated to a certain cell can interfere with the allocation of the same chunk in neighboring cells. Therefore, in order to minimize the interference in the neighboring cells of negotiating cells, a maximum allowable interference threshold $P_{threshold}$ is defined as the maximum allowable interference within ST negotiation agreed between cells of first tier in RAN_1. If a neighboring cell cluster is chosen to calculate the interference inflicted on the other cells of the negotiated network, the probability of interference of a simultaneous allocated chunk P in a single cell is represented as a binomial distribution such as:

$$P = \frac{n!}{x!(n-x)!}k^x(1-k)^{n-x} \tag{4}$$

Where n is the total number of cells, x is the number of cells considered for negotiations, and k is the probability of having a successful spectrum negotiation. Moreover, for a successful spectrum assignment at the cell level, an interference level constraint $P_{threshold}$ is enforced.

Figure 5 depicts the chunk usage in negotiating cell C_1 with a 20% average chunk usage and different interference thresholds. It is seen that when the number of agreed cells for negotiation x increases, the percentage of available chunks for negotiation decreases. In addition, two cell pair selections are investigated: the first one is based on cell pair selection with least satisfaction in which the generous cell satisfies the minimum requirement of the greedy cell whereas the second algorithm is based on cell pair selection with the most flexibility in allocating chunks. Having more resources than required allows flexibility in resource allocation for the greedy cell thus avoiding interference to neighboring cells of the generous cell. Average gain in spectrum resources versus the average offered load for both algorithms are depicted in Figure 6 along with the impact of traffic pattern variance σ. It turns out that the amount of negotiation chunks or gain in terms of frequency chunks is higher with higher variation independent of the cell selection algorithms. Having more bursty traffic demand patterns at cell level contributes towards positive performance gains in ST assignment. Furthermore, by scheduling extra spectrum chunks gain from ST assignment, the maximum flexibility algorithm has a greater degree of freedom compared to the least satisfaction algorithm.

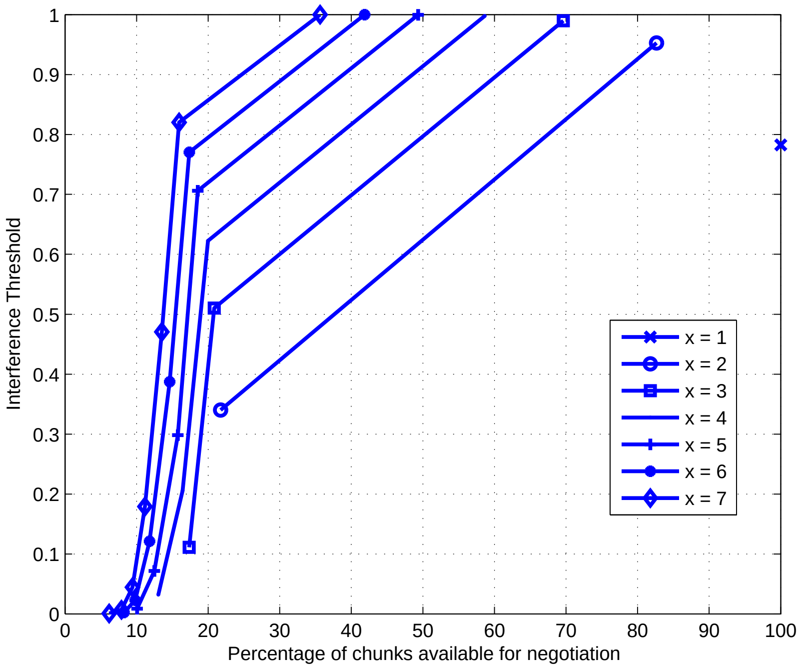


Fig 5. Probability of interference threshold versus percentage of chunks for negotiation (average chunk usage 20%) ((157) published by permission of WILEY).

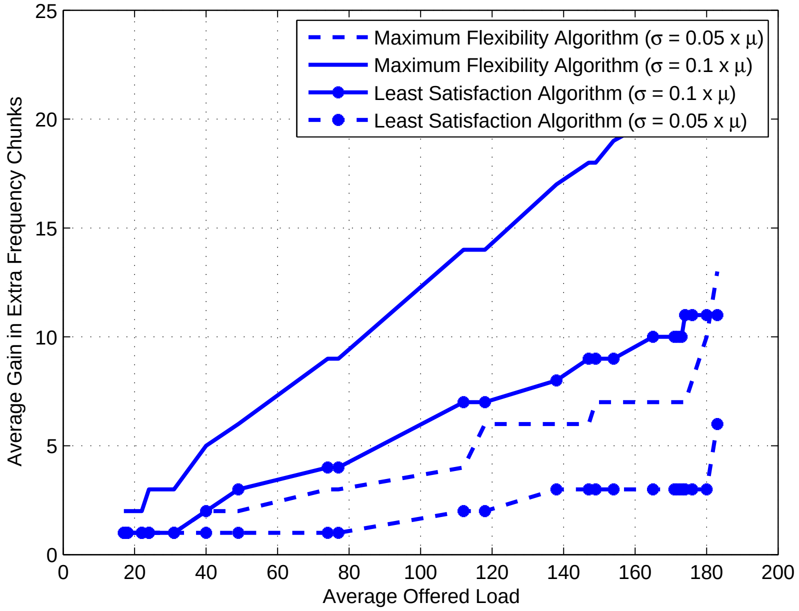


Fig 6. Comparison between the least satisfaction and maximum flexibility algorithms for $\sigma = 0\ 1 \times \mu$ and $\sigma = 0\ 05 \times \mu$ ((157) published by permission of WILEY).

In addition to ST spectrum assignment gains, round robin (RR) scheduling algorithms are introduced to further improve the overall system performance. Because users in different areas of the cell experience different interference conditions, different scheduling rules are introduced for mobile terminals in different areas of the cell: users in the central area are scheduled according to RR mechanisms while users in marginal areas are scheduled according to local interference conditions depending on neighboring cells. Simulation results show that with the least satisfaction algorithm resources are used more efficiently yielding more gains, especially for high load. As a result, by using more efficient scheduling approaches, the spectrum is used more efficiently.

3.2.3 Inter-operator spectrum sharing for different service classes

Under the taxonomical category of spectrum sharing and coexistence, Articles III and IV quantify the achievable performance gains of resource sharing in a cellular network. Mobile stations belonging to different operators share their resources in two ways: as a *last resort* or *always best connected* resource sharing scenario. The former deals with the case when mobile stations are assigned to their home base stations whereas in the latter case, mobile stations are always connected to the *best* (regardless of whether it is served by home or foreign operator) base stations. For comparison purposes, performances are also compared to the case when mobile stations are only assigned to their home operators (*non sharing*). Figure 7 depicts an illustration of the sharing algorithms. In the always best connected case, mobile station MS_1 connects to base station BS_4 from a different operator. The system operates under a TDMA-based scheduled medium access scheme, based on a packet-switched cellular network where both physical layer and geographical constraints are taken into account. System-level parameters can be found in Table 1. To provide greater traffic capacity, a sectorized cell layout is used where at the BS sites, the cell is divided into three sectors.

Table 1. Relevant Physical Layer Parameters.

Parameter	Value
Deployment	Wide Area
Modulation	16-QAM
Bandwidth	20 MHz
FFT Size	264 + 64 cyc. pref.
No. Data Carriers	192
Noise Figure	9 dB
Super-Frame Duration	10 ms
Number of drops	50
Minimum Allocation Entity	TDMA slot
Path-loss model	Okumura-Hata
Coding rate	1/2

In a WA network spread over approximately 1 5 km^2, operators use non co-located base stations, even though each will ensure that it has coverage over the entire region. Mobile stations are randomly distributed in this area, and randomly assigned to a home operator from whom they regularly buy service. Finally, the same mobile station distribution and call pattern are used for sharing and non-sharing cases. A standard Poisson traffic model is used, where the length of calls are drawn from an exponential distribution. Operators use their slot allocations to schedule data to their mobile stations, which will request slots from their home or foreign operators. The proposed resource sharing algorithm takes into account the distance between a mobile station and the other base stations, as well as the signal strength quality (i.e., SNR). Finally, it is assumed that interference between mobile stations does not occur and time synchronization is idealized among operators (i.e., non-overlapping time-slots). This scenario can be envisaged when operators, willing to share, are synchronized if that provides them more revenues to handle subscribers from other networks.

If no excess resource exists, the unscheduled packets experience a delay in service and take priority in the next super-frame. For overloaded systems, delays are on the order of several super-frames, degrading the QoS. Not all of the data in the base station buffer will be transmitted, causing service denials or blocked calls.

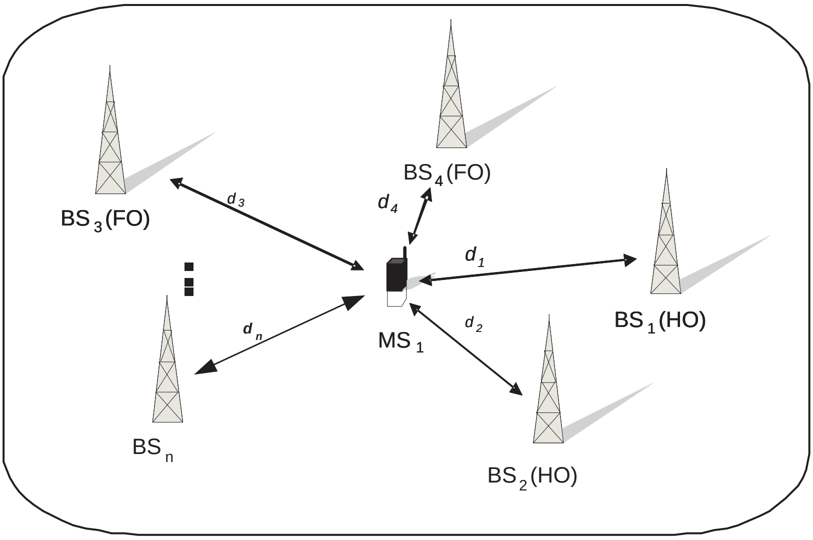


Fig 7. Algorithm illustration: $d_4 < d_2 < d_1 < d_3$. **Mobile station** MS_1 **connects to** BS_4 **(foreign operator). If a base station is heavily-loaded (**BS_4**), therefore** MS_1 **connects to the next best base station (**BS_2**), if it has enough resources ((158) published by permission of IEEE).**

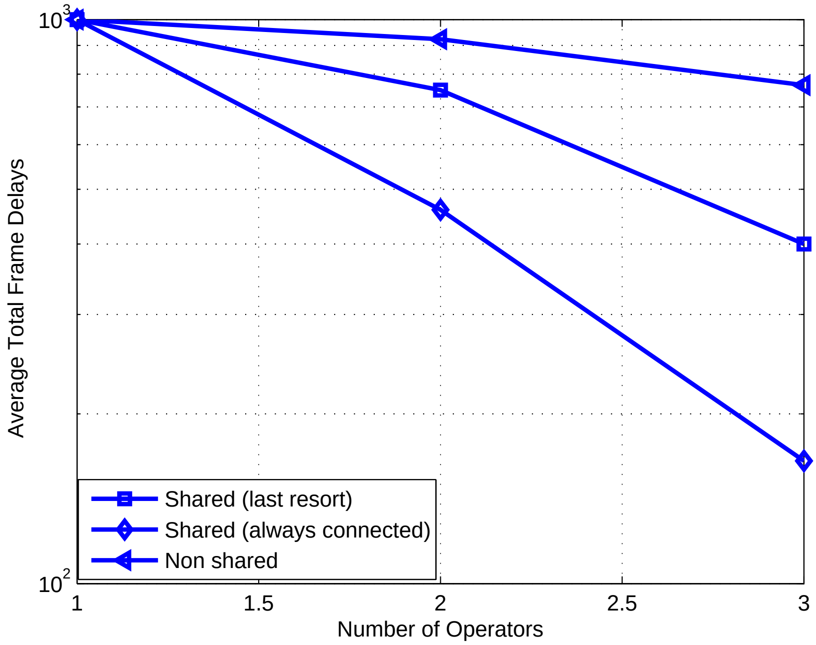


Fig 8. As the number of operators increases, the gains from sharing increases also. In this figure, 10 base stations serving 200 mobile stations were considered ((158) published by permission of IEEE).

Figure 8 depicts the average total number of frames delayed in the network for one, two, and three operators. It is clearly seen that the performance improves when the number of operators increases. Because the mobile stations are served by more operators, whether on their home operator or not, the probability of a free slot increases, hence higher sharing gains are seen. With only one operator, the average total of delayed frames remain the same, but decrease with increasing the number of operators. So, it is expected that the more number of operators are available in the network, the less average delayed frames is obtained. Finally, the always best connected scenario outperforms the non-sharing and *last resort* sharing case.

The effect of spectrum sharing on the QoS of different service classes is also studied. Table 2 shows the average number of users, data rates and mean call durations, for each class of service. In this setup, a network consists of 42 base stations belonging to 2 operators to which 3900 mobile stations are assigned. Clearly, sharing affects different types of service in different ways as seen in Table 3. There are gains between the non-sharing case compared to both sharing scenarios. For instance, there is a 81 7% (resp. 89 9%) decrease in delayed frames for photo messaging in the last resort (resp. always connected) sharing case. For the streaming video class, there is a 68 2% (resp. 77 9%) decrease in delayed frames in the last resort (resp. always connected) sharing case. For voice and web service classes (low data rates), the average number of delayed frames is zero due to their higher priorities. In contrast, with higher data rates, the services start experiencing delays.

Table 2. Type of Service, Data Rate Demands, Durations and Average No. of Users.

Service	Data Rate	Mean Duration	Average No. of Users
Voice	19.2 Kbps	180 sec	2400
Web	400 Kbps	5 sec	450
Photo Messaging	1 Mbps	15 sec	300
Interactive Video	1 Mbps	600 sec	150
Streaming Video	2 Mbps	30 sec	600

Because tables 3 and 4 show that sharing does not improve the performance of low data rate services (voice and web), the number of web-users is therefore increased to see the effect on the quality of service. As a result, non-zero frame delays are noticeable where sharing has lower delays than non-sharing. Moreover, the effect of mean call duration on average frame delays is investigated in which a gain improvement is obtained when resources are shared. Furthermore, QoS is also measured in terms of service interruptions, which occur when the mobile buffer empties and users experience a pause in the data stream. This is modeled by dumping the data at the BS, such that the non-transmitted information is discarded and never reaches the mobile. A smaller mobile buffer should give more service interruptions, since less congestion is tolerated. However, congestion in the downlink buffer caused by a larger mobile buffer can persist for a longer period of time, before being cleared either by transmission or data dumping. Thus, an interesting trade-off exists between mobile buffer size and overall network congestion in which smaller mobile buffers experience more interruptions, but larger mobile buffers cause more network congestion in our model.

As a consequence, by stretching the system, it is shown that sharing outperforms non-sharing case for both low and high data rate services. These results serve as a baseline to advocate resource sharing as a strong paradigm for improving the overall efficiency of a network.

Table 3. Average Number of Delayed Frames for Each Class of Service.

Service Class	Always Connected	Last Resort	Non Sharing
Voice	0	0	0
Web	0	0	0
Photo Messaging	38	69	378
Interactive Video	377	525	3182
Streaming Video	3948	5684	17914

Table 4. Average Number of Drops for Each Class of Service.

Service Class	Always Connected	Last Resort	Non Sharing
Voice	0	0	0
Web	0	0	0
Photo Messaging	0.54	1	5
Interactive Video	4	11	61
Streaming Video	66	132	369

3.2.4 Terminal-to-terminal communication

Article V first looks at the integration of relaying and sharing paradigms as a means of improving the overall efficiency of a network. A network topology is considered where several base stations serve several mobile stations. Mobile stations are uniformly distributed within the cell and can directly connect to BSs, or via a relay station (RS). Moreover, good channel conditions are assumed between RSs and BSs. In the system-level simulations, two scenarios are compared. First, a base station belonging to a certain operator *A* serves its mobile stations via one of the six available RSs. In the second scenario, MSs that cannot be served by their corresponding BSs due to overloaded relay stations, can use RSs of operator *B*. As a result, resource sharing is combined with the efficient use of relays and the overall efficiency of the network is consequently improved. Furthermore, mobile stations are assumed to belong to several service classes requiring variable data rates (Table 3). Simulation results show that voice and web service classes do not experience delays. This is mainly due to their low-data rate requirements and priority in the super-frame. When service classes are more demanding in terms of data rates, such as interactive and streaming video, average frame delays become significant. A significant gain is obtained when relays of an operator are overloaded, since mobile stations can be served by relays of a different operator.

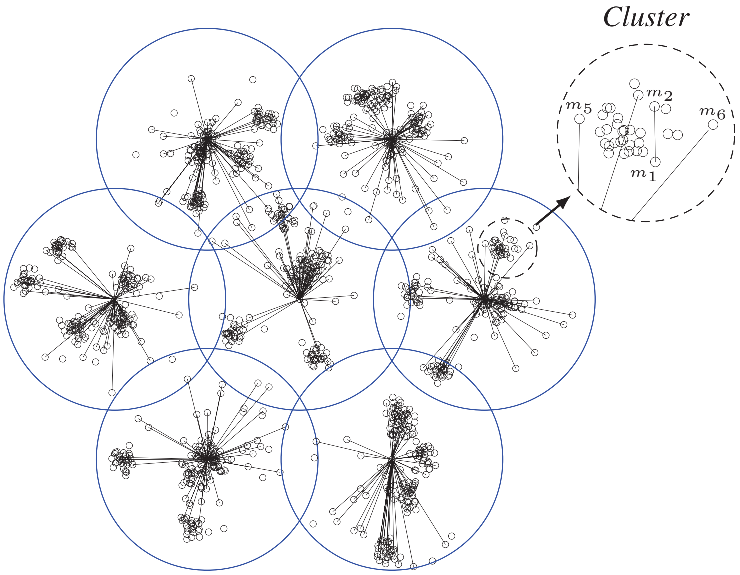
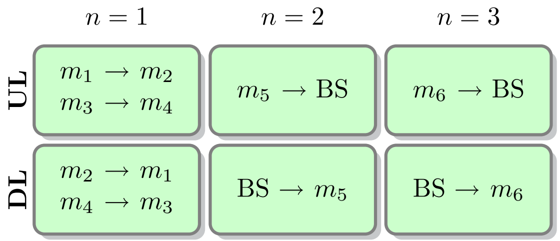


Fig 9. Cellular networks with T2T communication. Mobile pairs (m_1, m_2) and (m_3, m_4) communicate directly in different clusters, while mobile m_5 and m_6 communicate directly to the base station ((160) published by permission of SPRINGER).



	$n = 1$	$n = 2$	$n = 3$
UL	$m_1 \rightarrow m_2$ $m_3 \rightarrow m_4$	$m_5 \rightarrow$ BS	$m_6 \rightarrow$ BS
DL	$m_2 \rightarrow m_1$ $m_4 \rightarrow m_3$	BS $\rightarrow m_5$	BS $\rightarrow m_6$

Fig 10. Resource reuse in the uplink and downlink super-frames. Here, mobiles m_1, m_2, m_3, m_4 communicate simultaneously in their respective clusters whereas mobiles m_5 and m_6 communicate directly with the base station. n denotes the time-slot ((160) published by permission of SPRINGER).

In the second part of Article V, terminal to terminal communication is proposed in the context of cellular networks to improve the overall efficiency of a network. This falls within the umbrella of spectrum assignment in the proposed taxonomy where the radio resource allocation stays under the control of the operator. T2T communication is a serious candidate for future radio mobile systems with the benefits of resource reuse and lower power consumption compared to conventional systems. In this context, two modifications are proposed to the existing cellular topology. First, mobile pairs communicate directly without the need for base stations and, second, simultaneous communications take place in the same time-slot between mobile terminals pairs. Figure 9 depicts an illustration of a network with T2T communication. Therein, mobile pairs (m_1, m_2) and (m_3, m_4) communicate directly in two different clusters whereas mobiles m_5 and m_6 communicate directly with the base station as done in conventional cellular systems. Moreover, the corresponding super-frame structure for resource reuse in the uplink and downlink of the cellular system is illustrated in Figure 10.

In essence, direct communication between mobile terminals located in the same cluster is proposed. A frequency division duplex-time division multiple access (FDD-TDMA) system is used in which each user is allocated one time-slot in uplink and downlink super-frames. Users communicate directly using lower power than those communicating with the base station. As such, directly communicating users generate less interference for surrounding users. For users communicating directly, sets of geographically separated users are allowed to communicate simultaneously, provided that they do not adversely impact each other’s SINR. First, users are clustered into sets separated by a minimum distance d_{min}. This essentially guarantees that if each cluster contains a local call, interference at each cluster is not sufficient to interrupt the call. In addition, locals calls are assigned from each cluster in a set to the same time-slot, iterating until all local calls are assigned while remaining calls requiring the base station are scheduled last.

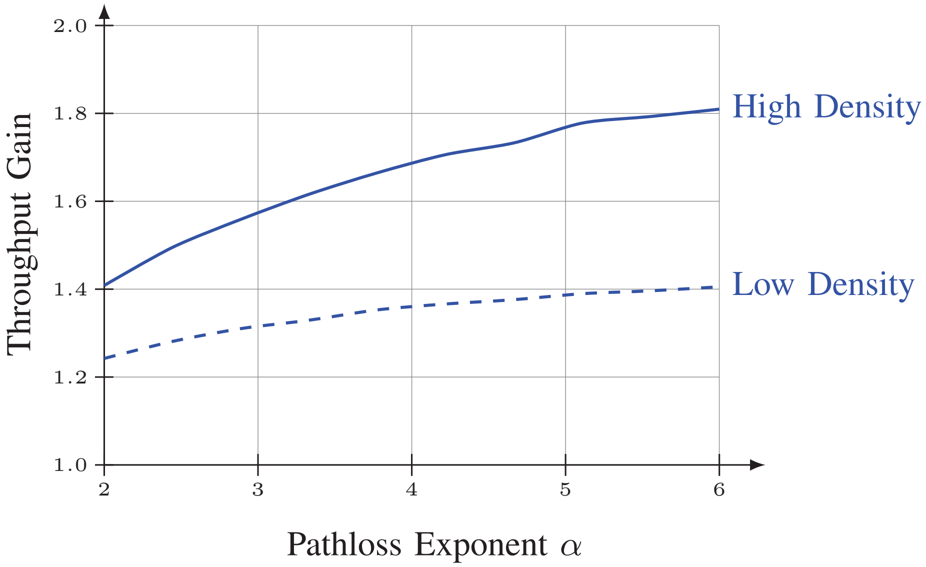


Fig 11. Cell-wide throughput gains from the reuse algorithm, shown as a fraction of the non-shared case. Throughput is calculated as the total data transmitted between mobiles and their destinations, either the base station or another mobile terminal ((160) published by permission of SPRINGER).

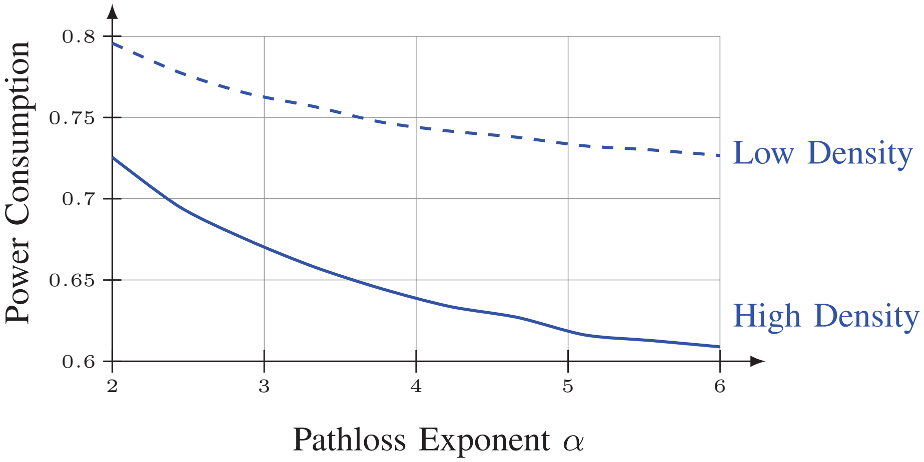


Fig 12. Normalized cell-wide power savings from the reuse algorithm, shown as a fraction of the non-shared case ((160) published by permission of SPRINGER).

Figure 11 depicts the potential throughput gains plotted against the path-loss exponent in which both the low density (composed of ten clusters of 250 users each) and high density (composed of thirty clusters) cases are presented. It is seen that throughput gains increase with the path-loss exponent, which is quite intuitive since a higher path-loss exponent allows more users in the geographic region to communicate simultaneously, as their interference drops off more quickly over distance. Additionally, in Figure 12, the power consumption shown as a function of the path-loss, decreases with increasing path-loss where more users are able to communicate simultaneously and less power consumption is needed. Finally, the gains are more pronounced in the high-density case as more users are placing local calls.

3.2.5 Enhancing spectrum sharing through hierarchy

Article VI deals with the problem of spectrum sharing where K *competitive* operators coexist in the same frequency band of width N. First, the problem is modeled as a *strategic* non-cooperative game where the goal of every operator $i \in \{1, \quad ,K\}$ is to choose its own power $\mathbf{p_i} = (p_i^1, \quad ,p_i^N)$ subject to its total power constraint $\bar{P_i}$:

$$\sum_{n=1}^{N} p_i^n \le \bar{P_i}, \quad n = 1, \quad ,N, \quad i = 1, \quad ,K \tag{5}$$

where p_i^n is the transmitter power of base station i on carrier n. This non-cooperative sharing scenario can be directly mapped into the open spectrum access umbrella of the proposed taxonomy.

The non-cooperative game can be completely described as:
$\Gamma^{NCG} \triangleq \{\mathcal{K}, \{\mathcal{P}_i\}_{i\in\mathcal{K}}, \{\mathcal{U}_i\}_{i\in\mathcal{K}}\}$ where the elements of the game are:

- The player set: $\mathcal{K} = \{1, \quad ,K\}$,
- The strategy set: $\{\mathcal{P}_1, \quad ,\mathcal{P}_K\}$, where the strategy of player i is:

$$\mathcal{P}_i = \{\mathbf{p}_i : p_i^n \ge 0, \forall n, \sum_{n=1}^{N} p_i^n \le \bar{P_i}\}, \tag{6}$$

- The utility or payoff function set: $\{u_1, \quad ,u_K\}$, where

$$u_i(\mathbf{p}_i, \mathbf{p}_{-i}) = \sum_{n=1}^{N} \log_2 \left(1 + \frac{|h_{i,i}^n|^2 p_i^n}{\sigma_n^2 + \sum_{j=1, j\neq i}^{K} |h_{j,i}^n|^2 p_j^n}\right) = R_i, \tag{7}$$

where $\mathbf{p}_{-i}$ denotes the power vector of player other than player (i.e., operator) i.

Since every operator i aims at selfishly maximizing its own rate, it therefore treats the power spectral density of other operators as noise. Moreover, the inter-operator spectrum sharing problem between K operator sharing N carriers can be formulated as follows:

$$\begin{aligned} \max_{p_i^1, \quad ,p_i^N} R_i = \max_{p_i^1,, \quad ,p_i^N} \sum_{n=1}^{N} \log_2 \left(1 + \frac{|h_{i,i}^n|^2 p_i^n}{\sigma_n^2 + \sum_{j \neq i}^{K} |h_{j,i}^n|^2 p_j^n} \right) \\ s\ t \ \sum_{n=1}^{N} p_i^n \leq \overline{P_i} \\ p_i^n \geq 0, \quad n = 1, \quad ,N \quad i = 1, \quad ,K \end{aligned} \tag{8}$$

where h_{ji}^n is the fading channel gain on the n^{th} carrier from transmitter i to receiver j. In addition, the noise process w_i^n is characterized by its received noise power on each carrier n, by σ_n^2, assumed to be the same for each sub-channel.

To gain insight on the full characterization of the Nash equilibria region, the case of 2 operators sharing 2 carriers is investigated ($g_{ij}^n = \frac{\bar{P_i}|h_{ij}^n|^2}{\sigma_n^2}$, $c_1 = \frac{g_{11}^1}{g_{11}^2}$ and $c_2 = \frac{g_{22}^1}{g_{22}^2}$). The existence and uniqueness of the NE are discussed. The operators were assumed to be non-cooperative, hence operating at the Nash Equilibrium was their best response in a selfish context. It is also shown that under certain channel realizations, the spectrum sharing game is predictable with a *unique* Nash equilibrium (Figure 13). However, in other regions and given a set of channel realizations, *non-unique* Nash equilibria exist. In this case, the spectrum sharing game is *no longer* predictable.

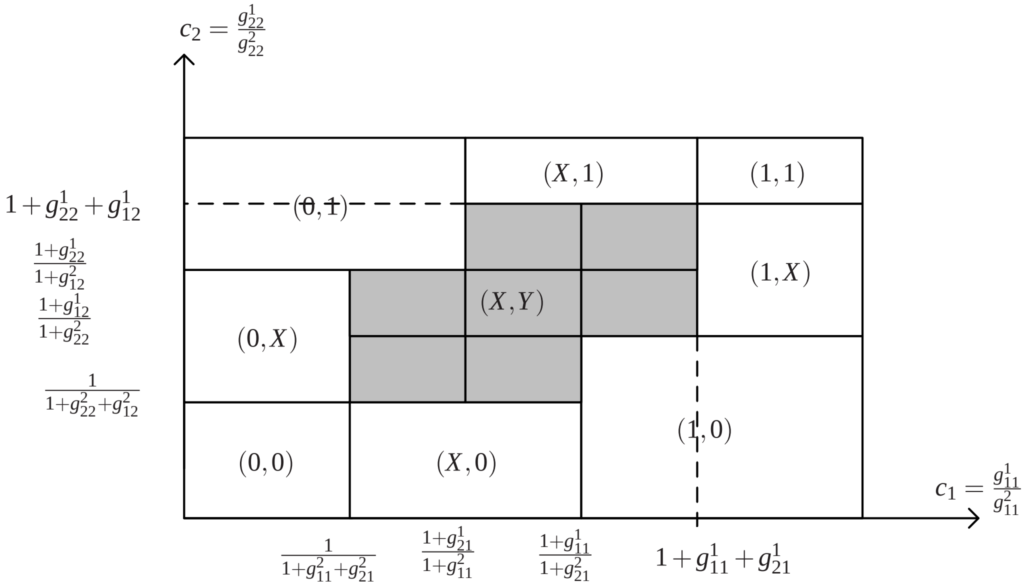


Fig 13. Characterization of the Nash equilibria regions given a set of channel realizations ((161) published by permission of EURASIP).

When primary and secondary operators coexist in the network, the inter-operator spectrum sharing problem is studied where the concept of hierarchy is accounted for. This setting is mapped into the hierarchical spectrum access umbrella of the proposed taxonomy. A Stackelberg game $\Gamma^{SG} \triangleq [\mathcal{K}, \{\mathcal{P}_i\}_{i\in\mathcal{K}}, \{\mathcal{U}_i\}_{i\in\mathcal{K}}]$ is proposed to model the spectrum sharing problem where $\mathcal{K}$ is the finite set of players, $\mathcal{P}_i$ is the set of strategies associated with player i and $\mathcal{U}_i$ is the utility function set. Furthermore, in the 2 operators case, operator 1 is the primary and operator 2 the secondary operator. Hence, operator 1 poses as the leader and operator 2 as a follower in the Stackelberg game. Using backward induction and given the best response of operator 2, the rate maximization problem of operator 1 (i.e., the leader) can be written as:

$$\max_{p_1^1, \quad ,p_1^N} \sum_{n=1}^{N} \log_2 \left(1 + \frac{|h_{11}^n|^2 p_1^n}{\sigma_n^2 + |h_{21}^n|^2 \left(\frac{1}{\mu_2} - \frac{\sigma_n^2 + |h_{12}^n|^2 p_1^n)}{|h_{22}^n|^2} \right)^+} \right) \tag{9}$$

$$\sum_{n=1}^{N} p_1^n \leq \bar{P_1}$$

$$p_1^n \geq 0 \quad n = 1, \quad ,N$$

The solution of (9) is the Stackelberg equilibrium of the hierarchical game Γ^{SG} in the 2 operators and 2 carriers case, whose solutions are detailed in Article VI.

The inter-operator spectrum sharing in the context of two operators can be extended to the more general case with K operators sharing the same spectrum. The problem is formulated in the same way, where the leader's optimization problem is written as:

$$\begin{aligned} \max_{p_1^1, \quad ,p_1^N} \quad & \textstyle\sum_{n=1}^{N} \log_2 \left(1+\frac{|h_{11}^n|^2 p_1^n}{\sigma_n^2+\sum_{j\neq 1}^{K}|h_{j1}^n|^2 p_j^n}\right) \\ & \textstyle\sum_{n=1}^{N} p_1^n \leq \bar{P}_1 \\ & p_1^n \geq 0, \quad n=1, \quad ,N \end{aligned} \tag{10}$$

and p_j^n depends on p_1^n.

Solving (10) becomes more involved in the general case in which the utility function of the primary operator is non-convex (p_j^n depends on p_1^n). Nevertheless, there exist sub-optimal and low-complexity methods to solve the problem. To this end and motivated by the work of (36), we use lagrangian duality theory wherein the *duality gap* (37) provides a tool for solving the non-convex optimization problem.

The lagrangian of (10) is given by:

$$\begin{aligned} g(\lambda) &= \max_{p_1^1, \quad ,p_1^N} \mathcal{L}(p_1^1, \quad ,p_1^N,\lambda) \\ &= \max_{p_1^1, \quad ,p_1^N} \sum_{n=1}^{N} \log_2 \left(1+\frac{|h_{11}^n|^2 p_1^n}{\sigma_n^2+\sum_{j\neq 1}^{K}|h_{j1}^n|^2 p_j^n}\right) + \lambda \left(\bar{P}_1 - \sum_{n=1}^{N} p_1^n\right), \end{aligned} \tag{11}$$

where λ is the Lagrangian dual variable associated with the power constraint.

Consequently, solving the Stackelberg problem is done by locally optimizing the lagrangian function (11) via coordinate descent (37). For each fixed set of λ, we find the optimal p_1^1 while keeping $p_1^2, \quad ,p_1^N$ fixed, then find the optimal p_1^2 keeping the other p_1^n ($n \neq 2$) fixed and so on. Such process is guaranteed to converge because each iteration strictly increases the objective function. Finally, λ is found using the subgradient (36) method. This is illustrated in Algorithm 1.

Numerical results are provided to validate the theoretical claims. In the setting of 2 operators and 2 carriers, $\bar{P}_1 = \bar{P}_2 = \bar{P} = 1$, $SNR = \frac{\bar{P}}{\sigma^2}$ and the channel fading realizations are independent and identically distributed (i.i.d) Rayleigh distributed. Figure 14 depicts the average achievable rate of both operators for the Stackelberg approach. A comparison is also provided with the centralized strategy to quantify the performance loss from the optimal solution.

```
Algorithm 1.
initialize $\lambda, \bar{P}_1, \bar{P}_2, ..., \bar{P}_K$
repeat
  for n = 1,...,N
    set $p_1^n = \arg\max_{p_1^1, \ ,p_1^N} \sum_{n=1}^{N} \log_2 \left(1 + \frac{|h_{11}^n|^2 p_1^n}{\sigma_n^2 + \sum_{j\neq 1}^{K} |h_{j1}^n|^2 p_j^n(p_1^n)}\right) +$
      $\lambda \left(\bar{P}_1 - \sum_{n=1}^{N} p_1^n\right)$
    by keeping $p_1^1, \ ,p_1^{n-1}, p_1^{n+1}, p_1^N$ fixed.
  end
until $(p_1^1, \ ,p_1^N)$ converges
update $\lambda$ using subgradient (36) method until it converges.
```

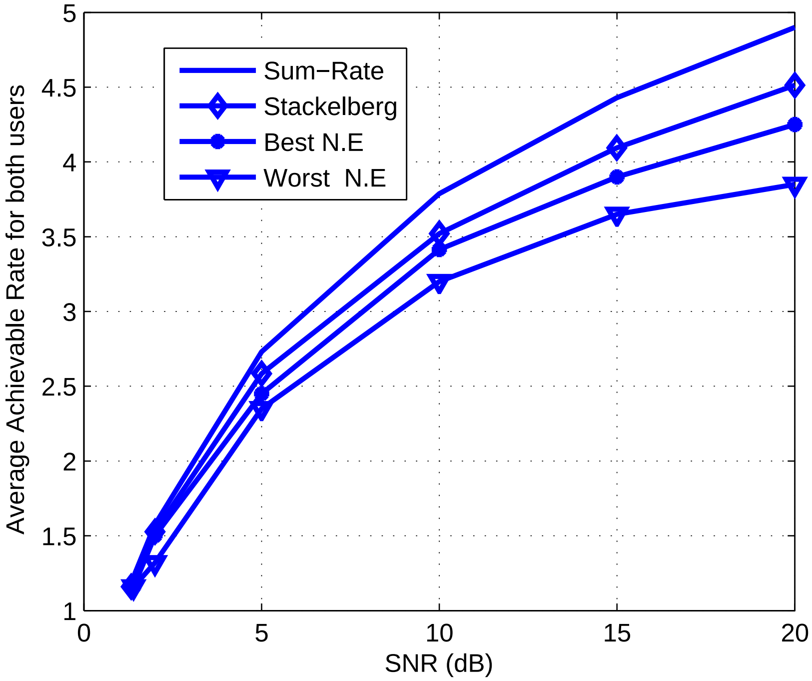


Fig 14. **Average achievable rate for both users versus the signal-to-noise ratio for the centralized and Stackelberg approach. Moreover, the best and worst Nash equilibria for the non-cooperative game are illustrated ((161) published by permission of EURASIP).**

The best and worst N.E are also depicted where the former refers to the equilibrium maximizing the sum-rate of both operators whereas the latter minimizes it. Note that the worst Nash equilibrium acts like a lower-bound for the Nash equilibrium. Furthermore, the Stackelberg approach is closer to the centralized approach as compared to the selfish case. This is due to the fact that in the Stackelberg approach, which maps to the vertical sharing case in the proposed taxonomy, operators take into account other operators' strategies whereas in the selfish case, operators behave carelessly by using water-filling.

In the case of multiple operators sharing the spectrum, Figure 15 depicts the cumulative distribution function of the ratio between the achievable rates of the hierarchical and non-cooperative approaches. $K = 4$ operators are assumed, 3 of which are secondary and 1 primary wireless operators sharing the spectrum composed of $N = 5$ carriers. As can be seen, the primary operator (operator 1) always improves his achievable rate compared to the selfish approach. The cumulative distribution function of the secondary operators also provides insight on their achievable rates.

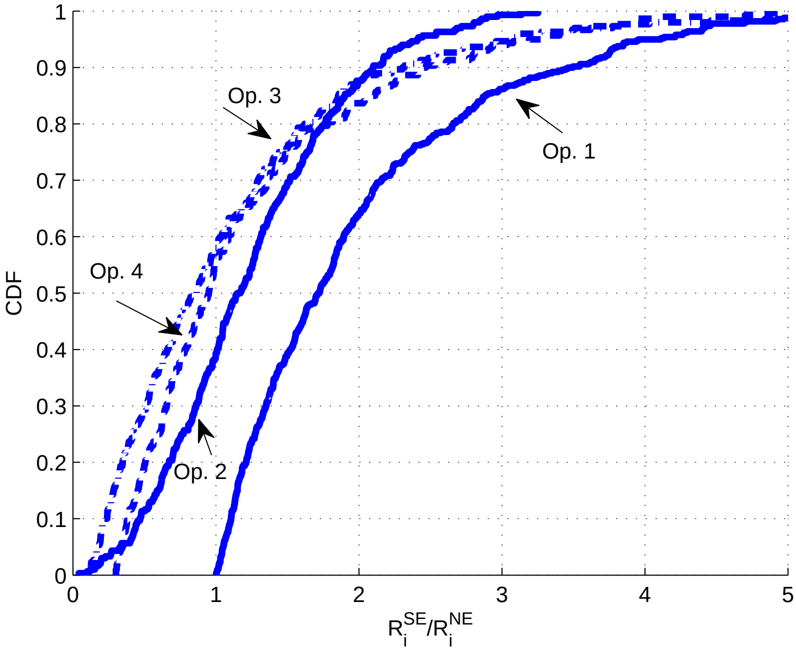


Fig 15. Cumulative distribution function (CDF) of the ratio of the rates between the hierarchical (Stackelberg) and non-cooperative (selfish) approaches $\frac{R_i^{SE}}{R_i^{NE}}$ for operator i, $i = 1,2,3,4$ ((161) published by permission of EURASIP).

Finally, in Article VII and due to the inefficiency and static nature of both non-cooperative and Stackelberg games to achieve all boundary points of the achievable rate region, the inter-operator spectrum sharing problem is modeled as a dynamic game using repeated games (14) (falls within the horizontal sharing with coordination umbrella in the proposed taxonomy). Within this setting, players interact over a longer period of time by playing the *one-shot* static game multiple times and learning from each other's strategies. Additionally, players are forced to cooperate under the risk of punishment. Infinitely repeated games are considered in which a utility function for the repeated game Γ^{RG} is first defined, then the punishment mechanism is explained after which a *perfect* equilibrium strategy is given which guarantees the players to achieve any Pareto-optimal solution.

The expected utility function of player i for the discounted repeated game is defined as:

$$\forall i \in K, \qquad R_i = \sum_{t=1}^{\infty} \lambda (1-\lambda)^{t-1} R_i[p^t] \tag{12}$$

where $R_i[p^t]$ is the payoff of player i at time t for the joint power vector $p^t = (p_i^t)_{i \in K}$ and λ is the uncertainty parameter.

Denote $\underline{p}_i^s$ the power vector of player i at stage s and $\underline{p}^s = (\underline{p}_i^s)_{i \in K}$ the power vector of all players at stage s. The history of the game until stage t is $h^t = (\underline{p}^1, \cdots, \underline{p}^s \cdots, \underline{p}^{t-1})$. A strategy of player i for the repeated game is a function $\sigma_i = (\sigma_i^t)_{t \geq 1}$ such that $\sigma_i^t : h^t \mapsto \underline{P}_i$. Moreover, the expected payoff of player i given a joint strategy $\sigma = (\sigma_i)_{i \in K}$ for the discounted repeated game is: $R_i(\sigma) = \mathbb{E}_\sigma \sum_{t=1}^{\infty} \lambda (1-\lambda)^{t-1} R_i[p^t]$.

Definition 4 *σ is a perfect equilibrium strategy if it is an equilibrium strategy: $\forall i$, $\forall \sigma_i'$, $R_i(\sigma) \geq R_i(\sigma_i', \sigma_{-i})$ and after every possible history σ is still an equilibrium strategy.*

Players are assumed to have perfect recall, full knowledge of the channel gains as well as perfect monitoring. Moreover, the channels gains are assumed constant during the game. The main idea is that if players do not cooperate with each other, the other players go back to the N.E strategy of the one-shot game. However, as long as players follow a set of predefined rules, cooperation will be sustained.

Let $\tilde{R}_i$ and $\tilde{p}_i$ represent the utility and power of player i at the social optimal point, R_i^* and p_i^* the utility and power of player i at the Nash Equilibrium, $\overline{R_i}$ and $\overline{p_i}$ the utility and power of player i if everyone maximizes the utility of player i.

Definition 5 *The strategy $\sigma = (\sigma_i)_{i \in K}$ is defined such that:*

$$\sigma_i = \begin{cases} \tilde{p}_i & \text{as long as player } j \neq i \text{ plays } \tilde{p}_j \\ p_i^* & \text{forever if someone deviates} \end{cases}$$

Theorem 1 *If the condition over the stopping probability:*

$$\lambda \leq \frac{\tilde{R}_i - R_i^*}{\overline{R_i} - R_i^*}$$

is satisfied, the strategy σ is an optimal perfect equilibrium strategy for the discounted repeated game.

Theorem 1 ensures that players cooperate by using Pareto transmit strategies $\tilde{p}$ as long as other players cooperate. If any player deviates, a punishment mechanism will be automatically triggered where players will choose the one-shot Nash equilibrium power. Because this punishment yields lower payoffs, it is in each players's interest to cooperate. If at one stage a player does not intend to cooperate, then the best strategy for all the other players is to play the Nash equilibrium equilibrium forever.

3.3 Interference avoidance

3.3.1 Uniform power control

Article VIII examines the problem of interference avoidance for point-to-point communication in self-organized networks, which is considered as a key component of spectrum sharing where different transmitter-receiver pairs share the same frequency band. A direct application of the considered setting lies in the open spectrum access bracket of the taxonomy. Given that these networks are self-configured, without any dependence on a central controller, they offer high flexibility of deployment and maintenance. An *information theoretic* framework is considered to determine the optimum transmission power enabling reliable communication between neighboring nodes at a certain user requested rate where the ergodic capacity is used as a criterion for information-theoretic analysis. Moreover, realistic channel models taking into account path-loss and fading are considered.

A two-dimensional network with average density of users d and radius R ($R \rightarrow \infty$) is considered where users are randomly distributed so the network contains $N = \pi R^2 d$ mobiles. The received signal y_j at a mobile j of the communication pair (i, j) is expressed as:

$$y_j = \frac{h_{ji}}{r_{ji}^{\alpha\;2}} \sqrt{P_i} s_i + \sum_{k \neq i} \frac{h_{jk}}{r_{jk}^{\alpha\;2}} \sqrt{P_k} s_k + n_{ji} \tag{13}$$

In which s_i is the useful signal, transmitted with power P_i to mobile j by mobile i, and affected by path-loss $\frac{1}{r_{ji}^{\alpha\;2}}$ (where r_{ji} is the distance between mobiles i and j, and α is the path-loss exponent usually between 2 and 6). h_{ji} is the fading component and n_{ji} is the additive white Gaussian noise. Signals sent by users are encoded in a Gaussian codebook and all channel coefficients h_{lm} and noise n_{lm} are supposed to be independent Gaussian variables, with zero mean and variance 1 and N_0, respectively.

Different power allocation strategies are investigated for point-to-point communication. First, in the uniform power analysis scenario, the optimal power allocation is computed assuming that each transmitter only knows the statistics of its channel (i.e., each communication pair (i,j) knows the distribution of r_{ji}, and the variances $\zeta_{ij} = \zeta$ and N_0). Given the random nature of the channel, the ergodic capacity can be approached using an appropriate coding scheme expressed as:

$$C(i,j) = \mathbb{E}_{h,r}\left[\log_2\left(1 + \frac{P\left|h_{ij}\right|^2 r_{ij}^{-\alpha}}{P\sum_{k\neq i}\left|h_{jk}\right|^2 r_{jk}^{-\alpha} + N_0}\right)\right] \tag{14}$$

In order to ensure that $C(i,j) > C$ for all users, an estimate of the interference sum is computed as: $\sum_{k\neq i}\left|h_{jk}\right|^2 r_{jk}^{-\alpha}$ which runs over all transmitting nodes except node i. As the number of interferers tends to infinity, asymptotic results are used where the interference sum is approximated by its expectation $\sum_{k\neq i}\mathbb{E}[\left|h_{jk}\right|^2 * r_{jk}^{-\alpha}] = \sum_{k\neq i}\mathbb{E}\left|h_{jk}\right|^2 * \mathbb{E}[r_{jk}^{-\alpha}] = \sum_{k\neq i}\mathbb{E}_r\left[r_{jk}^{-\alpha}\right]$ since the random variables r and h are independent and $\mathbb{E}_{h_{ij}}\left[\left|h_{jk}\right|^2\right] = 1$ for all k.

The interference term is therefore written as:

$$I = \sum_{k\neq i}\mathbb{E}_r\left[r_{jk}^{-\alpha}\right] = \frac{1}{2}\int_0^{+\infty}\frac{2u^{1-\alpha}}{\rho^2}\left(1 - e^{-\frac{u^2}{\rho^2}}\right)du \tag{15}$$

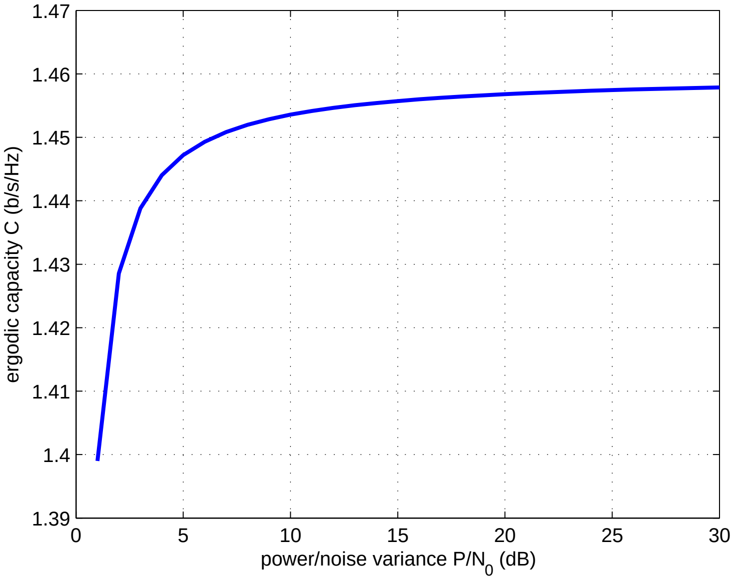


Fig 16. Interference case, Uniform power allocation, $\alpha = 3$ ((163) published by permission of IEEE).

Using this result, the transmission power corresponding to the requested rate C can be deduced thanks to the equation:

$$\mathbb{E}_{h,r}\left[\log_2\left(1+\frac{P\,|h|^2\,r^{-\alpha}}{PI+N_0}\right)\right]=C \tag{16}$$

In this case, the ergodic capacity is an increasing function of P with a horizontal asymptote for some capacity C_0, given by:

$$C_0=\mathbb{E}_{h,r}\left[\log_2\left(1+\frac{|h|^2\,r^{-\alpha}}{I}\right)\right] \tag{17}$$

Figure 16 shows the ergodic capacity as a function of the transmission power. All capacity requirements strictly below C_0 can be met. However, if mobiles try to meet capacity requirements above C_0, they will increase their power without bound, without reaching those requirements. Hence, since not all the values can be met, a communication range needs to be defined where any rate C can be satisfied introducing thereby the concept of close-talker.

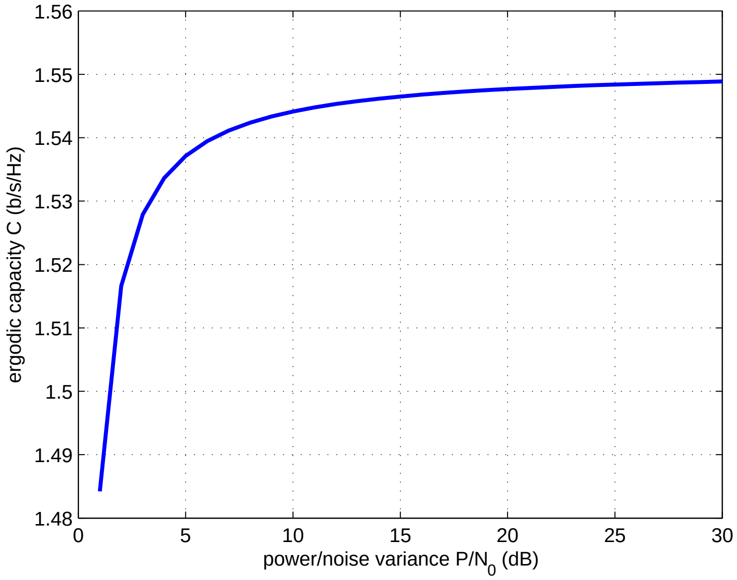


Fig 17. Same Power, Maximum Distance $a=1$, $\alpha=3$ ((163) published by permission of IEEE).

3.3.2 *Close talker*

When mobiles can estimate whether the closest mobile to them is within a distance a, a communication pair forms between two mobiles only if their distance is smaller than a. According to (42) and (43), the optimal strategy is to confine to nearest neighbor communication and maximize the number of simultaneous transmissions, through spatial reuse. Under this setting, the interference term becomes:

$$I=\left(1-e^{-\frac{a^2}{\rho^2}}\right)\int_0^{+\infty}\frac{u^{1-\alpha}}{\rho^2}\left(1-e^{-\frac{u^2}{\rho^2}}\right)du \tag{18}$$

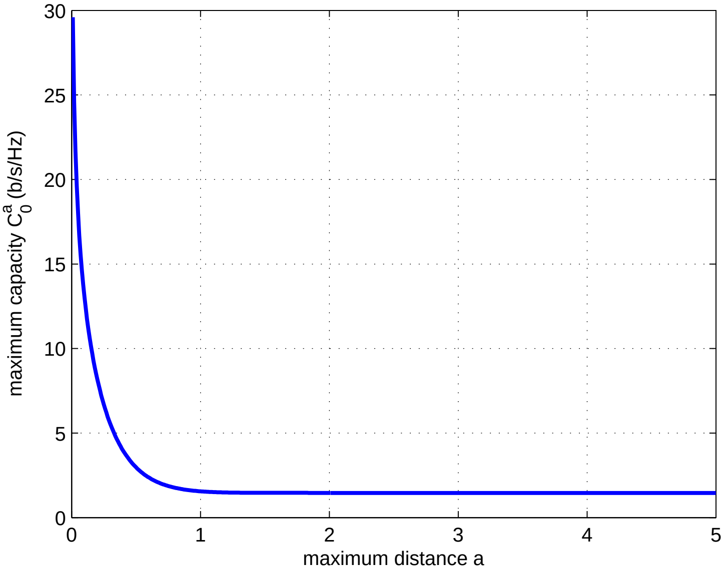


Fig 18. Same Power, maximum distance a**,** $\alpha = 3$ **((163) published by permission of IEEE).**

The transmission power is deduced corresponding to the requested rate C thanks to equation(17).

Moreover, for a given C, the optimum communication range a is given by:

$$\int_0^a \mathbb{E}_h \left[\log_2 \left(1 + \frac{P\,|h|^2\,r^{-\alpha}}{PI + N_0} \right) \right] dr = C \tag{19}$$

In Figure 17, the ergodic capacity is plotted for $a = 1$. The shape of the curve is the same as in the general case above, but the capacity obtained with a given power is higher. This is due to the fact that the capacity is higher within the communication range a. There is also a maximum capacity C_0^a, that depends on the value of a as shown in Figure 18. As a decreases, the maximum attainable capacity C_0^a given by (17) increases. Even though any rate can be satisfied, a delay is incurred by this scheme depending on the mobility pattern. This paradigm has also been reported in (64).

3.3.3 Opportunistic approach

Article VIII deals with the opportunistic approach where different communication pairs use different transmission powers, according to their channel's realizations within the close-talker scenario. Inspired by the power adaptation described in (133), the power $P(t)$ is allowed to vary with $t = |h|^2$ following a Rayleigh distribution. Thus, a time water-filling is obtained where the average power will be:

$$\bar{P} = \int_0^a \int_0^{+\infty} P(t,r) e^{-t} f_1^a(r) dt dr \tag{20}$$

Given an average power constraint $\bar{P}$, the capacity of the pair (i, j) is given by:

$$C(i,j) = \max_{\bar{P}} \mathbb{E}_{h,r} \left[\log_2 \left(1 + \frac{P_{ij} \left| h_{ij} \right|^2 r_{ij}^{-\alpha}}{\bar{P} I + N_0} \right) \right] \tag{21}$$

where the interfering term is given by:

$$I = \left(1 - e^{-\frac{a^2}{\rho^2}} \right) \int_0^{+\infty} \frac{u^{1-\alpha}}{\rho^2} \left(1 - e^{-\frac{u^2}{\rho^2}} \right) du$$

Note that the average power defined in (20) uses water-filling on a channel that is independent of the channel h_{jk} where $k \neq i$. The power adaptation which maximizes (21) is:

$$\frac{P(t,r)}{PI + N_0} = \begin{cases} \frac{1}{t_0} - \frac{1}{tr^{-\alpha}} \text{ if } t \geq t_0 r^{\alpha} \\ 0 \text{ if } t < t_0 r^{\alpha} \end{cases}$$

for some "cutoff" value t_0 that satisfies:

$$\int_0^a \int_{t_0 r^{\alpha}}^{+\infty} \left(\frac{1}{t_0} - \frac{1}{t\, r^{-\alpha}}\right) e^{-t} f_1^a(r) dt dr = \frac{\bar{P}}{PI + N_0} \tag{22}$$

It is worth mentioning that in contrast to (133), this water-filling approach takes the path-loss α and interference into account. These parameters are necessary in order to compute the cutoff value t_0. Finally, the capacity is given by:

$$C(i,j) = \int_0^a \int_{t_0\, r^{\alpha}}^{+\infty} \log_2 \left(1 + \left(\frac{t}{t_0} - r^{\alpha} \right) r^{-\alpha} \right) e^{-t} f_1^a(r) dt dr \tag{23}$$

Figure 19 shows a comparison between the ergodic capacity for both the opportunistic and non-opportunistic approach. In particular, focus is made on the close-talker approach where nodes communicate within a distance a. Clearly, the capacity is higher

(46% increase) in the opportunistic approach where mobile terminals have knowledge of their channels.

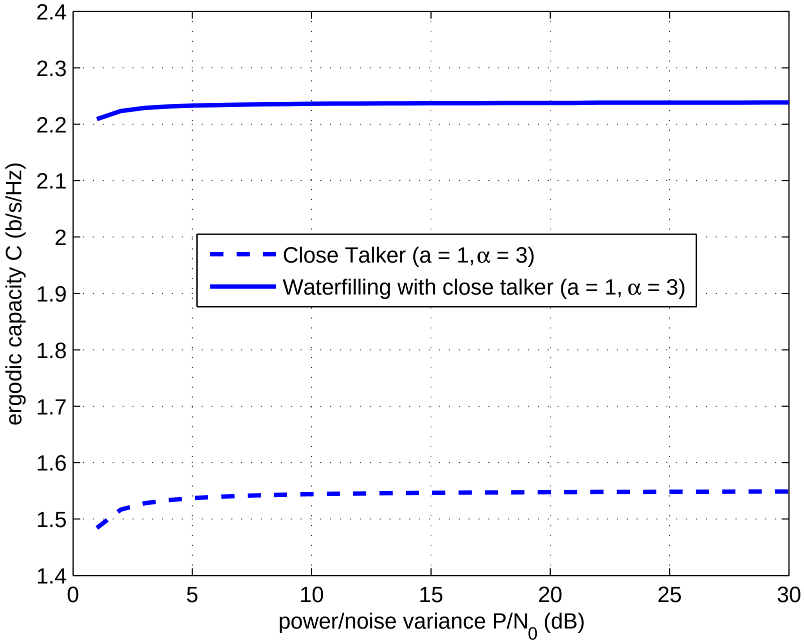


Fig 19. Comparison of the ergodic capacity for the opportunistic case (with close-talker) versus the close-talker approach, for $a = 1$ and $\alpha = 3$ ((163) published by permission of IEEE).

3.3.4 With dynamic frequency reuse

At last, the impact of frequency reuse on the ergodic capacity of point-to-point communication is investigated. One frequency band is assumed $B = f_{ru} \times W$ of width W and frequency reuse f_{ru}. R is the radius of the considered area. Equation (15) is rewritten as:

$$\begin{aligned} I &= \sum_{k \neq i} \mathbb{E}_r \left[r_{jk}^{-\alpha} \right] \\ &= \sum_{k=1}^{R} \int_{a f_{ru}(k-1)}^{a(f_{ru}k - f_{ru}+1)} \frac{u^{1-\alpha}}{\rho^2} \left(1 - e^{-\frac{u^2}{\rho^2}} \right) du \end{aligned} \tag{24}$$

The capacity is defined as:

$$C = \frac{B}{f_{ru}} \times \mathbb{E}_{h,r} \left[\log_2 \left(1 + \frac{P\,|h|^2\, r^{-\alpha}}{PI + N_0} \right) \right] \tag{25}$$

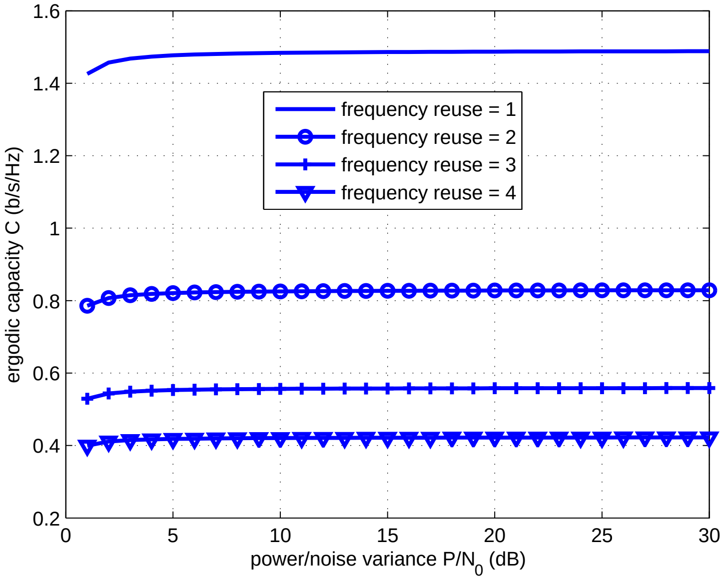


Fig 20. The impact of the frequency reuse on the ergodic capacity, for frequency reuse 1**,** 2**,** 3 **and** 4 **((163) published by permission of IEEE).**

Figure 20 depicts the impact of frequency reuse on the ergodic capacity. Frequency reuse *one* yields a higher capacity (around 75% increase) with respect to frequency reuse 2 and the capacity decreases with increasing frequency reuse.

4 Conclusions and future work

The present dissertation deals with the problem of spectrum sharing, which is examined from different perspectives. A taxonomy is proposed serving as a map for the discussed papers, which collectively address the spectrum sharing problem. Firstly, an extensive review of the literature of spectrum sharing techniques was carried out. Drawing on the existing literature, a radio resource management architecture was investigated in Chapter 3 followed by a performance evaluation of the short-term spectrum assignment which was proposed to cope with the "dynamicity" of the spectrum. System-level simulation results capturing resource sharing between radio access networks taking interference into account have shown that the spectrum efficiency can be improved. The effect of scheduling was also addressed showing substantial gains. Secondly, the issue of inter-operator spectrum sharing was studied in which different sharing algorithms were compared to the non-sharing case and the impact of spectrum sharing on different service classes was examined. It was shown that sharing improves both low and high data rates services. Another way to improve the efficiency of a cellular network is through direct terminal-to-terminal communication advocating resource reuse and simultaneous communications. Better throughput gains and lower power consumptions were obtained compared to conventional networks. Interference avoidance mechanisms were also investigated for point to point communication, in which different power allocation strategies were examined in addition to the impact of frequency reuse on the ergodic capacity of the network. It was shown that a trade-off exists where nodes achieve their target rates at the expense of a delay due to the mobility of the nodes. The effect of clustering was also shown to improve the ergodic capacity. Finally, dynamic frequency reuse was examined for point-to-point communication in a self-organized network. Frequency reuse one was shown to yield a capacity increase of about 75% with respect to frequency reuse 2 and the capacity decreases with increasing frequency reuse.

Furthermore, the inter-operator spectrum sharing was studied from a game theoretical perspective by first modeling it as a strategic non-cooperative game. Using the concept of hierarchy, the same sharing game was modeled as a Stackelberg game where it was shown that operators are better off by adopting the hierarchical approach compared to the non-cooperative and selfish approach. Therefore, the hierarchical approach is shown to bridge the gap between the non-cooperative and cooperative (centralized) approach. Finally, the inter-operator spectrum sharing game is modeled as a repeated game in an effort to attain Pareto-boundary points. A condition was provided forcing players not to deviate, thereby sustaining cooperation.

While the problem of spectrum sharing has been tackled from different perspectives in this thesis, there are still some open problems. With the introduction of femtocell networks as underlay and overlay to already deployed networks, efficient spectrum sharing is at high stake. In this respect, the hierarchical approach can be readily applied. This thesis deals also with the study of the different equilibria of the spectrum sharing game. An interesting work would be to devise decentralized algorithms to reach those equilibria, which is hard in general. Finally, in this thesis, a static model was assumed, in which the communicating pairs and the channel conditions are fixed. An interesting future direction is to consider dynamic environments, in which the network topology and channels change with time.

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Original articles

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