# Capacity Issues for Cognitive Radio Systems

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***Abstract***—*The development of software radio toward the cognitive radio brought the hope that the spectrum scarcity would be finally an issue of the past. Due to the characteristics of the cognitive operation and environment (including spectrum sharing), the operation of such a system has to take into account the interference to and from other wireless systems. Interference exploited via cognition could also improve spectral utilization and end-to-end performance, and the interference channel model could provide a good choice when evaluating these systems. However, the determination of the capacity region for the interference channel has been an open problem for more than 30 years, showing that the fundamental questions about networks and interference is not well understood until now. In spite of that, some researchers have already presented capacity analysis for cognitive radio systems under certain conditions.*

*This paper presents a survey of some works done in order to evaluate the capacity of cognitive radio systems, even if these have to be restricted by certain particularities.)*

*Keywords- cognitive radio, capacity, interference, wireless communication, multiple user, spectrum sharing*

## I. Introduction

One of the main concerns of a communications system designer is to dimension the resulting reliable transmission capacity. Wireless communication systems are commercially available since the early years of XX Century, but their susceptibility to interference and their need for spectrum license in order to operate were always a handicap that favored technical solutions using cabled media. However, in the last years, the increasing demand for wireless communication services enhanced the necessity for the technical evolution of wireless equipments. One of the obstacles to the growth of the wireless systems is the scarcity of the spectrum [1], which is the result of the first-come, first-served licensing policy adopted in the beginning of radio transmission in order to avoid interference between the various users sharing this media. Even though this policy worked well in the beginning, it leaves the majority of this licensed spectrum empty when and where the license holder is not active. As the demand for wireless services started to grow, new low power wireless devices for wireless data communication were designed to share the spectrum parts that were not allocated for licensed services, such as the ISM bands (industrial, scientific, and medical). The devices using such bands do not need a license to operate, but must comply with some restrictions, such as limited transmission power, in order avoid mutual interference.

In order to overcome the spectrum scarcity, the evolution of communication systems design led to equipment that could use the spectrum more efficiently, including technologies such as spread spectrum (wideband), and its evolution, the ultra-wideband; smart antennas, using multiple of these devices in order to aim a signal in a particular direction; mesh networking, in which each receiver of a signal also retransmits it, becoming a node or router on its network (such as ad hoc wireless networks). Portable user terminals also evolved into smaller devices (reduced hardware size, weight and power through fewer radio units), with greater signal processor capacity and using improved batteries that lasted longer, and the digital systems could carry more information per share of spectrum as their analog predecessors did. New technologies for wireless devices included software programming, cooperative techniques, and self-organizing networks. All that led to an overwhelming demand for wireless products and the scarcity of spectrum became the main obstacle for innovation, what resulted in a pressure to change the spectrum policy and thus make more parts of spectrum available. The evolution of radio systems led to the software defined radio that could have reconfiguration ability features such as modulation and coding adaptation, beam performing and power control.

The growing number of wireless systems and services, as well as the development in microelectronics and software technologies provided increased flexibility and seamlessness of software radios that became platforms for multiband multimode personal communication systems. The following step of this evolution was the cognitive radio [2], a software defined radio that includes artificial intelligence. Its ability to sense and react to environment changes could make them the solution for the optimization of the spectrum use, and therefore to improve the capacity of wireless systems.

This work presents a survey of approaches to analyze the capacity possibilities of the cognitive radio. This survey begins, in Section II, with an overview of the evolution of radio systems toward cognitive radio, which is considered to be a solution for the spectrum scarcity. Section III outlines the main concepts used for the analysis of multiple user communication systems capacity, including limits for digital transmission, the capacity region diagram, and the models for multiple user communication channels. In this section, we will discuss the interference channel, which is very suitable to evaluate the transmission capacity of cognitive radio systems. Section IV presents an overview of the various approaches for the evaluation of the cognitive radio transmission capacity systems, and Section VI concludes the work.

## II. THE RADIO EVOLUTION

The evolution of radio systems led to the software implementation for many functions of the newer equipments. That freed radio services from dependency on hard-wired characteristics, such as frequency band, channel bandwidth, and channel coding, and enabled them to use a combination of techniques in general-purpose programmable processors. Thus the software radio became a highly flexible alternative to the old "dumb radio", being able to introduce new channel access modes into bands for a limited length of time.

Adding artificial intelligence to the software defined radio, the cognitive radio is able to be self aware, being able to learn from its environment and to adapt itself to changing conditions. It can occupy the voids in the wireless spectrum improving spectrum efficiency, and manage its power transmission control. Cooperation and competition have to be considered in order to model the system behavior. [3].

As "communication is no longer a matter of frequency, but of computation" [4], cognitive radios technology could herald the end of spectrum scarcity, if the policy of licensed spectrum should change. Wireless standards, such as IEEE 802.22, already begun to incorporate cognitive techniques, and the Federal Communications Commission (FCC) decision on November 4, 2008 [5], to allow the use of TV white spaces (unoccupied TV channels) will probably enhance the research searching to develop technologies that can best use this prized ultrahigh- frequency spectrum together with its desirable propagation characteristics. Regulatory agencies around the world will probably follow the FCC initiative re-farming their TV spectrum.

## III. THEORY FOR MULTIPLE USERS COMMUNICATION SYSTEMS

Modeling cognitive networks can be done in a variety of ways, and one of them is to use information theory together with a multiple user communication model.

The early transmission limits were established for the one-transmitter-one-receiver system by Nyquist and Shannon. Shannon also stated that if this limit is respected, the error probability at the receiver could be kept arbitrarily low, and if a redundant encoding was used for the signal, the error rate could be kept below a chosen level for the same transmission rate [6]. Some years latter Shannon analyzed the capacity of multiple users communication systems through the use of Capacity Region Diagrams [7], which show the maximum set of all reliable rates that can be simultaneously achieved. The simplest case happens when two different users share the same channel and only one of them can transmit at a time: without interference or necessity to share the spectrum, each transmitter could achieve its highest possible rate. However, if they have to share the spectrum, like a push to talk radio, each transmitter could achieve maximum capacity only if the other transmitter is not working. Finding the inner and outer bounds on the capacity region is a research objective for a channel whose capacity is unknown. The inner bound is called achievable rate region. Figure 1 shows the capacity regions for each possibility.

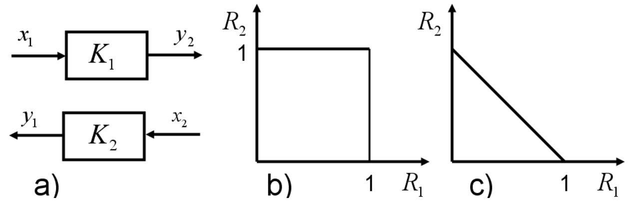


Figure 1: a) The Two-User Chanel, and its Capacity Regions: b) Maximum individual capacity, c) time-sharing between the two transmitters

For a memoryless discrete channel there exists a convex region G of approachable rates. For any point in G, denoted by $(R_1, R_2)$, there are codes signaling with rates arbitrarily close to the point and with arbitrarily small error probability. This region is made from the convex hull of the set of simultaneously achieved rates, as shown in Figure 2a, 2b and 2c. The final result of the capacity region has the form shown in Figure 2d, bounded by the middle curve G and two axis segments. This curve is set by a limiting expression of mutual information for long sequences of inputs and outputs.

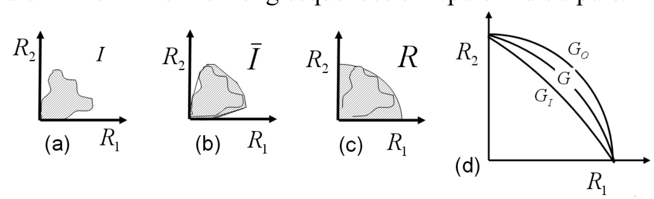


Figure 2: Building the Capacity Region for a multiple user Channel (a,b,c); d) The result of the convex region G of achievable rates plus the inner ( $G_I$ ) and outer bound ( $G_O$ )

The boundary presented by Shannon is the best theoretical limit that could be reached, but practical systems can not achieve such performance. Thus the systems designer has work in order to get the closest possible to this theoretical maximum boundary. In the following years, there were many contributions for multiple-user communication channels in order to set their constraints and capacity [8].

When multiple users share the spectrum, there are three possibilities: the MAC (multiple-access channel), that is the case in which two or more terminals compete for one input in the media available; the BC (broadcast channel), when one terminal transmits for many receivers; and the IFC (interference channel), which models the system in which many transmitters send data to many receivers, and as a result the performance of these wireless systems is limited by interference between these multiple links. The interference channel [9] is shown in Figure 3a (signal flux) and 3b (interference channel model).

The interference channel model describes a very common situation in wireless communication. However, the largest known achievable region for a two-user interference channel was not improved in 30 years [10]. In wireless communications, there are typical and significant fluctuations in the transmission rate, and if the transmission rate is greater than the channel capacity, then there would be an outage. Thus the outage capacity is defined as the maximum bit rate that can be maintained across the wireless link for a prescribed probability of outage.

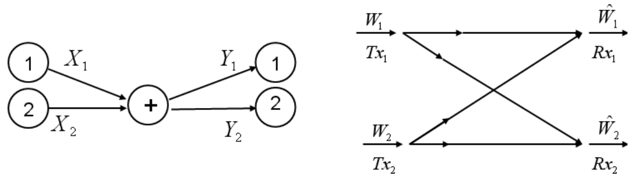

Figure 3: Interference channel

In the simplest analyzed configuration of interference channel model (two-transmitter, two-receiver scenario), the message transmission is affected by the random noise and the other user's transmission. In order to find the capacity region of the channel through information theory one has to: (1) set particular coding and decoding schemes in order to find the achievable rate; (2) set the upper bound of the capacity region that can not be enhanced by any coding scheme. If both bounds are the same, the capacity region is known and the proposed coding has an achievable capacity.

## IV. Cognitive Radio Capacity: an Overview

Maybe the greatest technological gain in wireless capacity will come from systems that work cooperatively in the same environment. Cognitive radio could analyze other nearby radios and adapt itself on the fly to avoid other transmissions. However, sharing the same environment also includes competition for the resources available. Therefore, it is also necessary to plan how the transmit power control will work. Cooperative work among the multiple cognitive radio users sharing the resources could include the use of protocols in order to set priorities. Cognitive radio could work without a fixed structure, as the ad hoc networks do cooperatively. Such advanced networks could have similarities with the large packet radio network using spread-spectrum modulation [11], or the ad hoc network [12].

Cognitive ideas have inspired research during the last years, but there are still many open questions and new directions to be explored about it. This section presents some works that considered issues on cognitive radio capacity.

### *A. Ways of Sharing the Spectrum*

The first paradigm to be considered is how the spectrum is organized in the service available band. There are two possibilities in sharing the spectrum:

*1)* Vertical sharing and protection of the incumbent (licensed radio services). The cognitive radio user should not harm the operation of licensed services. It has to control its emissions to prevent interference to the primary system.

*2)* Horizontal sharing (coexistence), in an open access spectrum: all systems have the same regulatory status and may access the spectrum, like the ISM bands which are shared also by WLAN and Bluetooth. The horizontal sharing can be: coordinated (when little can be done to avoid interference) or without coordination (there is a spectrum etiquette, to be followed by all involved systems).

### *B. Exploring Side Information: Three Paradigms:*

There are three paradigms corresponding to the different ways in which the side information about the radio environment is processed [13]:

*1) Underlay networks:* strict constraints are imposed on the interference caused by a cognitive radio to other users; allows cognitive users to operate if the interference caused to noncognitive users is below a given threshold-(constrained to cause minimal interference to non-cognitive radios); spread spectrum is an example of underlay system.

*2) Overlay networks:* they seek to exploit interference through sophisticated coding strategies built into the cognitive transmitters that allow communication with other users. Cognitive radios use sophisticated signal processing and coding to maintain or improve the communication of noncognitive radios while also obtaining some additional bandwidth for their own communication (e.g., 802.11a Dynamic Frequency Selection) can share spectrum with incumbent licensed users.

*3) Interweave networks:* they involve cognitive radios communicating with other users through the use of spectrum holes in space, time, and frequency. In interweave systems, the cognitive radios opportunistically exploit spectral holes to communicate without disrupting other transmissions-interweave (should find and exploit spectral holes to avoid interfering with non-cognitive radios).

### *C. Model for the Cognitive Radio*

The cognitive radio model used is derived from the interference channel model, and it is shown in Figure 4: the dotted line between transmitter 1 ($Tx_1$) and transmitter 2 ($Tx_2$) shows that the cognitive user has knowledge of the other user's message and/or encoding method.

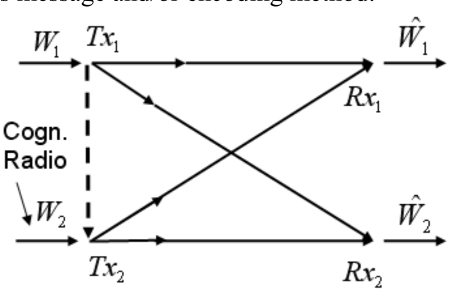

Figure 4: the cognitive radio model

### *D. Cognitive Radio Capacity- Different Approaches*

Even though intuitively one is used to think of strong interference as having a more detrimental effect than weak interference, at least in information theory [14] [15] shows that strong interference is less harmful than weak interference, and that very strong interference can be as good as no interference at all. Due to this characteristic, a modified interference channel model is frequently used to analyze the cognitive radio behavior, as shown in Figure 4.

In [16] a general model of a cognitive radio Channel is proposed for the analysis of its theoretic limits. The system presented has two transmitters and two receivers, and each transmitter knows the message transmitted by the other pair. They combine ideas from coding for channels with known interference at the transmitter [17], dirty-paper coding [18], the interference channel [9], the Gaussian multiple-input multiple- output (MIMO) broadcast channel [19], and compare to the achievable region of the interference channel as described by Han and Kobayashi [10]. They find a capacity region as shown in Figure 5, showing that a certain set of rates in which two (cognitive radio) senders can transmit simultaneously over a common channel to two independent receivers, and the cognitive sender is aware of the message to be sent by the other sender. However in spite of the depth of the analysis, this model has only two users.

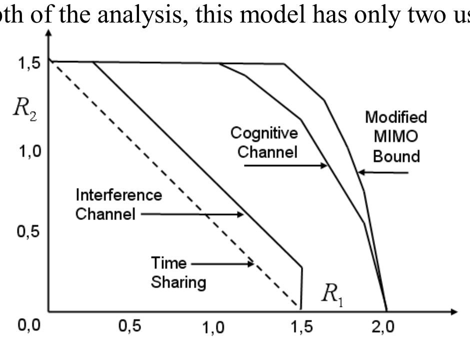


Figure 5: Capacity Region for Cognitive Radio [16]

In [20] the authors investigate the capacity of opportunistic communication in the presence of dynamic and distributed spectral activity (when the time varying spectral holes sensed by the cognitive transmitter are correlated but not identical to those sensed by the cognitive receiver). They develop a two switch model that captures the localized spectral activity estimates at the transmitter and receiver. The information theoretic framework of communication with side information is used to characterize the capacity of the cognitive link with both causal/ noncausal side information at the transmitter and/or the receiver. They conclude that the capacity benefit from non causal side information over the causal case is very small, and that while the feed forward overhead improves underpopulated environments better thn feedback overhead, in overpopulated scenarios the opposite holds. They find that the cognitive radio performance is robust to the uncertainties arising out of distributed and dynamic spectral environments, and that the performance depends strongly on the correlation of the spectral activity in the vicinities of the transmitter and receiver.

In another work [21] the authors develop inner and outer bounds on the secondary radio capacity using the two switch model [20] in order to explore the throughput potential of cognitive communication. They investigate the throughput improvements offered by the overlay methods and propose channel selection techniques that can be used for opportunistic access such as frequency hopping, frequency tracking, and frequency coding. The inherent tradeoff between the sensitivity of primary detection and the cognitive link capacity is investigated. Numerical results provide comparison of the throughputs of the different cognitive radio models to show that the overlay technique can increase the throughput of secondary communications significantly over the interweave technique. However, this improvement, is critically dependent on the availability of interference knowledge at the secondary transmitter and quickly disappears as the distance between the primary and secondary transmitters increases. The fundamental question for the coexistence of heterogeneous wireless devices is one of autonomy vs. regulation. Licensing is found to be best suited to high duty cycle traffic, but opportunistic access is optimal for bursty low-duty-cycle traffic.

In [13] the authors also explore capacity of opportunistic secondary/ cognitive communication over a spectral pool of two independent channels (independent and identically distributed occupancy processes). Since the spectral activity of the primary user has a distributed nature, the cognitive receiver does not know completely the channel used for cognitive communication at the transmitter. Using multi-state switches to model the cognitive link at either end, they can simulate the distributed channel information in order to make the system track the transmitter state at the receiver. Using genie based outer bounds and training based lower bounds, they estimate the capacity of the secondary link. By estimating the probability of the receiver and transmitter being matched to the same state, they derive both upper and lower bounds on the capacity. The bounds can be used to explore the benefits and costs associated with the forward and feedback overheads. The capacity analysis shows that the benefits of spectral pooling are lost in dynamic spectral environments.

In another different approach, the authors of [22] present a decomposition of arbitrary wireless networks with cognitive and noncognitive nodes, reducing the network to a set of clusters which behave in competitive, cognitive and cooperative fashions. They explore two examples of this cognitive behavior, one is the two sender two receiver channel where one sender knows the message to be transmitted by the other and thus may cooperate in an asymmetric manner; the other one is an example of collaborative communications, where a single sender may be aided by one or more cognitive users, or relays to transmit to a single receiver over a compound channel. They obtain fundamental limits as achievable rate (regions) which demonstrate the potential gains for both schemes. Here also the analysis is limited to few transmitters and receivers

In [23], the authors present cognitive radio as a solution for spectrum congestion. They consider that cognitive radio exploits available side information about the channel conditions, activity, codebooks and messages, and that it could be implemented following three paradigms: underlay, interweave and overlay. Capacity formulas for these results are generally quite cumbersome and yield little insight, so they opt to illuminate the degrees of freedom in cognitive networks as a metric for their sum capacity. They find that in a system with two transmitter-receiver pairs and different assumptions about cognition, the network degrees of freedom ranges from one to two. They say that a surprising and promising result for large networks is the degrees of freedom possible via interference alignment (in an interference channel with K users, assuming global knowledge of the time-varying channel coefficients, the network degrees of freedom is K=2, i.e. it grows with the number of users).

In [24] the authors characterize the capacity region of the discrete Z-interference channel where the transmitter of the pair that suffers from interference is cognitive, and the channel between the interference-free pair is noiseless. They show that in contrast to the Gaussian case, and under certain conditions, superposition encoding is the optimal way to minimize interference, even if the transmitter of the interference suffering pair has cognitive capabilities. Their results also apply to a generalized Gel'fand-Pinsker problem in which a transmitter-receiver pair communicates in the presence of interference noncausally known at the encoder.

In [25] the authors derive an achievable rate region for 2-transmitter–2-receiver causal cognitive interference channels with combined cooperation at each transmitter. A coding scheme is proposed to achieve the rate region. For Gaussian channels, numerical results have shown that the derived rate region extends the rate region achieved by pure "decode-and-forward" cooperation, indicating better spectrum efficiency by using combined "decode-and-forward" and "compress-and forward" cooperation.

Finally, in [26] the authors study a K>2 users cognitive radio network (one licensed transmit-receive pair and K-1 cognitive transmit-receive pairs wishing to communicate simultaneously). They show that for the case of a class of "very strong" interference channels all users can simultaneously communicate as if all cross-channels in the interference network were absent from the system. Even though there are more than two users, their work also has the constraint of considering very strong interference channels.

## V. Conclusion and Future Works

There are still many open questions and many new directions to be explored about cognitive radio. For instance, burstiness and end-to-end delay are major components in the study of networks, but are not as remarkable in Shannon theory, in which channels assume a source with infinite data and delay can be infinite. Maybe one way to overcome this difficulty should be to create practical protocols addressing network characteristics (end-to-end delay, source burstiness) in order to deal with a wide range of applications [23].

Even though many researchers have focused their efforts in solving the capacity of cognitive radio systems, most works still present a particular situation. Systems design issues remain an important problem, and with cognition one expects that almost all the gains of a fully co-operative centralized network can be achieved. It is also expected that as number of available bands increase, the capacity will tend towards the theoretical limit of Shannon's capacity.

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