



STUDY OF OPPORTUNISTIC ROUTING ALGORITHMS FOR MULTI-HOP COGNITIVE RADIO NETWORKS

A Degree Thesis

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Abstract

As a consequence of the growing spectrum saturation, new alternatives like Cognitive Radio are considered. Cognitive Radio (CR) networks have as a purpose to route information through the CR network without interfering the present licensed users or decreasing their quality of service as less as possible. Some alternatives to solve this routing difficulties have been investigated. The existent users can have quite diverse kind of activity models. This project wants to study if the PU activity model is critical for the used algorithm and if there exists any routing algorithm which runs better indistinctly of the assumed model. According to this, an existing routing algorithm [7] based on local spectrum knowledge has been taken as a benchmark to assess the behaviour of routing algorithms under different primary users' activity models. At the same time, a new routing algorithm is proposed that does not need too much PU activity information and shows, in some situations, an acceptable routing cost deterioration regardless of the statistical model considered.

Resum

Com a conseqüència de la creixent saturació de l'espectre radioelèctric, s'han començat a considerar noves alternatives com la Radio Cognitiva. Les xarxes Cognitives tenen com a propòsit encaminar la informació a través de la xarxa sense interferir els usuaris amb llicència ja existents o bé, empitjorant la seva qualitat de servei en la menor mesura possible. Algunes alternatives per abordar aquests problemes ja s'han començat a investigar. Els usuaris amb llicència poden tenir diversos tipus de models d'activitat radioelèctrica. Aquest projecte el que vol és estudiar si en efecte, els models d'activitat són crucials en base l'algorisme utilitzat i si existeix algun algorisme d'encaminament que funcioni millor independentment del model utilitzat. Per tant, un algorisme ja existent [7] basat en el coneixement de l'espectre a nivell local, s'ha agafat com a punt de referència per avaluar el comportament dels algorismes en funció del model d'activitat dels usuaris primaris. Alhora, s'ha proposat un nou algorisme que no necessita massa informació de l'activitat dels usuaris primaris i mostra en alguns casos, un empitjorament acceptable del cost d'encaminament sense tenir en compte el model estadístics considerat.

Resumen

Como consecuencia de la creciente saturación del espectro radioeléctrico, se han empezado a considerar nuevas alternativas como la Radio Cognitiva. Las redes Cognitivas tienen como propósito encaminar la información a través de la red sin interferir a los usuarios con licencia o bien, empeorando su calidad de servicio en la menor medida de lo posible. Algunas alternativas para abordar estos problemas ya se han empezado a investigar. Los usuarios con licencia pueden tener diversos tipos de modelos de actividad radioeléctrica. En este proyecto, se pretende estudiar, si los modelos de actividad son cruciales de acuerdo con el algoritmo utilizado i si existe algún algoritmo de enrutamiento que funcione mejor independientemente del modelo utilizado. Por consiguiente, un algoritmo ya existente [7] basado en el conocimiento del espectro a nivel local, se ha tomado como punto de referencia para evaluar el comportamiento de los algoritmos en función del modelo de actividad de los usuarios primarios. Al mismo tiempo, se ha propuesto un nuevo algoritmo que no necesita demasiada información de la actividad de los usuarios primarios y muestra en algunos casos, un empeoramiento aceptable del coste de enrutamiento sin tener en cuenta el modelo estadístico considerado.

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These are my last words in my university degree experience. I have had diverse kinds of moments: some bad and others very good. I think that one of the most important things that I have learnt is responsibility and become a true liven up person. Just thank to others lectures that I had, especially Albert Aguasca and all the partners that I had during the degree.

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1. Introduction

1.1. Inception

The project was born as an inquisitiveness of Javier Villares and Francesc Rey to explore novel routing techniques in cognitive radio scenarios. The existence of a saturated spectrum and an increase of demand of high throughput, low latency, energy-saving and an increase of number of users, leads wireless networks to review their own communication methods.

In cognitive radio scenarios users in an unlicensed network (secondary network) transmit packets occupying a frequency licensed to another network (primary network). Since licensed users have priority over unlicensed ones, secondary users must transmit without interfering primary network. In consequence, links in the secondary network typically cover short distances and thus, to communicate two secondary nodes separated by a long distance, a dense deployed network of unlicensed users acting as relays can be used to route packets between origin and destination nodes. The options to carry out this transmission can be multiple and the presence of different types of scenarios may occur. This project studies a routing algorithm that considering, statistically, the presence of a primary user designs the route that optimizes a key parameter (either minimum delay or maximum energy-saving) while mitigating the interference produced over the primary network.

1.2. Statement of purpose, requirements and specifications

Evaluating the performance of routing algorithm in cognitive radios [7], the purpose of this project is to demonstrate that efficient and optimal routing protocols for cognitive radio networks can be reached. The design of the optimum route is done under two perspectives: one assuming a scenario in which every unlicensed spectrum user has a deep and perfect knowledge of network parameters and other assuming a scenario which is poorer in terms of statistically network information but knows more parameters than the first exposed scenario.

The packet routing protocol is designed under the basis of approaching hop by hop the final destination optimizing some parameter (distance, delay, energy...). The project assesses and evaluates the impact on routing algorithms of different metrics and different knowledge of the primary activity statistics.

As some requirements and specifications can be considered that simulations should be done with MATLAB software and programmed scenarios will have to fulfil a realistic sense. At the same time, access to IEEEExplore browser in the course of project was fundamental to conclude this thesis.

One of the most important requirements is the workday. My workday has been with a duration of 3 hours per day approximately. Constant work and assume that all the labour fall back into myself is essential for a successful project.

The thesis main goals are:

- Evaluate the routing algorithm: Minimum Potential Based Routing [7].
- Evaluate alternative routing algorithms in CRN.

- Go in depth with statistical knowledge of users' activity.
- Compare routing algorithms behaviour according the statistical model used.
- Check improvements and deteriorations (either minimum delay or maximum energy-saving) according to the statistical model of users' activity.
- Transform hypothetical improvements observed into feasible Quality-of-Service upgrades in CRN.

1.3. Work Plan

1.3.1. Work Packages

In the following tables there are the work packages of this project.

Project: Introduction and planning	WP 1	
Major constituent: Documentation and Planning	Sheet 1 of 6	
Short description: Planning and description of the project defining the objectives of the project, tasks and weekly working schedule.	Planned start date: 14/09/2015 Planned end date: 27/09/2015	
	Start date: 14/09/2015 End date: 27/09/2015	
Internal task T1: Define Objectives Internal task T2: Planning of the project Internal task T3: Define Work Plan	Deliverables:	

Project: Research about the state of the art	WP 2	
Major constituent: Documentation	Sheet 2 of 6	
Short description: Read and find out novel papers about cognitive radio routing algorithms.	Planned start date: 21/09/2015 Planned end date: 04/10/2015	
	Start date: 21/09/2015 End date: 11/10/2015	
Internal task T1: Search papers about the topic Internal task T2: Summarize and understand papers	Deliverables: Project Proposal	

Project: Analysis the project simulator	WP 3	
Major constituent: Documentation	Sheet 3 of 6	
Short description: Study and analyse the baseline paper in which the thesis is based on.	Planned start date: 05/10/2015 Planned end date: 18/10/2015	
	Start date: 12/10/2015 End date: 25/10/2015	
Internal task T1: Go through the paper "Minimizing the Routing Delay in Cognitive Radios Using Potential Fields" in depth. Internal task T2: Think of how to organize and program the simulator	Deliverables:	

Project: Program the simulator	WP 4	
Major constituent: Software development	Sheet 4 of 6	
Short description: Translate into the simulation software the analysis and knowledge collected during the previous work package. This workspace will allow to design alternative algorithms and extract final results from the simulations.	Planned start date: 19/10/2015 Planned end date: 27/12/2015	
	Start date: 26/10/2015 End date: 14/02/2016	
Internal task T1: Program system model Internal task T2: Program Minimum Potential Based Routing [7] Internal task T3: Design and program Geometric Filtering Routing	Deliverables: Project Critical Review	

Project: Simulations & Results	WP 5	
Major constituent: Assessment results	Sheet 5 of 6	
Short description: Prepare an environment for simulations and carry out them. Consequently, a deep assessment of simulations in order to obtain concluding results.	Planned start date: 28/12/2015 Planned end date: 10/01/2016	
	Start date: 08/02/2016 End date: 01/05/2016	
Internal task T1: Prepare environment Internal task T2: Make simulations Internal task T3: Assessment of simulations	Deliverables:	

Project: Degree Thesis Redaction	WP 6	
Major constituent: Documentation	Sheet 6 of 6	
Short description: Write and prepare the thesis dissertation. In addition, prepare the oral defence.	Planned start date: 04/01/2016 Planned end date: 13/01/2016	
	Start date: 08/02/2016 End date: 06/05/2016	
Internal task T1: Degree Thesis redaction Internal task T2: Prepare the oral defence	Deliverables: Final document of degree thesis	

1.3.2. Gantt Diagram

This Gantt Diagram reflects the main tasks that should be carried out during the degree semester.

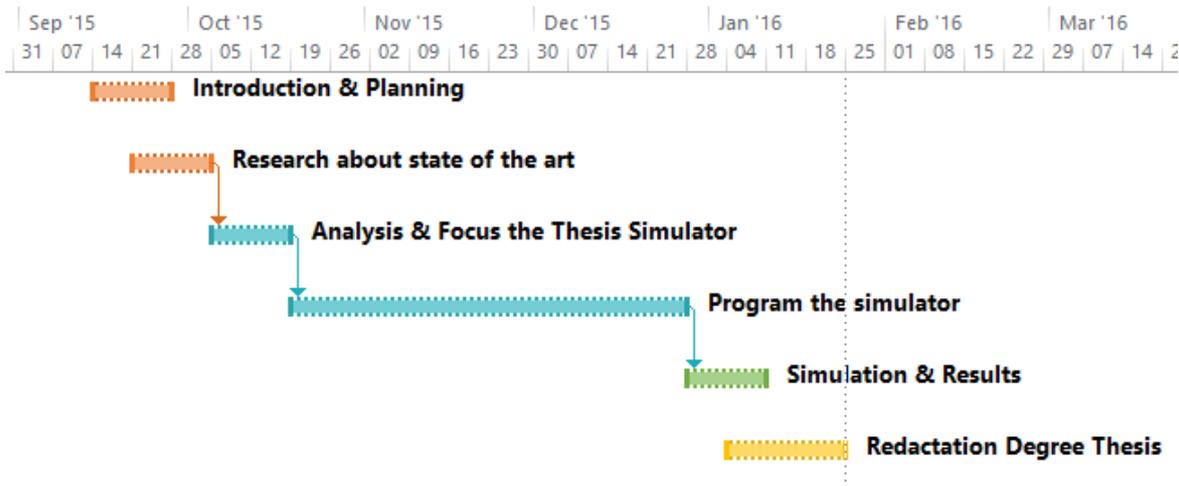


Figure 1 Expected Gantt diagram of degree thesis

1.3.3. Incidences

The degree thesis has been incurred in an important delay in the programmed tasks. A first simulator demo was not optimal to program project system model and routing algorithms. I decided not to continue with it because an extension of it should unleashed a large amount of problems. The system model was becoming more sophisticated and routing algorithms too. According to this, a reconsideration of the simulator structure has been carried out.

For another hand, the unexpected slowness in MATLAB simulations due to large number of implementations for extract statistical results and choose a realistic setting of tuning simulator parameters have become critical affairs too.

This is the Gantt Diagram according to the real time-plan carried out.

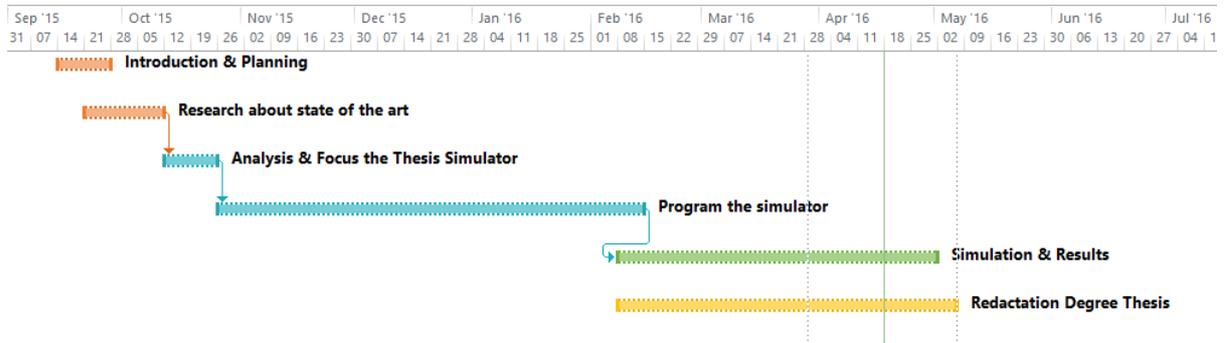


Figure 2 Final Gantt diagram of degree thesis

2. State of the art of the technology used or applied in this thesis:

Radio is a broadcast medium, in which can coexist different users in the same frequency band interfering with each other. In the last two decades the number of wireless devices has grown exponentially demanding higher quality and higher data rate and it leads to a severely limited spectrum. In order to find out some solutions a new kind of communications has been thought calling Cognitive Radio.

There exist different frequency bands: with license (i.e. GSM) or not (i.e. ISM band). In the licensed band users have an assigned spectrum or a multiple access control which allows avoiding hypothetical interferences and thus improving its quality-of-service (QoS). For the other hand, in unlicensed bands, users transmit in a chaotic way (just following a little set of rules) where high interference levels can be reached and hence lead to unsuccessful communications. At the same time, these unlicensed bands can contain a large number of users which occupy whole spectrum and consequently let it saturated (without reliability).

Both types of bands may accommodate many additional wireless devices if these devices are able to exploit some advanced technology to only minimally disrupt and lead to an increase of successful communications of coexisting non-cognitive devices.

2.1. Cognitive Radio

Cognitive Radio was born to solve the impact problem to non-cognitive users and at the same time can establish own cognitive radio communications. So, cognitive radio can be understood as a wireless communications system which collects channel and users' information and uses them in an astute way: improve or degrade just a little bit non-cognitive QoS and allow unlicensed users use spectrum for communicate too.

Based on large kind of network types, cognitive radio can be faced in three different paradigms which can be complementary: underlay, overlay and interweave paradigms [1].

2.1.1. Underlay Paradigm

Assuming a knowledge of the interference cause by its transmitter to the receivers of all non-cognitive users it's allowed a communication by the cognitive radio. According this scenario, is often called the cognitive users as secondary users (SU) and the users which cannot be too much interfered are referred as primary users (PU).

Basically, the underlay paradigm points to allow secondary users' communications with the limitation of no-interfere non-cognitive receivers under a threshold pre-established. In [1], talks about improve this interference-aware making use of multiple antennas to guide cognitive signals or using ultra-wide bands where the signals can be covered up by noise floor. This paradigm is closer to secondary users' power control which implemented making use of low-power transceivers can limit cognitive users range.

2.1.2. Overlay Paradigm

Overlay paradigm is based in main terms of the non-cognitive users' codebooks and alternatively its messages as well. Basically this model assumes the non-cognitive message is known at the cognitive transmitter when the primary user begins its transmission. A non-cognitive user message might be obtained by decoding the message at the cognitive receiver.

A hypothetical no-correct decoding of a non-cognitive message due to fading or interference allows cognitive users that have decode correctly a message send it to primary user and transmit part of power for his own communication. On the one hand, can exploit the scenario of a retransmission and at the same time a secondary user transmit his own information in order to cancel or mitigate the interference produced at cognitive receiver by sophisticated techniques like dirty paper coding [1]. On the other hand, cognitive users have the message knowledge which will be utilized for transmit the non-cognitive message and his own message. In this way the non-cognitive transmissions will be relayed.

2.1.3. Interweave Paradigm

The major part of the spectrum is not being utilized while time passes. "There exist temporary space-time-frequency voids, referred to as *spectrum holes* that are not in constant use in both the licensed and unlicensed bands. Thus, the utilization of spectrum is improved by opportunistic frequency reuse over the spectrum holes" [1].

Interweave cognitive radio paradigm can be explained as a smart wireless communication system that periodically knows the spectrum status. Using different kinds of techniques (in this project, a sensing spectrum), spectrum can be detected as occupied or idle and then opportunistically communicates over spectrum holes with minimal interference to the active users.

2.2. Cognitive Radio Routing

Most of the research on cognitive radio networks has focused on Physical Layer and Medium Access Control layer issues [2]. Recently, the research community has started to apply the cognitive radio in network layer to further extend its applications. The work in the area of routing protocols in cognitive ad-hoc wireless networks can be classified into two main categories: full spectrum knowledge and local spectrum knowledge. In this thesis, local spectrum knowledge is assumed. Making use of an opportunistic technique which broadcast spectrum and network information between closer cognitive users, each node will be able to reach appreciate network state information useful for forward packets. Moreover, according to the need of the network, a different routing strategy could be selected because the large number of routing metrics that exist leads to different feasible solutions [3].

Some routing strategies like greedy geometric or gradient routing [4-5] makes use of local spectrum knowledge. Opportunistically each node can obtain cost tables according established metrics and use them for routing decisions. In greedy routing [4] is required global topology information to decide which route is the best. Using location information, the SU source and each SU intermediate will select the next-hop node closest to the destination. Thus, packets will be greedily forwarded (in some cases these routes can

seem unappropriated at first glance but always have an intelligent reason) with the purpose to decrease their distance until destination is reached. In that case, it is done using geometric distance between nodes using a decay power constant.

Basically, the main regards in cognitive radio networks are delay routing schemes generally based on end-to-end delay and energy routing schemes to minimize the total power consumption between source and destination too. One of the things to take into account is world's future has a tendency to smart what can make our lives easier. It could be done taking use of wireless sensor networks or any transceiver object, which have as a critical point the energy consumption and delay aspects. In Wireless Sensors Networks (WSNs) [6] some design challenges, routing issues and routing protocols are list in different purposes and detached as guidelines.

2.2.1. Routing Metrics

The rules of a routing scheme are: to reach the final destination and at each node to choose the best option as possible according network status. The most part of cognitive routing researches point to delay and energy aware parameters to optimize. Probably, an increase of connections and throughput will lead to use many additional transceivers in CRN. Therefore, these devices can become out of energy (life-time) depending of their use. At the same time, latency requirement has become critical due to new live user applications. Delay problems in wireless sensors are not too much important. However, wireless sensors are designed to be placed with a long life-time. So, energy quandary is quite important in wireless sensor networks. Some researches [7-11] in this way evaluate these routing metrics searching different solutions making use of novel strategies.

2.2.1.1. Potential Fields

Potential fields can be one of the ways to carry on a routing decision scheme. At each node the best route is known according the assumed statistical model. In [4,7], use of potential fields have been done. It is inspired by robotics that use these techniques for navigating autonomous robots and avoiding obstacles [5]. In potential field based routing, packets are forwarded in the descent direction of potential field ϕ . Assuming a fixed destination, exact rules of how to determine the next hop depend on the used potential field. The routing condition is usually based on choose the node which has as less as possible cost. This cost is computed as the addition of: cost to reach the node and the potential field in this node. Therefore, the established route will be optimal if the potential values have converged perfectly. As said above, these potential fields can be selected using different potential fields metrics, putting an emphasis on delay and energy metrics.

2.2.1.1.1. Delay Aware

Cognitive radio paradigms have been tackled to get success routing algorithms. In this way, some delay based routing algorithms have been proposed. An interesting research can be found in [8] which mixes delay metrics (originally based on multi-channel environments and then adapted to Cognitive Radio Networks (CRNs)) and metrics specifically designed for CRNs based especially in careful analysis of primary users assuming statistically models. In order to stablish another routing protocol based on a single channel spectrum sensing

(no exploit the diversity channel effect) and at the same time have an accuracy knowledge of cognitive radio channel, a recent paper [7] has been considered as a benchmark.

This paper [7] lay the basis for an optimal routing protocol with the goal of minimize routing delay using potential fields. The main idea is that each node knows the potential field using delay metric based on a statistically potential field (form other users) broadcasted recurrently along the users deployed. The delay cost used is reviewed in this project in order to improve and reconsider it in a more real problematic case.

2.2.1.1.2. Energy Aware

There already exist some energy routing schemes [9,10,11]. Basically, they have as cornerstone the energy consumption in transmission mode. Moreover, cognitive users have an idle, reception and processing energy consumption which can be dealt with. In [9] authors propose an algorithm that uses energy potential fields with the purpose to get some CRNs metrics like energy density and transmission energy which can ensure an energy-balanced routing scheme. Moreover, some realistic power consumption models and energy-aware WSNs have been reviewed to relate in a routing protocol scheme [10-11].

Any metric can be selected and exported in the optimal-efficient routing scheme [7] to minimize routing energy cost and reach the destination as better as possible.

2.2.1.1.3. Other Metrics

Energy and delay metrics have been tackled but it could be the chance to explore different types of metrics and consider some hybrid cases. It can be extrapolated to a function cost making more regard using weighting-aware metric.

3. Methodology / project development:

As a cognitive radio routing casuistry some paradigms exposed above should be taken as a reference. In this case it will be a mix of underlay paradigm and interweave paradigm. On the one hand, some cognitive users will transmit interfering non-cognitive users but guaranteeing a QoS provided that the interference level signal received by non-cognitive users doesn't exceed a threshold. On the other hand, interweave paradigm is been assumed because its verified that non-cognitive users have an intermittent behaviour generating some spectral holes that cognitive users will take as a benefit.

This project first evaluates the routing algorithm proposed in [7] which aims to transmit packets through the path that minimizes the aggregated delay between transmitter and receiver nodes. As complement to this work the project extends the paper algorithm to introduce a different optimization criterion while keeping the same routing strategy. Specifically, the project designs the optimum route that minimizes delay and energy consumption.

In order to analyse from a critical perspective the routing algorithm in [7], the statistically of the primary user activity is also reviewed having in mind that, one of the more critical aspects when designing the optimum routing algorithm in the presence of a primary user is the amount of information that the secondary users have of the primary user activity. In particular, the paper in [7] assumes a Bernoulli statistic to model this activity and performs simulations implementing the same statistic. In order to evaluate how critical the algorithm is to the statistical model, the algorithm in [7] has been tested when the primary user activity is modelled with a Markov chain. This aspect, a relevant contribution of the project, is important because it allows to introduce and control the primary user coherence time, a critical parameter when evaluating the performance of the routing algorithm as it will be shown in section 4.

Finally, to complete the analysis of the routing algorithm in [7] an alternative algorithm has been presented and evaluated. The motivation for presenting this novel alternative algorithm is the large amount of prior information that the algorithm in [7] requires to design the optimum route using potential fields. Although the performance of the proposed algorithm will be poorer in some cases it will allow us to better understand the behavior of the routing algorithm.

In this thesis, a MATLAB simulator has been programmed to simulate the operation of a Cognitive Radio Network explained above using a system model detailed in the following sections.

3.1. Simulator

The programmed simulator has a main script 'point_creator.m' which is formed by a set of another scripts. These scripts deploy in a space region a number of cognitive users and each one carries out operations and steps to achieve all the network parameters and useful information for itself.

The simulator is sensitive to some tuneable parameters which describe the CR scenario and are list as follows:

- Link budget parameters

- Primary users parameters
- Density of secondary users deployed
- PHY layer parameters
- Sensing parameters
- Metrics parameters

3.2. System Model

Next, we will describe the scenario planned to carry out the routing protocol and which are the aspects and features to take into account focusing in the critical requirements that will allow to communicate the devices.

Let us assume a SU network composed by N SUs, whose are without available licensed spectrum. The SUs exploit opportunistically a licensed frequency band used by a PU that is active at random with probability $P_1 \in [0, 1]$. Therefore, this random behaviour becomes as a key point to understanding the scenario and will be useful for following routing guidelines.

PU is assumed that operates at one frequency band but the extensions to multiple PU transmitters and multiple frequency bands could be interesting to be analysed. This issue that will not take part in this thesis. However, it's an interesting system which can be left for future work.

3.2.1. Path Loss

The propagation model adopted in these scenarios for both kind of users follows a Line-of-Sight (LOS) model, where the losses caused by propagation from transmitter to receiver depends on distance [12].

$$PL(d) = \left(\frac{d}{d_0} + 1\right)^{-\alpha} \quad (1)$$

Where α is the path loss exponent and d_0 is the distance reference.

The path loss exponent is assumed to be known and his value, typically between 2 and 5, depends on the environment as shown in next table.

Environment	Path Loss exponent α
Free space	2
Urban Area	2.7 to 3.5
Suburban Area	3 to 5
Indoor (Line-Of-Sight)	1.6 to 1.8

Table 1 Path Loss exponent values according to environment

In this project, the path loss exponent has been chosen as $\alpha = 4$. This will lead an urban/suburban scenario where communications will be enough close and this exponent is considered more restrictive.

With respect to the distance reference this parameter is chosen according to scenario environment:

Environment	Reference Distance d_0
Indoor	1m
Outdoor	100m to 1km

Table 2 Reference distance used depending environment

Until electromagnetic wave doesn't achieve the reference distance, receiver power can be assumed, approximately, like transmit power. It can be seen as a near-field region environment where electromagnetic radiation is reactive.

In order to avoid the first region of the path loss, the scenario will try to establish distance between SUs over reference distance set to $d_0 = 1$.

3.2.2. PU User

As said above, just one PU user is placed in the scenario. The location of the PU receiver may be either known or unknown. PU uses a licensed frequency band and establish communications with other PU receivers opportunistically. Thus producing some spectral holes which SUs transmitters will profit. Packets send between PUs will assumed to be received correctly if the SINR receiver is above a desired threshold by γ_p .

The transmit power of the PU transmitter is set such that the SINR of a PU receiver at the edge of its coverage area is $G\gamma_p$, where $G \geq 1$ and fading casuistry is considered. Therefore, scalar G simulates the loss caused by fading and hypothetical interferences caused by secondary users' network. This scalar is a tuned parameter that can be more restrictive or aid SU communications reliability. The transmit power of the PU is then assumed to be given by $P_p^{tran} = \frac{G\gamma_p\sigma_p^2}{PL(d_c)}$, where σ_p^2 is the noise variance at the primary receiver and d_c is the PU coverage distance.

These primary users can transmit when either they want or under a multiple access protocol. The basic idea is that PU transmits when a new packet is available. The arrived packets should be transmitted as soon as possible.

Therefore, PU activity will be considered as active when it would be transmitting packets. The spectrum will be occupied using the same frequency band that SUs uses for communicate. When SUs will sense the spectrum they will see it as occupied.

When the PU is active the state of the spectrum is denoted as $S = 1$ and when the PU is idle the state is denoted by $S = 0$, leading to $S \in \{0, 1\}$. SUs recollect information about the occupancy of sensed spectrum and can consider it as a statistically conduct. This statistically behaviour can be focused in several ways.

3.2.2.1. Bernoulli Statistical Model

The status of PU can be assumed like a random variable which at each time slot with probability p can be transmitting or contrary with probability $1 - p$ not transmitting. Thus $p \in [0, 1]$ it's the parameter used for describe a Bernoulli statistical model.

One of the interesting things computable is the coherence time. In other words, the average number of time slots before an idle state is observed. Notice that for a Bernoulli random variable this is not a tuneable parameter but can be calculated and potentially used in the design of the routing algorithm.

$$\mu_0 = \frac{1}{1 - p} \quad (2)$$

3.2.2.2. Markov Statistical Model

An alternative model to characterize the primary user activity is a Markov model with two states and its associated transition probabilities, where state 0 means an idle PU status and state 1 means that PU is transmitting. Unlike the Bernoulli model, that assumes that packets are transmitted in a single slot without memory, this model can be interesting to consider a scenario in which PU transmits long packets that take more than one slot to be transmitted. Moreover, if the observation includes ∞ time slots, the Markov Chain can be considered like a Bernoulli statistical model with two state probabilities.

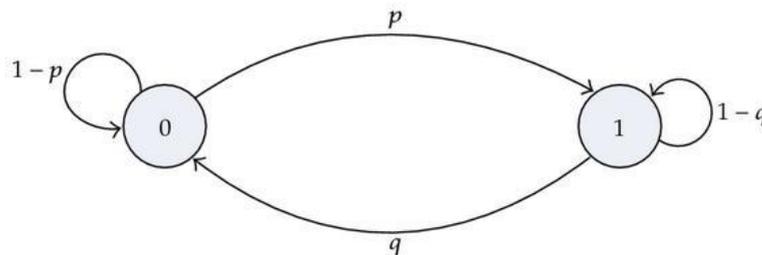


Figure 3 Phase diagram of a Markov chain with transition probabilities

Both state probabilities can be easily computed combining state transitions probabilities according to probability theory $q = 1 - p$.

$$P(1) = \frac{p}{1 + p - (1 - q)} = \frac{p}{p + q} \quad (3)$$

$$P(0) = 1 - P(1) = \frac{q}{p + q}$$

In fact, these stabilized status can be tackled relating them to an average number of time slots until the other state is observed calling them as coherences times. So, μ_{01} means the average number of time slots until a PU transmitting state is observed and μ_{10} means the average number of time slots until a PU idle state is observed and they are calculated as follows:

$$\mu_{01} = \sum_{n=1}^{\infty} n(1-p)^{n-1}p = \frac{1}{1-(1-p)} = \frac{1}{p} \quad (4)$$

$$\mu_{10} = \sum_{n=1}^{\infty} n(1-q)^{n-1}q = \frac{1}{1-(1-q)} = \frac{1}{q}$$

In addition, the coherence time is the average numbers of time slots to change the state so, mandatorily should be more than 1 or equal.

$$\mu_{10}, \mu_{01} \geq 1$$

Substituting equation (4) into (3), a relationship between average number of time slots and state probabilities can be obtained:

$$P(1) = \frac{p}{p+q} = \frac{1}{1+\frac{q}{p}} = \frac{1}{1+\frac{\mu_{01}}{\mu_{10}}} \quad (5)$$

$$P(0) = \frac{q}{p+q} = \frac{1}{1+\frac{p}{q}} = \frac{1}{1+\frac{\mu_{10}}{\mu_{01}}}$$

Notice that in order to maintain the same state probability when one of the coherence times is increased the other one should be increased proportionally. These coherence times should fulfil a bound to maintain real state probabilities.

$$P(1) = \frac{p}{p+q} \rightarrow p = \frac{qP(1)}{1-P(1)} \leq 1 \quad (6)$$

$$P(1) \leq \frac{\mu_{10}}{\mu_{10} + 1}$$

3.2.3. SU Users

A set of SUs are deployed setting a CRN which want as a purpose interfere as less as possible guarantying the correct reliability of PU communications. At the same time, SUs will profit the same frequency band for stablish their own communications.

SU packets are assumed to be received correctly if SINR at the receiver is above a desired threshold denoted by γ_s . This threshold is given by a Packet Error Rate (PER) previously established. In linear scale, the SINR observed at the receiver when SU j transmits to SU k is:

$$\gamma_{j,k} = \frac{P_j^{tran} PL(d_{j,k})}{\sigma_k^2 + I_k} \quad (7)$$

Where P_j^{tran} is the transmit power of SU j and it must be bounded by a maximum transmit power and maximum bearable interference (both explained in section 3.3.), σ_k^2 and I_k are the noise variance and the received interference power caused by PU and other SUs, respectively.

In this project we consider that only a SU is transmitting in a time slot. So, if SU j is transmitting not one else SU can't transmit at the same time except PU transmitter.

3.2.3.1. Neighbours

To ensure the capability of establish a CRN each SU must have a set of neighbours in both status conditions, PU transmitting or idling. The neighbours of SU j are determined based on the observed SINRs at each SU receiver. Denote the set of neighbours of SU j according to the spectrum status to $S \in \{0, 1\}$ as $\mathcal{N}_j(S)$. Denote the SINR between SU j and k when the state of the spectrum is S by $\gamma_{j,k}(S)$. If $\gamma_{j,k}(S) \geq \gamma_s$, then $k \in \mathcal{N}_j(S)$.

If the spectrum is occupied, the SU transmitter will route with one of $\mathcal{N}_j(1)$. When an occupied status is considered, it means that PU presence is nearby. Consequently, the number of neighbours in $\mathcal{N}_j(1)$ will be more limited than $\mathcal{N}_j(0)$. This reduction is due to a fewer SINR at SU k receiver caused by PU interference power and the reduction of SU power available commented in 3.2.3.4. Otherwise, when the spectrum is considered to be idle $\mathcal{N}_j(0)$ will be used.

3.2.3.2. SU Deployment

It's assumed that all the SUs are deployed randomly in a region space where a PU is present. The fact is that the number of SU and the size of the region should ensure connectivity between all of them or with a highly probability of connection.

In [13] a deep research about connectivity have been done. In this paper it is computed and expression which ensures with a probability of connection p_{con} that there are no isolated nodes.

$$p_{con} \cong (1 - e^{-\pi\rho r_0^2})^n \quad (8)$$

Where r_0 is the coverage radius of SU, n the number of SUs and ρ SUs density. The coverage radius can be obtained by SUs SINR expression (7). The radius r_0 correspond to $d_{j,k}$ at the edge of coverage area.

$$r_0 = \left(\frac{P_{SU}^{max}}{G\gamma_s\sigma_s^2} \right)^{1/\alpha} - 1 \quad (9)$$

Then, setting a SU density deployment and the number of SUs, the probability p_{con} can be calculated. This probability in our scenario should be very high about 0.99 or higher. Remember that a routing scenario is planned and each node have to ensure more than 1 link to get more options when a packet must be forwarded.

Then the needed density to comply a specified connectivity probability is calculated as follows:

$$\rho = \frac{-\log(1 - p_{con}^{1/n})}{\pi r_0^2} \quad (10)$$

The size of the space region and the number of SU deployed are a tuneable parameters. The setting of them can lead to highly density scenarios or on the contrary could establish a disconnected and blocked network.

3.2.3.3. Spectrum Sensing

SUs will sense the spectrum in order to determine if PU is transmitting. This sensing is assumed to be ideal (without error probability). This means that the time spent sensing should be large enough, infinite theoretically. Actually, in practice, at each time slot, SU wants to know the availability of transmit. So, to fulfil this time slotted access using sensing decision, it should be measured in the first part of time slots $\frac{T_{slot}}{11}$ (explained in 4.1.) and then transmit according to spectrum status the rest of time slot. This time is considered to fulfil the past statement; it is sufficiently large enough. Therefore, this acceptance involve to assume an ideal proper functioning of spectrum sensing.

To know this spectrum status SU should sense spectrum and take a decision. Basically the idea is an integer RF which collects power received and if it exceeds a threshold pre-established it's considered that there exist PU activity. This threshold is assumed to be 10 times smaller than SU sensibility. Therefore, a SU can sense spectrum in a distance away from PU that mean power is smaller than the threshold. The PU status will be considered as idle. The distance which PU cannot be sensed should be larger than:

$$d \geq \alpha \sqrt{\frac{10P_{PU}}{\sigma_p^2}} - 1 \quad (11)$$

Spectrum sensing has collateral effects in metrics. In the case of energy metrics, there is an increase of metric cost due to a RF receiver enabled during the allotted time to sense. At the same time, there exist an increase of delay metrics too. As mentioned above, time slots should be larger than transmission time.

3.2.3.4. SU Power Control

In order to protect the PU from interference, a SU needs to limit its maximum allowed transmit power. When the spectrum is idle the SU transmitter may ideally use its maximum transmit power, if channel conditions are favourable. However, if a PER target is established, transmit more power than just the strictly required is not necessary. If a routing algorithm in an energy aware scenario does not take it into account power consumption, could create and produce a non-optimum routing protocol.

When the spectrum is occupied the SU needs to bound the transmit power such that SINRs of the PU receivers inside the PU coverage area do not fall below γ_p . The interference level at the PU receiver can be estimated when the SU knows the PU transmit power, the path loss conditions, locations of itself and that of the PU transmitter and the PU coverage distance. Alternatively, if the PU receiver is also a transmitter (i.e. transceiver) the interference caused to the PU may be estimated by assuming channel reciprocity. For simplicity, it's just considered one PU transmitter with a circular coverage area of d_c radius.

Next, we consider two cases: when the PU receiver location is known and when the location is unknown.

Next, we present the SU power control, taken from [7], which is considered quite reasonable and feasible. If the PU receiver location is known, it is easy to control the interference caused to the PU receiver based on the location information and the path-loss model. The expression assumes that the PU receiver is at a distance $d_{r,p} \leq d_c$ (within coverage PU region) from the PU transmitter and at a distance $d_{r,j}$ from SU transmitter j . Given the path loss model in Path Loss section the maximum allowed transmit power of SU j is given by

$$P_j^{tran} \leq \frac{\frac{P_p^{tran} PL(d_{r,p})}{\gamma_p} - \sigma_p^2}{PL(d_{r,j})} \quad (12)$$

If the PU receiver location is unknown, the SUs need to presume the worst case location. On the one hand, when the SU transmitter is outside of the PU coverage region, the worst case location for the PU receiver is at the edge of the PU coverage region closest to the SU transmitter. Then, assuming only propagation path loss, the received PU signal power is at its minimal required level and the received interference power from the SU is maximal within the coverage region. On the other hand, when the SU transmitter is inside the PU coverage region the worst case PU receiver location is determined as follows. Assuming that SU j is at distance $\lambda d_c, \lambda \in [0, 1]$ from the PU transmitter and at distance $(\beta - \lambda)d_c, \beta \in [\lambda, 1]$ from the PU receiver

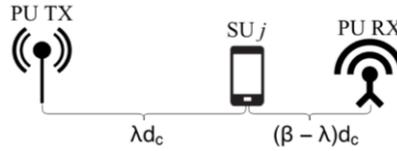


Figure 4 The worst case location for the PU receiver, when the SU transmitter is inside the PU coverage region. $\lambda \in [0, 1]$ and $\beta \in [\lambda, 1]$.

Hence, the maximum allowed transmit power of SU j is given as

$$P_j^{tran} \leq \frac{\frac{P_p^{tran} PL(\beta d_c)}{\gamma_p} - \sigma_p^2}{PL((\beta - \lambda)d_c)} \quad (13)$$

The worst case location for the PU receiver is on a line from the SU transmitter to the closest point on the edge of the coverage region. Minimizing the past equation with respect to β we find that the worst case location is either $\beta_{wc} = \lambda, \beta_{wc} = 1$, or $\beta_{wc} = \tilde{\beta}$, where $\tilde{\beta}$ is the zero of the derivative of the right-hand side of allowed transmit power equation. Given the path loss only propagation model we see that

$$\tilde{\beta} = \left(\frac{\alpha+1}{\sqrt{\frac{\lambda d_c P_p^{tran}}{\gamma_p \sigma_p^2} - 1}} \right) d_c^{-1} \quad (14)$$

The worst case location is then found by taking the minimum transmit power using the three possible values of $\beta_{wc} = \lambda$, $\beta_{wc} = 1$, or $\beta_{wc} = \tilde{\beta}$. In order to achieve generic simulations and results, unknown PU receiver location is assumed.

3.2.4. Multiple Access Control Layer

In a frequency band established, PUs will communicate between them. The fact is that SUs will take the advantage of inactivity of primary users and at the same time, make use of poorer regions of PUs coverage.

The licensed users are assumed to use any classical division duplexing technique. When they transmit, make use of time slots belonging in a frequency bandwidth or an assigned frequency rang. Unlicensed users should use a kind of access control that uses spectrum sensing before start a transmission.

Carrier sense multiple access with collision avoidance (CSMA/CA) is a quite good option to be considered. Packets will be forwarded after a spectrum sensing supposed to be "idle". Cognitive radio allows to transmit packets between SUs when PUs are transmitting at the same time. Actually, CSMA/CA will not only keep to transmit in idle status. CSMA/CA will use neighbours set $\mathcal{N}_j(1)$ at each node (these neighbours take into account to not interfere PU receivers) when an occupied spectrum will be observed.

Each packet transmitted must be verified and answered if the reception have been done correctly. These control parameters like acknowledge, errors and some network parameters will make use of a control channel allotted before start the communication that will ensure cognitive radio network reliability.

3.3. Minimum Potential Based Routing – MPBR [7]

For a given scenario that combines cognitive radio paradigm and a routing protocol for the SU users, many strategies to route packets can be chosen. MPBR routing algorithm is the solution proposed in [7]. Making use of a Bernoulli distribution formed by state probabilities, optimal potential field can be computed iteratively. SUs advertise their potential values to the neighbours and update them when a neighbour reports a lower potential value. Due to this iterative process, the computation of the optimal potential values requires a higher communication overhead. The value of the optimal potential field at a given SU represents the minimum routing metric from the SU to the destination statistically.

3.3.1. Scenario MPBR

Let us assume a region with a PU is located at the centre transmitting in a determined frequency band of radio frequency spectrum. Let us assume that in the same region there are N randomly distributed SUs with N large enough to guarantee communications between them with a very high probability and not letting SU without connection available [13]. Both, PU and SUs are static and do not change its own position while a routing is carried out.

Each SU knows useful information to deal the packets routing. Some values known by SU are:

- Oneself position
- PU transmitting probability
- SU neighbours with occupied spectrum ($\mathcal{N}_j(1)$)
- Position of each SU belonging $\mathcal{N}_j(1)$
- SU neighbours with idle spectrum ($\mathcal{N}_j(0)$)
- Position of each SU belonging $\mathcal{N}_j(0)$
- Potential value (depending the metric used)
- Cost to reach each neighbour (depending the metric used)
- Network parameters ($PER, \gamma_p, \gamma_s, \sigma_p^2 \dots$)

3.3.2. Algorithm MPBR

MPBR assumes that SU j wants to route a packet to a destination. Denotes the cost function to forward one packet from SU j to $k \neq j$ when the state of the spectrum is \mathcal{S} as $T_{j,k}(\mathcal{S})$. This cost function can be formed by different kinds of metrics (metrics used are explained in 4.2.). Furthermore, assumes that each SU has an internal cost of a determined metric T^{in} caused by very different reasons. The total metric from j to k when the spectrum is idle then becomes $C_{j,k}(0) = T_{j,k}(0) + T^{in}$. If j senses that the spectrum is occupied it has two options: try to transmit in the occupied slot with expected increase of metric $C_{j,k}(1) = T_{j,k}(1) + T^{in}$, or wait until the spectrum becomes idle. Denotes the expected metric if j decides to wait for idle spectrum before forwarding the packet as $C_{j,k}^{wait}$. It is reasonable to assume that the transmit cost during an idle spectrum status is less than the cost when spectrum is occupied, especially for delay metric. Hence, a SU would never wait for occupied spectrum if it has sensed the spectrum to be idle. The expected increase of metric caused by waiting for an idle spectrum is $C_{j,k}^{wait} = T_{j,k}(0) + T^{in} + T^{wait}$, where T^{wait} is the wait cost until an idle spectrum status is observed. Let $M_0(t)$ represents the minimum expected cost from j to the destination, given that j has sensed the spectrum to be idle. $M_1(t)$ represents the corresponding cost when j has sensed the spectrum to be occupied.

$$\begin{aligned}
 M_0(t) &= \min_{k \in \mathcal{N}_j(0)} \{C_{j,k}(0) + \phi_k(t)\} \\
 M_1(t) &= \min \left\{ \min_{k \in \mathcal{N}_j(1)} \{C_{j,k}(1) + \phi_k(t)\}; \min_{k \in \mathcal{N}_j(0)} \{C_{j,k}^{wait} + \phi_k(t)\} \right\}
 \end{aligned} \tag{15}$$

Where $\phi_k(t)$ is the potential value of SU k after the t^{th} update.

The proposed methods proceeds as follows.

- a. Initially all potential values are set to ∞ , except for the potential value at the final destination which is 0. SU j iterates its potential value until convergence after receiving the information about the potential value of its one-hop neighbours. Denote the old potential value of SU j after the $(t - 1)^{th}$ update as $\phi_j(t - 1)$. Then $\phi(t)$ is updated as

$$\phi_j(t) = \min \{ \phi_j(t - 1); P_0 M_0(t) + P_1 M_1(t) \}, \tag{16}$$

Where $P_0 = 1 - P_1$. In the rest of the thesis the converged potential values are denoted by ϕ_j . The potential values shared between all nodes must be updated if

the position of PU has changed. It can be done updating potential values periodically. If the position of SUs also changes, the potential values must be updated as soon as possible because could exist fictitious links. Therefore, both neighbours sets $\mathcal{N}_j(1)$ and $\mathcal{N}_j(0)$ must also be updated.

- b. After the potential values have converged, SU j determines the next hop based on the sensed state of the spectrum as follows.

If the spectrum is sensed idle, the next hop is $k^* = \arg \min_{k \in \mathcal{N}_j(0)} \{C_{j,k}(0) + \phi_k\}$. If the spectrum is occupied, j will wait for an idle slot if $\min_{k \in \mathcal{N}_j(0)} \{C_{j,k}^{wait} + \phi_k\} < \min_{k \in \mathcal{N}_j(1)} \{C_{j,k}(1) + \phi_k\}$, otherwise it forwards the packet to $k^* = \arg \min_{k \in \mathcal{N}_j(1)} \{C_{j,k}(1) + \phi_k\}$.

Actually, the iteration of potential field values between SUs can be considered that has converged if convergence has reached a convergence threshold. This threshold is obtained computing the difference between old and updated potential value. Once the potential differences between actual SU potential values are around 1% it's assumed that these values have converged.

This routing algorithm is appropriate for PUs without mobility. In this project has assumed a static scenario where both PU and SUs do not change its position.

3.4. Geometric Filtering Routing - GFR

In order to get more versatility and complement previous routing algorithm, a novel routing algorithm has been proposed. Basically, it is based on a geometric multi-hop routing that each SU must know some more values than MPBR to provide this strengthening in users' mobility scenarios. Use more values does not mean that the complexity is higher. Potential values are not agreed according to the PU statistical model.

Basically, following the idea of update potential values according local links like MPBR. In this proposed routing algorithm some filters and considerations for cognitive radio paradigm are taken into account to avoid zones out of cognitive radio range.

3.4.1. Scenario GFR

Let us assume a region with a PU is located at the centre transmitting in a determined frequency band of radio frequency spectrum. It is considered that in the same region there are N randomly distributed SUs with N large enough to guarantee communications between them with a very high probability and not letting SU without connection available [13].

Each SU knows useful information to deal the packets routing.

Some values known by SU are:

- PU position
- PU Coverage Radius
- PU Safety Radius

And the other values known by SU are the same like MPBR:

- Oneself position
- PU transmitting probability
- SU neighbours with occupied spectrum ($\mathcal{N}_j(1)$)
- Position of each SU belonging $\mathcal{N}_j(1)$
- SU neighbours with idle spectrum ($\mathcal{N}_j(0)$)
- Position of each SU belonging $\mathcal{N}_j(0)$
- Potential value (depending the metric used)
- Cost to reach each neighbour (depending the metric used)
- Network parameters ($PER, \gamma_p, \gamma_s, \sigma_p^2 \dots$)
-

To tackle the algorithm, some interest areas must be defined previously called PUs areas:

- *PU Coverage Area*: circular area where PU is located in the centre. Fixed a SINR γ_p and a radius d_c any communication established with a PU receiver located inside this area will achieve a successful transmission as a general rule.
- *PU Safety Area*: this is a circular area defined to avoid PU coverage area. Radius area is defined like the largest distance of these two statements as follows: radius of PU safety area should include the 95% of SUs which have less than 10 neighbours when spectrum is occupied or $r_{safe} = d_c + 1.5r_0P(1)$. This area will allow SUs know prone-ways to route packets. Communications set by SUs in this region could produce fail transmissions with a high probability or try to work with a low density of cognitive radio links.

3.4.2. Algorithm GFR

The main idea in this algorithm consists in route packets to others SU which has the lowest possible potential value obtained without PU assumption. Next hop will be selected from a set of neighbours according to spectrum status. A filter is applied to $\mathcal{N}_j(1)$ for each SU node. This filter deletes links that guide packets towards PU coverage area. In this way, it's expected that established route will avoid situations where routing protocol can be blocked and the number of neighbours is lacking.

In order to search the best SU in terms of lowest potential value some procedures are carried out as follows:

- a) *Geometric filter*: A filter is applied in each SU $\mathcal{N}_j(1)$. This filter deletes the neighbours that head to PU Coverage area. This filter is defined using the edge of the larger PU radius defined as $\max\{PU\ Coverage\ Area, PU\ Safety\ Area\}$. The filter is performed as follows:

$$k \in \widetilde{\mathcal{N}_j(1)} \leftrightarrow \alpha_{PU,k}^j > \alpha_{PU,edge}^j \quad (17)$$

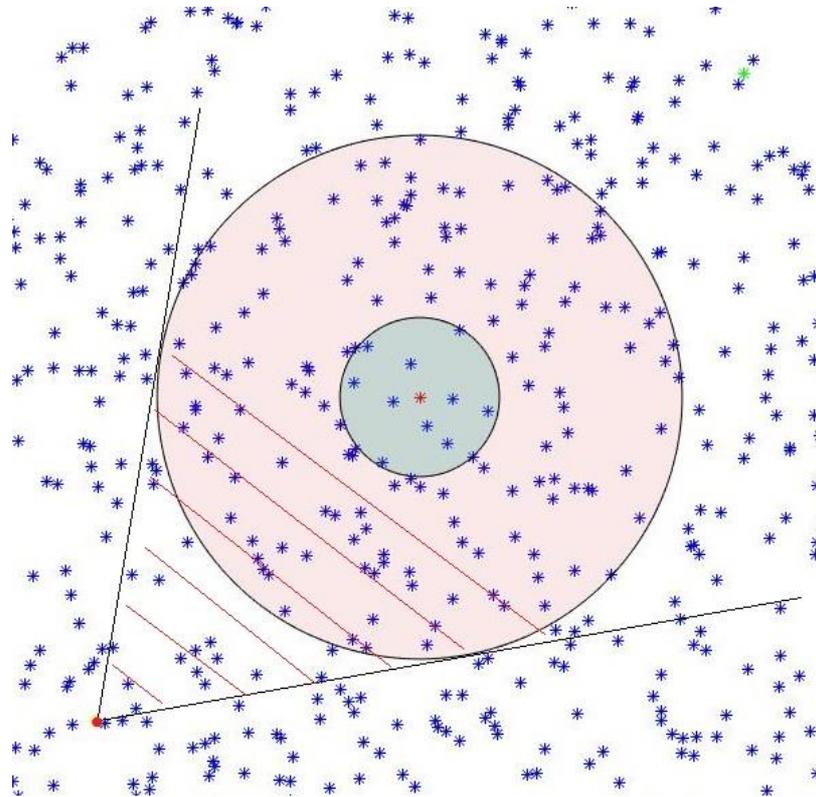


Figure 5 Geometric Filter Schematic with probability PU transmitting equal to 0.8

Where α^j is an angle calculated in SU j and $edge$ corresponds to the point which passes the tangent defined between j position and the point where tangent cuts the maximum PU Area edge. The set obtained after filter $\widehat{\mathcal{N}}_j(\overline{1})$ has neighbours of j SU with status occupied. This way will avoid links near to PU.

Besides exists the possibility that SU j could be inside PU Area. Then it's assumed that angles condition is fulfilled.

In the Figure 5, PU coverage area corresponds to the circular blue area, PU Safety area is the red one and there is represented the exclusion zone defined by tangent lines.

- b) *Communications Status*: for both sets of neighbours $\widehat{\mathcal{N}}_j(\overline{1})$ and $\mathcal{N}_j(0)$ of j has knowledge about bidirectional communications $CS_j(S)$ between all their neighbours. $CS_j(S)$ is formed by binary variables which indicate if the link establish with this SU is bidirectional or not. At the same time, it allows to know each SU which bidirectional links are available according capability and route conditions. In fact, a link without response after a Timeout will assumed as no bidirectional. It will be useful to avoid dead-ends or inability to return a packet. It can happen that j do not detect spectrum occupied and transmit to k SU which detects PU activity and have to return back the packet to j . Using this system will allow to prevent these situations.

The cost definitions SU j to SU k are the same like explained above in 3.3.2.

Once upon prior actions are done the algorithm can be run as follows:

- a. Initially all potential values are set to ∞ , except for the potential value at the final destination which is 0. SU j iterates its potential value until convergence after receiving the information about the potential value of its one-hop neighbours. Denote the old potential value of SU j after the $(t - 1)^{th}$ update as $\phi_j(t - 1)$. Then $\phi(t)$ is updated as

$$\phi_j(t) = \min\{\phi_j(t - 1); M_0(t)\} \quad (18)$$

In the rest of the thesis the converged potential values are denoted by ϕ_j . This potential values are exempted to PU movements and position changes.

- b. After the potential values have converged, SU j determines the next hop based on the sensed state of the spectrum as follows. If the spectrum is sensed idle the next hop is $k^* = \arg \min_{k \in \mathcal{N}_j(0) \cup k \in CS_j(0)} \{C_{j,k}(0) + \phi_k\}$. If the spectrum is occupied j will wait for an idle slot if $\min_{k \in \mathcal{N}_j(0) \cup k \in CS_j(0)} \{C_{j,k}^{wait} + \phi_k\} < \min_{k \in \widehat{\mathcal{N}}_j(1) \cup k \in CS_j(1)} \{C_{j,k}(1) + \phi_k\}$, but otherwise it forwards the packet to $k^* = \arg \min_{k \in \widehat{\mathcal{N}}_j(1) \cup k \in CS_j(1)} \{C_{j,k}(1) + \phi_k\}$.

Once determined the k^* , it is necessary to check if this SU belongs to the established route until actual SU is reached. If so indicate the no ability k^* in $CS_j(S)$ to set a next hop and search again a new SU to transmit according to the method explain above.

This routing algorithm is appropriate for PUs with high mobility. A hypothetical mobility will not affect potential field values. Merely, only SU filter will have to be recalculated if PU is moving.

4. Results

The proposed and studied routing algorithm in [7] (MPBR) is optimum in a Bernoulli statistical model or if the primary user is active or inactive all the time (i.e. with probability one). By optimum, we mean that it selects the route of minimum average cost. The intention of this chapter is to assess which behaviour has MPBR in a Bernoulli statistical model and compare it with the performance it has in a Markov statistical model. According to the results obtained, the designed routing algorithm GFR is assessed and it is checked in both statistical models whether GFR can beat MPBR.

As said before, the MPBR algorithm has a deep knowledge of the network and its chosen route is assumed to be statistically optimal if potential values have been converged perfectly and spectrum sensing works without error probability. On the other hand, the proposed GFR algorithm uses more network data than the MPBR algorithm and these extra data make GFR more robust and consistent to any PU movement in the interest space region.

This Figure 6 shows the scenario set out in this section. Four different routes are painted using: both algorithms and delay and energy metrics exposed previously. The blue and red circular areas corresponds to the PU Coverage area and PU Safety area respectively.

Let's take a look to the routing algorithms behaviours assuming a PU transmitting probability of 0.8 with a Bernoulli statistical model. Especially, when an idle spectrum sense is assumed by SUs.

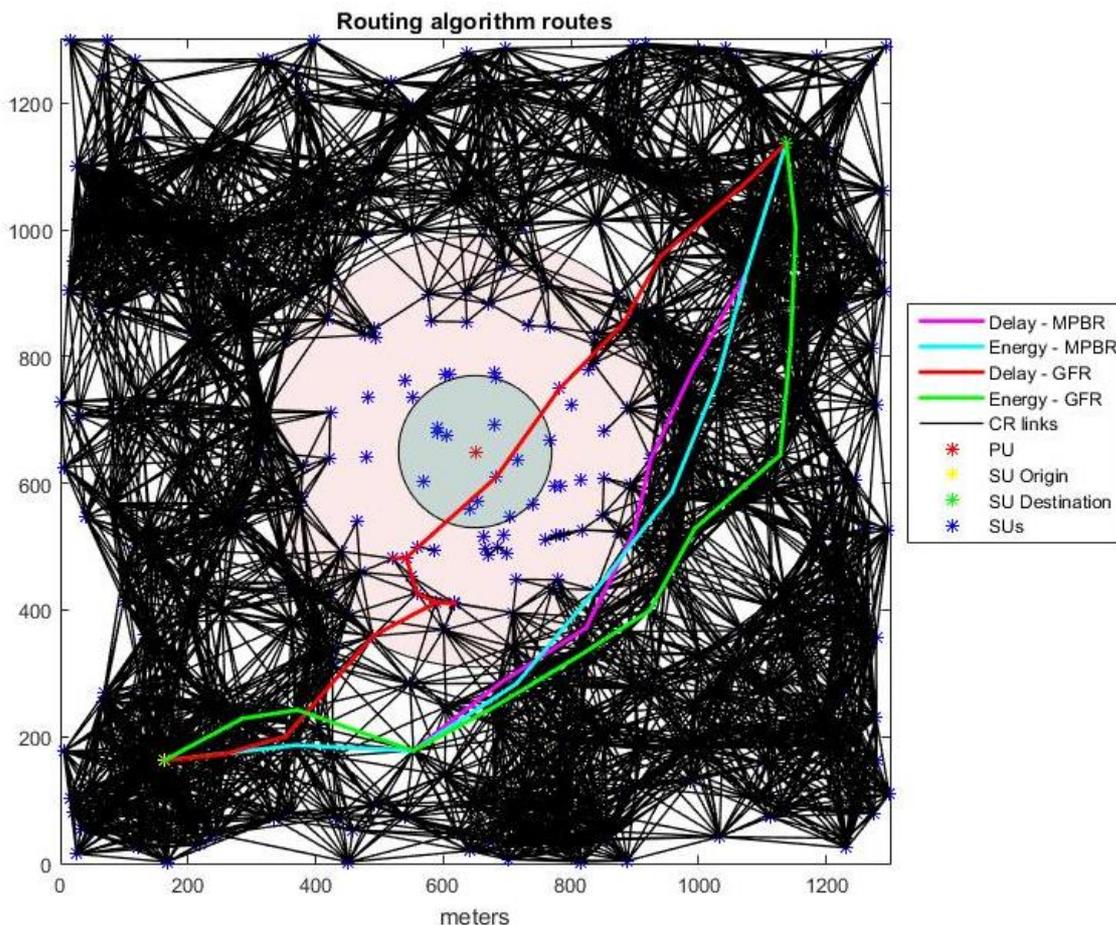


Figure 6 Routing algorithm routes example

GFR delay route, in third hop, sense the spectrum and consider that it is idle. Then, transmit to another SU which is inside the PU Safety area. Hereafter, GFR will have to transmit with the CR links available inside that and if spectrum sensing allows it. Otherwise, GFR energy route starts transmitting with the spectrum occupied. After some hops, GFR has avoid the most conflict region (the case when SU destination is behind the PU areas). The MPBR in this figure seems to work quite good in both metrics.

4.1. Coding scheme

To assess the implemented and designed algorithms, a coding scheme based on digital modulations should be defined.

Each packet it is assumed to be composed of 133 bytes like the frame length of ZigBee and WSN protocol (IEEE 802.15.4)[14] and with a baud rate of about 1Mbaud.

The modulation chosen is QPSK and the error correcting code is a LDPC code of code rate 0.5.

According to this packet size, the duration of time slots is set to:

$$T_{slot} = 1.1 \frac{\text{bits packet}}{\text{bitrate}} \quad (199)$$

The penalty factor 1.1 corresponds to an increase of time slot to sense the spectrum and know PU activity status.

Bitrate after coding stage and modulator process is computed as follows:

$$\text{bitrate} = R_b = bR_cR_s \quad (20)$$

In which b means the number of bits represented in just one symbol. In the case of QPSK modulation, $b = 2$.

The system bandwidth can be computed using the following formula:

$$BW = R_s(1 + \alpha) = \frac{R_b}{bR_c}(1 + \alpha) \quad (21)$$

Parameter α is the roll-off factor of transmitted pulses, which is set to 0 for simplicity. In this way, in the studied set-up, the bitrate and bandwidth are considered to be equal.

The coding system chosen for transmit information is based in LDPC-codes. From tables that emulate a relation between PER and SINR of LDPC-codes, an accurate PER vs SINR have been used to simulate the different scenarios, previously presented.

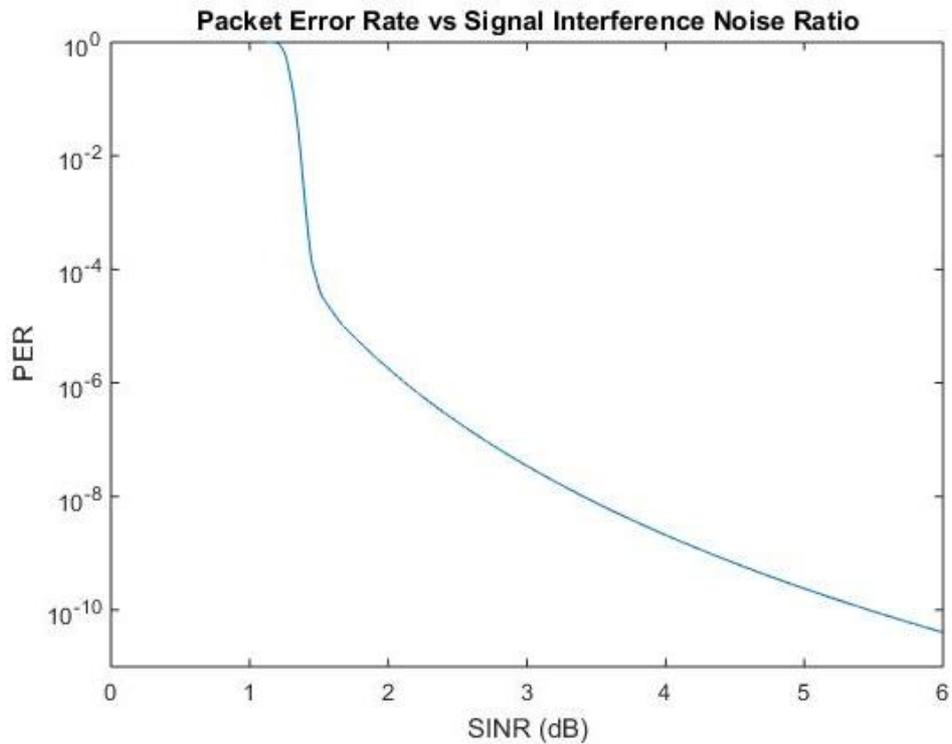


Figure 7 Packet Error Rate vs Signal Interference Noise Rate using LDPC-codes

To sum up all the values presented before, we have included the following table:

Coding Scheme Parameters	
R_s	1Mbauds
b	2
R_c	0.5
R_b	1 Mbps
Frame length (N_{bits})	1064 bits
Bandwidth	1 MHz
T_{slot}	1.064 ms

Table 3 Coding Scheme parameters used for simulate different scenarios

4.2. Metric Settings

Routing algorithms exposed above are based on forwarding packets according to potential values that are calculated using different metrics for particular statistical models. It has been selected two kinds of metrics: delay and energy. These metrics will be used in the two routing algorithms previously presented: MPBR and GFR.

The following metric expressions in 1.2.1 and 1.2.2 define the whole cost, in terms of the adopted metric, of transmitting a packet from a SU transmitter to a neighbouring SU receiver. These expressions assume that both SUs are neighbours or, additionally, $CS_j(S)$ should be available.

One important factor that will appear recurrently is the number of retransmissions N_{rtx} . According to the PER (packet error rate), which provides the fraction of incorrectly decoded packets and is assumed to be 0.01, we can compute the average number of retransmissions as follows:

$$N_{rtx} = \sum_{n=0}^{\infty} n(1 - PER)PER^{n-1} = \frac{1}{1 - PER} \quad (20)$$

4.2.1. Delay Metric Setting

In order to route packets making use of the studied algorithms, a delay metric has been developed. This metric contemplates three situations:

- 1) PU is transmitting (an information that is obtained after sensing the spectrum and observing that the primary is active). In that case, the delay of transmitting the packet from node j to node k is given by:

$$C_{j,k}(1) = N_{rtx} \left(T_{proc,j} + \frac{d_{j,k}(1)}{c} + T_{slot} + T_{queue,k} + T_{proc,k} \right) + T_{route,k} \quad (213)$$

- 2) PU has an idle status. In that case, we have the same expression for the delay but the set of neighbours of node j has changed and the transmitted power of node j will be higher than in case 1.

$$C_{j,k}(0) = N_{rtx} \left(T_{proc,j} + \frac{d_{j,k}(0)}{c} + T_{slot} + T_{queue,k} + T_{proc,k} \right) + T_{route,k} \quad (224)$$

- 3) Finally, if the primary is transmitting, we can decide not to transmit immediately but waiting some time slots until the primary stops to transmit. In that case, the delay will be as follows:

$$C_{j,k}^{wait} = C_{j,k}(0) + \mu T_{slot} \quad (235)$$

These expressions above are composed of different terms. The delay of reading and decoding a packet is T_{proc} . The time spent in the buffer before the packet is processed is T_{queue} . The required time to know which is the best option to route packets is T_{route} (delay of the routing algorithm) and c is the speed of light.

According to CC2420 specifications [15], T_{proc} is 3 μ s and PER is considered to be 0.01.

To simplify the analysis, $T_{route,k}$ is assumed to be negligible. In this project the simulations are done considering single simultaneous SU transmissions, that is, only one SU transmits simultaneously. So, we are implicitly considering that the SU network is hardly congested. Consequently, $T_{queue,k}$ is disregarded for simplicity. The rest of values are assumed to be known by secondary users and they are listed in the following table:

Delay Metric Parameters	
PER	0.01
N_{rtx}	1.0101
T_{slot}	1.064 ms
T_{proc}	3 μ s
c	$3 \cdot 10^8$ m/s

Table 4 Delay Metric Parameters used for simulate different scenarios

4.2.2. Energy Metric Setting

The energy metric setting is particularized like in the delay case: three situations in which the metric value will be different.

- 1) PU is transmitting. The energy cost is computed as:

$$\begin{aligned}
 C_{j,k}(1) &= N_{rtx}(E_{sens} + E_{T0} + E_{paq} + E_{R0}) \\
 &= N_{rtx} \left(\frac{0.1}{1.1} P_{sens,j} T_{slot} + \frac{1}{1.1} P_{T0} T_{slot} + E_b^{tx}(1) N_{bits} + P_{R0} T_{slot} \right)
 \end{aligned} \tag{246}$$

- 2) PU is idle. In that case, the expression is identical to the previous one but the energy per bit is not limited by the maximum tolerated interference on the PU receivers and, at the same time, the set of neighbours changes:

$$\begin{aligned}
 C_{j,k}(0) &= N_{rtx}(E_{sens} + E_{T0} + E_{paq} + E_{R0}) \\
 &= N_{rtx} \left(\frac{0.1}{1.1} P_{sens,j} T_{slot} + \frac{1}{1.1} P_{T0} T_{slot} + E_b^{tx}(0) N_{bits} + P_{R0} T_{slot} \right)
 \end{aligned} \tag{257}$$

- 3) A waiting scenario is also taken into account. This happens when the SU senses the spectrum and it observes that is occupied and decide to remain idle. After time slot finishes, SU wakes up and follows the same strategy until PU is idle. The energy cost is calculated as follows:

$$C_{j,k}^{wait} = C_{j,k}(0) + \mu T_{slot} \left(\frac{0.1}{1.1} P_{sens,j} + \frac{1}{1.1} P_{idle} \right) \tag{268}$$

When a transmitter wants to forward packets, a part of time slot is dedicated to sense spectrum if there is PU presence. According to the scenario contemplated, exists different

factors which are part of the metric cost expressions exposed above. These factors are explained as follows: sensing power is set to be P_{sens} , baseband digital signal processing circuit and Tx and Rx circuits consumes power called P_{T0} and P_{R0} respectively. In the case of waiting until next time slot the SU transmitter will remain in idle status consuming P_{idle} . Finally, the energy per bit that is transmitted is defined as E_b^{tx} , where this energy is determined based on the available power at the transmitter, the intended PER at the receiver (which determines the required SINR γ_s), the interference generated by the PU when it is transmitting I_k , the sensibility of the receiver σ_k^2 and the target bit rate R_b (throughput). So, energy per bit should ensure that not exceed the SU maximum transmit power. On the contrary, the link will not have reliability.

$$E_b^{tx} = \frac{\gamma_s(I_k + \sigma_k^2)}{\eta PL(d_{j,k})R_b} \quad (279)$$

Fixing the communications PER rate, SINR γ_s is obtained from the PER curve (see Figure7). We have also considered in the energy per bit expression the power amplifier drain efficiency by means of parameter η . This is a factor to take into account when transmitter power is not high (about a few mW).

Power values selected come from an analysis of energy-aware consumption in wireless sensor networks [10, 11].

Power Consumption Parameters	
$P_{SU,max}^{tran}$	0 dBm
P_{sens}	22.2 mW
P_{T0}	26.5 mW
P_{R0}	59.1 mW
P_{idle}	22.06 mW
η	3.7%

Table 5 Power Consumption parameters used for simulate different scenarios

4.3. MPBR Assessment

In order to evaluate the routing algorithm proposed in [7], the following parameters characterize the assessed scenario:

- 500 secondary users that are deployed randomly
- Region of 1300 m²
- PU coverage radius of 120m
- SU coverage radius of 182m
- SU sensibility σ_s^2 of -95dBm [15]
- PU sensibility σ_p^2 of -90dBm [7]

- SINR γ_p of 10 dB
- PER equal to 0.01
- SU origin transmitter and SU destination receiver placed at the opposite ends of the simulated area.
- PU transmitter placed in the centre of the simulated area.

4.3.1. MPBR Bernoulli scenario

With a Bernoulli statistical model for the PU transmitter, delay and energy metrics have been simulated. The results for each probability have been averaged over 500 realizations.

Next figures illustrate the cost until the packet transmitted by SU origin reach the SU destination. The simulated costs are two: delay and energy. In x-axis shows the PU transmitting probability and the y-axis the total cost according to the selected metric. The purpose is observe and assess which effect has the PU transmitting probability to the total cost when this probability is increased.

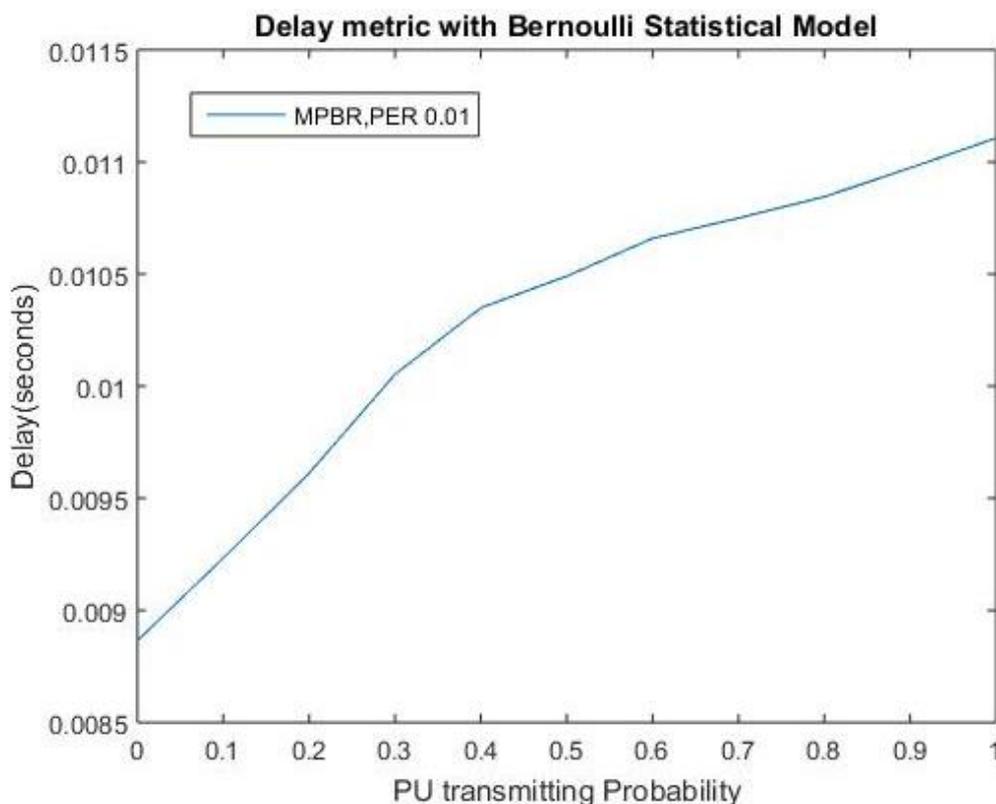


Figure 8 Delay metric results with Bernoulli Statistical Model

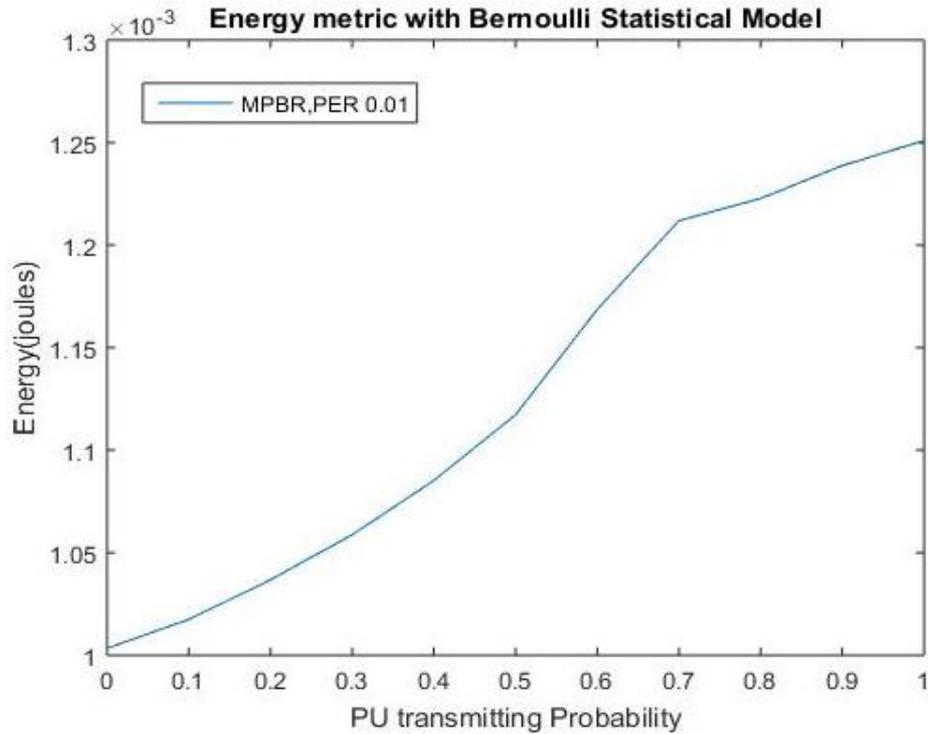


Figure 9 Energy metric results with Bernoulli Statistical Model

In both metrics as the probability of PU transmitting is increased the delay cost too. For high values of the PU probability, packets are not routed through the PU coverage area but they are deviated in order to avoid this forbidden area, resulting in an increase of spent time slots and hops until the destination is reached. For low levels of PU activity, these results seem that wait cases have been produced because the Bernoulli coherence time (2) is quite low (around $\mu_0 = [1.11-1.67]$ for $p = [0.1 - 0.4]$ respectively).

4.3.2. MPBR Markov scenario

For evaluate MPBR with a Markov statistical model of PU activity, different Markov coherence times have been simulated in order to observe if the coherence time is related directly with the total cost in function of the PU transmitting probability. In x-axis of next figures, there are the simulated coherence times and in y-axis the total cost according to the metric used (delay or energy). On the one hand, the coherences times simulated are $\mu_{10} = [1,2,3,4,5,7,9,11]$. These times are not larger because the final destination is reached in 11 times slots approximately. It makes no sense to simulate larger times because then, the spectrum status sensed at the starting SU will keep in most realizations the same until routing finishes. On the other hand, in the Markov model, the coherence time can be changed but for a fixed PU transmitting probability. So, three different probabilities ($P(1) = [0.2,0.5,0.8]$) have been simulated in order to see which behaviour has MPBR as probability and coherence time change. So, these figures show the average costs until the destination is reached.

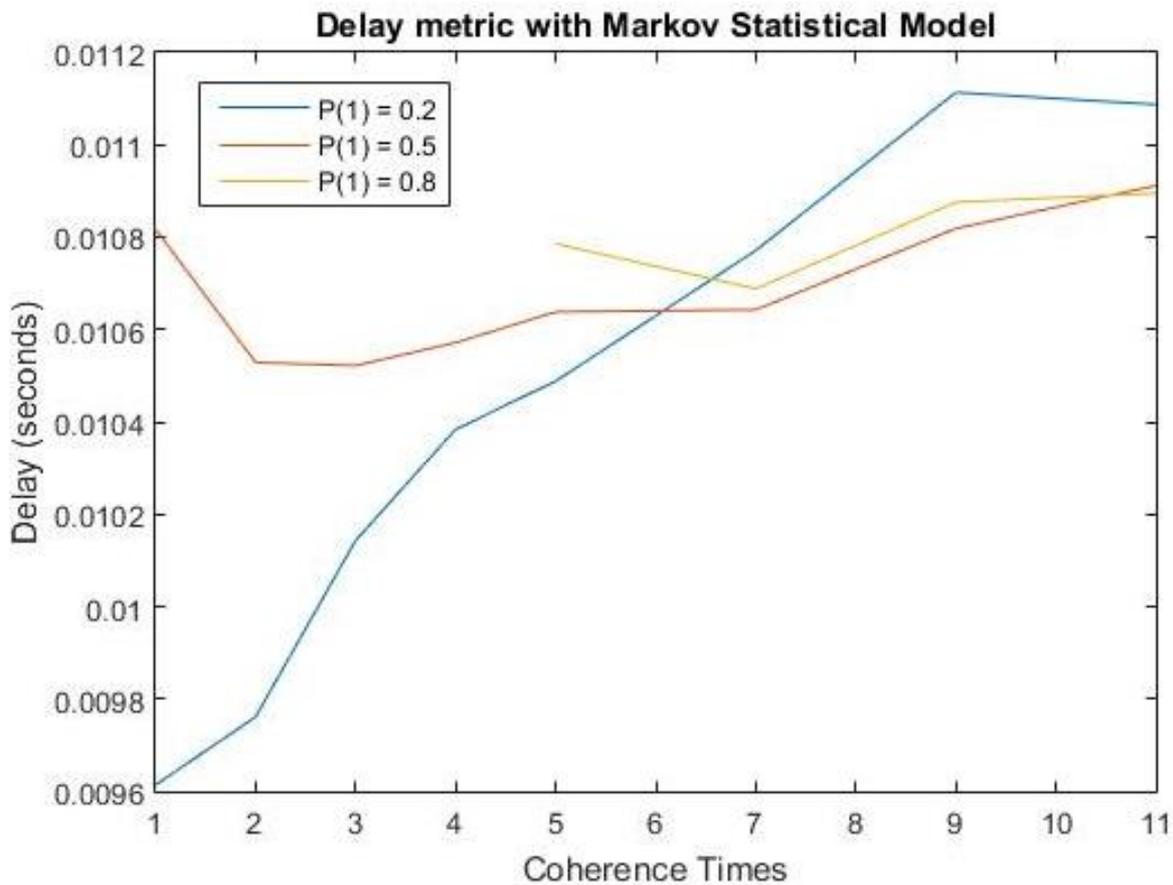


Figure 10 Delay metric with Markov Statistical Model assuming different PU transmitting probabilities

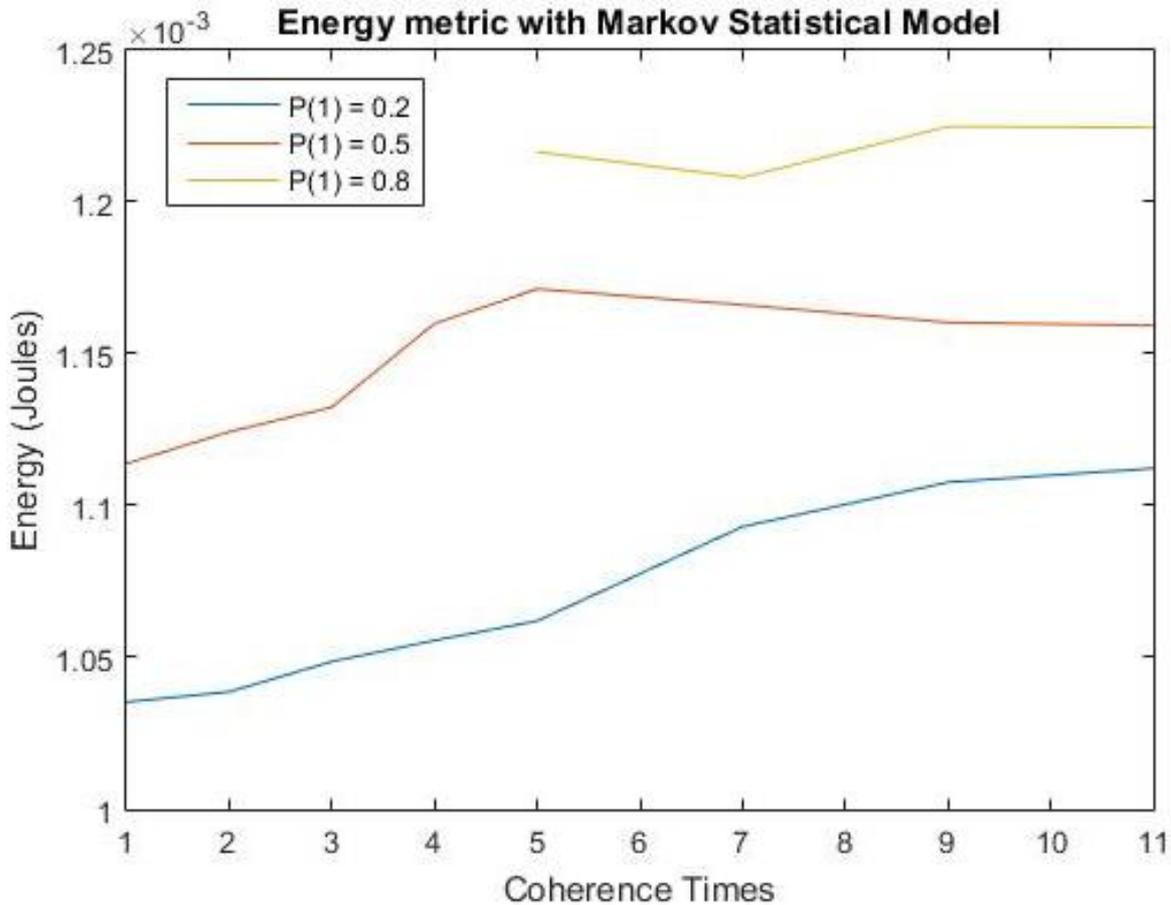


Figure 11 Energy metric with Markov Statistical Model assuming different PU transmitting probabilities

I would like to emphasise that Markov statistical model results are just assessed for coherence times larger than 5 with PU transmitting probability of 0.8. This is because the bound exposed in (6) has been taken into account in order to not simulate impossible transition probabilities in the Markov state diagram.

The results in Figure 9 are interesting to be analysed. On the one hand, as coherence time is increased, the delay cost to route across the cognitive radio network increases too. MPBR knows that T^{wait} is higher and consequently turns around PU Coverage area. On the other hand, as coherence time is increased MPBR seems to work better for higher PU transmitting probabilities. However, it is necessary to remember that the simulations are quite noisy and this could not be absolutely certain.

In Figure 10, as the primary probability grows the energy cost too. In fact, it was the expected situation because larger routes are used. What it was not expected was the improvement in delay results with higher coherence times.

I would like to emphasize that results presents quite variance and thus, more realizations could be done to improve the average results.

4.4. GFR Assessment

Once the performance of MPBR has been simulated in different statistical models, let us simulate GFR to see if it is able to beat MPBR in some cases. Before, it is reasonable to think that GFR will not be able to decrease the routing cost in case of the Bernoulli statistical model because MPBR is optimal in this model. However, it could be possible to observe an advantage in case of the Markov model because higher coherence times would produce a detour to the PU coverage area (higher waiting times) which GFR is non-sensitive in this sense. When an idle spectrum will be sensed, GFR will route forward the packet inside PU areas.

MPBR routes packets on average assuming that PU has an intermittent statistical model until the destination is reached. If higher coherence times are simulated in comparison to the number of hops in the selected route, then, MPBR will not choose the optimal route which belongs to $P(1) = 0$ or $P(1) = 0$ respectively.

The assumed scenario is exactly the same like used in MPBR Assessment 4.3.

4.4.1. GFR Bernoulli Scenario

With a Bernoulli statistical model, the scenario has been simulated again and now both routing algorithms can be compared.

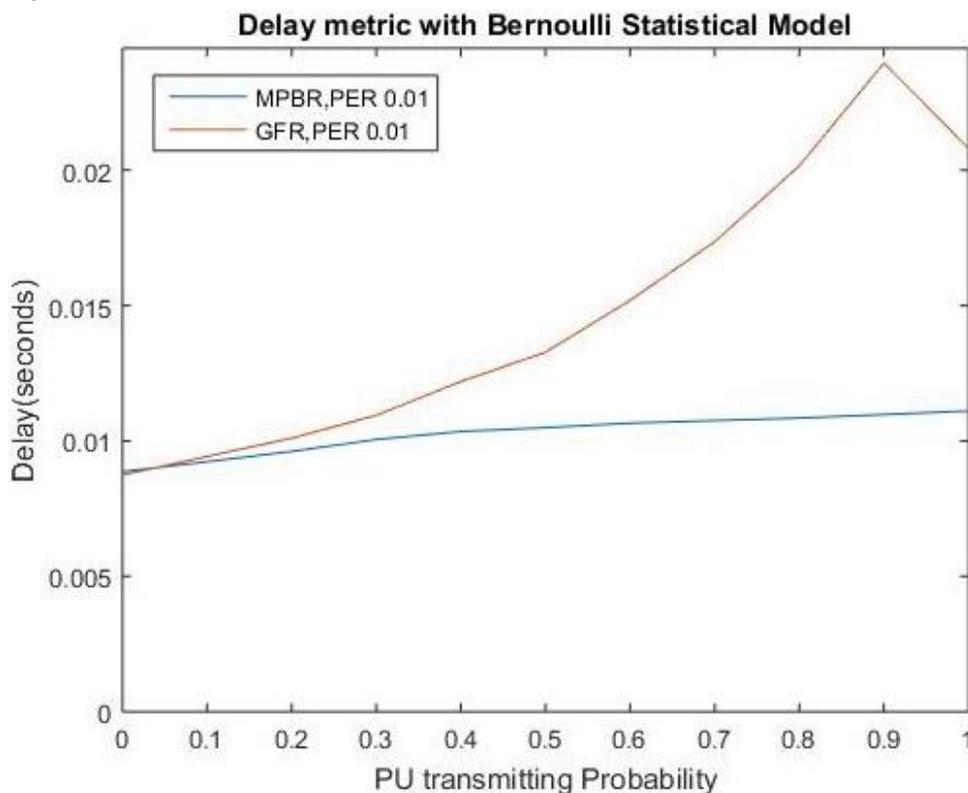


Figure 12 Comparison Delay metric results with Bernoulli Statistical Model

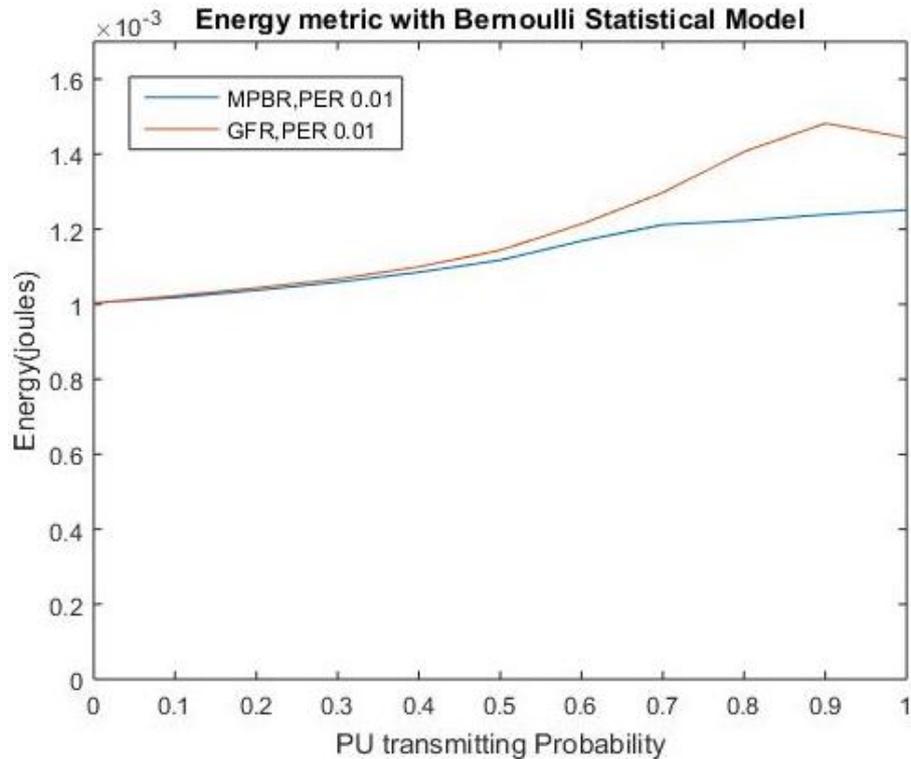


Figure 13 Comparison Energy metric results with Bernoulli Statistical Model

It can be observed that for low probabilities the performance is quite similar, being the GRF algorithm a little worse, especially for the delay metric. As the primary probability is increased the routing cost gets worse faster. The reason is the GFR routing strategy. When an idle spectrum is sensed, GFR route packet entering into the PU coverage area. Within the coverage area, the number of neighbours decrease and consequently the number of possible routes too. Moreover, as PU transmitting probability is higher, the presence of a packet inside these areas cause an erratic behaviour until the packet can be route forward. It leads automatically to an increase of the used metric.

With PU transmitting probability of 1 the delay cost of GFR is lower than the one with probability 0.9. This is because the packets are not route thorough PUs areas and are deviated in order to avoid the forbidden area.

4.4.2. GFR Markov Scenario

It has been done a simulation for GFR and MPBR in a Markov scenario (the primary activity follows a Markov model). Therefore, some conclusions can be drawn when comparing the performance of the two routing algorithms.

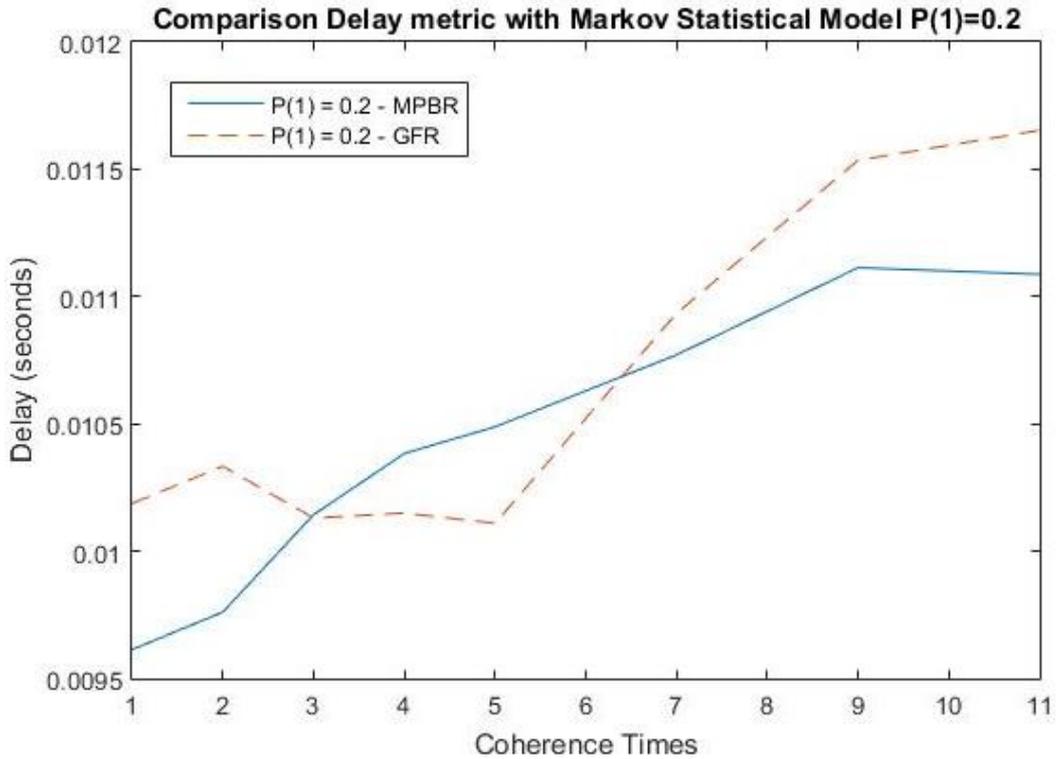


Figure 14 Comparison Delay metric with Markov Statistical Model assuming $P(1) = 0.2$

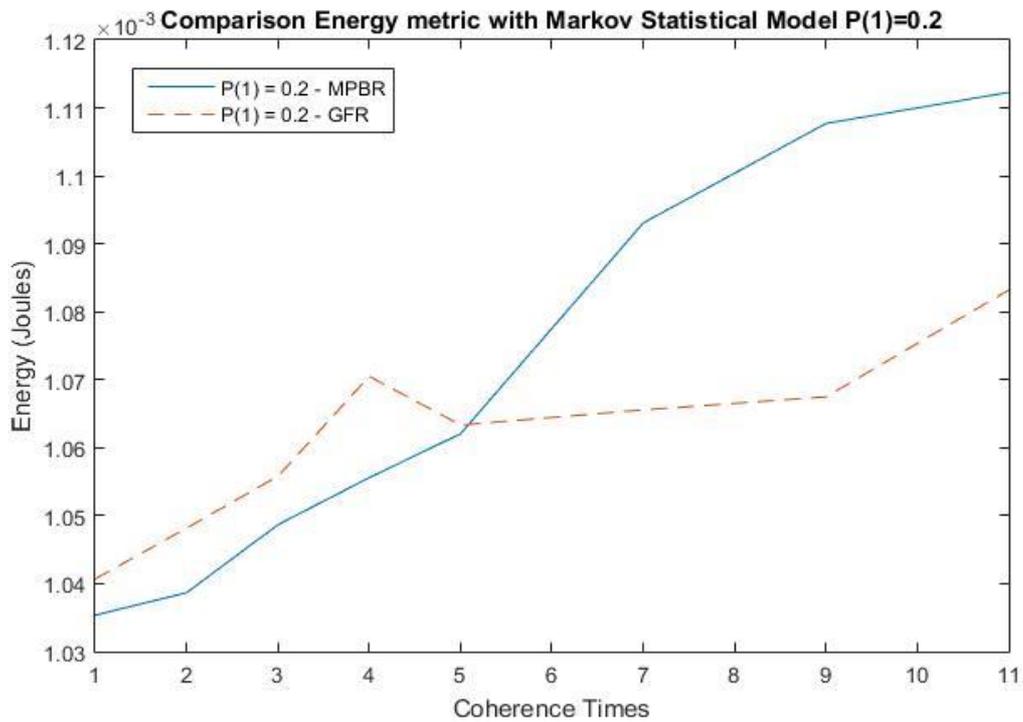


Figure 15 Comparison Energy metric with Markov Statistical Model assuming $P(1) = 0.2$

The delay cost is evaluated under different coherence times. In Figure 13, it is observed that GFR can take advantage of the PU activity coherence time. MPBR considers that an increase of waiting time has to cause a modification on the chosen route deviating packets around PU location. GFR is not sensitive to the waiting time since it always prefers to forward the packet to the destination. So, when GFR sense an idle status it goes through PU areas, near the PU location. If the SU responsible to forward the packet is near PU, has the advantage that idle status will remain a number of time slots with the same status (in average) according to coherence time μ_{01} . Alternatively, when MPBR senses an idle status will use the set of neighbours $\mathcal{N}_j(0)$ to route the packet but, closer SUs to PU will have higher potentials due to coherence time μ_{01} (wait time). Hence, MPBR will route packets to further SUs than closer SUs regarding to PU location. It leads to route packets in larger routes and causing higher total costs. So, that is why GFR can beat MPBR in terms of the delay metric for some coherence times. However, for longer times, GFR lose this capability and MPBR returns to be better than GFR GRF has higher total costs under a Markov statistical model with high coherence times because any forward packet inside PU areas and the PU status changes suddenly, will remains many more time slots without capability to continue the packet routing.

In Figure 14, a similar behaviour occurs. Delay metric is more restrictive to time penalizations than energy metric. For small values of the coherence time MPBR does not modify its route and GFR can not beat MPBR using energy metric. On the contrary, with higher coherence times, the improvement appears with more clearly than delay case but these coherence times must be higher than 7 time slots.

To sum it up, GFR has the capability to beat MPBR depending on the adopted metric and on the statistics of the primary user activity. This improvement could allow to transmit larger packets in the SU network according to the coherence time of the PU activity.

Let us now study what happens when the PU transmitting probability is increased.

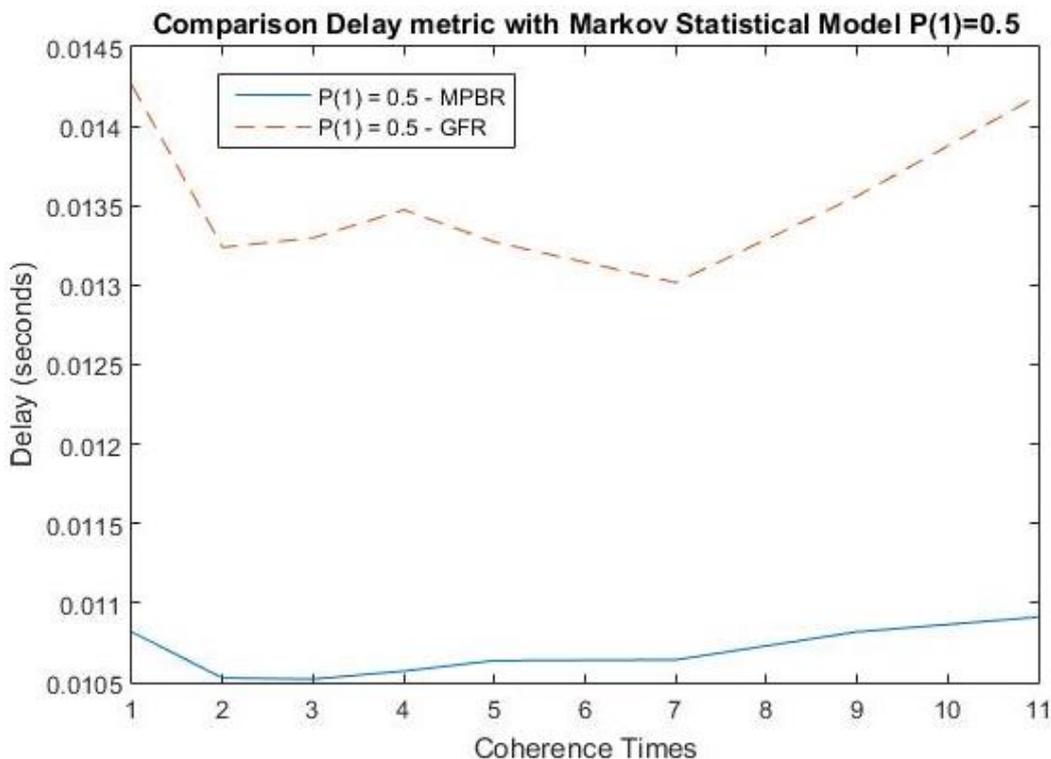


Figure 16 Comparison Delay metric with Markov Statistical Model assuming $P(1) = 0.5$

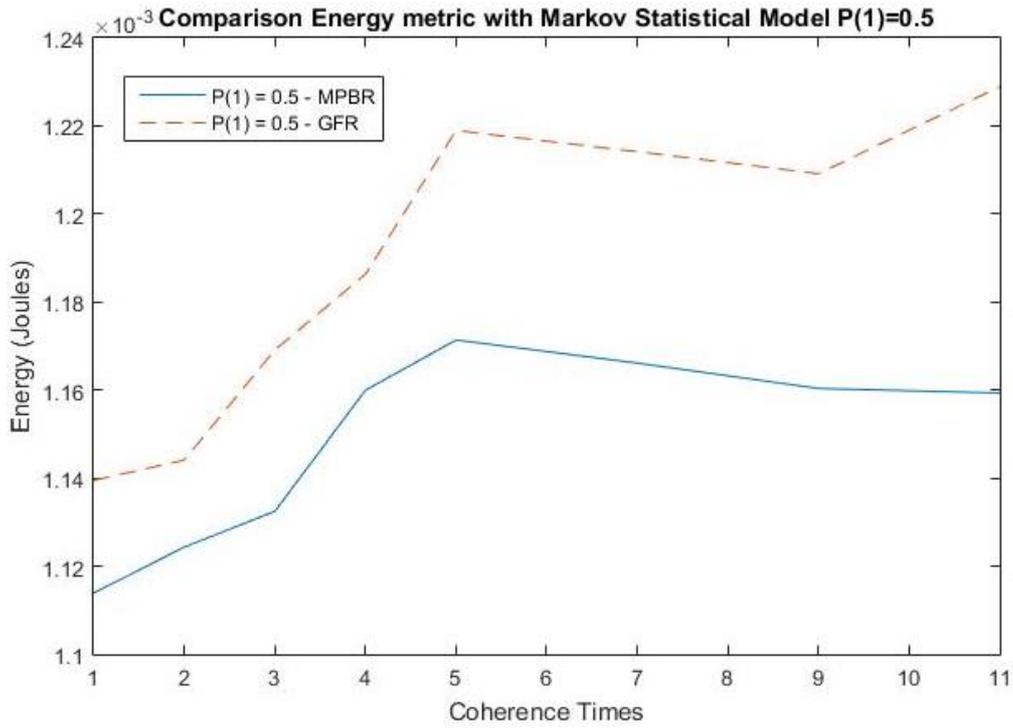


Figure 17 Comparison Energy metric with Markov Statistical Model assuming $P(1) = 0.5$

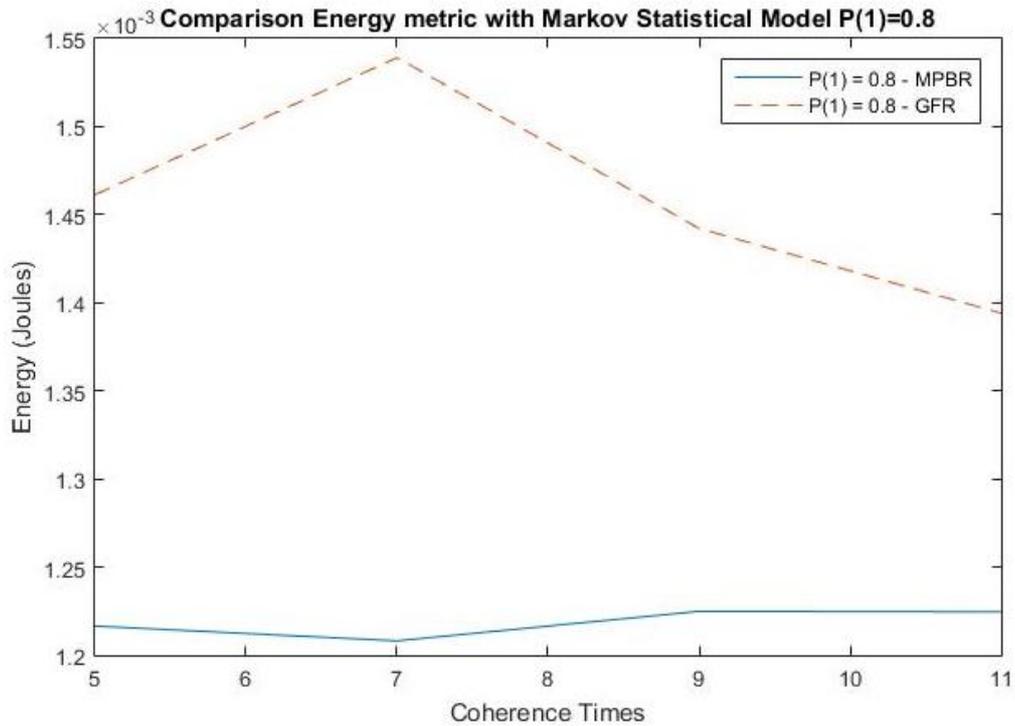


Figure 18 Comparison Delay metric with Markov Statistical Model assuming $P(1) = 0.8$

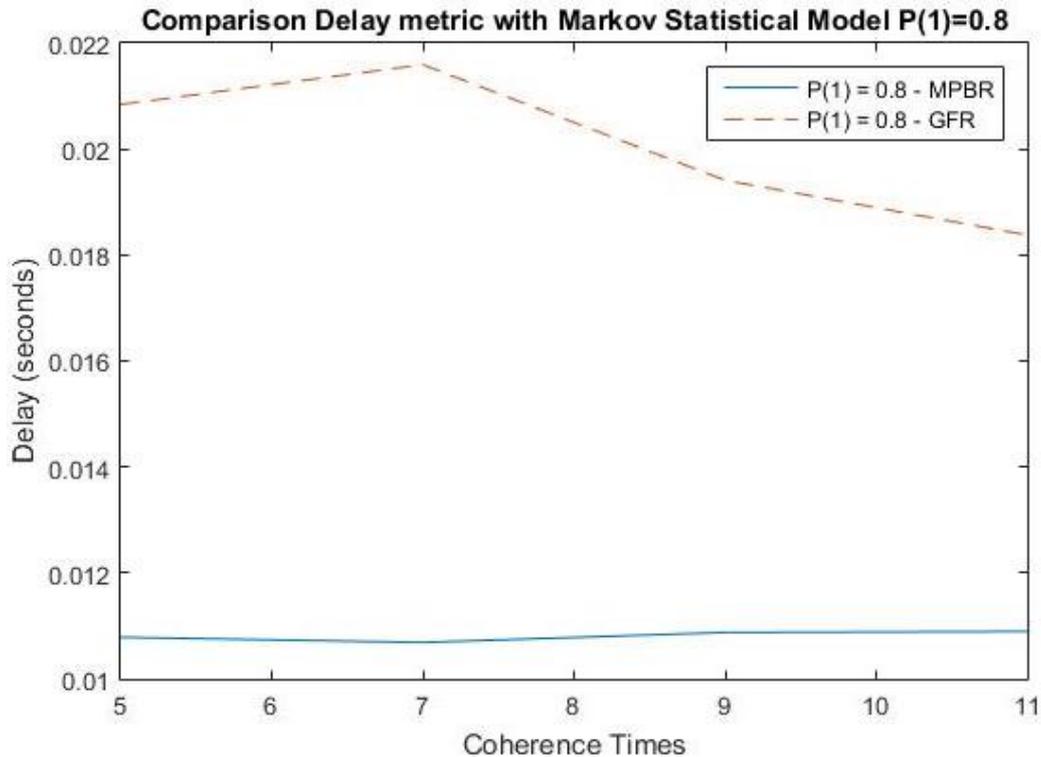


Figure 19 Comparison Energy metric with Markov Statistical Model assuming $P(1) = 0.8$

As PU transmitting probability is increased, there is no improvement of the GFR algorithm anymore. In Figure 15, the delay cost is quite higher with GFR than the cost in MPBR. The same happens with a probability of 0.8 in Figure 17.

For the energy metric, it occurs the same deterioration of total cost as with the delay metric. However, in Figure 16 (i.e. $P(1)=0.5$), the energy cost, as the coherence time grows, the total cost loss is not as high as happens in Figure 18 (i.e. $P(1) = 0.8$). This similarity points to consider that the improvement of GFR with respect to MPBR could be produced for some higher probabilities than $P(1) = 0.2$ but not exceeding $P(1) = 0.5$ (they are not just simulated). This improvement of GRF between MPBR can also be considered for higher probabilities than $P(1)=0.5$ but with an enhancement of GFR scheme or at the same time, use more suitable metric costs. As a last comparison, for a PU transmitting probability of 0.8 (Fig. 18), the energy cost shoots up regarding to GFR and there is not any improvement observed.

5. Budget

The budget of this thesis has consisted basically in the elaboration of a simulator in MATLAB becoming the backbone of the project. Consequently, the entire budget collects all those things that can produce a charge as following: the license of MATLAB software and wages for human work which has spent time in preparing, developing and concluding the thesis mentioned.

Task	Weeks	Hours	Cost per hour (€)	Cost (€)
<i>Planning & State of The Art Researches</i>	4	60	12	720
<i>Analysis the thesis simulator</i>	2	30	12	360
<i>Programming the simulator</i>	15.5	232.5	12	2790
<i>Simulation & Results</i>	5.75	86.25	12	1035
<i>Degree Thesis Redaction</i>	6.75	101.25	12	1215
<i>Software License</i>	-	-	-	2000
TOTAL				8120

Table 6 Degree Thesis Budget

6. Conclusions and future development:

Cognitive radio is one of the hot topics in the field of wireless communications which in the next years we will hear to talk about. The demand of low latency, the increase of devices and the apparition of new services leads to the saturation of the spectrum due to an increment of devices' activity and wider bandwidths. Cognitive Radio tries to solve this allowing more devices to operate in the same frequency band but without decreasing the quality of service of the present ones. Some novel strategies are required to route the information across the cognitive radio network. In this project, a few of them have been explored. There already exist novel routing algorithms but always under the assumption of minimizing some routing metrics. In this degree thesis I just explored an existing routing scheme and a new one proposed by myself which has as a purpose to beat the first one. The proposed algorithm is not tied to the present PU statistical model. This is an advantage because it can be used under any PU model and be robust to hypothetical PU movements just knowing the PU location. In fact, the routing scheme developed in [7] uses a PU activity that follows a Bernoulli distribution but without knowing the PU position. Our intention is to doubt this statistical model and to simulate the two routing algorithms under a Markov statistical model, which is more realistic when the packets lengths of PU network are larger than the time slots of SU network. In this way, SUs could take this model as an advantage and transmit using variable packet lengths (more than one time slot depending on coherence times) instead of one packet for each time slot.

On the whole, it can be concluded that with a Bernoulli statistical model MPBR algorithm is optimum and GFR has a similar performance for low PU transmitting probabilities. MPBR was designed to be used under the Bernoulli model and, when PU activity model is changed, its behaviour is not anymore as good as with the Bernoulli model. On the other hand, GFR is a versatile routing algorithm that can be applied to any statistical model on the primary network activity. This is why GFR has the capability to beat MPBR in some Markov scenarios. For PU transmitting probabilities of 0.2, GFR is able to route a packet towards the final destination with less metric cost than MPBR. In delay metric scenario, it is produced by $\mu_{10} = [3 - 5]$ and $\mu_{10} = [7 - 11]$ for energy case. For the others two probabilities assessed, there is not possibility of enhancement. Additionally, the probabilities between 0 and 0.5 could present some cases where the GFR cost would be fewer. At the same time, MPBR is an algorithm which works rather well in all the simulated scenarios but some reconsiderations like a statistical update of potential values taking into account transition probabilities and coherence times, could be done in order to enhance its performance in case the Markov statistical model is considered. This could be one of the potential future developments to improve this routing algorithm.

Finally, GFR could be also considered for a future development looking for reach better metric settings and reducing its high routing cost in case of high PU transmitting probabilities. Then, a reassessment of Markov scenarios could show better performance for higher probabilities.

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Glossary

SU: Secondary User

PU: Primary User

QoS: Quality-of-Service

WSN: Wireless Sensors Network

CRN: Cognitive Radio Network

CR: Cognitive Radio

SINR: Signal Interference Noise Rate

PER: Packet Error Rate

RF: Radio Frequency

CSMA/CA: Carrier sense multiple access with collision avoidance

MPBR: Minimal Potential Based Routing

GFR: Geometric Filtering Routing

LDPC: Low Density Parity Check

QPSK: Quadrature Phase-Shift Keying