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BATTERY-AWARE PROBABILISTIC ACCESS SCHEME WITH NATURE AND RF ENERGY HARVESTING FOR COGNITIVE RADIO NETWORKS

A Degree Thesis

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by

Francesc Molina Oliveras

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Advisor: N. Javier Villares Piera

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Abstract

In this work, a short-range unlicensed link intends to coexist with a directional-nodes licensed network, deployed as a 2D Homogeneous Poisson Point Process. The unlicensed transmitter uses two energy harvesting mechanisms and implements a probabilistic scheme in order to access the channel according to the available energy in its battery. The aim of this work is to optimize the throughput of the proposed cognitive radio link, employing linear programming methods, provided that the licensed network QoS constraint is satisfied.

It is demonstrated the effectiveness of the mixed energy harvesting scheme for energy-restricted scenarios, and it is tested as well in which scenarios the energy detection would be useful, considering different packet length cases. It is also considered non-energy restricted scenarios in which is demonstrated that a Vehicle-To-Vehicle link can coexist with a wireless network.

Resum

En aquest treball, un enllaç de curta distancia sense llicència intenta coexistir amb una xarxa de nodes direccionals llicenciada, desplegada com una xarxa de Poisson homogènia 2D. El transmissor sense llicència utilitza dues tècniques de recol·lecció d'energia i implementa un esquema probabilístic d'accés al canal d'acord amb l'energia disponible a la seva bateria. L'objectiu d'aquest treball és optimitzar el *throughput* de l'enllaç cognitiu, a través de mètodes de programació lineal, garantint que la restricció de QoS imposada per la xarxa llicenciada sigui satisfeta.

Es demostra l'efectivitat de l'esquema mixt de recol·lecció d'energia per a escenaris limitats per l'energia de la bateria i es prova també en quins escenaris la detecció d'energia té sentit, considerant serveis amb paquets de diferents longituds. A més a més, es consideren escenaris no limitats per l'energia de la bateria, on es demostra que un enllaç V2V pot coexistir amb una xarxa sense cables.

Resumen

En éste trabajo, un enlace de corta distancia sin licencia intenta coexistir con una red de nodos direccionales licenciada, desplegada como una red de Poisson homogénea 2D. El transmisor sin licencia utiliza dos técnicas de recolección de energía e implementa un esquema probabilístico de acceso al canal de acuerdo con la energía disponible en su batería. El objetivo de este trabajo es optimizar el *throughput* del enlace cognitivo, a través de métodos de programación lineal, cumpliendo con la restricción de QoS impuesta por la red licenciada.

Se demuestra la efectividad del esquema mixto de recolección de energía para escenarios limitados por la energía de la batería y se prueba también en que escenarios la detección de energía tiene sentido, considerando servicios con paquetes de diferente longitud. Además, se consideran escenarios no limitados por la energía de la batería, donde se demuestra que un enlace V2V puede coexistir con una red inalámbrica.

To my parents.

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- To Javier Villares, for the help and interest expressed during the course of the work. Furthermore, I wish to express my most sincere gratitude and appreciation to him for the motivation and help provided in some critical moments.

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0	25/06/2015	Document creation
1	28/06/2015	Introduction and environmental impact
2	04/06/2015	State of art of the technology used or applied in this thesis
3	05/06/2015	Project Development
4	06/06/2015	Project Development
5	06/06/2015	Annexes 1 and 2
5	07/06/2015	Results
6	07/06/2015	Conclusions and future development
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Name	e-mail
Francesc Molina Oliveras	franmolina93@hotmail.com
N. Javier Villares Piera	javier.villares@upc.edu

Written by:		Reviewed and approved by:	
Date	08/07/2015	Date	09/07/2015
Name	Francesc Molina Oliveras	Name	N. Javier Villares Piera
Position	Project Author	Position	Project Supervisor

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1. Introduction

This chapter is organized as follows. In section 1.1, the objectives of the work are presented. In section 1.2 there are stated the requirements and specifications regarding the software and the considered scenario. In section 1.3, is given the work plan as well as the Gantt diagram, which shows the temporal planning of the project. Finally, the main deviation and incidences occurred during the project regarding the initial planning are shown in section 1.4.

1.1. Statement of purpose

The aim of this work is to analyse and optimise the performance of an interesting cognitive radio scenario. The goal is to maximize the throughput of the secondary link provided that the primary network QoS and the secondary nodes finite energy-harvesting constraints are satisfied.

This project consists in the improvement of Ali, R.E and collaborators' work [8]. An extended primary network with multiple randomly deployed directive nodes is considered, which accesses the channel using a slotted-time technique. The secondary transmitters perform a mixed nature and RF energy-driven probabilistic scheme to access the channel, that is, in function of the available energy in its battery they performs with certain probability one of the following operations: channel sensing, access without sensing the channel, in order to save energy, or remain idle.

As far as the environment is concerned, the considered scenario is subject to a Rice fading channel and a path loss propagation model with falloff exponent alpha, different for primary and secondary users. It is assumed that both the secondary transmitter (ST) and receiver (SR) are moving at such velocity that they allow different scenario realizations to be perceived in each time slot.

1.2. Requirements and specifications

- The software must be able to work with different path loss propagation and statistical fading channel models support.
- The primary network does not allow multi-packet reception (MPR) and establishes a forwarding packets protocol to cross the network.
- The primary nodes have a packet to transmit in its queue with probability less than 0.5, ensuring that statistically there exist more receivers than transmitters.
- The ST battery capacity has a maximum number of 40 energy units, aiming to work with vector probabilities of manageable size.
- The system is evaluated in favourable climatological conditions, in such a way that the nature energy harvesting mechanism collects more energy than the recycling RF power technique.

1.3. Work plan and Gantt diagram

Work Packages

Project: Battery-aware probabilistic access scheme with nature and RF energy harvesting for CR networks.	**WP1**	
Major constituent: Workspace definition	Sheet 1 of 4	
Short description: This WP aims to characterize the working scenario as well as its main parameters in a qualitative way. Finally the constraints of the optimization problem are defined.	**Planned start date**: 17/02/2015 **Planned end date**: 03/03/2015	
Internal task T1: Define the working scenario. **Internal task T2**: Main parameters and constraints definition.	**Deliverables**: Work Plan	**Dates**: 06/03/2015

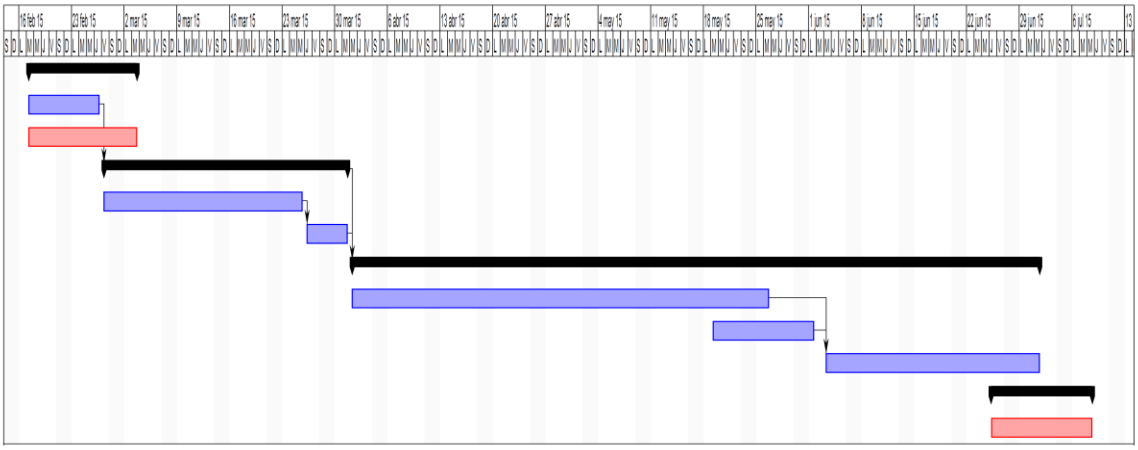
Project: Battery-aware probabilistic access scheme with nature and RF energy harvesting for CR networks.	**WP2**	
Major constituent: Mathematical analysis	Sheet 2 of 4	
Short description: An analysis of main parameters is carried out. In addition, are found closed expressions to each parameter to improve the speed of the future simulator. Finally a summary of the current scenario is performed before the simulator's development.	**Planned start date**: 27/02/2015 **Planned end date**: 31/03/2015	
Internal task T1: Parameters' analysis and mathematical development. **Internal task T2**: Global resume.	**Deliverables**: -	**Dates**: -

Project: Battery-aware probabilistic access scheme with nature and RF energy harvesting for CR networks.	**WP3**	
Major constituent: Simulation	Sheet 3 of 4	
Short description: The aim of this WP is to create a simulator that emulates the current scenario. The optimization is based on linear programing methods. Finally different scenarios are simulated to obtain the interplay between the access techniques and the energy harvesting mechanisms.	**Planned start date**: 1/04/2015 **Planned end date**: 1/07/2015	
Internal task T1: Simulator's development. **Internal task T2**: Linear programming optimization. **Internal task T3**: Scenario simulations.	**Deliverables**: Critical Review	**Dates**: 24/04/2015

Project: Battery-aware probabilistic access scheme with nature and RF energy harvesting for CR networks.	**WP4**	
Major constituent: Final Report	Sheet 4 of 4	
Short description: Write the final report.	**Planned start date**: 25/06/2015 **Planned end date**: 08/07/2015	
Internal task T1: Write the final report. **Internal task T2**: Final revision.	**Deliverables**: Final Report	**Dates**: 10/07/2015

Tasks and Gantt diagram

		Nombre	Duracion	Inicio	Terminado	Predece...
1		**Workspace definition**	**11 days**	**17/02/15 8:00**	**3/03/15 17:00**	
2		Working scenario	8 days	17/02/15 8:00	26/02/15 17:00	
3		Parameters & Constraints	11 days	17/02/15 8:00	3/03/15 17:00	
4		**Mathematical analysis**	**23 days**	**27/02/15 8:00**	**31/03/15 17:00**	**2**
5		Parameters' analysis	19 days	27/02/15 8:00	25/03/15 17:00	
6		Global resume	4 days	26/03/15 8:00	31/03/15 17:00	5
7		**Simulation**	**66 days**	**1/04/15 8:00**	**1/07/15 17:00**	**4;6**
8		Simulator's development	40 days	1/04/15 8:00	26/05/15 17:00	
9		LP Optimization	10 days	19/05/15 7:00	1/06/15 17:00	
10		Scenarios simulation	21 days	3/06/15 8:00	1/07/15 17:00	8;9
11		**Final Report**	**10 days**	**25/06/15 7:00**	**8/07/15 17:00**	
12		Write the Final Report	10 days	25/06/15 7:00	8/07/15 17:00	



1.4. Deviations from the initial plan and incidences

At first, it was considered that the secondary network was also deployed as a 2D HPPP of different density, because of its ad hoc distribution. However, it was shown that the mathematical equations of the ST battery were so complicated and the convexity of the optimization problem could not be ensured, and thus, neither a unique solution. In that case, it was decided to consider a secondary network of short-distance links where the interference caused between links is assumed to be contemptible.

During the project development a first software, which was inefficient in power computation, was partially developed. Due to the high time delay to execute operations, a new software that worked in a much efficient way was created.

On the other hand, the probabilistic access scheme optimization needed less computational time than it was planned. In contrast, the simulation work package required more time than expected due to the fact that all the simulations had to be averaged to guarantee the convergence of the probabilistic results. In addition, new innovations that extend the initial purpose were programmed and introduced in this work, delaying a little more the ending of this task.

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

The research is focused in terms of *underlay cognitive radio* systems, *channel sensing techniques*, *energy harvesting* mechanisms and *Vehicle-To-Vehicle* communications in the *ISM band*.

Cognitive radio (CR) technology allows the opening up of frequency bands to users operating in unlicensed bands taking advantage of the unoccupied spectrum band or interfering in a controlled way the primary users. This work is focused in the both purposes. The first one, interweave CR, where the cognitive users sense the channel in order to detect spectrum holes. The last purpose is the so-called underlay CR, where the cognitive users are allowed to access the channel provided that the primary users QoS degradation, due to the secondary users interference is controlled [1].

In order to avoid interference, cognitive users may sense the channel to track the primary activity. Each node can implement different sensing techniques according to the available knowledge on the primary users signals, (matched-filter and wavelet detection, wideband compressed detection, etc) [2] in local or cooperative sensing way. In [3], it is detected the energy of an unknown signal over different fading channels for the non-diversity and diversity cases. In [4], n-nodes implement a cooperative sequential detection technique. Every node computes the LLR and sends its local measurement to the central node, which sequentially accumulates these statistics in order to make a more robust detection.

The energy harvesting (EH) techniques provide a free source of energy able to impulse mobile devices through ambient energy harvesting mechanisms or recycling the RF power, which besides being autonomous devices are also environmentally friendly [5]. The nature EH techniques allow the utilization of renewable energies to charge the node's batteries, as in [6], where the battery-driven nodes of a wireless sensor network harvest energy through a photo-voltaic system. Radio frequency based EH provides the device a power recycling mechanism to charge its battery, as in [7], where the interference power is harvested through a RF-DC converter of non-ideal efficiency**.**

Nowadays, CR and EH networks are expected to have a huge impact in the near future. In [8], a CR system formed by a unique primary and secondary link is considered. The ST access the channel using a mixed nature and RF energy-driven probabilistic access scheme based on the available energy in the ST battery, which decides the probability of performing each of the following actions: channel sensing, access without sensing, in order to save the sensing energy, or remaining idle. The throughput maximization is carried out by adjusting the above access probabilities, the decision threshold and the sensing time provided that the average primary QoS is satisfied. In [9], a CR system is considered where the cognitive users harvest the ambient RF energy from the primary transmissions. The primary users define a guard radius to protect the intended receivers and a harvesting radius to charge the cognitive users battery. The cognitive users harvest RF energy if they are inside any harvesting zone and access opportunistically the channel if they are outside the guard zones. The throughput and emitted power optimization of the cognitive network are studied provided that the outage-probability constraints from both networks are satisfied. In [10], a CR system is considered where the cognitive users harvest energy from nature sources and recycle the wireless power.

At the beginning of each time slot the secondary transmitter decides between sensing the channel to track the primary spectrum occupancy and remaining idle to save energy. The throughput maximization problem is carried out adjusting the detection threshold of the spectrum sensor under the energy and collision constraints.

These days, a variety of safety and entertainment applications are pledged by Vehicular ad hoc networks (VANET), applied to vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [11]. As it is clarified in the standard 802.11p, V2V allows the communication between automobiles, operating at a high ISM band, classified as a dedicated short-range communication (DSRC). When talking about the physical layer, a wide range of MAC protocols which support steady broadcast services, for a variety of scenarios, have been proposed [11]. In [12], VeMAC protocol designed for highway and city scenarios allows one-hop and multi-hop broadcast service on multiple TDMA channels. This protocol reduces transmission collisions by assigning disjoint sets of time slots to vehicles moving in opposite directions and to roadside units.

As far as the V2V channel is concerned, many works [13, 14] have concluded that it is prone to generate guided propagation in the multipath components as a result of the great number of reflective objects scattered throughout the surroundings, thus, the falloff exponent with distance tends to have a value near 2. Depending on the scenario, it can even reach values below 2 demonstrating in this way the strength of guided propagation. Nevertheless, in order to work with a simplified mathematical model, the two-ray model tends to be the one chosen since it fits well and represents, in many scenarios, a worst case when talking about guided propagation under a Rice fading channel with K-factor depending on the environment conditions.

In this work, it is considered the main idea of Ali & collaborators [8], in which only a unique primary link formed by two omnidirectional nodes is evaluated. An extended primary network with directional nodes is considered under a path loss propagation model of alpha exponent [7] and a Rice fading channel. It is assumed that due to the unawareness of its spatial distribution or owing to the fact that it is an ad hoc network; the primary network is deployed as a HPPP of a given density. Contrary to the original work, the considered primary nodes do not allow multi-packet reception (MPR). A forwarding protocol is built in order to cross the network, capable of establishing half-duplex links, whose distance depends on the primary network density. Both the sensing scheme based on energy detection [3, 8] and the original mixed energy harvesting scheme [8] are maintained while in this project, in contrast with the original work, the secondary link travels at a constant velocity. Furthermore, it has been added an additional approach totally different to the one proposed in the original paper. In a similar way to [9], it is proposed the optimization of the ST transmitted power assuming the sensing time to be contemptible regarding the time slot.

3. Project development

First of all, in section 3.1 the system model is presented in order to introduce the CR scenario. In section 3.2, the problem is stated and the studied scenario characterized mathematically. In section 3.3 it is addressed the problem of maximizing the secondary throughput under the defined constraints.

3.1. System model

It is considered a CR system with a directional-nodes primary network (PN) deployed as a Homogeneous Poisson Point Process (HPPP) of density ρ nodes/m^2 and one secondary link as shown in Figure 1, where it is presented a possible configuration of the considered system. The ST harvests energy from nature resources and recycles the RF interference of the primary network. The system is subjected to a path loss environment with falloff exponent with distance of value α under a Rice fading channel, which in each slot, behaves as a block fading channel.

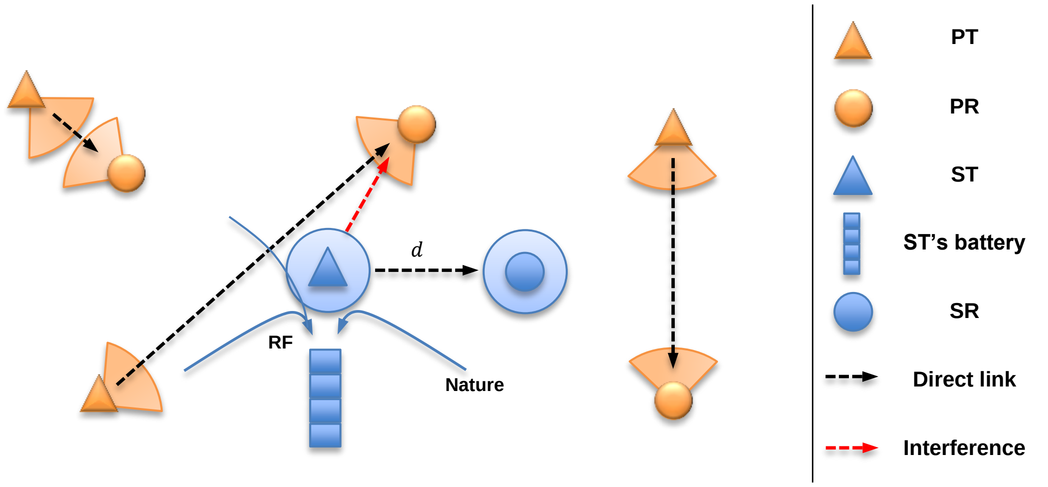


Figure 1. System model

The remainder of this chapter is organized as follows. In section 3.1.1, the features of the primary network and the packets forwarding protocol are exposed. Regarding the secondary link, the used energy harvesting mechanisms and the probabilistic access scheme are introduced in section 3.1.2.

3.1.1. Primary network characteristics

The primary transmitters access the channel using a slotted-time access technique, in which the time is divided in slots of T seconds. The transmitted signal is a f_c - centered pass band signal of bandwidth B Hz.

The primary nodes are equipped with identical antennas having a radiation pattern consisting in a three-dimensional circular sector of vertical and horizontal beamwidth angle ϕ, as formulated in Appendix 1. It is assumed that both, transmitters and receivers, are capable of guiding their antennas to their target with no pointing losses and that the transmitters access the channel with a power P_p able to guarantee a certain no PN outage probability $\bar{P}^p_{nsu,out}$, with spectral efficiency $R_{p,th} = n_{b,p}/T/B$, when the secondary link does not exist.

Each primary node has a packet of length $n_{b,p}$ bits in its queue (active node) with probability p_A in each time slot, and performs the nearest-neighbour forwarding protocol with half-duplex links as a way to route the information throughout the network. In a given time-slot, the entire network is decomposed as the sum of two HPPP of densities ρp_A (active nodes) and $\rho(1-p_A)$ (non-active nodes). Every active node searches its nearest non-active one in order to start the transmission. If more than two active primary nodes point to the same receiver, only one of them, randomly chosen, becomes the transmitter. Therefore, the network of active primary nodes can also be decomposed into two HPPP of densities $\rho p_A p_{tx}$ (transmitters) and $p_A(1-p_{tx})$ (active nodes that remain silent), with p_{tx} the probability of an active node becoming a transmitter, as described in Appendix 2.It is assumed that, when an active node is unable to transmit a packet, it tries to transmit it with the same probability p_A in the following time slots, and that a protocol above the physical layer manages the packets retransmissions.

3.1.2. Secondary link characteristics

The secondary link is formed by a unique transmitter (ST) and receiver (SR), separated by a short distance d. Due to the fact that both nodes are assumed to travel at the same constant velocity during the whole communication time, they behave as if they were static nodes and it is like it was the primary network the one moving at constant speed.

The ST has a finite battery of capacity N_{max} energy packets of E_u Joules per packet unit, modelled as a Markov chain of $N_{max}+1$ states, and has two energy harvesting mechanisms in order to charge the battery. The nature energy mechanism harvests energy from a nature source in a random way, and so, the energy arrival rate is assumed to follow a Poisson process of rate λ_e energy packets per second. The RF energy mechanism harvests energy from the primary network when the secondary node is not transmitting, through the same transmitting antenna and using a RF-DC converter with non-ideal efficiency η.

The number of required energy packets to transmit and sense, respectively, is $N_t = \lceil E_t/E_u \rceil$ and $N_s(\tau) = \lceil E_s(\tau)/E_u \rceil$, which depends on the sensing time τ.

The ST transmits packets of length $n_{b,s}$ bits with E_t Joules of energy. It uses a spectral efficiency without sensing of $R_{ws}^s = n_{b,s}/T/B$ and a spectral efficiency $R_S^s = n_{b,s}/(T-\tau)/B > R_{ws}^s$ when it access after sensing the channel, where $\tau = n_s/f_s$ is the sensing time, n_s is the number of sensed samples and f_s is the sampling frequency, that fulfils the *Nyquist* sampling theorem, thus, $f_s = B$. The energy required to sense the channel is therefore$E_s = n_s e_{proc}$, which depends on the energy required to process 1 sample e_{proc}.

The ST performs a probabilistic access scheme in order to access the channel depending on the available energy in its battery Q_e.

- If it does not have enough energy to transmit $Q_e < N_t$, it has to remain idle charging its battery.
- If it has enough energy to transmit but it does not have enough energy to sense and transmit, $N_t \le Q_e < N_t + N_s$, the secondary node accesses the channel without sensing with probability α_{q_e} and so, it remains idle with probability $1-\alpha_{q_e}$.

- If it has enough energy to sense and transmit $N_t + N_s \leq Q_e \leq N_{max}$, the secondary node accesses the channel without sensing with probability β_{1,q_e}, it senses the channel with probability β_{2,q_e} and it remains idle with probability $1 - \beta_{1,q_e} - \beta_{2,q_e}$.

3.2. Problem formulation

In this section, the equations required to develop the software that optimizes the system's performance of the previous cognitive radio scenario are described.

First of all, a draft version of the low-level software was created to simulate the previous scenario, in which the software replicated exactly the network operations step by step. It could be observed that the time required to evaluate one point was too long, so an upgrade of the software with more mathematical support was generated. In fact, the first software can be wrongly classified as a waste of time, but the truth is that the first one helped to verify the mathematical expressions of the new software, checking how close the values given by both software were. The following sections only show the methods used regarding the new software.

As in [8], the optimization is carried out by evaluating the primary and secondary success rates. In order to accomplish the primary network QoS constraint, it is computed the degradation of the spectral efficiency of the transmitter corresponding to the nearest interfered receiver, since it had been assumed that statistically it would be the most affected by the interference of the ST. In this way, by just ensuring the QoS of this receiver, the quality of service constraint is assumed to be fulfilled in each and every node of the primary network. The Shannon-Hartley formula is used for the mathematical modelling of both success rates expressions, as in [8]. Therefore, is assumed that, for each spectral efficiency threshold value, there exists a channel code and a digital modulation capable of reaching the specified spectral efficiency.

In the following sections, the main expressions of the simulation software, together with the hypothesis that had to be considered for developing the proposed scenario, are stated. It is important to highlight the fact that the expressions presented hereafter have been evaluated with MATLAB software, running a large number of realizations. Furthermore, since for every simulation computers with a normal calculus power have been used, various simulations have been averaged in order to obtain a tighter result.

3.2.1. Primary success rate

The primary success rate μ_p is the probability that the PN nodes could access the channel with a spectral efficiency higher than the minimum required to transmit the primary packet $R_{p,th}$. The following equation shows the primary network success rate:

$$\mu_p = \sum_{q_e=0}^{N_t-1} \pi_{q_e} \bar{P}^p_{nsu,out} + \sum_{q_e=N_t}^{N_t+N_s-1} \pi_{q_e} \left(\alpha_{q_e}\bar{P}^p_{ws,out} + (1-\alpha_{q_e})\bar{P}^p_{nsu,out}\right) + \sum_{q_e=N_t+N_s}^{N_{max}} \pi_{q_e} \left(\beta_{1,q_e}\bar{P}^p_{ws,out} + \beta_{2,q_e}\bar{P}^p_{s,out} + (1-\beta_{1,q_e}-\beta_{2,q_e})\bar{P}^p_{nsu,out}\right)$$

In the equation, $\bar{P}^{p}_{nsu,out}$ and $\bar{P}^{p}_{ws,out}$ are the no PN outage probabilities when the ST remains idle and accesses without sensing the channel, respectively. $\bar{P}^{p}_{s,out}$ is the no PN outage probability when the ST senses the channel and π_{q_e} is the probability that the ST's battery is in the state q_e.

The goal of the following sections is to provide mathematical expressions for the previous defined no PN outage probabilities.

3.2.1.1. No PN outage probability when the ST remains idle

Centring the origin of coordinates to one primary receiver and owing to the nearest neighbour forwarding protocol, each active node intends to establish a half-duplex link with its nearest non-active node. Regardless of the number of conflicts, each primary transmitter has selected its nearest receiver from the network with density $\rho_1(1-p_A)$. Thus, the distance to the nearest non-active user is random and follows the following distribution: $d_u \sim Rayleigh\left(1/\sqrt{2\pi\rho_1(1-p_A)}\right)$. The rest of the primary interference nodes, n_I, are spatially deployed as a HPPP of density $\rho_1 p_A p_{tx} p^2$, with $p^2 = (\phi/2\pi)^2$ the probability of electromagnetic visibility between two directional nodes of the primary network. Taking this into account, it follows that:

$$\bar{P}^{p}_{nsu,out} = Pr\left\{\log_2\left(1 + \frac{P_p D^2 |h_u|^2 / L_u}{P_{n,p} + P_p D^2 \sum_{i=1}^{n_I} \frac{|h_{iu}|^2}{L_{iu}}}\right) > R_{p,th}\right\}$$

where P_p is the primary transmitted power, D is the directivity of the primary nodes (see Appendix 1) and $P_{n,p} = N_0 B F_p$ is the noise power at the receiver's input being F_p its noise factor. In the equation $|h_u|^2, L_u$ denote the channel gain and path loss coefficient of the direct primary link and $|h_{iu}|^2, L_{iu}$ the channel gain and path loss coefficient between the interferer i and the useful receiver.

The channel gain of the link k is $|h_k|^2 = |h|^2/(2(K_{Rice,p}+1))$ with $|h|^2$ the canonical form of a non-central chi-squared distribution with 2 degrees of freedom and non-centrality parameter $2K_{Rice,p}$.

The path loss coefficient is $L_k = (4\pi d_0/\lambda)^2 (d_k/d_0)^{\alpha}$ if d_k is further than the Fraunhofer limit, assuming that the far field equations are valid for distances larger than $d_0 = 10\lambda$. Below the Fraunhofer limit, the energy transfer is so efficient that it will be considered that the received power has not been attenuated.

3.2.1.2. No PN outage probability when the ST access without sensing

As it has been previously explained, the QoS constraint is imposed onto the nearest interfered primary receiver because it is statistically the most degraded one. The nearest primary receiver pointing to the ST is located at distance $d_{su} \sim Rayleigh\left(/\sqrt{2\pi\rho_1 p_A p_{tx} p}\right)$, which corresponds to the minimum distance distribution of the ST to the network containing the primary receivers with electromagnetic visibility with it. The target probability is equivalent to the computed in the previous section but with an additional interference term coming from the secondary node.

$$\bar{P}^{p}_{ws,out} = Pr\left\{\log_2\left(1+\frac{P_p D^2 |h_u|^2/L_u}{P_{n,p}+\frac{E_t}{T} D \frac{|h_{su}|^2}{L_{su}} + P_p D^2 \sum_{i=1}^{n_I} \frac{|h_{iu}|^2}{L_{iu}}}\right) > R_{p,th}\right\}$$

where $|h_{su}|^2, L_{su}$ denote the link gain and path loss coefficient between the ST and the useful transmitter.

3.2.1.3. No PN outage probability when the ST senses the channel

The ST senses the channel with m samples using a scaled version of the energy detector in [3], $P_{est} = \frac{1}{m}\sum_{n=1}^{m}|s[n]+w[n]|^2$ being $s[n] = s_i[n] + js_q[n]$ the complex received signal with amplitude components $\sqrt{P_r}$, constant in each time slot, and $w[n]$ the complex zero-mean Gaussian noise with power $P_{n,s} = N_0 B F_s$, where F_s is the receiver's noise factor of the ST.

On account of the large deployment of transmitters at any point a certain primary power level is received. In this case, there are not two clearly differentiated hypotheses as in [3, 8]. Therefore, the ST works only with one hypothesis, that is, there always exists a receiver that will be interfered more or less depending on its range to the ST.

The ST senses the channel and takes a decision about access or not by comparing the estimated envelope power P_{est} with the decision threshold $\lambda_{SNR} P_{n,s}$. Thus, it accesses the channel if $P_{est} \le \lambda_{SNR} P_{n,s}$, owing to the fact that the primary nodes are further the ST. Otherwise (i.e. $P_{est} > \lambda_{SNR} P_{n,s}$) the node remains idle.

The node accesses the channel following the Bernoulli random variable q with $\Pr\{q = 1\} = Pr\{P_{est} \le \lambda_{SNR} P_{n,s}\}$.

The target probability is equivalent to the expression in section 3.2.1.1 but with an additional interference term coming from the ST, only when it is not idle, and so, introducing the random variable q, defined previously. In this case, the ST has to increase the transmitted power as the penalty for the time required to sense the channel.

$$\bar{P}^{p}_{s,out} = Pr\left\{\log_2\left(1+\frac{P_p D^2 |h_u|^2/L_u}{P_{n,p}+q\frac{E_t}{T-\tau} D \frac{|h_{su}|^2}{L_{su}} + P_p D^2 \sum_{i=1}^{n_I} \frac{|h_{iu}|^2}{L_{iu}}}\right) > R_{p,th}\right\}$$

3.2.2. Secondary success rate

The secondary success rate μ_s is the probability that the ST could access the channel with a spectral efficiency higher than the minimum required to transmit the secondary packet, which is set to R^s_{ws} if the ST access the channel without sensing or to $R^s_s(\tau) > R^s_{ws}$ in the sensing case. Accordingly, the success rate of the secondary transmitter is given by the following expression:

$$\mu_s = \sum_{i=N_t}^{N_t+N_s-1} \pi_i \alpha_i \bar{P}^{s}_{ws,out} + \sum_{i=N_t+N_s}^{N_{max}} \pi_i \left(\beta_{1,i} \bar{P}^{s}_{ws,out} + \beta_{2,i} \bar{P}^{s}_{s,out}\right)$$

where $\bar{P}^s_{ws,out}$ is the no ST outage probability when accessing without sensing the channel, and $\bar{P}^s_{s,out}$ is the no ST outage probability when accessing after sensing the channel.

The goal of the following sections is to provide mathematical expressions for the previous defined no ST outage probabilities.

3.2.2.1. No ST outage probability when accessing without sensing the channel

The secondary distance link is d (deterministic). Centring the origin of coordinates to the ST, the primary interferers n_I, are spatially deployed as a HPPP of density $\rho p_A p_{tx} p$, which corresponds to the primary transmitters' network with electromagnetic visibility to the SR. When the channel is not sensed, the ST power is E_t/T and it accesses the channel with a spectral efficiency R^s_{ws}. The no outage probability is therefore given by:

$$\bar{P}^s_{ws,out} = Pr\left\{\log_2\left(1 + \frac{\frac{E_t}{T}\frac{|h_s|^2}{L_s}}{P_{n,s} + P_p D \sum_{i=1}^{n_I}\frac{|h_{is}|^2}{L_{is}}}\right) > R^s_{ws}\right\}$$

where $P_{n,s} = N_0 B F_s$ is the noise power at the ST receiver's input, being F_s its noise factor. In the same way as before, $|h_s|^2, L_s$ denotes the channel gain and path loss coefficient of the direct secondary link and $|h_{is}|^2, L_{is}$ the channel gain and path loss coefficient between the primary interferer i and the SR.

The channel gain of the direct link is $|h_s|^2 = |h|^2/(2(K_{Rice,s} + 1))$ with $|h|^2$ the canonical form of a non-central chi-squared distribution with 2 degrees of freedom and non-centrality parameter $2K_{Rice,s}$.

Regarding the path loss coefficient in the secondary link, it is assumed that there exists direct vision between ST and SR, and thus, the free space path loss model is applied. That means, $L_s = (4\pi d/\lambda)^2$ for distances farther the Fraunhofer limit.

3.2.2.2. No ST outage probability when accessing sensing the channel

Using the same notation as in the previous section, it is defined the no ST outage probability, where the ST accesses the channel with probability determined by the Bernoulli random variable q. The ST transmitted power is $E_t/(T-\tau)$ and accesses the channel with a spectral efficiency $R^s_s(\tau)$, both depending on the sensing time.

$$\bar{P}^s_{s,out} = Pr\left\{\log_2\left(1 + \frac{q\frac{E_t}{T-\tau}\frac{|h_s|^2}{L_s}}{P_{n,s} + P_p D \sum_{i=1}^{n_I}\frac{|h_{is}|^2}{L_{is}}}\right) > R^s_s(\tau)\right\}$$

3.3. Optimization

Once both success rates are defined, the following optimization problem is proposed in order to maximize the secondary success rate, provided that the primary network allows a maximum r - reduction of its no outage probability as when there is no secondary link.

$$\max_{\underline{\alpha},\underline{\beta_1},\underline{\beta_2},\underline{\pi},n_s,\lambda_{SNR}} \quad \mu_s\left(\underline{\alpha},\underline{\beta_1},\underline{\beta_2},\underline{\pi},n_s,\lambda_{SNR}\right)$$

Subject to the constraints:

- $\underline{\alpha} = \left[\alpha_{N_t},\alpha_{N_t+1},\dots,\alpha_{N_t+N_s-1}\right]^T, \quad \alpha_{q_e} \in [0,1]$
- $\underline{\beta_1} = \left[\beta_{1,N_t+N_s},\beta_{1,N_t+N_s+1},\dots,\beta_{1,N_{max}}\right]^T,$
  $\underline{\beta_2} = \left[\beta_{2,N_t+N_s},\beta_{2,N_t+N_s+1},\dots,\beta_{2,N_{max}}\right]^T \quad \beta_{1,q_e},\beta_{2,q_e} \in [0,1]$
- $\underline{0} \leq \underline{\beta_1} + \underline{\beta_2} \leq \underline{1}$
- $\underline{\pi} = \left[\pi_0,\pi_1,\dots,\pi_{N_{max}}\right]^T, \quad \pi_{q_e} \in [0,1], \quad \underline{\underline{P}}^T\underline{\pi} = \underline{\pi}, \quad \underline{1}^T\underline{\pi} = 1$
- $n_s \in \mathbb{Z}^+, \quad n_s \leq n_{s,max} = \lfloor BT \rfloor$
- $\lambda_{SNR} \in \mathbb{R}^+$
- $\mu_p\left(\underline{\alpha},\underline{\beta_1},\underline{\beta_2},\underline{\pi},n_s,\lambda_{SNR}\right) \geq \mu_{p,th} = (1-r)\cdot \bar{P}^p_{nsu,out}, \quad r \in [0,1]$

where $\underline{\underline{P}}$ is the transition matrix, whose element P_{ij} is the probability that the battery passes from the state "i" to the state "j" as defined in [8].

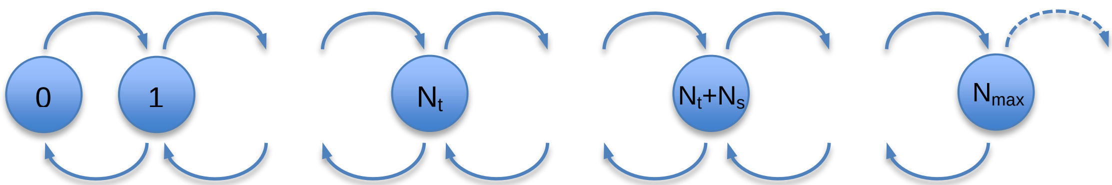


Figure 2. Markov chain

The elements of the transition matrix P_{ij} are defined as follows, where $p_H(k)$ is the probability of harvesting k energy packets from both nature $\left(N \sim Poisson(\lambda_e T)\right)$ and the RF power recycled $\left(R = \left\lfloor \eta \frac{T}{E_u} P_p D \sum_{i=1}^{n_I} \frac{|h_{is}|^2}{L_{is}} \right\rfloor\right)$:

$$p_H(k) = Pr\{H = k\} = \sum_{n+r=k} p_N(n)p_R(r)$$

For $j < N_{max}$

- $i < N_t \qquad P_{ij} = p_H(j-i)$
- $N_t \leq i < N_t + N_s \qquad P_{ij} = \alpha_i p_H(j-i+N_t) + (1-\alpha_i)p_H(j-i)$
- $N_t + N_s \leq i \leq N_{max} \qquad P_{ij} = \beta_{1,i} p_H(j-i+N_t) + \beta_{2,i} Pr\{q=0\} p_H(j-i+N_s) + \beta_{2,i} Pr\{q=1\} p_H(j-i+N_t+N_s) + \left(1-\beta_{1,i}-\beta_{2,i}\right) p_H(j-i)$

For $j = N_{max}$, the previous transition probabilities have different formulas due to the battery limited capacity. They can be derived from the above equations by replacing $p_H(H=k) = p_H(k)$ by $p_H(H \geq k)$.

For a given λ_{SNR} and n_s, the following variable change is introduced:

$$\tilde{\alpha}_{q_e} = \alpha_{q_e}\pi_{q_e} \quad N_t \leq q_e < N_t + N_s$$

$$\tilde{\beta}_{1,q_e} = \beta_{1,q_e}\pi_{q_e} \quad N_t + N_s \leq q_e \leq N_{max}$$

$$\tilde{\beta}_{2,q_e} = \beta_{2,q_e}\pi_{q_e} \quad N_t + N_s \leq q_e \leq N_{max}$$

Now the problem is linear in $\tilde{\alpha}_{q_e}, \tilde{\beta}_{1,q_e}, \tilde{\beta}_{2,q_e}$ and π_{q_e}, that can be solved efficiently using the software package in [15].

In the same way as [8] there are defined the access without sensing and sensing probabilities, $p_a = \sum_{q_e} \tilde{\alpha}_{q_e} + \sum_{q_e} \tilde{\beta}_{1,q_e}$ and $p_S = \sum_{q_e} \tilde{\beta}_{2,q_e}$ but as a function of the new variables.

4. Simulation and results

In order to study the effectiveness of the energy-driven probabilistic access scheme proposed in [8] and extended in this project to a primary network with directive nodes, two main scenarios are contemplated.

The type A scenarios correspond to systems where the ST is restricted by the battery energy. Therefore, the concept of energy harvesting is brought to light and is intended to demonstrate the effectiveness of the combination of both access strategies (access with or without sensing) to save energy for each one of the primary activity values.

The type B scenarios correspond to a ST with an excess of energy, which could correspond to a V2V scenario where the ST is plugged to the car high-capacity battery. In this way, the energy required to sense the channel is not relevant for the ST.

In all the scenarios, the aim is to discern in which of them sensing is relevant and on which parameters the sensing depends. In order to see the relationship between the sensing time and both access techniques, both scenarios are evaluated for different latency services.

4.1. Type A scenarios

Let's consider a short-range link limited by the battery energy, immersed in a primary network with directional nodes working at ISM 2.4GHz, which owing to the ignorance of its actual spatial distribution is assumed to be deployed as a 2D HPPP, where the primary transmitters power is fixed to guarantee a no outage probability of 0.5 and allows a maximum 3% of throughput reduction to be "offered" to cognitive users. It is inferred that due to the environment configuration each node has a direct vision of a 100x100 square metres while the rest of the nodes contribution is assumed to be contemptible. The free space model is applied and the channel is assumed to have a Rice fading behaviour with $K_{Rice} = 2$.

The table below shows the characteristics of type A scenarios.

$\rho = 10^{-2}\ nod/m^2$	$\phi = 180º$	$F_{n,p} = 6dB$	$d = 3m$
$F_{n,s} = 6dB$	$\lambda_e = 300\ paq/s$	$\eta = 0.5$	$e_{proc} = 10^{-14}J$
$N_{max} = 40$	$B = 20kHz$ [a]	$E_u = 2 \cdot 10^{-14}$	$\alpha = 2$

Table 1. Simulation parameters for the A1 and A2 scenarios.

Note: The simulation area is limited to a square of 100x100 square meters.

Note: The no outage probability threshold has been chose to guarantee the maximum no outage in the worst case regarding the primary network activity (0.45). Although for lower primary activity values the system could guarantee a higher no outage, is maintained in order to compare the results.

[a] Even working at ISM 2.4GHz, it is considered a convenient signal bandwidth in order to limit the maximum number of samples entering the energy detector for channel sensing and, therefore, reduce the simulation time.

4.1.1. Type A1 scenario

Let's contemplate the fact that both networks execute low latency packet commutation services, which are associated to short length packets, described in the following table:

$n_{b,p} = 32\ bits$	$n_{b,s} = 16\ bits$	$T = 1ms$	$E_t = 10^{-13}J$ [a]

Table 2. Simulation parameters for the A1 scenario.

[a] The energy value has been chosen to guarantee a non-zero secondary success rate and a non – contemptible interference on the primary network.

Below, the obtained results for the type A1 scenario are presented.

- First Study

The aim of this study is to see the gain of the adopted mixed energy harvesting scheme along with the trade-off between the simple access (no sensing) and channel sensing, for each probability of activity value of the primary network.

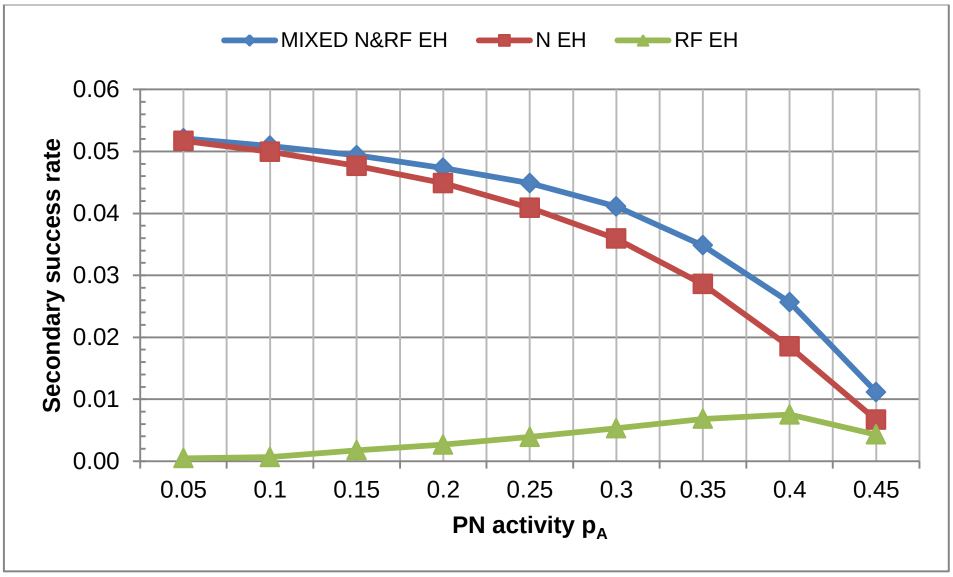


Figure 3. Secondary success rate as a function of the primary network activity for the nature (N), radio frequency (RF) and mixed (N&RF) cases in the A1 scenario.

As it can be observed in Figure 3, the mixed energy scheme benefits from both EH techniques to increase the secondary success rate, significant when the primary network access is more frequent. In fact, the gain with the RF harvesting mechanism is emphasized when the ST is near a primary transmitter. In that case, it charges a great number of energy units in its battery. As the activity in the primary network increases, the prior statement appears with higher probability since the primary transmitters are statistically closer.

On the one hand, as for the secondary link success rate, it is important to underline the fact that it is low, inasmuch as the system is restricted by the battery energy, and, therefore, it has to wait some slots in order to have enough energy to transmit. On the other hand, as the primary activity increases the ST perceives a reduction of its throughput because its transmitted power is not enough to compensate the primary interference.

Once demonstrated the benefit of the mixed EH scheme, from now only the results for this scheme are presented.

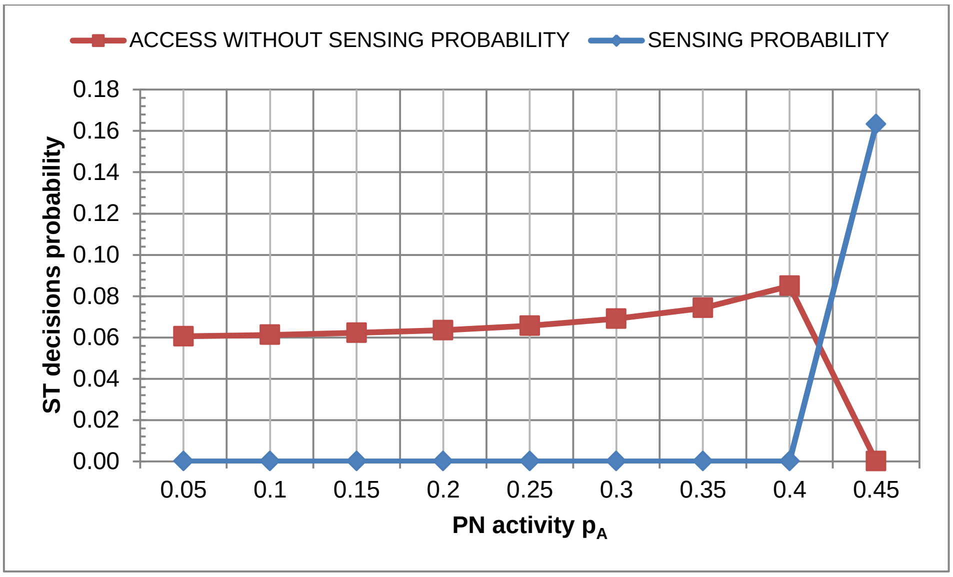


Figure 4. ST decisions as a function of the primary network activity in the A1 scenario.

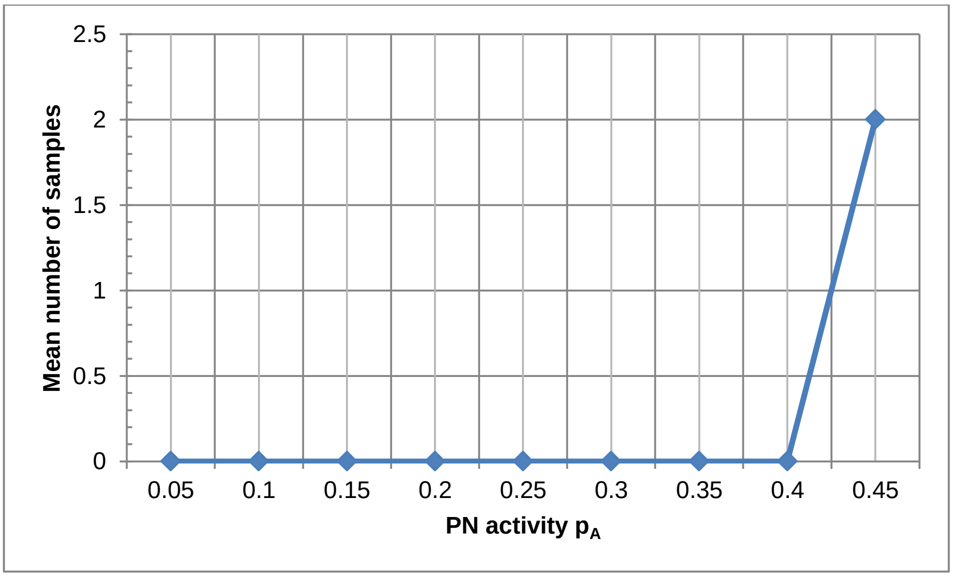


Figure 5. Mean number of sensed samples as a function of the primary network activity in the A1 scenario.

Sensing the channel has interest only when the activity values are rather high, since it is then when the primary transmitters are statistically closer (see Figure 4). In these cases, it is favourable to sense the channel in order to detect when the secondary connection is not possible. Furthermore, when sensing the channel, the number of used samples is quite low, which illustrates the restriction of the battery energy. For very low activity values it is worth accessing the channel without sensing, in a controlled way, due to the fact that the primary nodes are far enough and the sensing technique must use a large number of samples to improve the detector SNR, which cannot be done because of its energy restriction.

It is seen that the secondary node decisions are not probabilistically complementary. That is, a high percentage of the time the ST cannot make a decision to access the channel since it does not have enough energy to do it; in that case, it remains idle, waiting for the arrival of new energy packets.

- Second study

In this study it is analysed the interplay between the mean harvested power and the falloff exponent with distance, α, for the proposed network model.

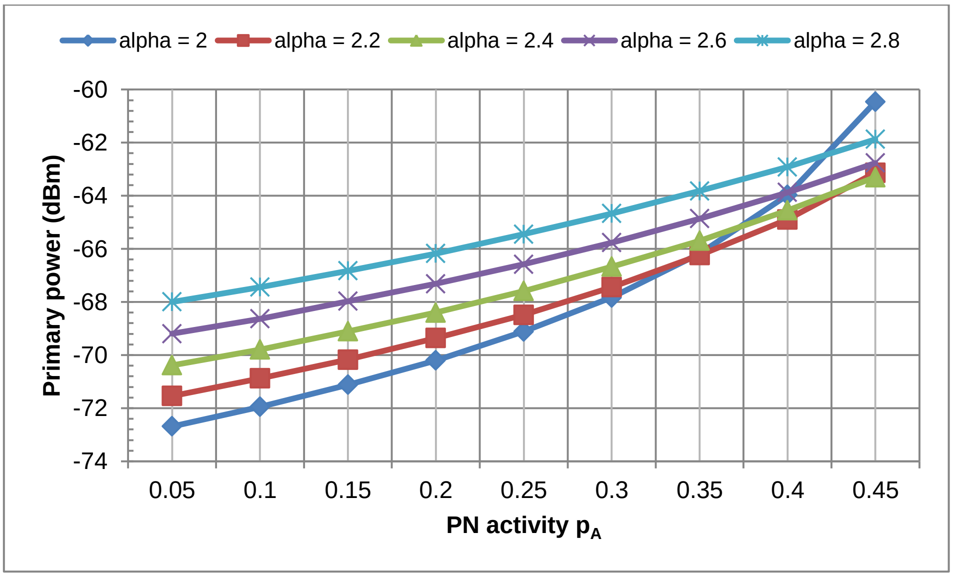


Figure 6. Primary transmitted power (dBm) as a function of its network activity for five different falloff exponent cases $\boldsymbol{\alpha = 2, 2.2, 2.4, 2.6}$ and $\boldsymbol{2.8}$ in the A1 scenario.

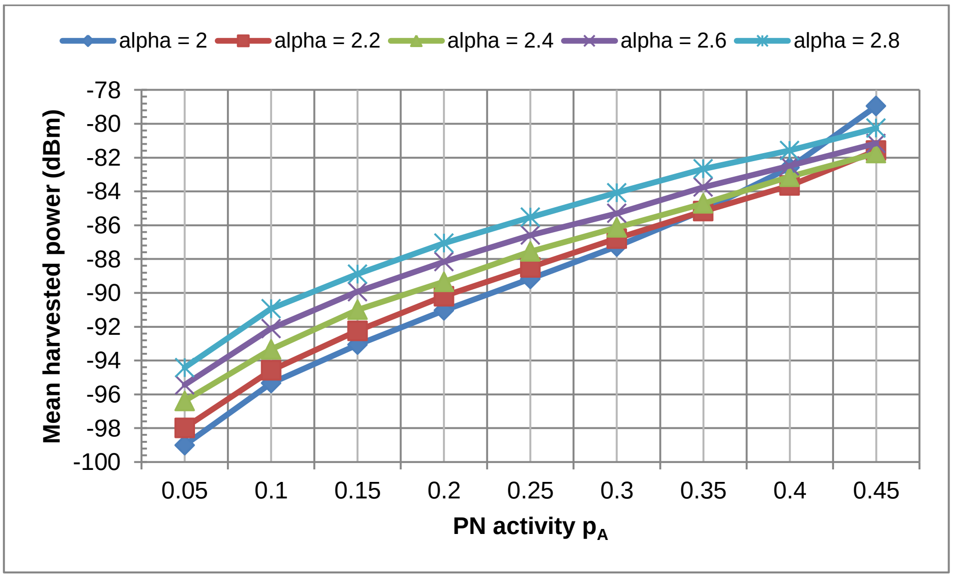


Figure 7. Mean ST harvested power (dBm) as a function of the primary network activity for five different falloff exponent cases $\boldsymbol{\alpha = 2, 2.2, 2.4, 2.6}$ and $\boldsymbol{2.8}$ in the A1 scenario.

As it is shown in Figure 6 and 7, the power transmitted by primary nodes and the mean ST harvested power are increasing monotonic functions of the primary activity rate p_A for any value of the falloff exponent.

For the case $\alpha > 2$, the higher the falloff exponent the more power the secondary node is able to harvest, due to the fact that the primary nodes have a power control mechanism that guarantees the same outage, and, therefore, the transmitted primary power compensates for he channel attenuation.

For the case $\alpha = 2$, there are two operating modes that can be distinguished in Figure 6. For primary activity probabilities below 0.35, the scenario is limited by EH. The primary nodes are further but the ST could not access the channel as it want due to its energy restriction. On the other hand, for primary activity values above 0.35 represents the best case regarding the harvested energy, as commented in [7], but a worst case in terms of primary interference. In this case, the primary interference limits the ST throughput.

- Third study

The effect of the primary nodes' directivity on the ST decisions for the primary activity probability of 0.45 is evaluated.

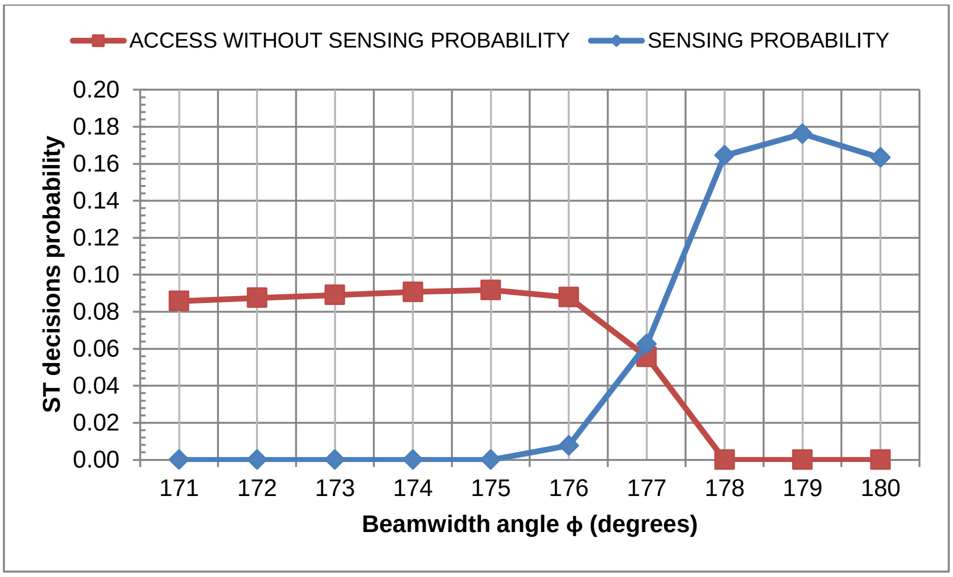


Figure 8. ST decisions as a function of the beamwidth angle in the A1 scenario.

It is demonstrated that the nodes' directivity causes indeed crossings between both channel accessing decisions. For the considered primary activity, the channel sensing results interesting near 180º.

4.1.2. Type A2 scenario

Let's consider now, that both networks carry out packet commutation services of higher latency, associated to longer packets, as described in the table 3:

$n_{b,p} = 160\ bits$	$n_{b,s} = 80\ bits$	$T = 5ms$	$E_t = 5 \cdot 10^{-13} J$

Table 3. Simulation parameters for the A2 scenario.

Note: Maintaining the spectral efficiency and the same transmitted power for both networks, the system has been scaled by a factor 5 regarding the packets length, the time slot and the secondary transmitted energy.

Below, the developed studies and the obtained results for the type A2 scenario are presented.

- First study

As in the low latency scenario, the trade-off between both channel access techniques for each activity value of the primary network is evaluated.

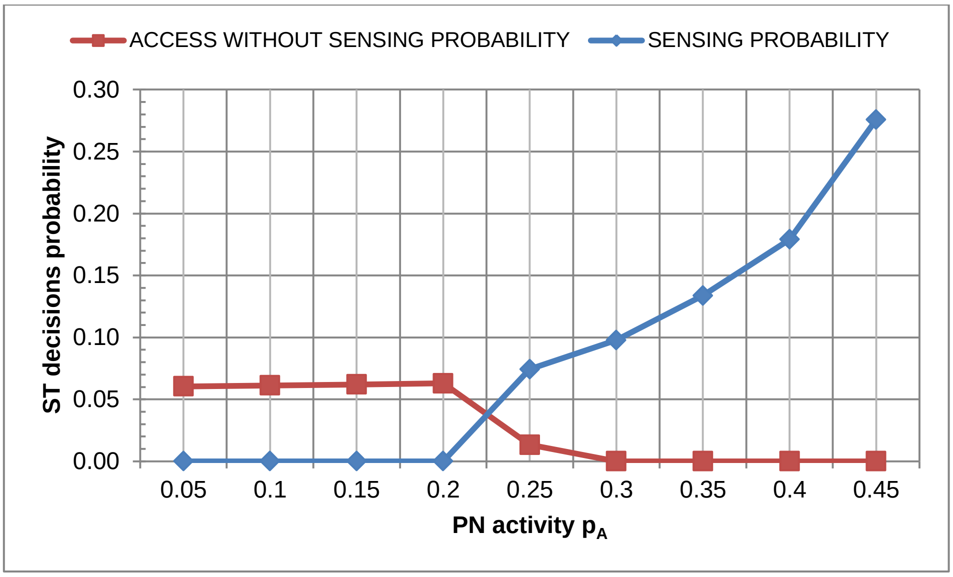


Figure 9. ST decisions as a function of the primary network activity in the A2 scenario.

In contrast with the low latency case, it is much more interesting to sense the channel before (see Figure 9), with a small number of samples as well (see Figure 10), due to the fact that the fraction of the slot time dedicated to the channel sensing is lower than in the scenario A1, for the same sensing time. Therefore, it results more effective to sense the channel since the increase of the ST power along with the penalty for the time dedicated to sense the channel is no so bad when the slot time is longer.

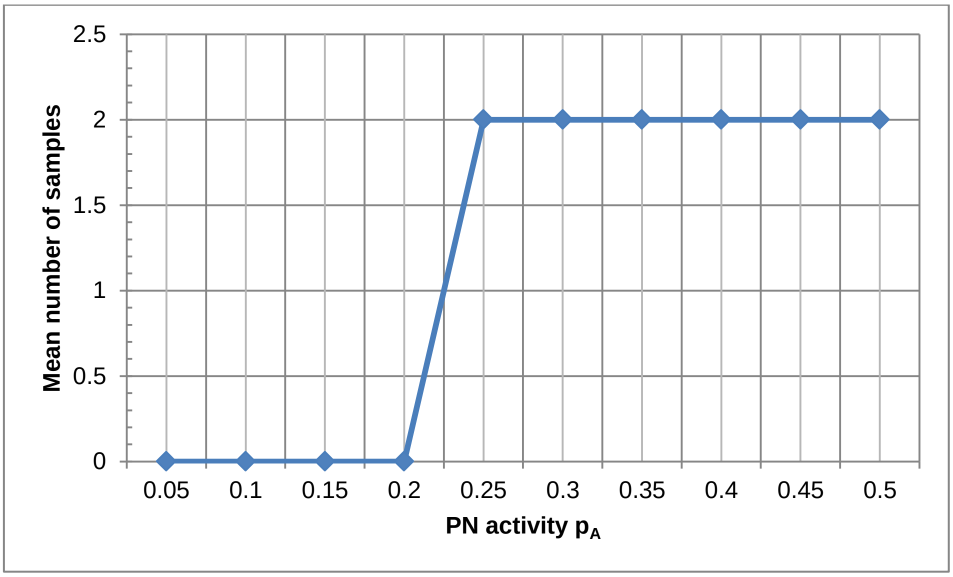


Figure 10. Mean number of sensed samples as a function of the primary network activity in the A2 scenario.

- Second study

Looking at the results of the previous study, it is analysed the relationship between the nodes directivity and the decisions to access the channel.

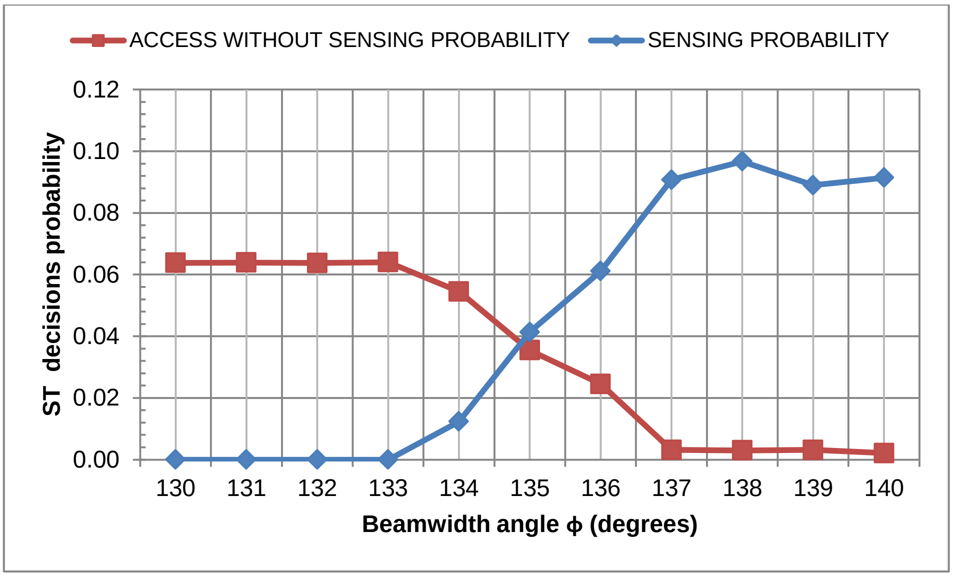


Figure 11. ST decisions as a function of the beamwidth angle in the A2 scenario.

In this case, as observed in Figure 11, the sensing scheme allows more flexibility when it concerns to the nodes directivity. The channel sensing is favourable for aperture values between 133 and 180 degrees. It is concluded that exists an equivalence relation between the primary network activity and the primary nodes directivity regarding the ST decisions (to sense or not to sense).

4.1.3. Common A1 and A2 scenario study

After looking at both latency results (see Figures 5 and 10), the mean number of sensed samples is quite low, thus, the transmitted power using both access techniques is almost the same. In this case, similarly as in [9], it is planned the optimization of the secondary transmitted power, assuming negligible the sensing time and as if the ST access without sensing the channel. In fact the optimal values are only ensured in the regions where the simple access dominates.

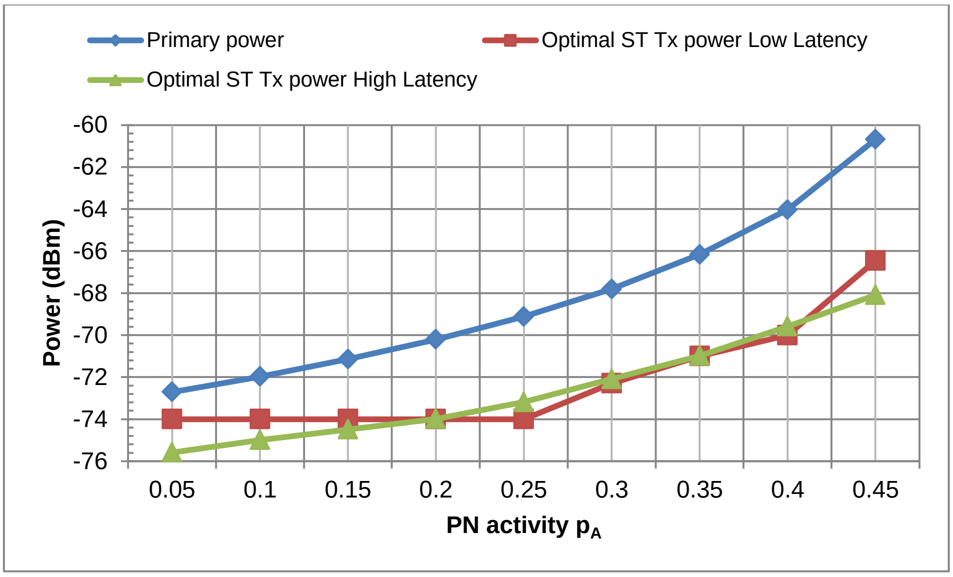


Figure 12. Primary and secondary optimal transmitted power (dBm) as a function of the primary network activity for A1 and A2 scenarios.

For both latency scenarios, it is demonstrated that the higher the primary power, the higher the ST transmitted power since it has to compensate for the increase of interference caused by the primary nodes. As it is shown in Figure 12, the optimal ST power values are very similar for both latency cases and its difference only depends on the relation between the number of transmitted packets and the ST battery's capacity.

Below is presented the secondary success rate computed using both the simple access and the channel sensing techniques.

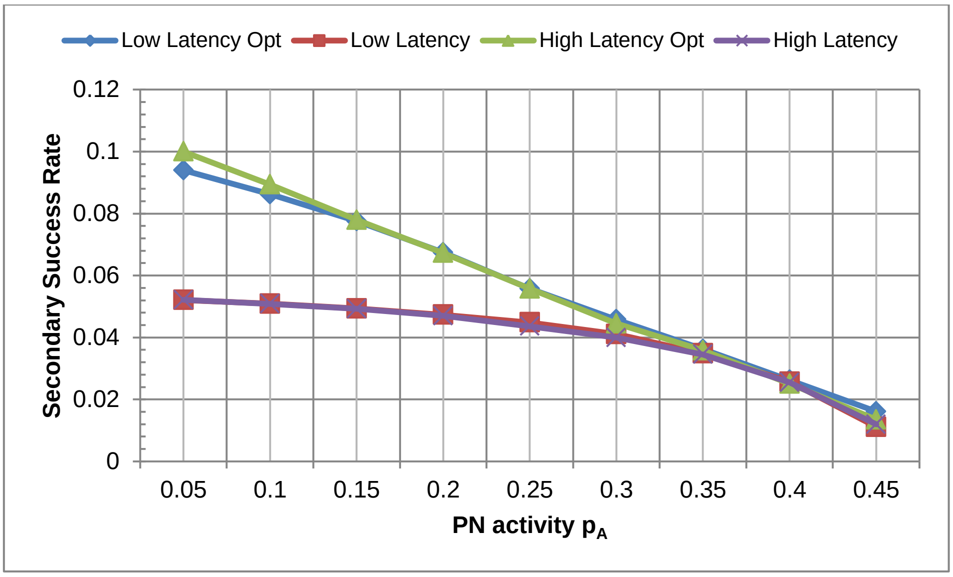


Figure 13. Secondary success rate as a function of the primary network activity for the A1 and A2 scenarios and its energy optimization cases.

In Figure 13 it can be observed that both latency cases provide the same secondary success rate. It is concluded then that in scenarios with battery limitation, the probabilistic access scheme optimization ensures the same secondary success rate regardless of the packets length.

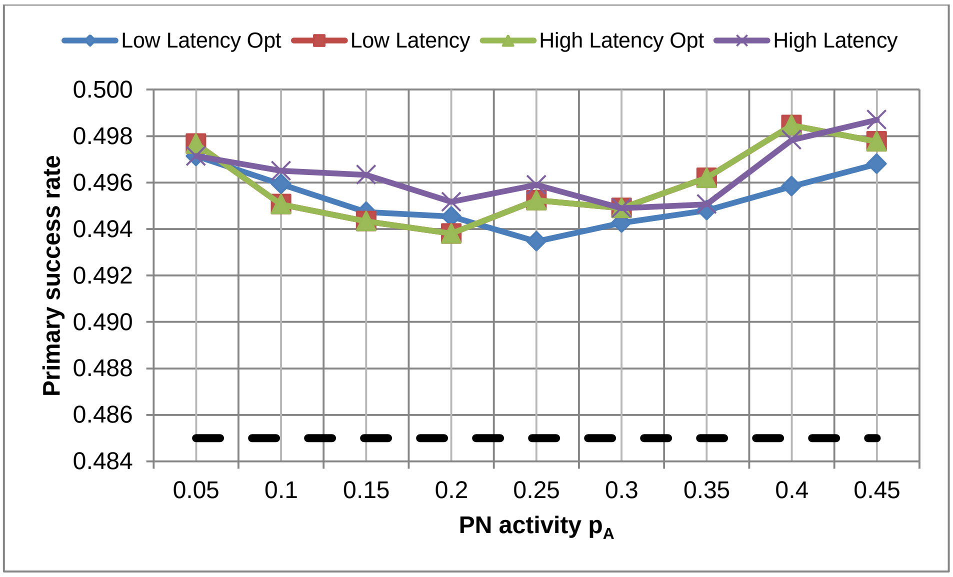


Figure 14. Primary success rate as a function of the primary network activity for the A1 and A2 scenarios and their energy optimization cases.

Note: The dashed line indicates the primary network QoS constraint.

The ST is strongly restricted in energy by the battery while In Figure 14, it is observed that the secondary link does not benefit from the throughput reduction allowed by the primary network, demonstrating in this way the battery limitation since the ST must remain idle in many time slots, waiting for the new packets arrivals.

4.2. Type B scenario

In this case, it is intended to establish a short-distance V2V link between two parallel vehicles travelling on a road at constant speed, immersed in a wireless sensor network working at ISM 2.4GHz. Due to the fact that the pair of secondary nodes is travelling at tens of kilometres per hour, the hypothesis of perceive different primary network distributions in each time slot is strengthen.

In this scenario, the same scenario in Table 2 but with an surplus of energy is simulated, that is, the ST is provided with an energy harvesting technique or power source able to perform the simple access or the channel sensing in many time slots.

4.2.1. Type B1 scenario

In the same way as in the section 4.1.1, it is considered that both the primary network and the secondary link are using a low latency packet commutation services, specified in Table 2.

Below, the results for the type B1 scenario are described.

Taking into account the studies carried out in sections 4.1.1 and 4.1.2, the aim of this study is to analyse both access techniques when the system is not limited by the battery energy.

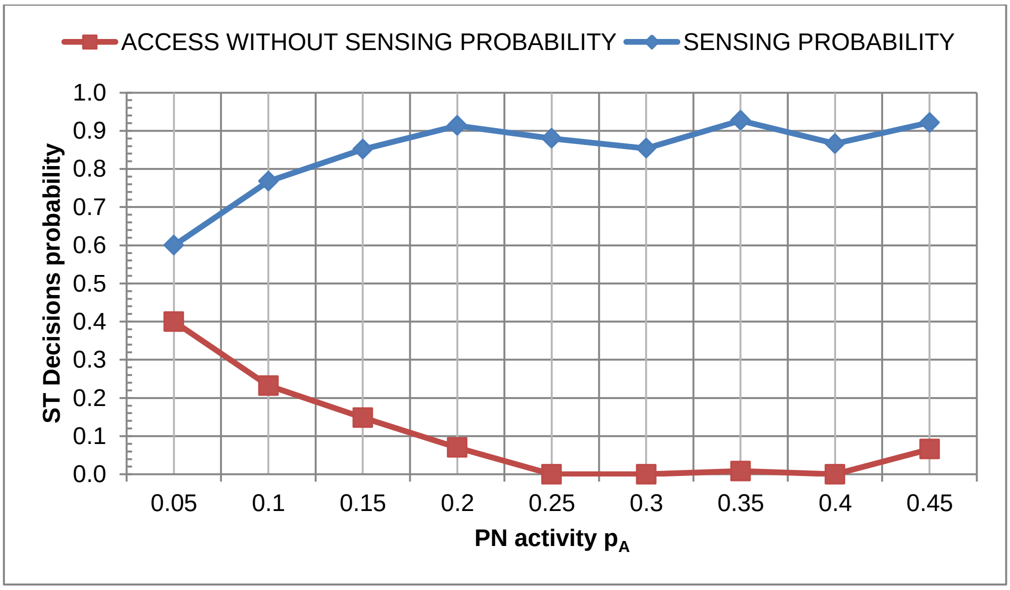


Figure 15. ST decision as a function of the primary network activity for the B1 scenario.

Due to the fact that for this scenario the ST always has enough energy to take any of both access decisions, it mainly prefers to sense the channel since it provides more certainty and allows an increase in its success rate. As in the type A scenarios, the ST senses the channel using a few number of samples. Nevertheless, in that case the ST is not energy restricted but it must take care about the transmitted power as a penalty for the time dedicated to sensing the channel.

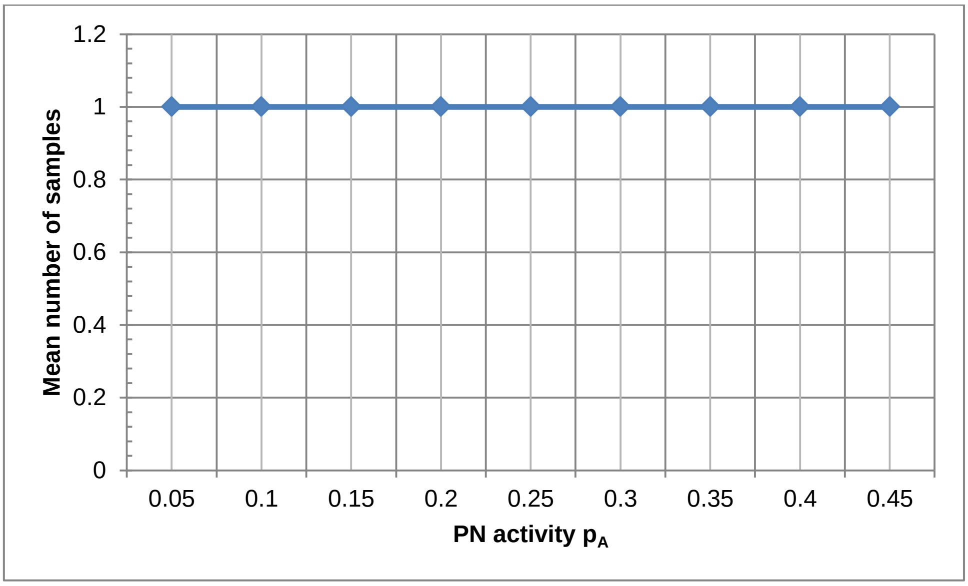


Figure 16. Mean number of sensed samples as a function of the primary network activity for the B1 scenario.

4.2.2. Type B2 scenario

The same study as in the previous section is realized, considering that both the primary network and the secondary link are using the high latency packet commutation service as in Table 3.

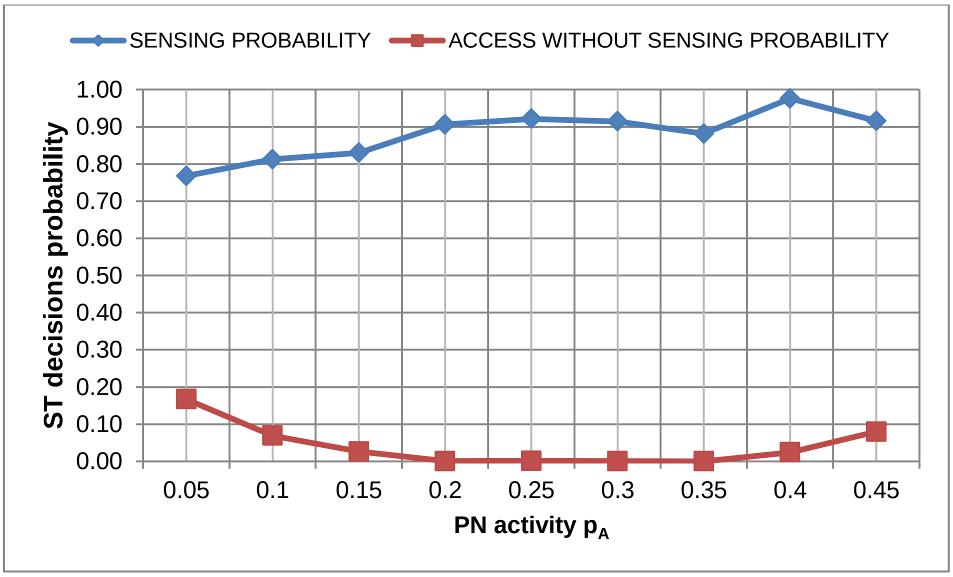


Figure 17. ST decision probabilities as a function of the primary network activity for the B2 scenario.

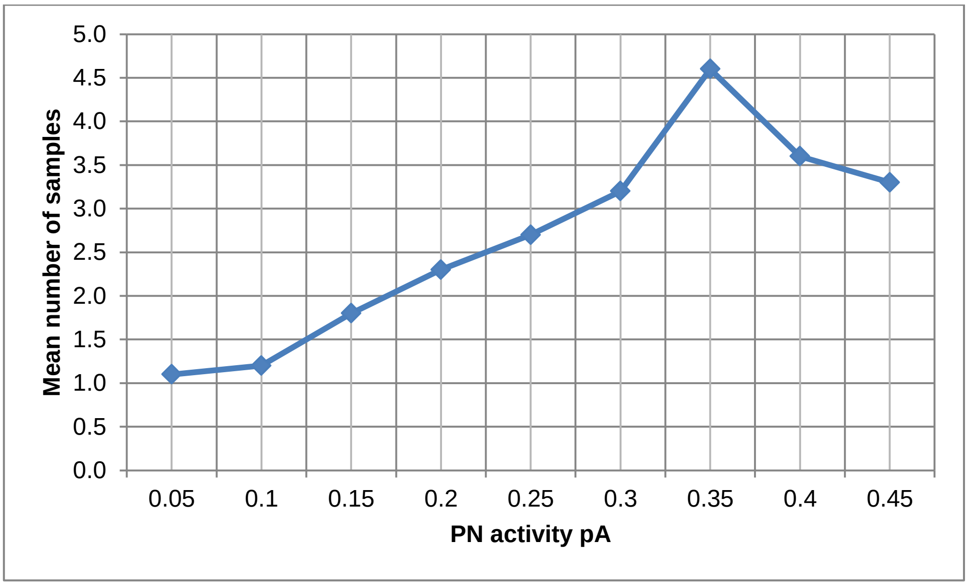


Figure 18. Mean number of sensed samples as a function of the primary network activity for the B2 scenario.

Similarly to the previous section, the surplus of energy provides the node the capability of sensing the channel whatever the primary activity probability (see Figure 17).

For low primary activity values, the primary links are weak owing to the fact that the received primary interference is low. In this case, although the primary receivers are further, the good propagation conditions and the weakness of the primary links caused the primary receivers a non-contemptible ST interference, and thus, the channel sensing has to be realized within the shortest possible time.

On the other hand, as the primary activity increases, the primary receivers are closer to the ST, but the primary control power mechanism, which ensures the same outage, makes more robust the primary links. Whereas the ST interference power is much greater due to the proximity of the primary receivers, its interference is less significance owing to the fact that the power received from the direct link is much higher.

In the simulated scenario, as the primary network activity increases, the ST can sense the channel with a higher number of samples in order to increase its SNR detection (see Figure 18). In fact, the ST senses the channel with a big enough number of samples so as to increase the SNR of detection and at the same time small enough in order not to interfere too much the primary receivers, as a penalty for the time dedicated to sense the channel.

4.2.3. Common B1 and B2 scenario study

In this section is realized a common observation of both latency scenarios, regarding the secondary throughput, when the ST is not limited by the battery energy.

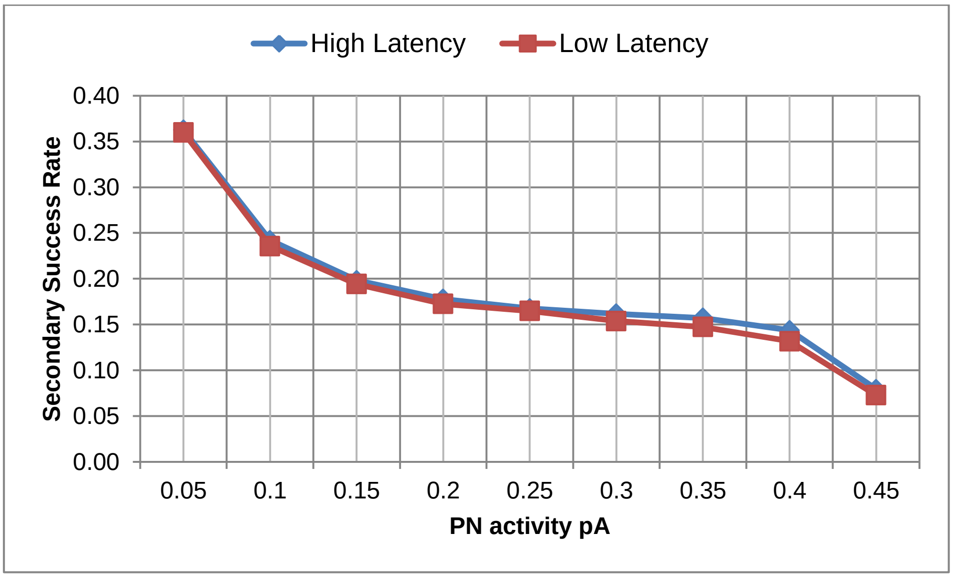


Figure 19. Secondary success rate as a function of the primary network activity for the B1 and B2 scenarios.

As in the type A scenarios, the secondary success rate is independent of the packets length (see Figure 19).

5. Budget

In this work, neither physical component nor prototype was designed. Therefore, this budget was estimated taken in to account the mean number of hours dedicated to the research, developing the software and the planning and execution of the simulations performed in this work. In addition, is also considered the MATLAB license, and a cost per hour of a junior engineer up to 8€/hour.

	Weeks	Mean number of hours per week	Cost per hour	Cost
Research	3	25	8€ / hour	600 €
Project Development	8	36	8€ / hour	2304 €
Optimization	2	36	8€ / hour	576 €
Simulations	3	45	8€ / hour	1080 €
MATLAB license	-	-	-	1000 €
TOTAL	-	-	-	**5560 €**

Table 4. Budget

6. Environment Impact

The environmental impact regarding the development of this work is positive. It is proposed the introduction of a secondary unlicensed link that uses the same spectrum as the primary licensed network. In addition, the secondary link uses two energy harvesting mechanisms, corresponding to the unique energy source to charge its battery either through a nature energy source, by recycling the received RF power from the antenna or both at the same time, depending on the node's action. The used energy harvesting techniques provides the nodes being self-sustaining devices and also environmentally friendly.

7. Conclusions and future development

The main conclusions drawn from this work are presented next.

The mixed energy harvesting scheme, based on nature and RF harvesting, along with the probabilistic channel access scheme, provide the cognitive system a way to manage efficiently the limited energy in the battery in order to optimize the secondary network throughput while preserving the QoS of in-band licensed communications.

Furthermore, it has been demonstrated that the energy-driven scheme attains the same throughput independently of the primary network framing (i.e., packet length) although the optimal access probabilities are in fact different depending on the actual packet length. It is proven that the sensing has to be as fast as possible (just one sample), except when the packets' length is long and the energy required for sensing is negligible with respect to the energy available in the battery. For those scenarios restricted by the energy of the battery, a small amount of samples has to be sensed, in order to save energy for future transmissions. For scenarios that have a surplus of energy, or when the energy required to sense the channel is not relevant, the number of sensed samples has also to be small enough so that the secondary transmissions do not interfere excessively onto the primary network bearing in mind that the power of secondary transmitters is increased after sensing to transmit reliably the same number of bits in a reduced interval of time. Only when the slot duration is sufficiently large, and the harvested energy is abundant, the sensing time can be increased without increasing significantly the interference onto the primary network.

Regarding the harvested power, it is concluded that, for $\alpha > 2$, the recycled RF power is an increasing monotonic function of the path loss exponent alpha, as a result of the power control mechanism of the primary network nodes. For the simulated scenario, the case $\alpha = 2$ is a particular one. For low primary activity values the system is EH limited while for high primary activity is interference restricted owing to the fact that represents the best case regarding EH but the worst one in terms of primary interference.

For energy-restricted scenarios, the optimization problem has been extended to also determine the optimal transmitted power of secondary nodes, resulting in an important increase of the secondary link throughput.

Regarding the future developments of this work, there are proposed 3 investigation lines in order to extend the energy harvesting, the optimization of the probabilistic scheme and the V2V application.

For the energy harvesting section, it is proposed a study on the variation of the obtained results when the system is not under favorable weather conditions, providing increasingly more importance to the RF power recycling. Moreover, as far as the optimization is concerned, it is proposed to optimize the power that the secondary nodes ought to transmit taking into account both channel access strategies (with or without sensing). Finally, for the V2V application, it would be interesting to evaluate during how much time the distance between two vehicles remains more or less constant in order to validate the approximation of temporal invariance of the V2V channel during the transmission time.

Bibliography

[1] Goldsmith, A., Jafar, S. A., Marić, I., & Srinivasa, S. (2009). Breaking spectrum gridlock with cognitive radios: An information theoretic perspective.*Proceedings of the IEEE*, *97*(5), 894-914.

[2] Akyildiz, I. F., Lo, B. F., & Balakrishnan, R. (2011). Cooperative spectrum sensing in cognitive radio networks: A survey. *Physical communication*, *4*(1), 40-62.

[3] Digham, F. F., Alouini, M. S., & Simon, M. K. (2007). On the energy detection of unknown signals over fading channels. *IEEE transactions on communications*, *55*(1), 21-24.

[4] Zou, Q., Zheng, S., & Sayed, A. H. (2010). Cooperative sensing via sequential detection. *Signal Processing, IEEE Transactions on*, *58*(12), 6266-6283.

[5] Lee, S., Zhang, R., & Huang, K. (2013). Opportunistic wireless energy harvesting in cognitive radio networks. *Wireless Communications, IEEE Transactions on*, *12*(9), 4788-4799.

[6] Bhuvaneswari, P. T. V., Balakumar, R., Vaidehi, V., & Balamuralidhar, P. (2009, July). Solar energy harvesting for wireless sensor networks. In*Computational Intelligence, Communication Systems and Networks, 2009. CICSYN'09. First International Conference on* (pp. 57-61). IEEE.

[7] Villares, J., Sala, J., & Rey, F. (2014, May). Interference power recycling in two-scale ad hoc wireless networks. In *Acoustics, Speech and Signal Processing (ICASSP), 2014 IEEE International Conference on* (pp. 4768-4772). IEEE.

[8] Ali, R. E., Digham, F. F., Seddik, K. G., Nafie, M., El-Keyi, A., & Han, Z. (2014, December). A probabilistic MAC for cognitive radio systems with energy harvesting nodes. In *Signal and Information Processing (GlobalSIP), 2014 IEEE Global Conference on* (pp. 143-147). IEEE.

[9] Lee, S., Zhang, R., & Huang, K. (2013). Opportunistic wireless energy harvesting in cognitive radio networks. *Wireless Communications, IEEE Transactions on*, *12*(9), 4788-4799.

[10] Park, S., & Hong, D. (2013). Optimal spectrum access for energy harvesting cognitive radio networks. *Wireless Communications, IEEE Transactions on*,*12*(12), 6166-6179.

[11] Wu, Q., & Zheng, J. Performance modeling and analysis of the ADHOC MAC protocol for vehicular networks. *Wireless Networks*, 1-14.

[12] Omar, H. A., Zhuang, W., & Li, L. (2011, April). VeMAC: a novel multichannel MAC protocol for vehicular ad hoc networks. In *Computer Communications Workshops (INFOCOM WKSHPS), 2011 IEEE Conference on* (pp. 413-418). IEEE.

[13] Onubogu, O., Ziri-Castro, K., Jayalath, D., Demmel, S., & Suzuki, H. (2014, November). Doppler and pathloss characterization for vehicle-to-vehicle communications at 5.8 GHz. In *Telecommunication Networks and Applications Conference (ATNAC), 2014 Australasian* (pp. 58-64). IEEE.

[14] Cheng, L., Henty, B. E., Stancil, D. D., Bai, F., & Mudalige, P. (2007). Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band.*Selected Areas in Communications, IEEE Journal on*, *25*(8), 1501-1516.

[15] Grant, M., Boyd, S., & Ye, Y. (2008). CVX: Matlab software for disciplined convex programming.

[16] Goldsmith, Andrea. *Wireless communications*. Cambridge university press, 2005.

[17] Cressie, Noel AC, and Noel A. Cassie. *Statistics for spatial data*. Vol. 900. New York: Wiley, 1993.

[18] Thompson, H. R. "Distribution of distance to nth neighbour in a population of randomly distributed individuals." *Ecology* (1956): 391-394.

Appendix 1. Primary nodes directivity

The directivity of an antenna with beam pattern equal to a spherical sector of horizontal and vertical angle ϕ is computed as $D(\phi) = 4\pi/\Omega_e(\phi)$, where $\Omega_e(\phi)$ is the equivalent solid angle seen from the antenna's focus.

Considering that the beam is orientated along the x-axis, the antenna's directivity $D(\phi)$ defines the following two-piecewise continuous function.

- For $\phi \leq \pi$, $t(\varphi, \theta) = 1 \quad |\varphi| \leq \frac{\phi}{2}, \left|\theta - \frac{\pi}{2}\right| \leq \frac{\phi}{2}$

$$\Omega_e(\phi) = \int_{-\frac{\phi}{2}}^{\frac{\phi}{2}} \int_{\frac{\pi}{2}-\frac{\phi}{2}}^{\frac{\pi}{2}+\frac{\phi}{2}} \sin(\theta) d\theta d\varphi = \phi \left[cos\left(\frac{\pi}{2} - \frac{\phi}{2}\right) - cos\left(\frac{\pi}{2} + \frac{\phi}{2}\right) \right] = 2\phi sin\left(\frac{\phi}{2}\right)$$

$$D(\phi) = \frac{2\pi}{\phi sin(\phi/2)}$$

- For $\pi \leq \phi \leq 2\pi$, $t(\varphi, \theta) = 1 \quad |\varphi| \leq \frac{\phi}{2}, \left|\theta - \frac{\pi}{2}\right| = \frac{\pi}{2}$

$$\Omega_e(\phi) = \int_{-\frac{\phi}{2}}^{\frac{\phi}{2}} \int_{0}^{\pi} \sin(\theta) d\theta d\varphi = 2\phi$$

$$D(\phi) = 2\pi/\phi$$

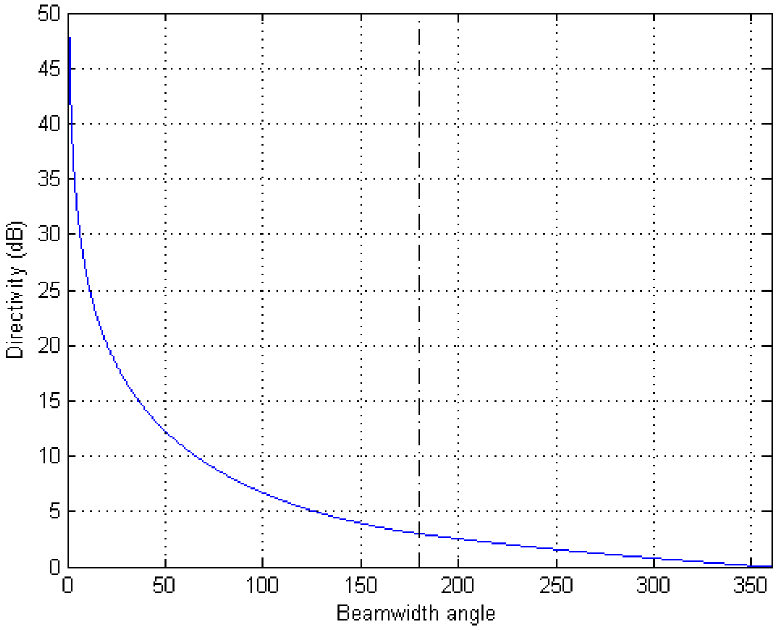


Figure 20. Primary nodes directivity.

Appendix 2. Probability of an active node becoming a transmitter

Given an HPPP of density ρ nodes/m^2 decomposed as the sum of two HPPP of densities ρp_A and $\rho(1-p_A)$, corresponding to the active nodes and the non-active nodes network, respectively, and whose active nodes follow the nearest neighbour protocol, then the probability that an active node becomes a transmitter, p_{tx}, follows the expression:

$$p_{tx} = E_{N_r,N_t}\left\{\sum_{k=0}^{N_t-1}\binom{N_t-1}{k}\left(\frac{1}{N_r}\right)^k\left(1-\frac{1}{N_r}\right)^{N_t-1-k}\frac{1}{k+1}\right\}$$

Where $N_t \sim Poisson(\rho p_A Area)$ and $N_r \sim Poisson(\rho(1-p_A)Area)$.

Demonstration

Let's assume that N_t and N_r are random variables conditioned to the values n_t and n_r, respectively.

In each slot realization, each $n_t(i)$ searches the nearest neighbour $n_r(j)$ with equal probability (i.e. $p = 1/n_r$). That is, the node $n_r(j)$ is the nearest non-active one to $n_t(i)$ following the Bernoulli random variable $I \sim B(1/n_r\,)$.

The probability that the node $n_r(j)$ has been chosen by k active nodes follows the Binomial random variable $I_1 + I_2 + \cdots + I_{n_t} \sim B(n_t, p)$. And so, the number of $k-$conflicts follows $X \sim B(n_t - 1, p)$.

When a non-active node $n_r(j)$ has k conflicts, then, statistically, each of the $k+1$ active nodes that has selected $n_r(j)$ have equal probability of being the chose transmitter.

Finally, the result is averaged by the $E\{\cdot\}$ operator regarding the RVs N_t and N_r.

$$p_{tx} = E_{N_r,N_t}\left\{\sum_{k=0}^{N_t-1} Pr\{X=k\}\frac{1}{k+1}\right\} = E_{N_r,N_t,X}\left\{\frac{1}{X(N_t,N_r)+1}\right\}$$

Corollary

Since the $Area$ leads to infinity, the number of conflicts X converges to a Poisson RV with parameter $(N_t-1)/N_r \approx N_t/N_r$, while the Poisson RVs N_t and N_r converge to Normal ones $N(\mu,\sigma^2)$ with the same mean and variance as before.

$$\frac{N_t}{N_r} \sim \frac{N(\rho p_A Area, \rho p_A Area\,)}{N(\rho(1-p_A)Area, \rho(1-p_A)Area)} = \frac{\rho p_A Area + \sqrt{\rho p_A Area}\,N(0,1)}{\rho(1-p_A)Area + \sqrt{\rho(1-p_A)Area}\,N(0,1)}$$

As $Area$ increases, the quotient N_t/N_r leads to a deterministic value, with better the approximation as the $Area$ increases.

The quotient N_t/N_r leads to $p_A/(1-p_A)$, regardless of the nodes' density ρ. Reducing the target probability to:

$$p_{tx} = E\left\{\frac{1}{X+1}\right\} \qquad X \sim Poisson\left(\frac{p_A}{1-p_A}\right)$$

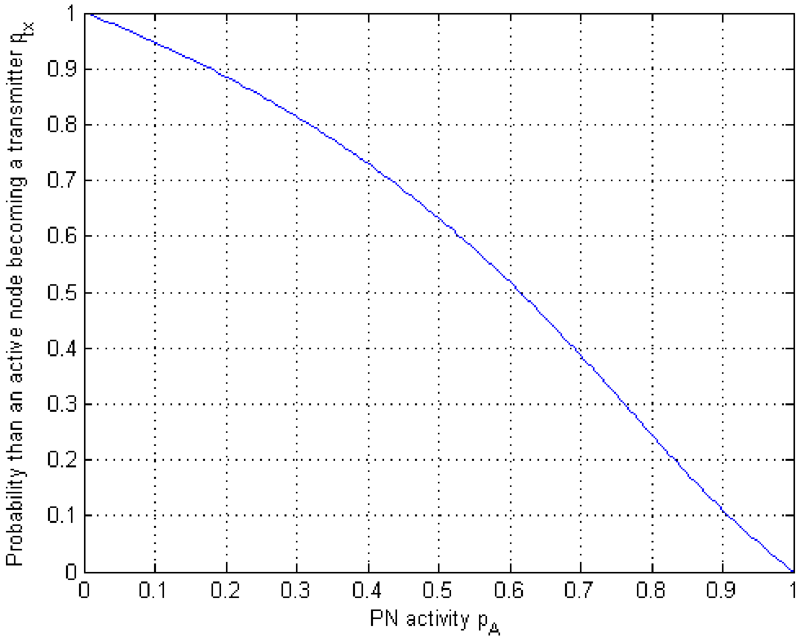


Figure 21. Probability than an active node becomes a transmitter as a function of the primary network activity.

As it shows the Figure 20, as increases the primary network activity the number of transmitter decreases due to the fact that statistically the fraction of active nodes regarding the non-active ones increases.

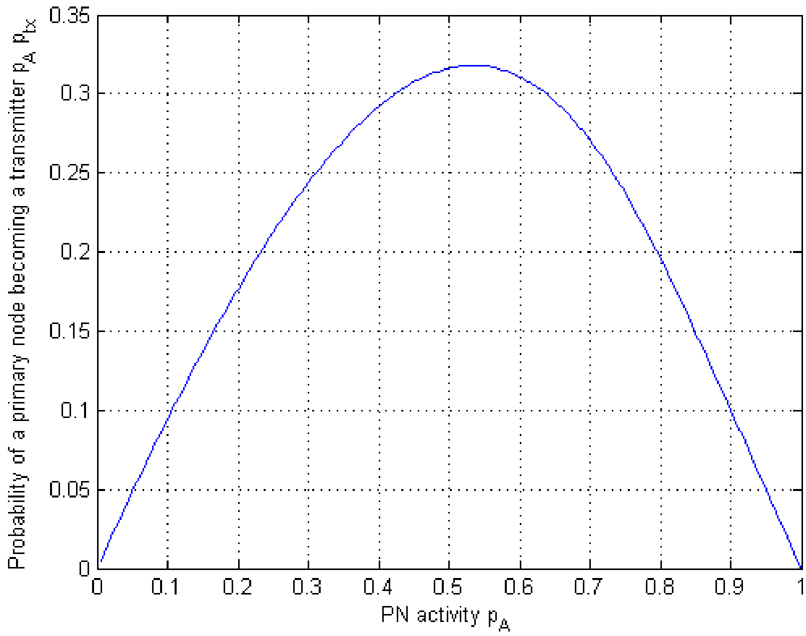


Figure 22. Equivalent transmitter's probability as a function of the primary network activity.

Glossary

A list of all acronyms and the meaning they stand for.

HPPP:	Homogeneous Point Poisson Process
QoS:	Quality of Service
MAC:	Medium Access Control
V2V:	Vehicle-To-Vehicle
CR:	Cognitive Radio
EH:	Energy Harvesting
RF:	Radio Frequency
MPR:	Multi-packet reception
ISM:	Industrial, Scientific and Medical
ST:	Secondary Transmitter
SR:	Secondary Receiver
PN:	Primary Network
PT:	Primary Transmitter
PR:	Primary Receiver