Cognitive networks: a Darwinian approach

Philippe Jacquet, Paul Muhlethaler

amsfonts,amsmath,amstext,verbatim amssymbsetspace ifpdf [pdftex]graphicx

Cognitive networks: a Darwinian approach

Philippe Jacquet, Paul Mühlethaler

ISSN 0249-6399 ISRN INRIA/RR--7892--FR+ENG

RESEARCH REPORT
N° 7892
February 2012
Project-Team HiPERCOM

Cognitive networks: a Darwinian approach

Philippe Jacquet*, Paul Mühlethaler†

Project-Team HiPERCOM

Research Report n° 7892 — February 2012 — 16 pages

Abstract: In this paper we present a new approach for cognitive radio. In the usual approach the secondary network is in charge of monitoring the channel to determine whether or not the primary network is active in the area. If not, the secondary network is allowed to use the spectrum. In the new scheme we propose, the primary network encompasses the techniques which allow it to capture the bandwidth even if the secondary network is transmitting in the area. The access scheme of the primary network is preemptive towards the secondary network. In this paper we present a scheme which is preemptive over the IEEE 802.11 decentralized access scheme. This protocol is a generalized Carrier Sense Multiple Access scheme using active signaling. Instead of only sensing the carrier, this algorithm also transmits bursts of signal which may be sensed by the other nodes. If so, they give up the selection process. We show that this scheme is preemptive over the IEEE 802.11 decentralized access scheme if the bursts transmitted by the node in the primary network are built with special sequences which alternate bursts of signal and periods of sensing. These sequences called (d, k) sequences [1] encompass a maximum number of zeros during which the node senses the channel to find other possible concurrent transmissions. In practice we use $d = 0$ and k depends on the duration on the IEEE 802.11 interframe and the duration of a signaling burst. We compute the number of $(0, k)$ sequences with respect to the length n of the sequence. We also show that (d, k) sequences (with $2d > k$) can used if by mistake during the the signaling phase one burst is not detected. We evaluate the number of such sequences. In a second part of this paper we propose a simple analytical model to compute the mean delay for the primary users versus the load of the primary and secondary users. We show that we have hierachical independence between the primary and secondary users [2]

Key-words: Cognitive network, primary and secondary network, Carrier Multiple Access (CSMA), active signaling, preemptive access, $d(d, k)$ sequences.

* Alcatel Bell Labs
† INRIA Paris-Rocquencourt

RESEARCH CENTRE
PARIS – ROCQUENCOURT

Domaine de Voluceau, - Rocquencourt
B.P. 105 - 78153 Le Chesnay Cedex

Réseaux cognitifs une approche darwinienne

Résumé : Dans ce papier nous présentons une nouvelle approche pour les réseaux cognitifs radio. Dans l'approche traditionnelle le réseau secondaire est en charge de la surveillance du canal pour déterminer si oui ou non le réseau primaire est actif dans dans la zone. Si ce n'est pas le cas, le réseau secondaire est autorisé à utiliser le spectre. Dans le nouveau mécanisme que nous proposons, le réseau primaire utilise une technique qui lui permet de préempter la bande passante même dans le cas où le réseau secondaire transmet dans cette zone. La technique d'accès du réseau primaire est préemptive sur le schéma décentralisé de la norme IEEE 802.11. Ce protocole est un système à détection de porteuse généralisé qui utilise un signalement actif. Au lieu d'uniquement sonder le canal avant la transmission, la technique d'accès envoie également des busrts de signal qui peuvent être détectés par les autres noeuds qui cherchent à transmettre. Si c'est le cas, ces noeuds abandonnent, pour ce cycle, leur tentative de transmission. Nous montrons que ce mécanisme est préemptif sur l'accès décentralisé de 802.11 si les enchaiments de transmission/écoute sont construits avec des séquences binaires spéciales. Ces séquences appelées (d, k) séquences doivent contenir un nombre un nombre maximal k de 0 successifs et un nombre minimum d. En pratique nous utiliserons $d = 0$ et k dépend de la durée des inter-trames dans 802.11 et de la durée des burts de signalement actifs. Nous calculons le nombre de $(0, k)$ séquences en fonction de k et de leur longueur n. Nous montrons également que des (d, k) séquences (avec $2d > k$) peuvent être utilisées pour pallier à la non détection d'un burst de signalement. Nous évaluons aussi le nombre de ces séquences. Dans une seconde partie de cet article nous calculons le délai moyen pour les utilisateurs du réseau primaires en fonction de la charge des réseaux primaire et secondaire. Nous montrons que nous avons une indépendance hiérachique des performances entre réseau primaire et secondaire.

Mots-clés : Réseau cognitif, réseau primaire et secondaire, détection de porteuse (CSMA), Signalement active, accès préemptif, (d, k) séquences

Cognitive networks: a Darwinian approach

Philippe Jacquet and Paul Mühlethaler
Alcatel Bell Labs - INRIA Paris-Rocquencourt
Philippe.Jacquet@inria.fr - Paul.Muhlethaler@inria.fr

February 22, 2012

n this paper we present a new approach for cognitive radio. In the usual approach the secondary network is in charge of monitoring the channel to determine whether or not the primary network is active in the area. If not, the secondary network is allowed to use the spectrum. In the new scheme we propose, the primary network encompasses the techniques which allow it to capture the bandwidth even if the secondary network is transmitting in the area. The access scheme of the primary network is preemptive towards the secondary network. In this paper we present a scheme which is preemptive over the IEEE 802.11 decentralized access scheme. This protocol is a generalized Carrier Sense Multiple Access scheme using active signaling. Instead of only sensing the carrier, this algorithm also transmits bursts of signal which may be sensed by the other nodes. If so, they give up the selection process. We show that this scheme is preemptive over the IEEE 802.11 decentralized access scheme if the bursts transmitted by the node in the primary network are built with special sequences which alternate bursts of signal and periods of sensing. These sequences called (d, k) sequences [1] encompass a maximum number of zeros during which the node senses the channel to find other possible concurrent transmissions. In practice we use $d = 0$ and k depends on the duration on the IEEE 802.11 interframe and the duration of a signaling burst. We compute the number of $(0, k)$ sequences with respect to the length n of th sequence. We also show that (d, k) sequences (with $2d > k$) can used if by mistake during the the signaling phase one burst is not detected. We evaluate the number of such sequences. In a second part of this paper we propose a simple analytical model to compute the mean delay for the primary users versus the load of the primary and secondary users. We show that we have hierarchical independence between the primary and secondary users [2].

1 Introduction

Economically, the existence of cognitive networks is justified by the fact that many spectra are not fully used by their dedicated users, and therefore allowing secondary users access will give the opportunity to fully use the bandwiths and provide more spectrum to users. This is particularly true when part of the bandwidth is reserved for applications that have not yet been developed. The time necessary for such applications to come on to market may be long or may simply never occur (due to reasons other than technological), and precious bandwidth may simply be wasted for a substantially long period. Therefore the FCC has edicted that any bandwidth dedicated to a new usage should also accept secondary users in the context of cognitive networks.

* Alcatel Bell Labs
† INRIA Paris-Rocquencourt

Cognitive networks are radio networks where each band of frequency is occupied by two groups of users: the primary users that form the primary network and the secondary users that form the secondary network. The primary users are supposed to have priority over the secondary users: *i.e.* the performance of the primary network should be protected against the traffic of the secondary network. By protection we mean that the performance of the primary network should be guaranteed independently of the demand from the secondary network. Furthermore, the throughput and occupancy of the secondary network should vanish when the traffic load of the primary network increases. In other words the secondary users are only allowed to take the blank periods left by the primary users.

The problem is that the protocol used by the primary users, in short the primary protocol, often comes after a standardization process that ignores the secondary users. The consequence is that the design of the secondary protocol is sometimes harder and more costly than the design of the primary protocol because the secondary protocol must indeed embed the features of the primary protocol in order to knowledgeably give priority to primary user. This is a kind of "Anti-Darwinian" approach because the technological burden is on the secondary users while the market success is guaranteed to the primary protocols. In an analogy with evolution, it is as if the most sophisticated specie should automatically lose against the less sophisticated. The result would be that the spectrum may not be fully used and result into an economic failure.

In this paper we present an alternative and more natural approach to cognitive networks that we call the "Darwinian Approach". The approach consists into identifying a priori an already standardized protocol for the secondary user, for example the IEEE 802.11 standards, and then giving the burden of designing a primary protocol that naturally pre-empt the secondary protocol. Pre-empting the IEEE 802.11 standard is not difficult it suffices to define a primary protocol with smaller DIFS. With this strategy the advantages are:

1. the succes to market of the secondary user is guaranteed, since the secondary protocol is already available; therefore the spectrum is immediately fully used;

2. the technological investment for the primary users is guaranteed by its enforced priority over the secondary users.

In contrast to previous approaches [3] we adopt a strategy where the sharing rules are mostly implemented in the primary network. Usually the secondary network encompasses mechanisms which allow this network to resume its transmission if the primary network is not using the channel. Here the secondary network uses the IEEE 802.11 decentralized MAC scheme. The key is a preemptive access implemented in the primary network. When both networks coexist, the secondary network captures the bandwidth, when there is no activity in the primary network and in a given area (or even no network nodes at all) the secondary network can use the bandwidth without any modification to its normal mode of operation.

The paper is organized as follows. Section 2 presents related work. Section 3 describes the technique used by the primary network to share the spectrum between its nodes and to preempt the bandwidth to the secondary users. This MAC access scheme is

2 Related work

In cognitive radio we can distinguish two different issues. The first issue is sensing which is a key feature in cognitive radio networks since it allows the secondary network to be aware of the existence of primary nodes within a given area. The other issue is medium access which is also a central issue since smart access techniques can be used by cognitive radio networks to efficiently share the medium.

Traditional approaches limit the transmitter power of the secondary nodes in order that the transmitted power be below a given threshold at a given distance from the transmitter. However with the mobility of nodes, it is difficult to constrain the transmitter power as new nodes may appear at any time. To cope with this issue, the FCC tried to introduce a new metric: the interference temperature. The goal was to keep the interference experienced by the receivers below a given threshold. The secondary nodes must ensure that their transmission plus the already existing noise does not exceed the interference temperature limit at the primary nodes. This can be controlled for instance by a sensor network [3] which monitors the energy in different locations of the network. However it has been argued that this concept of temperature tends to increase the interference in the frequency bands where it would be used and that it is not a workable concept. Thus in 2007 the FCC gave up trying to build coexistence rules based on interference temperature. Energy detection is the most common type of spectrum sensing. The presence or the absence of transmissions of the primary network must be established based on measurements of the radio signal. We are faced with the usual paradigm of detection which must be done with the contradictory goals of minimizing the probability of missing a detection while also minimizing the probability of a false alarm (detecting a primary node when no such node exists). The detection usually uses the inherent periodicities such as the modulation rate, carrier frequency, etc. see [4, 5]. If the secondary nodes have access to information about the signal sent by the primary network, then the matched filter is the optimal detection method, see [6]. There are many other sensing techniques such as those described in [3, 7, 8, 9]

As regards cognitive access techniques, an interesting classification distinguishes between DAB (Direct Access Based) protocols and DSA (Dynamic Spectrum Allocation) protocols. In DAB protocols there is no global network optimization, each sender-receiver pair in the cognitive network tries to take the best advantage of the available resources using very simple algorithms. In contrast, DSA protocols look for the optimization of a global criterion and use much more complex schemes.

In DAB protocols we can again distinguish between contention-based protocols and coordination-based protocols. In contention-based protocols the cognitive nodes exchange their sensing results using a simple handshake, examples of such protocols are given in [10, 11, 12] . Then the sender-receiver pair analyzes available resources and negotiates the channel that will be used to communicate. In coordination based protocols each cognitive node shares its channel usage information with its neighbors to gain a better view of the overall utilization of the channels. Examples of such protocols are given in [13, 14, 15, 16]

DSA protocols exploit complex optimization algorithms to optimize a global criterion. For instance DSA protocol may use graph coloring theory [17], game theory [18], stochastic theory [19] or also genetic algorithms.

3 Primary network CSMA technique with active signaling

The IEEE 802.11 decentralized medium access scheme uses a linear backoff. At the end of a transmission i.e. after the end of the packet (followed by its acknowledgement packet for point-to-point packets), a node which has pending packets waits for the interframe spacing. After this time interval, the node waits for a random number of collision slots (it decrements its backoff time) and after this time interval elapses, the node sends a packet. If another node sends a packet before the first node has finished decrementing its backoff, the first node resumes decrementing its backoff after the current transmission. We have an example of this situation in Figure 1. Station B has a backoff of 4 mini-slots whereas station C has a backoff of 6 mini-slots. Thus station B sends its packet at the end of station A's transmission (including the acknowledgement for point-to-point packets) and 4 mini-slots. Station C waits for the end of station B's transmission and waits for an additional 2 mini-slots before sending its packet. We notice that the interval between a packet and its acknowledgement packet is a Short InterFrame Space (SIFS). After the acknowledgement packet, the other nodes which are waiting to transmit a packet must wait for a Distributed InterFrame Space (DISF) to start decrementing their backoff. This mechanism requires that the duration of a SIFS is smaller than the duration of a DISF, with this situation the backoff is not decremented between a packet and its acknowledgement.

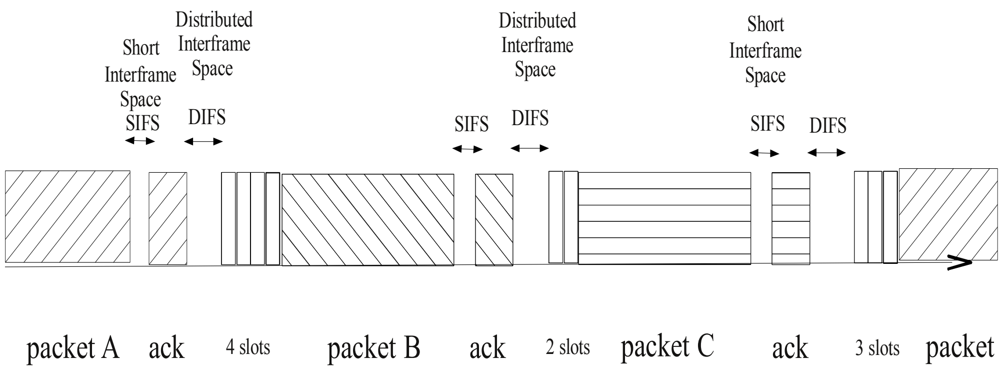

Figure 1: Example of the linear back-off used by the IEEE 802.11 MAC.

The generalized CSMA technique we propose introduces the concept of active signaling, which is the basis of HiPERLAN type 1 [20]. Rather than performing the carrier sense during a time interval, the technique we propose allows the protocol to switch between bursts of signal and periods of sensing. The general CSMA rule remains the same: as soon as an energy above a given threshold is sensed then the station quits the selection process and waits for the end of the current selection process with the transmission of a packet to start competing again. A simple way to describe the station's activity during the signaling period is to code the signaling period with "1" or "0". 1 represents a transmission burst and "0" a sensing interval. Thus the signaling burst "101" is composed of a signaling burst, a sensing interval and another signaling burst. The active signaling burst which is shown in Figure 3 can be represented by the binary sequence "111001110000110". We can notice that this sensing rule is such that the station with the highest binary sequence is selected for transmission. Then comes the second highest and so on. The interframe between a packet and its acknowledgement is still a SISF but the time interval between the end of the acknowledgement packet and the beginning of the signaling part is a Burst InterFrame Space (BIFS). If each node always uses the same binary sequence to govern its access then the nodes which use binary sequences coding large integers in base 2 should have more access opportunities than nodes which use binary sequences coding small integers in base 2. To cope with this fairness issue we can add the following rule : the same node must observe an idle interval of at least one Large Burst InterFrame Space (LBIFS) to be allowed to start its signaling phase, see Figure 4. In order to preserve the priority of the primary network over the secondary network, the duration of the LBIFS must be smaller than the duration of the DIFS. The duration of the LBIFS should also be larger than the duration of BIFS. This implies that nodes even with binary sequences coding smaller integers in base 2 than the binary sequence used by node A will have priority to send their packet. This mechanism creates “epochs”, two successive epochs being separated by an idle period with a duration of at least one BIFS. Another solution to obtain a fair access is to draw the binary sequences used in the primary network at random.

In the following we study the timing constraints to insure that the secondary network nodes only get access to the channel when the primary network nodes have no traffic to send. The first constraint is that the BIFS is smaller than the DIFS. This gives a prioritized access to the primary network nodes. Moreover, to insure that a BIFS can not be interpreted as a DIFS it is mandatory that the first bit of the binary sequences used in the generalized CSMA be a ’1’. A little less strict condition is that the duration of the BIFS plus the duration of the beginning of listening bursts at the head of the binary sequence have a duration smaller than the duration of the DIFS.

If we satisfy the constraints the generalized CSMA technique used for the primary network will preempt the access of a secondary user using the decentralized IEEE 802.11 MAC protocol. However another constraint is necessary to ensure that the secondary network can not insert transmissions in the signaling period of the primary network. To avoid that the binary sequence used in the primary network must not contain too many successive zeros. The duration of a sequence of listening coded by successive zeros should be shorter than a DISF, see Figure 1. In this case the nodes using the IEEE 802.11 access scheme do not start decrementing their backoff during the sensing intervals of the signaling bursts of the primary network and no packet of the secondary nework can be inserted.

Burst or interframe	duration
1 burst	9 μs
SIFS	10 μs
BIFS	30 μs
LBIFS	40 μs
DIFS	50 μs

Figure 2: Duration of the bursts and the interframes

In Figure 2 we find the values used in the IEEE 802.11 for the SIFS and DIFS. We have also proposed values for the duration of the BIFS ($30\mu s$) and the LBIFS ($40\mu s$).

An interesting tool to govern access in the primary network is the (d, k) binary sequences as introduced in [1]. These binary sequences contain strings of ’0’ where 0 appears at least d times and at most k times between two successive ’1’. For our application we use $d = 0$ and the maximum value of k can be easily computed with the duration of the Distributed Interframe Space of the IEEE 802.11 MAC scheme d_{DIFS} and the duration of the signaling burst d_{sb}, $k = k_1 = \lfloor \frac{d_{DIFS}}{d_{sb}} \rfloor$. If the primary network uses the CSMA technique with active signaling and $(0, k_1)$ binary sequence then we are sure that during the signaling period of a primary network node there is no listening period (i.e. idle period) of length greater than d_{IFS}. In other words, the IEEE 802.11 access scheme can not start decrementing its backoff in the signaling period of the primary network and thus no transmission can be inserted in the active signaling period of the primary network.

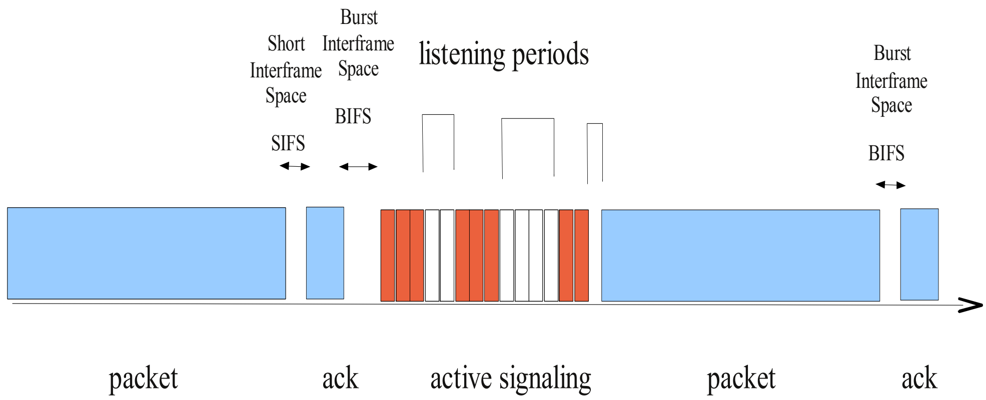

Figure 3: Signaling burst in the generalized CSMA technique proposed.

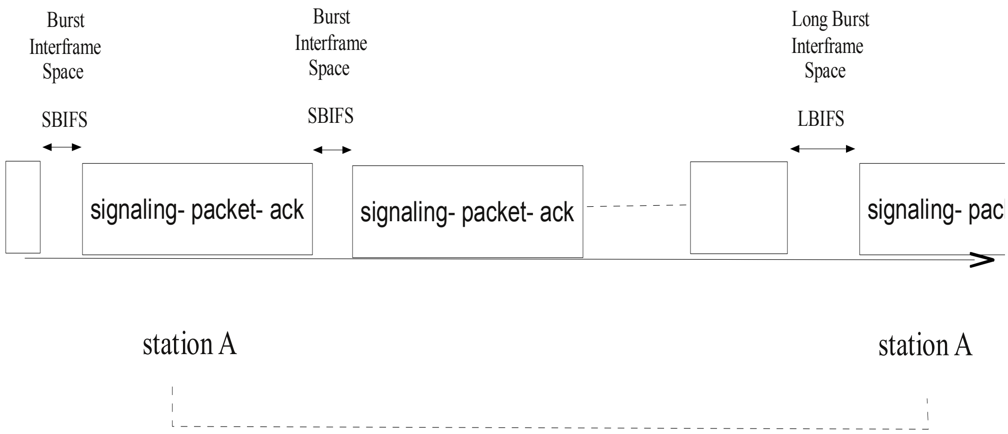

Figure 4: Fairness with the signaling burst CSMA technique proposed.

4 k sequences

In this section, we recall results obtained in [1] concerning $(0, k)$ sequences; for simplicity we use the same notations. We compute the number of $(0, k)$ sequences for a given length n. In these strings the number of zeros between two consecutive 'ones' is larger or equal to 0 and less or equal to k. We introduce the generating function $W(z)$ of these $(0, k)$ sequences which start with one 'one'. We also introduce the generating function $X(z)$ of $(0, k)$ sequences which start by up to l zeros. Let us denote by n the length of these strings, $W(z)$ is defined by

$$W(z) = \sum_{n \geq 0} W_n z^n$$

where W_n denotes the number of $(0,k)$ sequences of length n. Similarily we denote $X(z) = \sum_{n\geq 0} X_n z^n$ A similar approach as that used in [1] allows $W(z)$ and $X(z)$ to be computed. If we introduce $A(z) = \sum_{n=0}^{k} z^n$ and $B(z) = \sum_{n=0}^{l} z^n$ then we have :

$$W(z) = \frac{1}{1 - zA(z)}.$$

$$X(z) = \frac{B(z)}{1 - zA(z)}.$$

The number of $(0,k)$ sequences of length n is simply the coefficient of z^n in the generating functions $W(z)$ and $X(z)$. We denote it $[z^n]W(z)$ and $[z^n]X(z)$. We can easily compute it using Maple. Another way to evaluate W_n and X_n is to use Cauchy's formula. Let us denote $E(z) = zA(z)$. We notice that $E(0) = 0$ and $E(1) = k + 1 \geq 2$. $E(z)$ is an increasing function. Let us denote ρ_0 the real root of $B(z)$, this root has the smallest norm $|\rho_0|$ among the other complex roots of $B(z)$. We fix $\lambda_0 = 1/\rho_0$ and we assume $r < \lambda_0$. Cauchy's formula gives :

$$W_n = \frac{\lambda_0^{n+1}}{\lambda_0 + A'(\rho_0)\rho_0} + 0(r^n).$$

$$X_n = \frac{B(\rho_0)\lambda_0^{n+1}}{\lambda_0 + A'(\rho_0)\rho_0} + 0(r^n).$$

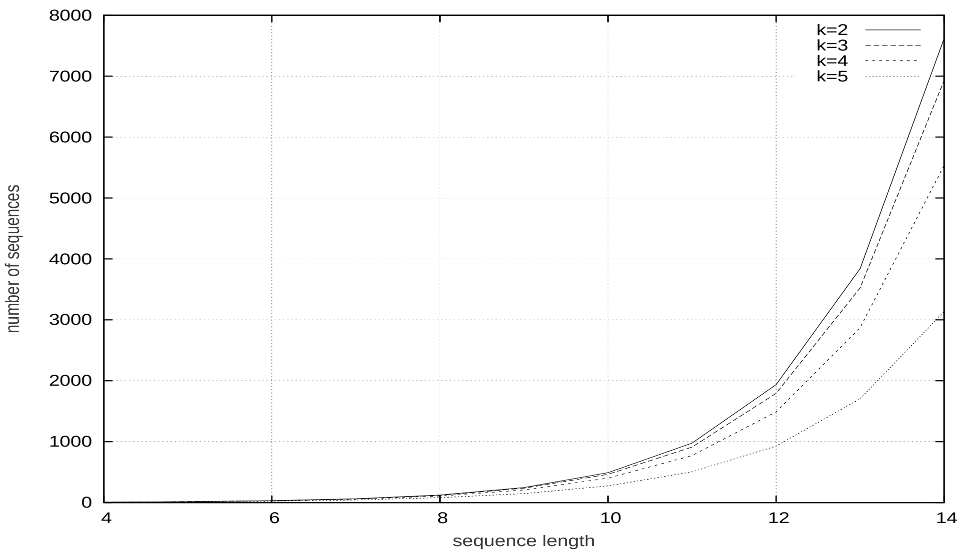

Figure 5: Number of $(0,k)$ sequences of length n.

In Figure 5 we give the number of $(0,k)$ sequences of length n starting with one 'one' for $k = 2, 3, 4, 5$. In this Figure we can observe the reduction in the number of sequences when k decreases. If we wish to have more sequences we can allow up to l zeros at the beginning of the $(0,k)$ sequences.

In Figures 6 we compare the number of $(0,k)$ sequences of length n starting with one 'one' with the number of $(0,k)$ sequences of length n which start with up to l zeros. With the values given in Figure 2 we take $k = 5$ and $l = 2$. We observe that putting the constraint of starting the $(0,k)$ sequence with one 'one' whereas the constraint concerning the maximum duration of a silent interval ($< d_{DIFS}$) allows one to use up to $l = 2$ zeros at the head of the sequence results in getting significantly more sequences. This may be useful if the primary network may contain a large number of nodes.

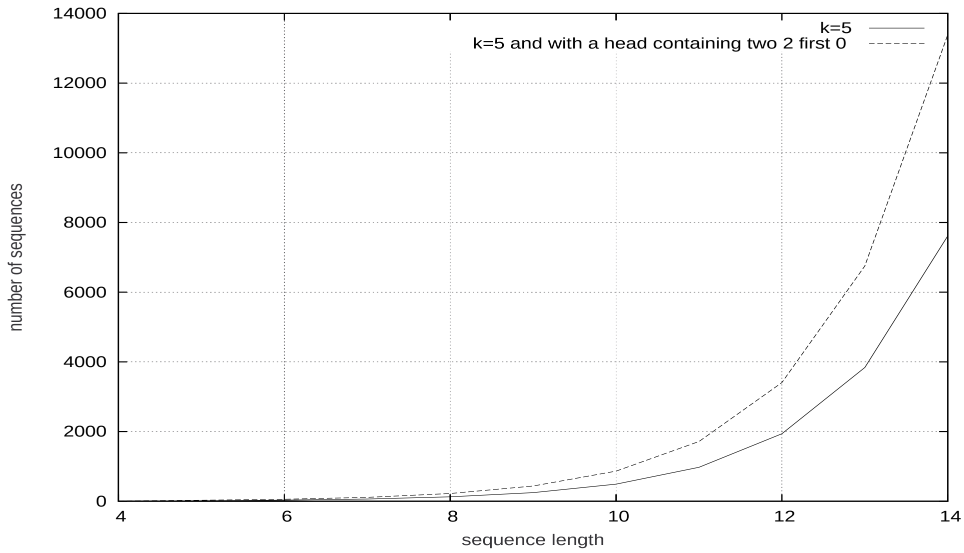

Figure 6: Comparison between the number of $(0,5)$ sequences of length n with 1 at the head and with the number of $(0,5)$ sequences of length n with up to 2 zeros at the head followed by a 1.

If by mistake during the signaling phase, one burst is not detected by a node which is in a listening period this may lead to two nodes sending simultneously a packet (collision). This can be avoid by using (d,k) sequences. It is obvious to show that two (d,k) sequences have a hamming distances greater or equal to 2 if and only if $2d > k$. With this condition the miss-detection of one burst can be tolerated without creating a collision. We can thus use sequence composed as follows one 'one' followed between d to k zeros (this pattern can be iterated an infinite number of times). The sequence is finished by one 'one' or nothing. We denote by $Y(z)$ the generating function of the length of these sequences. We can also use sequence composed as follows up to l zeros at the head and 'one' followed between d to k zeros (this latter pattern can be iterated an infinite number of times). The sequence is finished by one 'one' or nothing. We denote by $Z(z)$ the generating function of the length of these sequences. Using the methodology of [1] and denoting $C(z) = \sum_{i=d}^{i=k} z^n$ it can be shown that

$$Y(z) = \frac{(1+z)}{1 - zC(z)},$$

$$Z(z) = \frac{B(z)(1+z)}{1 - zC(z)}.$$

Thus we have:

$$Y_n = \frac{B(\tau_0)(1+\tau_0)\mu_0^{n+1}}{\mu_0 + C'(\tau_0)\tau_0} + 0(r^n).$$

$$Z_n = \frac{B(\tau_0)(1+\tau_0)\mu_0^{n+1}}{\mu_0 + C'(\tau_0)\tau_0} + 0(r^n).$$

with $0 < \tau_0 < 1$ satisfying $\tau_0 C(\tau_0) = 1$ and $\mu_o = 1/\tau_0$.

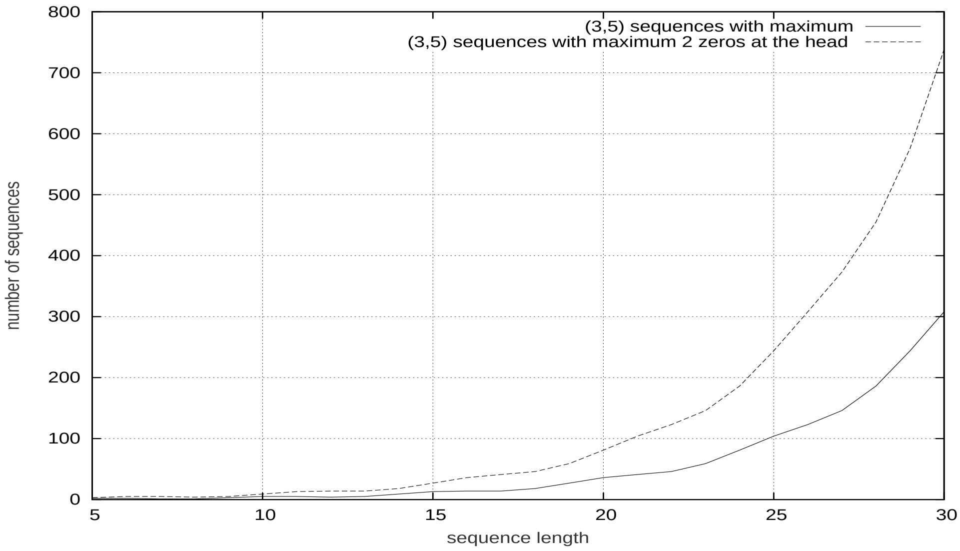

Figure 7: Number of $(3,5)$ sequences of length n starting with one 'one' and number of $(3,5)$ sequences with up to 2 zeros at the head.

In Figure 7 we show the number of $(3,5)$ sequences of length n of length n starting with one 'one' and the number of $(3,5)$ sequences with up to 2 zeros at the head. We observe that the number of available sequences is very significantly reduced compared to the number of $(0,5)$ sequences as shown in Figure 6. If the primary network contains a large number of nodes it may be better to cope with collisions than to use $(3,5)$ sequences because in this case we must set n to a large value. Thus we have to pay for a large signaling overhead for each transmission.

5 Performance analysis in the presence of secondary users

In the following we consider N primary users and an indefinite number of secondary users. We assume that the input load of the primary users is λ_p uniformly distributed over the N primary users and expressed in packets per second. The output traffic of the secondary users is μ_s, including collisions.

We evaluate the average delay of the primary protocols in the presence of the secondary traffic and show that it has a stable upper-bound depending on λ_p.

To simplify, we assume that all packets (primary and secondary) have the same length L. Notice that in this case $\mu_s L \leq 1$. Primary users add a (d,k) signal overhead of length d_N to each packet. We have seen that $d_N = O(\log N)$ when $N \to \infty$.

Our aim is to give an estimate of the performance of the primary protocol when $N \to \infty$. To this end we assume the *non congestion condition*, i.e., there exists $\epsilon > 0$ such that $\lambda_p = \lambda_p(N)$ is a decreasing sequence such that for all N: $\lambda_p(N)L < 1 - \epsilon$.

The nature of the primary protocol ensures that the busy periods for the primary users are equivalent to the busy periods of an M/D/1 system with Poisson arrival of rate λ_p and deterministic service time $L_N = d_N + L$, except for the first service which is L only. The consequence is that the average primary busy period is equal to $\frac{\lambda_p L}{1-\lambda_p L_N}$ which is bounded according to the non congestion condition.

Since the inter-arrival time between packets on each primary node is equal to $\frac{N}{\lambda_p}$, the probability that a packet must wait after another packet in a primary node buffer is $O(\frac{\lambda_p}{N})$ and the average delay in such a situation is therefore $O(\frac{\lambda_p L_N}{N})$.

More precisely, the number of packets in an M/D/1 busy period starting with n packets is M_n with

$$M_n = \alpha n$$

with $\alpha = (1-\lambda_p L_N)^{-1}$. Similarly, the average cumulated delays (excluding transmission delays) in an M/D/1 busy period starting with n packets is W_n with

$$W_n = \frac{L_N}{2}\left(\alpha n(n-1) + (\beta+\beta^2)n\right) ,$$

with $\beta = \alpha\lambda_p L_N$.

Consequently the average additional packets $E(M)$ in a primary busy period starting with a packet of length L and the average cumulated delays $E(W)$ satisfy:

$$E(M) = \alpha\lambda_p L \tag{1}$$

$$E(W) = \frac{L_N}{2}\left(\alpha(\lambda_p L)^2 + (\beta+\beta^2)\lambda_p L\right) \tag{2}$$

Let a be the average duration of the blank period between primary busy periods and p be the probability that the first packet that initiates a primary busy period is a primary packet.

We have the equilibrium condition:

$$\begin{cases} \lambda_p & = & \frac{p+E(M)}{a+L+LE(M)} \\ \mu_s & = & \frac{1-p}{a+L+LE(M)} \end{cases}$$

This leads to:

$$\begin{cases} a & = & \frac{1+E(M)}{\lambda_p+\mu_s} - L - LE(M) \\ p & = & \frac{\lambda_p}{\lambda_p+\mu_s} - \frac{\mu_s}{\lambda_p+\mu_s}E(M) \end{cases}$$

We notice that since $p > 0$ we must have $\lambda_p > \alpha\lambda_p L\mu_s$, which implies that $\mu_s L + \lambda_p L_N < 1$. When the input load of the secondary network exceeds the quantity $1-\lambda_p L_N$, then the output load is bounded by $\frac{1}{L}(1-\lambda_p L_N)$. The interpretation of the factor a is that when $a = 0$, then the network is overloaded by the primary and secondary demand, but the primary network is not necessarily congested. When $p = 0$ then either $\lambda_p = 0$ or the secondary network is congested (in this case $a = 0$).

Consequently the average delay (excluding transmission delay) of the primary packets is equal to:

$$\frac{E(W)}{p+E(M)} = (\lambda_p+\mu_s)\frac{1-\lambda_p L_N}{1-\lambda_p d_N}\frac{LL_N}{2}(\alpha\lambda_p L + \beta + \beta^2) .$$

We fix $L = 1000\mu$sec and $d_N = 100\mu$sec, therefore compatible with a primary network of $N = 1000$. In figure 8 we show the average delay of the primary network when $L\lambda_p = 0.5$ with a varying μ_s. We see that the average delay is bounded. In fact μ_s cannot exceed $\frac{1}{L}(1-\lambda_p L_N)$; a higher value means that the input load of the secondary network exceeds this limit but does not affect the performance of the primary network. In figure 9 we display the average delay in the primary network when the output load in the secondary network is fixed to $\mu_s L = \frac{1}{2}$.

The analysis of higher moments requires a refined analysis, since the average delay in the busy periods does not need to take into account the order in which the packets are transmitted.

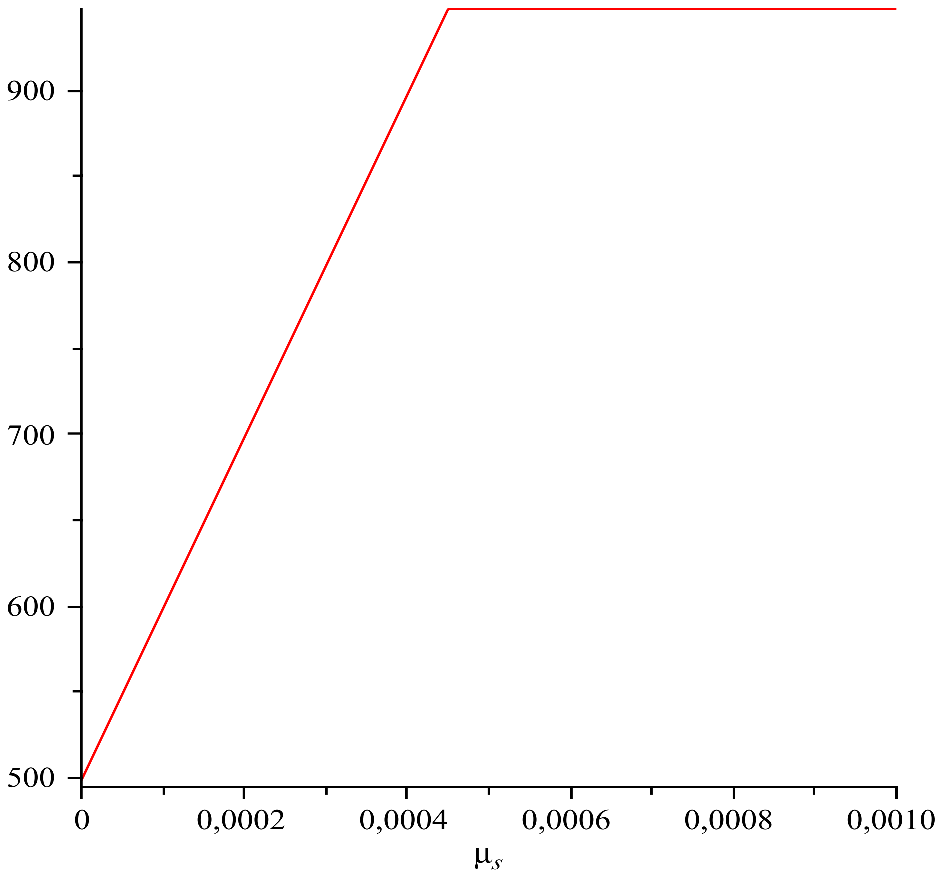

Figure 8: Average delay in μsec for $\lambda_p L = \frac{1}{2}$ and variable μ_s.

A busy period of the primary network is made up of a sequence of epochs that follow a first packet which is either of primary or secondary origin. We denote by N_k the number of primary packets in the k-th epochs that follow a given first packet. The busy period ends at the first k such that $N_k = 0$. By convention we assume that the $N_{k'} = 0$ for all $k' \geq k$. In this way, we can consider that each busy period is represented by an infinite sequence $\{N_k\}$, with only a finite number of non zero coefficients.

In the following,we assume that all packets generated on the $k-1$-th epoch are transmitted during the k-th epoch. This is not really true, since for the sake of fairness we assume that nodes only transmit their *first* packet in their buffer at each epoch. Nevertheless, this modification does not change the performance when $N \to \infty$ since we already know that the buffering has a vanishing effect.

We denote $P_k(z) = E(z^{N_k})$ for z complex undefined. We know that the number of packets generated during the emission of a packet of length L is Poisson of parameter $\lambda_p L$. In other words:

$$P_1(z) = \exp(\lambda_p L(z-1)) \ .$$

The duration of the first epoch is equal to $N_1(d_N + L)$, therefore for N_1 fixed, the number N_2 is Poisson of parameter $\lambda_p N_1(d_N + L)$. In other words:

$$P_2(z) \quad = \quad P_1(\exp(\lambda_p(d_N + L)(z-1))$$

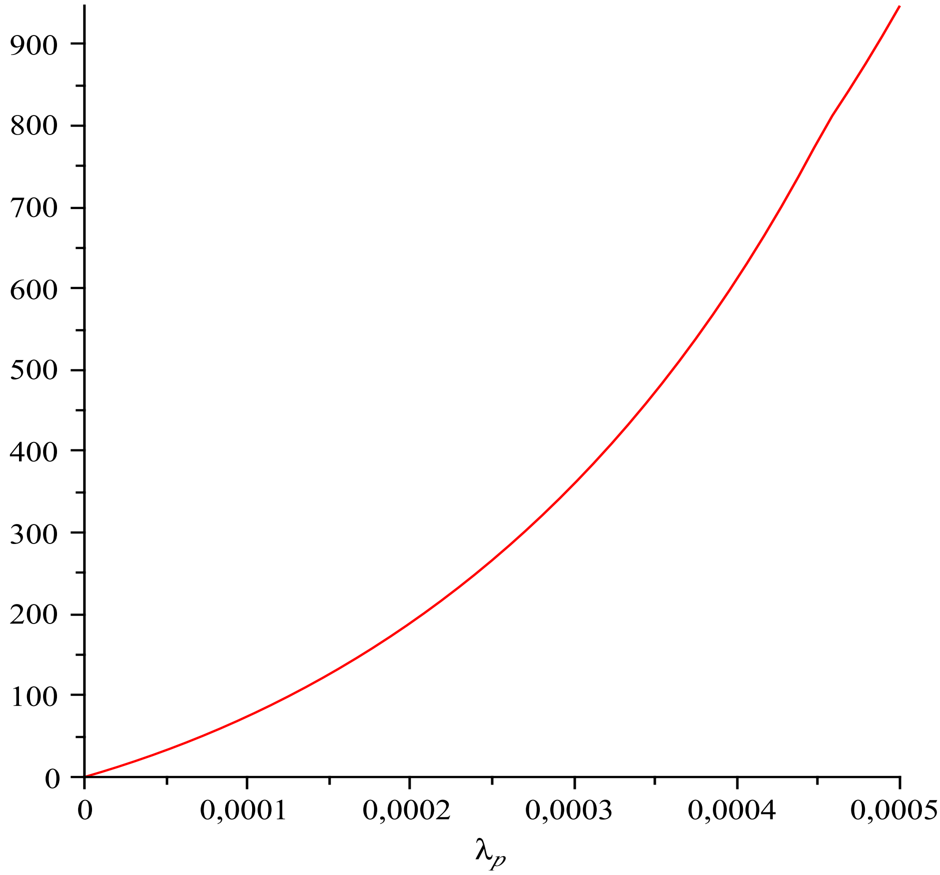

Figure 9: Average delay in μsec for $\mu_s L = \frac{1}{2}$ and variable λ_p.

$$= \exp(\exp(\lambda_p(d_N + L)(z-1) - 1) \ .$$

And similarly:

$$\begin{aligned} P_{k+1}(z) &= P_k(e(z, \lambda_p)) \\ &= \exp(e^{(k)}(z, \lambda_p) - 1) \ , \end{aligned}$$

with $e(z, \lambda_p) = \exp(\lambda_p(d_N + L)(z-1)$ and $e^{(k)}(z, \lambda_p)$ is the k-th composition of function $e(z, \lambda_p)$ by itself (on the variable z).

If the length L of the packets had been variable, then $e(z, \lambda_p) = E(\exp(-\lambda_p L(z-1))$, a function of the Laplace generating function of the packet length.

6 Conclusion

In this paper we have proposed a new scheme for cognitive radio in which the intelligence lies in the primary network. The active signaling technique is used by the primary network to preempt the channel when the secondary uses it. The access is fair among the nodes of the primary network. The nodes of the primary network preempt the bandwidth to the nodes of the secondary network. We study the timing constraints to obtain the previous property. We also define the rule to obtain a fair distribution among the nodes in the primary network if these nodes always use the same pattern in the signaling phase.

The main constraint to ensure that the primary nodes have always the priority when they acccess the channel with nodes of the secondary network is that there is no idle interval in the signaling phase of the primary network greater that the Distributed InterFrame Space (DIFS). The primary network must use (d, k) binary sequences in which to successive ones are separated by at least d zeros and at most k zeros to build the signaling burst. Here we must use $d = 0$ and $k = \lfloor \frac{d_{DIFS}}{d_{sb}} \rfloor$. We study the number of these sequences in function of their length n. We investigate how the constraints can be slightly relaxed and the benefit in terms of number additional sequences which can be used. We also consider the case where a primary node may miss the detection of one burst (in exactly one interval). To cope with such a case, we propose to use (d, k) with $2d > k$. For a given length, we compute the number of available sequences. We observe that the number of sequences is very reduced. Thus it may be better to allow a few collisions to occur and to resolve them by retransmitting rather than using (d, k) sequences with $2d > k$ which lead to a large overhead if a large number of sequences is needed.

In a second part of this paper we propose a simple analytical model to compute the mean delay for the primary users versus the load of the primary and secondary users. We proove that we have hierachical independence between the primary and secondary users [2].

References

[1] P. Jacquet and B. Szpankowski, "On (d, k) sequences not containing a given word," in *Proc. of IEEE ISIT*, Seattle, 2006.

[2] R. Rom and F. A. Tobagi, "Message-based priority functions in local multiaccess communication systems," *Computer Networks (1976)*, vol. 5, no. 4, pp. 273 – 286, 1981. [Online]. Available: http://www.sciencedirect.com/science/article/pii/0376507581900040

[3] S. Haykin, "Cognitive radio: Brain-empowered wireless communications." *IEEE J. Sel. Areas Comm*, vol. 23 no 2, pp. 201–220, 2005.

[4] W. Gardner, "Signal interception: a unifying theoretical framework for feature detection," *IEEE Trans. CommunJ. Sel. Areas Comm*, vol. 36 no 8, pp. 897–906, 1998.

[5] M. Oner and F. Jondral, "Air interface recognition for a software radio system exploiting cyclostationarity," in *PIMRC*, Barcelona, 2004.

[6] J. Proakis, *Digital Communications*. New-York: McGraw-Hill, 2001.

[7] B. Farhang-Boroujeny, "Filter bank spectrum sensing for cognitive radios," *Signal Processing, IEEE Transactions on*, vol. 56, no. 5, pp. 1801 –1811, may 2008.

[8] H. Li, C. Li, and H. Dai, "Quickest spectrum sensing in cognitive radio," in *Information Sciences and Systems, 2008. CISS 2008. 42nd Annual Conference on*, march 2008, pp. 203 –208.

[9] H. Kim and K. Shin, "Fast discovery of spectrum opportunities in cognitive radio networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, oct 2008, pp. 1 –12.

[10] J. Jia, Q. Zhang, and X. Shen, "HC-MAC: A hardware-constrained cognitive MAC for efficient spectrum management," in *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, jan 2008, pp. 106–117.

[11] X. Wang, P.-H. Ho, and A. Wong, "Towards efficient spectrum sensing for cognitive radio through knowledge-based reasoning," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, 2008, pp. 1 –8.

[12] H. B. Salameh, M. Krunz, and O. Younis, "MAC protocol for opportunistic cognitive radio networks with soft guarantees." vol. 8, no. 10, oct 2009, pp. 1339–1352.

[13] H. Su and X. Zhang, "Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio wireless networks." in *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, jan 2008, pp. 118–129.

[14] C. Cordeiro and K. Challapali, "C-MAC: A cognitive MAC protocol for multi-channel wireless networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, 2007, pp. 147 –157.

[15] T. Chen, H. Zhang, G. Maggio, and I. Chlamtac, "Cogmesh: A cluster-based cognitive radio network," in *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, 2007, pp. 168 –178.

[16] J. Zhao, H. Zheng, and G.-H. Yang, "Distributed coordination in dynamic spectrum allocation networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 2005, pp. 259 –268.

[17] H. Zheng, "Collaboration and fairness in opportunistic spectrum access," in *in Proc. of IEEE International Conference on Communications*, 2005, pp. 3132–3136.

[18] C. Zou and C. Chigan, "On game theoretic DSA-driven MAC for cognitive radio networks," in *Computer Communication Journal*, vol. 32, no. 18, dec 2009.

[19] Q. Zhao, L. Tong, and A. Swami, "Decentralized cognitive mac for dynamic spectrum access," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2005*, pp. 224–232.

[20] "ETSI *HIPERLAN functional specifications*, ETS 300-654," June 1996.

RESEARCH CENTRE
PARIS – ROCQUENCOURT

Domaine de Voluceau, - Rocquencourt
B.P. 105 - 78153 Le Chesnay Cedex

Publisher
Inria
Domaine de Voluceau - Rocquencourt
BP 105 - 78153 Le Chesnay Cedex
inria.fr

ISSN 0249-6399