Opportunistic Secondary Spectrum Sharing Protocols for Primary implementing an IR type Hybrid-ARQ Protocol

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OPPORTUNISTIC SECONDARY SPECTRUM SHARING PROTOCOLS FOR PRIMARY IMPLEMENTING AN IR TYPE HYBRID-ARQ PROTOCOL

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ABSTRACT

In this paper, we propose, analyse and compare three different methods for opportunistic spectrum sharing access when the primary users implements an Incremental Redundancy (IR) type Hybrid Automatic ReQuest (H-ARQ) protocol. The first method consists in allowing the secondary user to communicate only during the first primary transmission round of the IR H-ARQ protocol. In this scenario, if the the secondary receiver fails to decode its message after the first round, it realizes a successive interference cancellation in the subsequent primary HARQ rounds by listening to the primary user. The second method consists in realizing a perfect interference cancellation at the secondary receiver with causal channel state information. In this method, the secondary user communicates only when the secondary receiver succeeds in decoding the primary message. To improve throughput performance at the secondary, the secondary pair is also considering the use of an IR-HARQ protocol. In a third method, the secondary user communicates following the same rule as in the proposed second method, but implementing an Adaptive Modulation and Coding scheme instead of HARQ. In particular, we show that this last protocol with a small number of interfered slots allows to limit the loss in the primary throughput needed for the secondary user to transmit.

Index Terms— Spectrum Sharing, Cognitive Radio, HARQ, AMC, Throughput

1. INTRODUCTION

In Cognitive Radio, two access strategies are generally considered in order to improve the spectrum access efficiency. The first strategy, called Opportunistic Spectrum Access, consists in detecting spectrum white spaces and communicating over those available spaces. For the second method instead, called Opportunistic Spectrum Sharing, both primary and secondary users share the same spectrum at the same time. The model for this channel is often referred to as the cognitive channel and has been introduced in [1]. Throughout this paper, we consider the second strategy as a framework for our study.

In the spectrum sharing context, different secondary protocols have been proposed. The developed protocols mainly differs from the different access protocols and link adaptation strategies considered for the primary users (ie. rate, power or combined adaptation strategies). Apart from power allocation only strategies as done in [2, 3], several contributions have considered rate adaptation with Adaptive Modulation and Coding (AMC) scheme at the secondary (see for example [4, 5] and references therein), where the ergodic capacity is often used as a measure of performance. In particular in [5], the primary users implement an AMC scheme with a training period and use that period in order to adapt to the channel variations. The secondary users communicate over this training period in order to enforce primary users to adapt their rate and power when facing secondary interferences. Authors have shown that using this active learning can improve the secondary performances under constraint of primary losses. Another strategy to perform rate adaptation is the use of Hybrid Automatic ReQuest (HARQ) mechanisms to adapt to the channel variations and to cope with other types of interferences. This strategy has been first considered in [6, 7] for a cognitive channel ([8]). In these works, the primary users implement an HARQ with only two HARQ transmission rounds. In both cases, the channel is assumed quasi-static fading Rayleigh channel where the channel gains remain constant over the whole duration of the protocol. In [7], the authors consider that more than one primary packet can be transmitted over one time coherence and propose four different secondary protocols depending on the primary state over the two transmissions. The performances of the system are evaluated in terms of *goodput*. In [6], only one primary packet (possibly two transmissions) can be sent during one coherence time. In both cases, the secondary users intend to exploit the opportunity to communicate during the retransmission HARQ rounds. This is achieved by listening to the first HARQ round of the primary, and then, depending on the secondary Channel State Information (CSI), the secondary pair intends to realize perfect interference cancellation, dirty-paper coding [8] or power control. The performances are given in terms of outage probability and expected throughput. Note that in [6, 7], no rate (eg. HARQ/AMC) and/or power adaptation is considered for the secondary users when accessing the cognitive channel.

In this article, we consider rate adaptation strategies for the secondary users when primary users implement a **slotted** Incremental Redundancy type HARQ (IR-HARQ) with **an arbitrary number of retransmission rounds** and with **rounds of different sizes**. Contrary to [6, 7], we consider a slotted block-fading channel where the Rayleigh coefficients change independently *at each slot*. In this context, we intend to compare three different protocols for the secondary users. The first protocol considers that the secondary users always communicate on the first primary HARQ round only and then try to realize successive interference cancellation by listening to the subsequent primary HARQ rounds if decoding of the secondary message failed. We refer to this policy as *HARQ with successive interference cancellation*. The second proposed policy is referred to as *HARQ with perfect interference cancellation*: the secondary system communicates only when it can realize perfect interference cancellation, ie. the secondary is listening to the primary user during its first HARQ round and then tries to decode. We further assume that the secondary pair uses an IR-HARQ protocol. The third proposed

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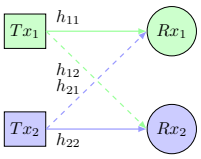

Fig. 1. Interference Channel

policy is similar to the second one and is referred to as *AMC with perfect interference cancellation*. For this policy, the secondary user also communicates only when it can realize perfect interference cancellation, but AMC is used instead of HARQ to adapt to the channel variation. For all these protocols, we perform a performance analysis in term of *long-term throughput*(cf. [9, 10]), since ergodic capacity cannot be used in an HARQ context.

This paper is organized as follows. In Section 2, we present the channel model and the different protocols considered for both primary and secondary users. In Section 3, we give the performance analysis of the studied systems in term of long-term throughput. In Section 4, some simulation results are given. Finally Section 5 concludes this paper.

2. CHANNEL AND SYSTEM MODEL

For the ease of presentation, we consider in this paper a simple network composed by a primary pair transmitter/receiver (Tx_1,Rx_1) and a cognitive pair transmitter/receiver (Tx_2,Rx_2) as presented in Figure 1. We consider that each channel link is a block-fading Additive White Gaussian Noise (AWGN) channel. The transmissions over these channels are slotted and each slot is assume to last L channel use (cu). The fading coefficients of the channel links remain constant over all the duration of a slot. Therefore, the model for the time slot m can be expressed by

$$\begin{aligned} \mathbf{y}_1(m) &= h_{11}(m)\mathbf{x}_1(m) + h_{21}(m)\mathbf{x}_2(m) + \mathbf{z}_1(m) \\ \mathbf{y}_2(m) &= h_{12}(m)\mathbf{x}_1(m) + h_{22}(m)\mathbf{x}_2(m) + \mathbf{z}_2(m) \end{aligned} \quad (1)$$

where $\mathbf{x}_1(m)$, $\mathbf{x}_2(m) \in \mathbb{C}^L$ are the messages issues from Gaussian codebooks transmitted by Tx_1 and Tx_2 respectively. $\mathbf{y}_1(m)$, $\mathbf{y}_2(m) \in \mathbb{C}^L$ are the messages received at Rx_1 and Rx_2 respectively. The channel coefficients $h_{ij}(m)$ are independent complex random Gaussian variables such as $\alpha_{ij}(m) = |h_{ij}(m)|^2$ are exponential random variables with mean $\overline{\alpha_{ij}}$. The Signal to Noise Ratio (SNR) for the link ij during the time slot m is denoted as $\gamma_{ij}(m) \triangleq P_i\alpha_{ij}(m)$. The Signal to interference plus Noise Ratio (SINR) at the receiver i is defined as $\beta_i(m) \triangleq \frac{\gamma_{ii}(m)}{1+\gamma_{ji}(m)}$.

If the secondary succeeds in decoding the primary message, we consider that the resulting interference cancellation is perfect leading to $\beta_2(m) = \gamma_{22}(m)$.

2.1. Primary Protocol

The primary pair implements a slotted Incremental Redundancy Hybrid-ARQ protocol (IR-HARQ) with infinite buffer at the emitter (fully-loaded queues) using one bit feedback for acknowledgement in order to adapt its rate to the channel variations [9, 10]. This protocol can be described as follows: Tx_1 encodes an information packet of size b_1 bits into a N code blocks $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N$ where $\mathbf{x}_1$ has a duration of B_1 slots and all other $\mathbf{x}_i$ have a duration of one slot. Let the total number of slots of the policy be denoted by $N_1 = B_1 + N - 1$. Let also introduce the rate of the first slot: $r_1 = \frac{b_1}{L}$. The primary user Tx_1 sends $\mathbf{x}_1$ through the channel to Rx_1 who then tries to decode. If the decoding at Rx_1 is successful, Rx_1 sends an ACKnowledgment (ACK) feedback bit to Tx_1 who generates a new information packet. This happens (cf. [10]) if $\sum_{s=1}^{B_1} C(\gamma_{11}(s)) \geq r_1$ where $C(\gamma_{11}(s)) = \log_2(1+\gamma_{11}(s))$ is the instantaneous mutual information of the channel on slot s. If the decoding at Rx_1 fails $\left(\sum_{s=1}^{B_1} C(\gamma_{11}(s)) < r_1\right)$, Rx_1 sends a Negative ACKnowledgment (NACK) feedback bit to Tx_1 who sends the next code block in the IR code policy. The HARQ process continues until either Rx_1 successfully decodes the information packet or the N code blocks are sent.

2.2. Secondary Protocols

In this subsection, we describe three protocols for the secondary users. The main idea of these three protocols is that the secondary users intend to benefit from interference cancellation of the primary user. For all these protocols, the considered feedback channels are assumed instantaneous and perfect (error-free feedbacks).

IR-HARQ with successive interference cancellation

This protocol can be seen as a generalization of what is proposed in [6] as a perspective. Note however that the channel considered here is the slotted block-fading channel compared to the quasi-static block fading channel as considered in [6]. The proposed protocol can be divided into two steps: (1) during the first primary HARQ round (ie. the first B_1 slots), Rx_2 considers the message sent by Tx_1 as noise to attempt, at each new slot, to decode its own message using an IR-HARQ protocol on a slot basis. To do so, Tx_2 encodes b_2 information bits into N_2 code blocks of length L. The rate of the first slot is denoted by $r_2 = \frac{b_2}{L}$. (2) If decoding has failed after sending its N_2 blocks (with $N_2 \leq B_1$), the secondary transmitter keeps quiet and the secondary receiver listens for the primary messages. If the secondary receiver succeeds in decoding the primary information at a new primary HARQ round, it uses this information to realize perfect interference cancellation to decode its own message.

IR HARQ with Perfect Interference Cancellation

This protocol can also be divided into two parts: (1) Rx_2 listens to the primary link. If Rx_2 succeeds in decoding the primary information before Rx_1, it sends a Clear To Send (CTS) message to Tx_2 through the feedback channel, (2) then, at the reception of the CTS message, Tx_2 and Rx_2 implement an IR-HARQ protocol with N_2 possible transmissions. Given that this protocol starts only if Rx_2 possesses the primary information, it can perform perfect interference cancellation.

AMC with Perfect Interference Cancellation

The third protocol is similar to the second one but implements an AMC scheme instead of an HARQ protocol during the second phase of the protocol. We consider that Rx_2 perfectly knows the $h_{22}(m)$ amplitude and phase for the slots on which it can communicate. Note that this CSI is not required for the two other protocols.

3. PERFORMANCE ANALYSIS

For both primary and secondary systems, the performance is given in term of throughput which is here define as the number of correctly received bits per unit of time. The computation of the throughput using renewal reward theory was firstly introduced by [11] and is used also in [9, 10].

3.1. Performance of the Primary System with Silent Secondary

The computation of the performance of the performance of the primary system alone is similar to the computation given in [10]. Let introduce the recurrent event at Rx_1 as *the transmitter Rx_1 stops transmitting the current codeword*. For each recurrent event, we attach a random reward $\mathcal{R}_1$ wich is equal to b_1 bits if the packet is successfully decoded at the receiver and is equal to 0 bit if not. The corresponding long-term throughput can be defined as

$$\eta_1 = \lim_{t\to\infty} \frac{b_1(t)}{t} = \frac{\mathbb{E}\left(\mathcal{R}_1\right)}{\mathbb{E}\left(\mathcal{T}_1\right)} \tag{2}$$

where $b_1(t)$ represent the total number of information bits received at Rx_1 between time 0 and time t and where the right-hand part of this equation is due to the renewal theory with $\mathcal{T}_1$ being the random time between two successive recurrent events. Let $p_1(m)$ be probability that Rx_1 cannot decode after m slots, $p_1(m)$ given by

$$p_1(m) = \mathbb{P}\left(\sum_{j=1}^{m} C(\gamma_{11}(j)) < r_1\right) \tag{3}$$

Finally, the throughput of the primary system is given by

$$\eta_1 = r_1 \frac{1 - p_1(N_1)}{B_1 + \sum_{m=1}^{N_1-1} p_1(m)} \tag{4}$$

3.2. Performance of the Primary and Secondary Systems

IR-HARQ with Successive Interference Cancellation

In this section, the secondary user implements the protocol described in 2.2. In order to evaluate the performances of the primary and secondary systems, let us introduce the following random variables: $\mathcal{K}$ which is counting *the time that Rx_2 needs in order to correctly decode its current packet if we suppose $N_2 = \infty$* and $\mathcal{I}$ which is counting *the number of slots on which the secondary user is communicating*. The probability density of $\mathcal{K}$ is given by

$$\mathbb{P}\left(\mathcal{K} = k\right) = \mathbb{P}\left(\sum_{m=1}^{k} C(\beta_2(m)) \geq r_2, \sum_{m=1}^{k-1} C(\beta_2(m)) < r_2\right). \tag{5}$$

The probability density of $\mathcal{I}$ is obtained considering that if $\mathcal{K} \leq N_2$ then $\mathcal{I} = \mathcal{K}$ and if $\mathcal{K} > N_2$ then $\mathcal{I} = N_2$.

$$\mathbb{P}\left(\mathcal{I} = i\right) = \begin{cases} \mathbb{P}\left(\mathcal{K} = i\right) \text{ if } i < N_2, \\ \mathbb{P}\left(\mathcal{K} \geq N_2\right) \text{ if } i = N_2, \end{cases} \tag{6}$$

Using these two quantities, the throughput of the primary system can then be written as

$$\eta_1 = \frac{\mathbb{E}_{\mathcal{I}}\left(\mathbb{E}\left(\mathcal{R}_1|\mathcal{I}\right)\right)}{\mathbb{E}_{\mathcal{I}}\left(\mathbb{E}\left(\mathcal{T}_1|\mathcal{I}\right)\right)}, \tag{7}$$

which modifies equation (4) as follows

$$\eta_1 = r_1 \frac{1 - \mathbb{E}_{\mathcal{I}}\left(p_1(N_1|\mathcal{I})\right)}{B_1 + \sum_{m=1}^{N_1-1} \mathbb{E}_{\mathcal{I}}\left(p_1(m|\mathcal{I})\right)}, \tag{8}$$

where

$$\mathbb{E}_{\mathcal{I}}\left(p_1(m|\mathcal{I})\right) = \sum_{i=1}^{N_2} f(m,i)\mathbb{P}\left(\mathcal{I} = i\right) \tag{9}$$

with $f(m,i) = \mathbb{P}\left(\sum_{s=1}^{i} C(\beta_1(s)) + \sum_{s=i+1}^{m} C(\gamma_{11}(s)) < r_1\right)$.

The throughput of the secondary user can be defined in a similar way to the primary user as follows

$$\eta_2 = \lim_{t\to\infty} \frac{b_2(t)}{t} = \frac{\mathbb{E}\left(\mathcal{R}_2\right)}{\mathbb{E}\left(\mathcal{T}_2\right)} \tag{10}$$

In this paper, we consider that, for each transmission of a new packet by the primary user, the secondary user also starts a new transmission which implies that $\mathbb{E}\left(\mathcal{T}_2\right) = \mathbb{E}\left(\mathcal{T}_1\right)$. The proof of this assertion is not given in this paper but remains true for the three secondary protocols. The computation of $\mathbb{E}\left(\mathcal{R}_2\right)$ in this case can be simplified by noticing that $\{\mathcal{R}_2 = 0\}$ is equivalent to $\left\{\sum_{s=1}^{N_2} C(\gamma_{22}(s)) < r_2\right\}$. The secondary throughput is finally given by

$$\eta_2 = r_2 \frac{\mathbb{P}\left(\sum_{s=1}^{N_2} C(\gamma_{22}(s)) < r_2\right)}{B_1 + \sum_{m=1}^{N_1-1} \mathbb{E}_{\mathcal{I}}\left(p_1(m|\mathcal{I})\right)} \tag{11}$$

HARQ with Perfect Interference Cancellation

For this analysis, we keep the random variable $\mathcal{K}$ and we add the random variable $\mathcal{J}$ which represents the number of primary slots that Rx_2 needs in order to correctly decode the information sent by Tx_1 supposing $N_1 = \infty$. The probability density of $\mathcal{J}$ is

$$\mathbb{P}\left(\mathcal{J} = j\right) = \mathbb{P}\left(\sum_{s=1}^{j} C(\gamma_{12}(s)) \geq r_1, \sum_{s=1}^{j-1} C(\gamma_{12}(s)) < r_1\right) \tag{12}$$

Using $\mathcal{K}$ and $\mathcal{J}$, the primary throughput is given by

$$\eta_1 = \frac{\mathbb{E}_{\mathcal{J},\mathcal{K}}\left(\mathbb{E}\left(\mathcal{R}_1|\mathcal{J},\mathcal{K}\right)\right)}{\mathbb{E}_{\mathcal{J},\mathcal{K}}\left(\mathbb{E}\left(\mathcal{T}_1|\mathcal{J},\mathcal{K}\right)\right)} = r_1 \frac{1 - \mathbb{E}_{\mathcal{J},\mathcal{K}}\left(p_1(N_1|\mathcal{J},\mathcal{K})\right)}{B_1 + \sum_{m=1}^{N_1-1} \mathbb{E}_{\mathcal{J},\mathcal{K}}\left(p_1(m|\mathcal{J},\mathcal{K})\right)}, \tag{13}$$

where

$$\mathbb{E}_{\mathcal{J},\mathcal{K}}\left(p_1(m|\mathcal{J},\mathcal{K})\right) = \sum_{j=B_1}^{N_1} \sum_{k=1}^{N_2} g(m,j,k)\mathbb{P}\left(\mathcal{J} = j\right)\mathbb{P}\left(\mathcal{K} = k\right), \tag{14}$$

$$\text{with } g(m,j,k) = \begin{cases} f(m,0) \text{ if } m \leq j, \\ f(m,k) \text{ if } m \geq j+k+1 \text{ and } k < N_2, \\ f(m,N_2) \text{ if } m \geq j+N_2+1 \text{ and } k \geq N_2, \\ f(m,m-j) \text{ if } j \leq m \leq j+k, \end{cases} \tag{15}$$

The secondary throughput is still given by equation (10) where we also have $\mathbb{E}\left(\mathcal{T}_2\right) = \mathbb{E}\left(\mathcal{T}_1\right)$ and $\mathbb{E}\left(\mathcal{R}_2\right) = \mathbb{E}_{\mathcal{J},\mathcal{K}}\left(\mathbb{E}\left(\mathcal{R}_2|\mathcal{J},\mathcal{K}\right)\right)$ and η_2 is given by

$$\eta_2 = r_2 \frac{1 - \sum_{k=1}^{N_2} \sum_{j=B_1}^{N_1-k} f(j+k,k)\mathbb{P}\left(\mathcal{J} = j\right)\mathbb{P}\left(\mathcal{K} = k\right)}{B_1 + \sum_{m=1}^{N_1-1} \mathbb{E}_{\mathcal{J},\mathcal{K}}\left(p_1(m|\mathcal{J},\mathcal{K})\right)} \tag{16}$$

AMC with Perfect Interference Cancellation

Using the same method as the two precedent analysis, we have

$$\eta_1 = \frac{\mathbb{E}_{\mathcal{J}}\left(\mathbb{E}\left(\mathcal{R}_1|\mathcal{J}\right)\right)}{\mathbb{E}_{\mathcal{J}}\left(\mathbb{E}\left(\mathcal{T}_1|\mathcal{J}\right)\right)} = r_1 \frac{1 - \mathbb{E}_{\mathcal{J}}\left(p_1(N_1|\mathcal{J})\right)}{B_1 + \sum_{m=1}^{N_1-1} \mathbb{E}_{\mathcal{J}}\left(p_1(m|\mathcal{J})\right)}, \tag{17}$$

where

$$p_1(m|\mathcal{J} = j) = \begin{cases} f(m,0) \text{ if } m \leq j, \\ f(m,m-j) \text{ if } j \leq m \leq N_2, \\ f(m,N_2) \text{ if } m \geq N_2 \end{cases} \tag{18}$$

In order to compute the secondary throughput, we need to carefully specify $\mathcal{R}_2$. In this case, we have $\mathcal{R}_2 = L\sum_{s=1}^{\mathcal{N}} C\left(\gamma_{22}(s)\right)$,

where $\mathcal{N}$ is a random variable representing the number of slots on which Tx_2 has sent packets during one primary transmission. We then redefine N_2 as the maximum slots on which the secondary can communicate, thus $\mathcal{N} \in [1, N_2]$. Given the definition of $\mathcal{N}$ and the protocol, $\mathcal{N}$ depends on the length of the primary protocol (which depends on h_{11} and h_{21}) and on the time that Rx_2 decode the message of Tx_1 (which depends only on h_{12}), thus $\mathcal{N}$ is independent of h_{22}. Because the $\gamma_{22}(s)$ are i.i.d, we can rewrite $\mathbb{E}(\mathcal{R}_2)$ as follows

$$\mathbb{E}(\mathcal{R}_2) = \mathbb{E}_{\mathcal{N}}(\mathbb{E}(\mathcal{R}_2|\mathcal{N})) = L\mathbb{E}(\mathcal{N})\mathbb{E}(C(\gamma_{22})), \quad (19)$$

where $\mathbb{E}(\mathcal{N})$ is given by

$$\mathbb{E}(\mathcal{N}) = \sum_{n=1}^{N_2} n \sum_{j=B_1}^{N_1-n} f(j+n-1, n-1)\mathbb{P}(\mathcal{J}=j) \quad (20)$$

and $\mathbb{E}(C(\gamma_{22}))$ is computed using the pdf of γ_{22} which is exponential. For this protocol, it can also be shown that $\mathbb{E}(\mathcal{T}_2) = \mathbb{E}(\mathcal{T}_1)$ which give the following result

$$\eta_2 = \frac{\sum_{n=1}^{N_2} n \sum_{j=B_1}^{N_1-n} f(j+n-1, n-1)\mathbb{P}(\mathcal{J}=j)\mathbb{E}(C(\gamma_{22}))}{B_1 + \sum_{m=1}^{N_1-1}\mathbb{E}_{\mathcal{J}}(p_1(m|\mathcal{J}))}. \quad (21)$$

4. RESULTS

In this section, we compare the three proposed secondary strategies. The primary users communicate with a power of 10 dBW and implement an IR-HARQ with $B_1 = 4$ slots, $N_1 = 8$ slots, $b_1 = 1024$ bits, $L = 215$ cu which leads r_1 to be $r_1 \approx 4.76$ $bpcu$. This values of L and r_1 have been chosen in order to maximise the throughput of the primary user when he is alone.

Five different secondary strategies have been tested for different secondary powers P_2 going from -20 dBW to 10 dBW:

- s_1 HARQ with successive interference cancellation with $N_2 = 3$,
- s_2 HARQ with perfect interference cancellation with $N_2 = 3$,
- s_3 AMC with perfect interference cancellation with $N_2 = \infty$,
- s_4 AMC with perfect interference cancellation with $N_2 = 3$ and
- s_5 AMC with perfect interference cancellation with $N_2 = 1$.

For the two strategies s_1 and s_2 and for each power, we have considered secondary rates going from 0 $bpcu$ to 20 $bpcu$ and we have kept the one maximizing the secondary throughput. The throughputs for both primary and secondary users for the different strategies are presented in Figure 2.

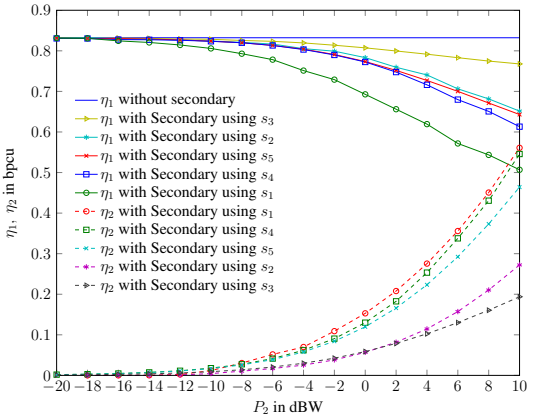

Fig. 2. Achievable throughputs for the proposed protocols versus the secondary transmit power

On these curves, one can remark that N_2 allows to trade off between the fairness with the primary ($N_2 = 1$) and the secondary throughput ($N_2 = \infty$) for AMC based protocols. In fact, it can be easily proven that $\eta_1(s_1) \geq \eta_1(s_2) \geq \eta_1(s_5)$ just by noticing that the expected number of interfered blocks will be higher for s_1 than for s_2 which will be higher for s_2 than for s_3. This is due to the fact that HARQ protocols require more slots in order to decode their data. Finally we can observe that the AMC protocol with a small number of interfered slots allows a small loss in the primary throughput.

5. CONCLUSION

In this paper, we analyse the throughput of three different secondary strategies when the primary users implement an IR-HARQ protocol. If the primary system implements an HARQ protocol with a multiple bits feedback, a power control can be used on top of one of the proposed strategies to control the primary loss in throughput. This strategy will be considered in a futur work.

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