Enhancing Coexistence within the ISM Band under Hidden Collision

Sebgui M., Bah S., Elgraini B.
LEC Laboratory, EMI, Mohammed V University Agdal, Rabat – Morocco
(sebgui,bah,elgraini)@emi.ac.ma

***Abstract*— IEEE 802.11 is a standard that makes use of CSMA/CA to allow WLAN communication while sharing the channel in competitive way. However, nodes may face Hidden Collision (HC) when they are sharing the spectrum with other nodes that are in, the same area. This is likely to be the case, since the standards, such as Zigbee and Bluetooth, use the same spectrum frequency (i.e the ISM band). In this paper we study the effect of HC, caused either by Zigbee and Bluetooth, on the performance of WLAN nodes that use CSMA/CA. To address this effect we propose a solution based on adding a transient state to the node behavior. Computation results show the effectiveness of our solution in term of throughput gain and time distribution.**

Keyword- Multiple Access; CSMA/CA; 802.11; Zigbee; Bluetooth; Hidden Collision

I. INTRODUCTION

The Industrial Scientific and Medical band (ISM) is an unlicensed band, shared among several protocol technologies like 802.11b Wireless Local Area Networks (WLAN), Bluetooth, Zigbee, and others. These communication technologies are separately designed and their coexistence is not supported by their respective standards. However as shown in Fig. 1 the frequency bands of these technologies overlap. Consequently when they are in the same area their signals are subject to high level interferences which negatively impact their performances. Many research works studied the coexistence of these technologies when they are located in the same area. Work in [1] analysed the packet error rate for Zigbee under both WLAN and Bluetooth interferences. In the other hand, [2] evaluated the packet error rate for the 802.11b WLAN under Zigbee interference. Both works studied the impact of frames collisions between different and ‘not cooperating’ protocols.

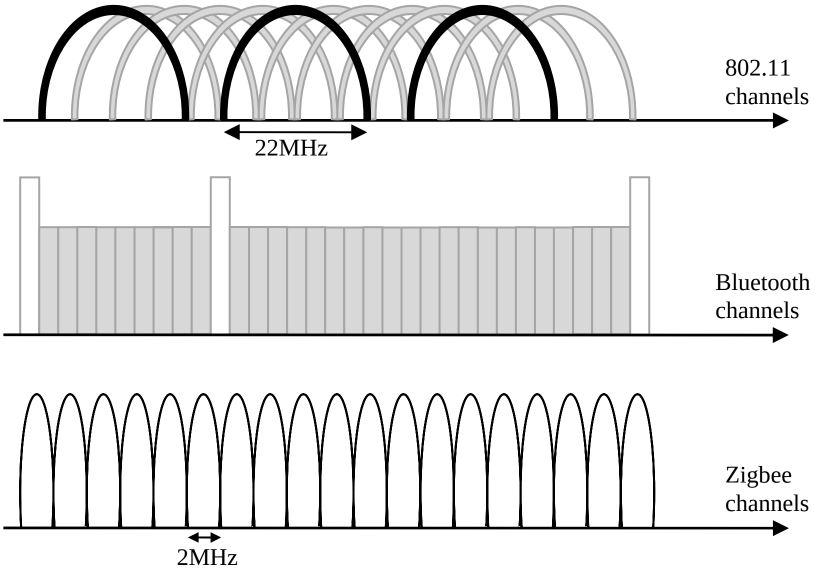

Fig. 1 spectrum channels for ISM standards

To avoid collisions between 802.11b and Bluetooth frames, authors in [3] proposed a dynamic spectrum access scheme for Bluetooth devices with adaptive frequency hopping policy making the assumption that the Bluetooth device will access only idle channel time spaces (i.e. when the WLAN node is not transmitting).

In our previous work in [4] we showed that this opportunistic access is not sufficient to protect WLAN nodes from performance degradation. Indeed, when a node A accesses the channel when a CSMA/CA node B is in the backoff window, the node B’s waiting time will be extend which negatively impact its performance. This effect is referred to as Hidden Collision (HC).

In this paper we consider two possible collisions: signal interference and hidden collision. We show the effect of the coexistence of different technologies on WLAN performances. In our work we target protecting

WLAN nodes from other coexisting nodes disruption, for that, we propose to add a transient state to the other coexisting standards in order to reduce HC effect. Computations results show the effectiveness of our solution.

The rest of the paper is organized as follows. Section II describes the hidden collision problem. In section III the system behavior is modelled and the effect of hidden collision is presented. The proposed solution and the evaluation of it performance are presented in section IV. We conclude in section V.

II. HIDDEN COLLISION PROBLEM

The hidden collision effect is related to the use of CSMA/CA by 802.11 nodes which imposed the use of backoff procedure to its nodes. This leads to less priority on the spectrum use compared with other technologies. In this section we will first present a brief background about CSMA/CA, and then we will present the hidden collision effect.

The CSMA/CA is a protocol that allows nodes in a distributed or centralized architecture to share the channel in a competitive way while avoiding collision. It's based on listen before talk scheme where each node has to sense the medium during a Distributed Inter-Frame Space (DIFS) before starting any packets transmission. If the medium is idle during the whole DIFS period, the node starts transmission. Otherwise it should defer its transition until the medium becomes available [5]. Furthermore, the CSMA/CA protocol uses a backoff procedure as an additional protection from collisions.

The backoff procedure is activated either when a collision occurs or after each successful transmission. The backoff procedure makes use of a window of a specific size i stored in a counter called Backoff Counter (BC). The initial value of i is an integer, randomly chosen using a uniform distribution over an interval $[0, W_k]$, W_k is the contention windows size defined as $W_k=2^k*W_0-1$, k is an integer that represents the contention windows level, and W_0 is the initial size of contention window. Each time an unsuccessful transmission is observed the contention level L is incremented by 1 until it reaches its maximal value W_m.

The system is supposed to be time slotted, which means it doesn't change its state within the slot duration, denoted by T_{Slot}. Each node in the backoff procedure senses the medium and decrements its BC by one if the channel is idle, otherwise it freezes its value. While the node is freezing the BC, it continues sensing the channel as long it is still busy. When the channel becomes available for at least a period equal to DIFS, the node resumes decrementing its BC. When the counter reaches zero, the node starts to transmit again.

Consequently when many users coexist in the same area, if a node is in BW and the channel is used by another node, the BC is frozen and the BW is prolonged. When all nodes are using CSMA/CA rules their global transmission is regulated, in opposition, if a node using another standard, which does not respect similar rules to access the channel, it leads WLAN transmissions to be delayed, and the WLAN user ends up with less priority on the channel access. This effect is referred to as Hidden Collision (HC) since there is a significant disruption that is not caused by signal interferences.

III. HIDDEN COLLISION EFFECT ON CSMA/CA NETWORK

In this section we highlight the effect of hidden collision on the CSMA/CA performances. First, we model the system behavior when it is subject to hidden collision effect, then we present computation results that demonstrate this effect.

A. Coexistence effect on CSMA/CA system behavior

Works in [6][7] modeled the node state in as a Markov chain where the state of each node by the pair the of integers (k,i) described above, $k \in [0,m]$ and $i \in [0,W_k]$. Two parameters govern the state transition, p_b, probability that the medium is busy and p_c the probability of collision during frame transmission. The state (-1,0) is special case where the transmitter node senses the channel idle and there is no collision, which allows this node to begin transmission without entering the backoff procedure.

Authors in [7] considers the saturation case where each user has always a packet ready to send, each time a node is not in backoff procedure (i.e being in $(k,0)$ states) it is transmitting. The probability that a node transmits during a slot time p_t is equal to p_{NBW} that is the probability that the node is not in BW. Equation (1) gives the relation between p_t, p_b and p_c for a saturated system. Where $A(p_c,p_b)$ is defined as in (2).

$$\begin{cases} p_t = A(p_c, p_b) \\ p_c = 1-(1-p_t)^{n-1} \\ p_b = 1-(1-p_t)^n \end{cases} \tag{1}$$

$$A(p_c,p_b)=\frac{2(1-p_b)(1-2p_c)}{2(1-p_b)^2(1-2p_c)(1-p_c)+W_0(1-2p_c)(p_b+p_c(1-p_b))+p_c(W_0-1)(p_b+p_c(1-p_b))(1-(2p_c)^m)} \tag{2}$$

In our work in [4] we considered also the non-saturation case. We assumed that all nodes have the same behavior i.e. each user is supposed to have a packet ready to send with a rate of γ_P. As we may see in equation (7), this has only impact on p_t. p_c and p_b are unchanged.

$$\begin{cases} p_t = \gamma_p \cdot p_{NBW} = \gamma_p \cdot A(p_c, p_b) \\ p_c = 1-(1-p_t)^{n-1} \\ p_b = 1-(1-p_t)^n \end{cases} \tag{3}$$

Notice that when $\gamma_P = 1$ we go back to saturation case, equations (2).

To evaluate the effect of coexistence within ISM band on WLAN network, we keep consistent, in this study, with the work in [2] and consider that the probability that a Zigbee or Bluetooth signal causes interferences to a WLAN node is expressed by (4), where X is the random variable expressed in (5).

$$p_{S\_W} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-X}^{\infty} \left(\frac{1}{\sqrt{2\pi}} \int_{-(\upsilon+X)}^{(\upsilon+X)} e^{\frac{-y^2}{2}} dy \right)^3 e^{\frac{-\upsilon^2}{2}} d\upsilon \tag{4}$$

$$X = \sqrt{20 \log\left(\frac{P_R}{P_{No} + P_i} \right)} \tag{5}$$

Here P_R is the received power from a node with similar standard, P_{No} is the noise power and P_i is the interference power received from a node using different standard.

The previous equations allow modeling the interferences caused by Zigbee or Bluetooth to the WLAN network. As a matter of fact this parameter will mainly affect the p_c formula in formula (3).

Furthermore in this study we consider the effect of HC which has impact only on p_b, with no changes to p_t and p_c in the set of equations (3). We can rewrite these equations as follows:

$$\begin{cases} p_t = \gamma_p \cdot p_{NBW} = \gamma_p \cdot A(p_c, p_b) \\ p_c = 1-(1-p_t)^{n-1}(1-p_{S\_W}) \\ p_b = 1-(1-p_t)^n (1-p_{hc}) \end{cases} \tag{6}$$

Where p_{hc} is the probability of hidden collision within a time slot. Its value depends on the availability of the channel and γ_s the arrival rate of Zigbee and Bluetooth packets. Equation (7) expresses this dependency.

$$p_{hc} = \gamma_s (1-p_t)^n \tag{7}$$

B. The effect on CSMA/CA throughput

Authors in [7] expressed the throughput as in (8)

$$T_p = \frac{p_{suc}.E[\lambda]}{p_{suc}.T_{SP} + (1-p_{suc})T_{CP} + E[\psi]T_{Slot}} \tag{8}$$

Where $E[\lambda]$ is the average payload length, T_{SP} is the average time needed for a successful transmission, T_{CP} is the average time that the channel is taken by a collision, and T_{Slot} is the time unit that schedules the system evolution. The average values of these parameters are given in Table I. $E[\psi]$ is the mean number of consecutive idle slot times before a transmission takes place and p_{suc} is the probability that a transmission succeed. $E[\psi]$ and p_{suc} are given by equation (9).

$$\begin{cases} p_{suc} = \dfrac{n.p_t(1-p_c)}{1-(1-p_t)^n} \\ E[\psi] = \dfrac{1}{1-(1-p_t)^n} - 1 \end{cases} \tag{9}$$

In this study we suppose that the WLAN nodes have more priority to the use of the medium (i.e the Primary User: PU), while Zigbee and Bluetooth nodes are supposed to be secondary users (SU) of the spectrum. Each time a SU node accesses the channel while a PU node is in backoff window the transmission of this node is delayed, this delay can be represented as a random variable D_{HC} with mean value $E[D_{HC}]$ given by:

$$E[D_{HC}] = E[N_{HC}] p_{hc} T_{SS} \tag{10}$$

Where T_{SS} is the average time needed to SU to transmit one packet; N_{HC} is the number of times a SU node accesses the channel within a single WLAN backoff window. The average of N_{HC}, $E[N_{HC}]$, is given in (11).

$$E[N_{HC}] = \max\left(\frac{E[\psi]\cdot T_{Slot}}{T_{SS}+T_W};1\right) \tag{11}$$

Where T_W is the minimum waiting time between two consecutives SU transmissions. $E[\psi].T_{Slot}$ is the average time of consecutive slots during which there is no PU transmission and node of other technologies will transmit, each transmission requires a period of time equal to T_{SS} plus a waiting time T_W. If the amount $(E[\psi].T_{Slot}/T_{SS}+T_W)$ is less than one, then it will be only one SU transmission.

The throughput, hidden collisions delay affects the denominator of equation (8) as shown in equation (12). Specifically, the term $E[\psi].T_{Slot}$ which represent the average idle time where primary users are in BW, will be rewritten as sum of two parts; $(1-p_{hc}).E[\psi].T_{Slot}$ and $E[D_{HC}].E[\psi]$.

$$T_p = \frac{p_{suc}.E[\lambda]}{p_{suc}.T_{SP} + (1-p_{suc})T_{CP} + (1-p_{hc})E[\psi]T_{Slot} + E[\psi].E[D_{HC}]} \tag{12}$$

In this equation, we consider the available throughput for all PU nodes. However, asymmetric and other effects, like starvation, flow-in-the-middle, and shadowed node discussed in [8] are ignored in our case.

C. Computations results

In this subsection we will compute effect of hidden collision for different number of PUs, using 802.11b protocol average values as suggested in [6][7] and showed in Table I, with arrival rate of packets γ_p=0.9. As for the SU, we will consider the packet arrival rate γ_s=0.25 and with T_{SS} value as suggested by [1][2] and shown in Table II.

Fig. 2 shows the degradation of WLAN nodes' throughput when the coexisting with a Zigbee or Bluetooth node including both disruptions caused by signal interference and hidden collision.

TABLE I. AVERAGE VALUES FOR 802.11B PARAMETTERS

T_{SP}	8886 µs	$E[\lambda]$	8184bits
T_{CP}	8635 µs	W_0	32
T_{solt}	20µs	m	5

TABLE II. TIME FOR SECONDARY USER TRANSMISSION

Technology	T_{SS}
ZigBee	4128 µs
Bluetooth	1250 µs

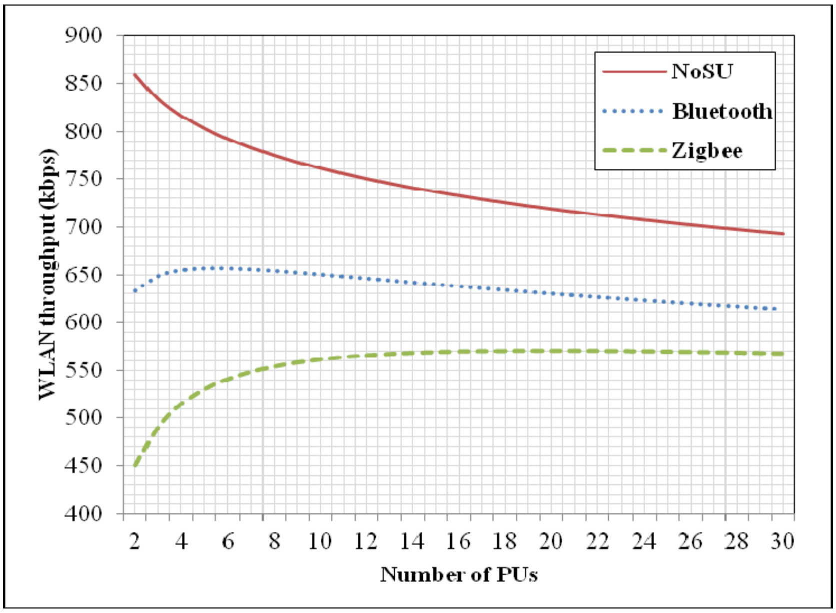

Fig. 2 Effect of hidden collision on WLAN nodes' throughput (kbps) when the coexisting with a Zigbee or Bluetooth node

IV. WAITING TIME TO ENHANCE CSMA/CA PERFORMANCES

In this section we describe our proposed solution that consists on a transient state added to the Zigbee or Bluetoth node behavior. And we will discuss its effect on WLAN throughput and time distribution.

A. Description of the proposed solution

To the best of our knowledge, existing research works in this area, [1][2][3], consider only collisions between PU and SU, (i.e. signals interferences) and ignore other types of disruption like hidden collision[4]. In this section, we will propose a solution to control its impact.

In this study we suppose that the WLAN nodes are supposed to be primary users, while Zigbee and Bluetooth nodes are secondary users. Consequently, we are asked to protect WLAN communication from hidden collision. In order to deal with hidden collision, we propose to impose the Zigbee, and Bluetooth nodes a new procedure which consist of two additional rules. First we propose the use of a Listen Before Talk (LBT) procedure, (i.e users are supposed to sense the medium and do not transmit when it is occupied). Secondly, we impose the SUs to enter a transient state each time they sense the medium being idle before considering it as a transmission opportunity.

In our solution in addition to a classical LBT procedure a Transient state (Trans) is added as seen in Fig. 3. From the Sensing (Sens) where SUs are sensing the channel, the SU is forced to enter the transient when the channel is sensed as idle before considering any opportunity to transmit. In the Transient state the SU is not allowed to access the channel even if it is sensed as idle. Once at the Transient state and under certain conditions, the SU can move either to what we call opportunity state (possibility of accessing the channel) or to sensing state (i.e. PU regains access to the channel).

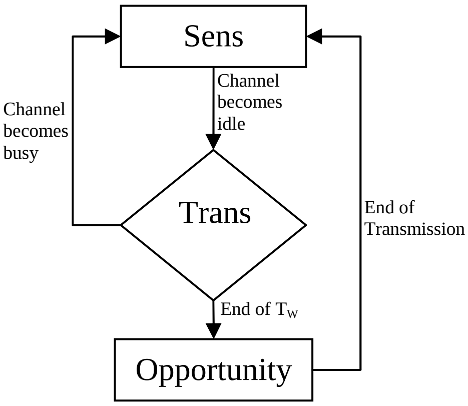

Fig. 3 The SU states transition.

In the case of CSMA/CA networks, we propose that the transient state imposes a holding time T_W on the SU before accessing the channel, which means when the SU senses the channel idle it will wait for T_W period before considering the white space as an opportunity to access the channel. If the PU regains access to the channel during T_W the SU has to wait for the next white space to compete again.

For the estimation of T_W, we assume that the following variables are known from the SU; the network parameters W_0 and m, the primary user time slot duration T_{Slot} and the number of active primary users n. The works in [9] show that the estimation of the number of user is possible using Kalman filter. T_W can be computed as shown in (13):

$$T_W = \hat{\imath} \cdot T_{Slot} \qquad (13)$$

Where $\hat{\imath}$ represents the estimated time that a PU spends in any BW. $\hat{\imath}$ is given in equation (14) as a function of p which is the probability limit of hidden collision required by PU rules. We expect the PU to be able to define rules that regulate SU access to the channel. Here $p_{k,h}$ is the probability of a node being in a state (k,h).

$$\hat{\imath} = \min_i \left\{ \sum_{h=0}^{i} \sum_{k=-1}^{m} p_{k,h} > 1 - p \right\} \qquad (14)$$

Since we added the transient state, the formula of p_b in the system described in (6) will be modified as p_{hc} is redefined in (15). The hidden collision occurs when the secondary user transmits (i.e. when he had a packet ready to send) and the n primary users do not transmit for $\hat{\imath}$ consecutive time slots.

$$p_{hc} = \gamma_s (1 - p_t)^{n(\hat{\imath}+1)} \qquad (15)$$

Notice that if we remove this new transient state i.e. $\hat{\imath}$=0, equation (15) will lead to equation (6).

B. *The effect of HC on WLAN throughput*

In this section we will compute effect our solution on WLAN throughput. For that we consider γ_p=0.9and γ_s=0.25 and parameters value presented in Table I and Table II.

First we examine the effect of *p* hidden collisions limit on the PUs throughput. Fig. 4 shows the throughput as function to the PUs numbers for two different values of *p*; 0.1 and 0.5. In addition, in Fig. 4, we plot the two limit cases 'NoSU' where the secondary user is not present, and the case 'NoTrans' where the SU shares the PU's spectrum without using the transient state. We observe that our solution improves the throughput; it increases as the *p* decreases.

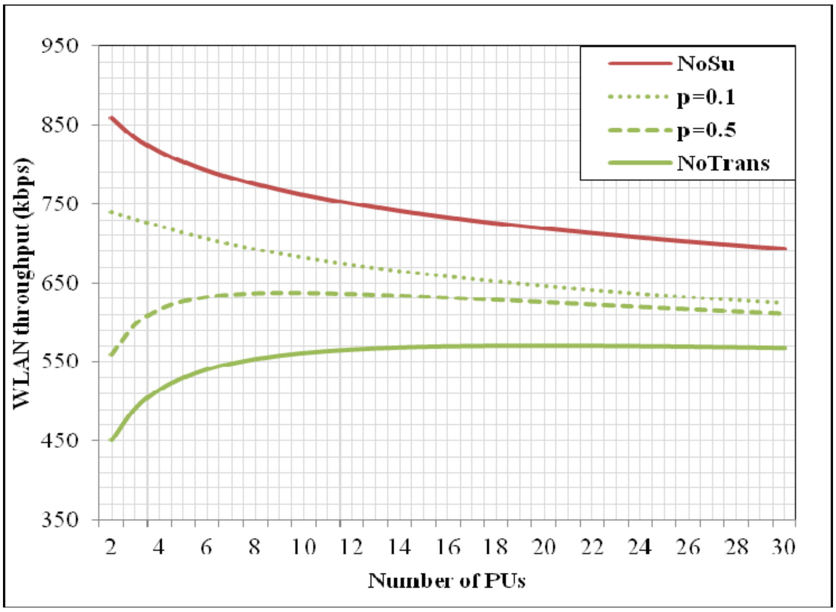

Fig. 4 The PU's throughput (kbps) for different limit values of *p*. SU uses Zigbee

In the following we will fix the value of *p*=0.5 and study the impact of the SU technology on PU performances. Fig. 5 shows the effect on PU throughput when the SU uses either Bluetooth or Zigbee. For each technology we compare the case with limited hidden collision, to the one where the SU access the channel without observing any holding time 'NoTrans'.

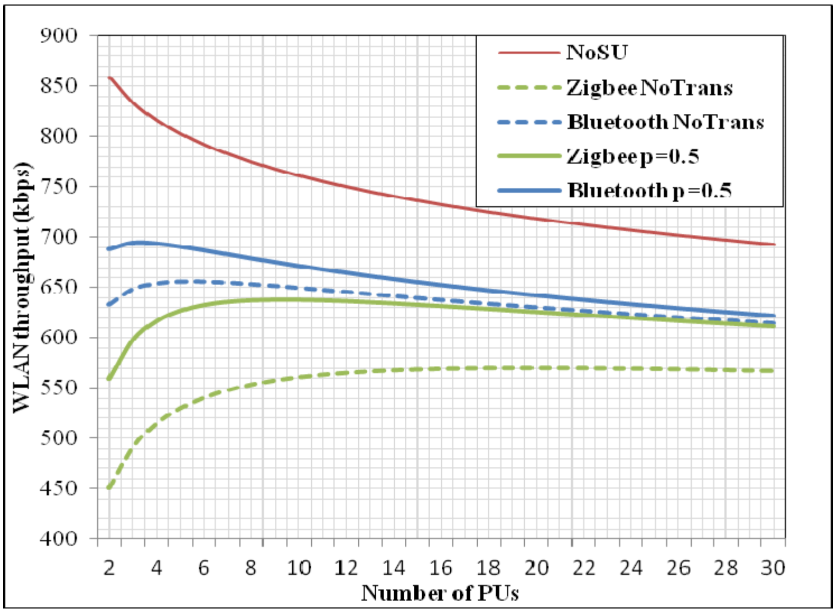

Fig. 5: The PU's throughput (kbps) in two cases; p=0.5 and no transient state. SU uses Zigbee or Bluetooth.

In order to better reflect the impact of our approach, we use the following gain formula for the PU's throughput.

$$G_S = \frac{T_P\big|_{p=0.5} - T_P\big|_{NoTrans}}{T_P\big|_{NoSU} - T_P\big|_{NoTrans}} \tag{16}$$

Where $T_p|_x$ is the throughput value for a specific setting x, for example; No SU is present (NoSU), No holding time (NoTrans), or the case of limited hidden collision with p=0.5.

Fig. 6 shows the PU gain in term of throughput as defined in (16) for Bluetooth, Zigbee. We observe that the gain obtained by our solution increases as the T_{SS} increases, in other words more protection to PU with bigger T_{SS} values. Also, this gain decreases with the number of PUs which is significant for a limited number of PUs and less important for a large number of users.

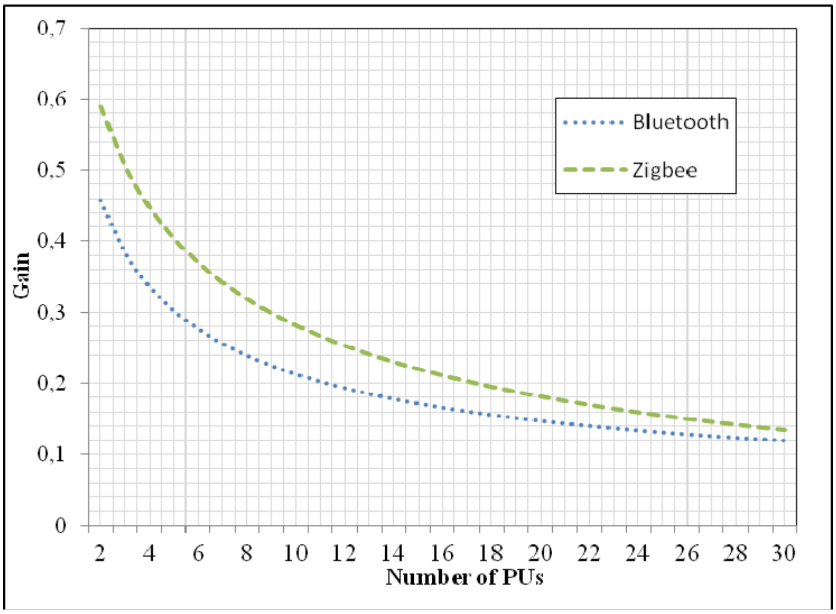

Fig. 6: The PU gain in term of throughput. SU uses Zigbee or Bluetooth.

In order to evaluate the impact of our solution on both PU and SU systems, we will first examine how the time is distributed among users and then give the SU's throughput formula. Finally, we will provide computation results.

C. The effect on time distribution

In each time slot, the channel is subject to one of the five possible usages; Useful to Primary User (*UPU*) where the primary user can transmit, Wasted due to Primary User's rules (*WPU*) where the PU is in backoff windows, Useful to Secondary User where the secondary user can transmit (*USU*), Wasted due to Secondary User's rules (*WSU*) where the SU is in a transient state, or No Data available to Send (*NDS*) where neither PU nor SU has a packet ready to send. Equations (17) define these five channel time usages.

$$\begin{cases} UPU = p_{SUC}T_{SP} \\ WPU = (1-p_{SUC})T_{CP} + (1-(1-\gamma_p)^n)E[\psi].T_{Slot} \\ USU = \gamma_S(1-p_{TX})^{\hat{\imath}+1}T_{SS} \\ WSU = \gamma_S.p_{TX}\sum_{h=0}^{\hat{\imath}} h(1-p_{TX})^h T_{slot} \\ NDS = (1-\gamma_P)^n(1-\gamma_S)E[\psi]T_{Slot} + (1-\gamma_P)^n(1-p_{TX})^{\left\lfloor T_{SS}/T_{Slot}\right\rfloor+\hat{\imath}+1}T_{Slot} \end{cases} \tag{17}$$

Where ⌊ . ⌋ is the floor function and p_{tx} is the probability that there is at least one PU using the channel, it is defined as in (18).

$$p_{tx} = 1-(1-p_t)^n \tag{18}$$

The *UPU* formula corresponds to the PU transmission occurrence probability multiplied by its duration. The *WPU* includes the collision time (1-p_{suc})T_{CP}, plus the BW time where at least one PU has a packet to send (1-(1-γ_p)^n). *USU* expresses the SU transmission time multiplied by probability of accessing the channel after $\hat{\imath}$+1 time slots where the PU is not transmitting. *WSU* is the SU waiting time in the transient state without being able to access the channel as the PU regains the channel before the $\hat{\imath}$-th slot. The time *NDS* is composed of two parts: the first (1- γ_S)(1- γ_p)^n $E[\psi].T_{Slot}$ represents the period where neither the PU nor the SU has a packet to send, and the second is idle time after a SU successful transmission.

Fig. 7 and Fig. 8 show respectively the ratio of useful time for the PU in two cases: the SU observes waiting time as required in our solution with *p*=0.5 and no waiting time (i.e. no transient state). In both figures we observe the impact of the technology used by the SU, worse results, lower UPU ratio, are obtained for Zigbee, which has the highest T_{SS}. Notice that the degradation is not linearly proportional to T_{SS} value. Furthermore when we compare Fig. 7 and Fig. 8, it is obvious that our solution improve the UPU ratio.

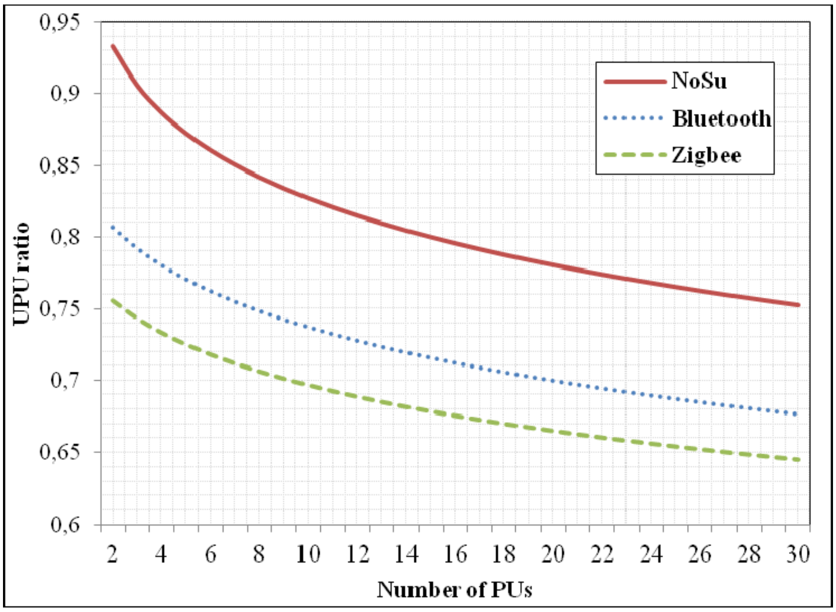

Fig. 7: The UPU ratio when SU uses WLAN, Zigbee or Bluetooth protocol. Case NoTrans.

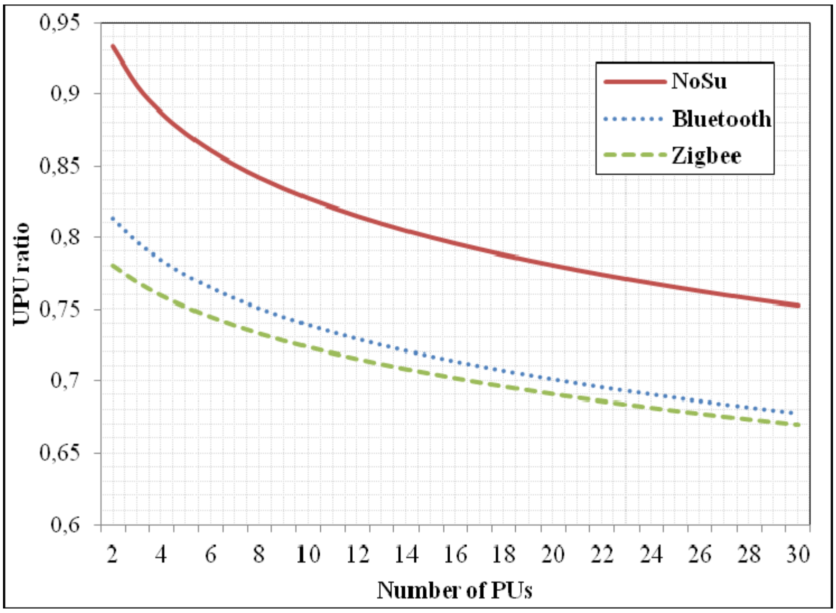

Fig. 8: The UPU ratio when SU uses WLAN, Zigbee or Bluetooth protocol. Case *p*=0.5.

Fig. 9 and Fig. 10 show respectively the ratio of useful time for the SU in the both cases discussed above. As see for the PU, the technology used by the SU has impact on USU, however the SU get better result with higher T_{SS} value. As our focus was on improving the PU performance, our solution reduces the USU ratio as expected.

It is important to note that *p* value should be chosen carefully according to the PU spectrum sharing policy. A greater value will offer little protection to the PU against HC while a smaller value will have more impact on the SU's performance as it leaves less opportunity to access the channel.

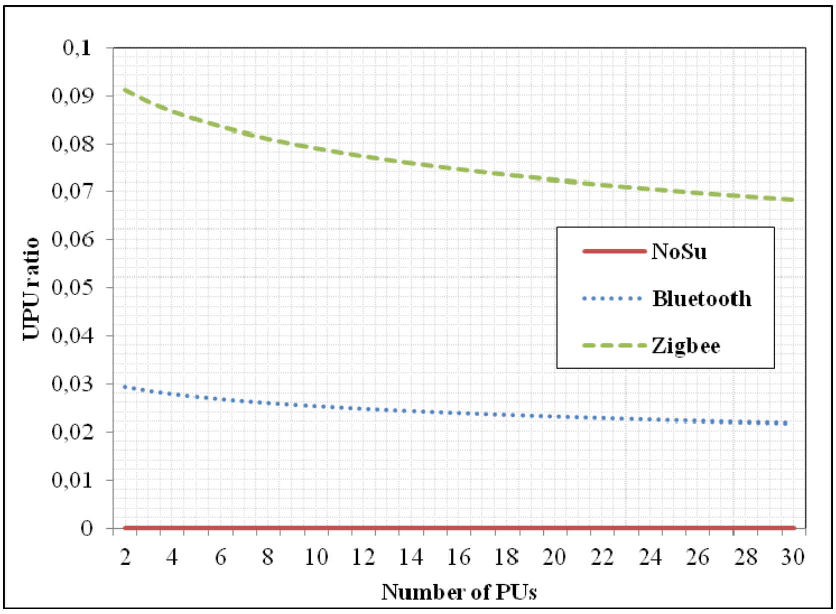

Fig. 9: The USU ratio when the SU uses WLAN, Zigbee or Bluetooth protocol. Case : NoTrans.

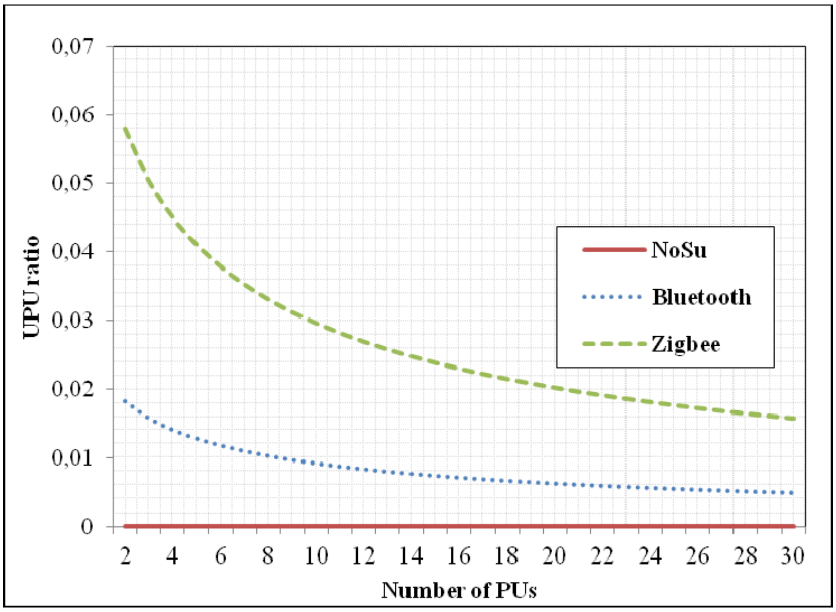

Fig. 10: The USU ratio when SU uses WLAN, Zigbee or Bluetooth protocol. Case : p=0.5.

V. CONCLUSION

In this paper, we studied the impact of hidden collision on WLAN nodes' performance when coexisting with Zigbee or Bluetooth nodes. Our work shows that the hidden collision effect is less noticeable when the SU transmission time is smaller, which corresponds to the Bluetooth technology in our study. Furthermore we proposed a solution that reduces its effect. This solution is based on a three states channel model. A Transient state, where we impose a waiting time, was added in order to better control the secondary user access to the channel. Analytic results showed the effectiveness of our solution in reducing the hidden collision effect, and consequently improving the WLAN nodes' throughput. As future work, we are studying a new solution based on a predictive approach to model the transient phase to improve the network throughput and spectrum utilization In fact, we are planning to explore other alternative based on state prediction model in which the secondary user will be able to predict the primary users' state before accessing the channel, hoping to obtain better use of the spectrum.

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AUTHOR PROFILE

Marouane SEBGUI Received the Ing. Degree in Networks and Telecommunication engineering from the Mohammadia School of engineers (EMI), Rabat, Morocco, in 2009. He is currently working toward the Ph.D. degree at LEC Laboratory, Mohammadia School of Engineers (EMI).

Dr. Slimane BAH is a professor at the computer science department of Mohammadia Engineering School (Ecole Mohammadia d’Ingenieurs) -Morocco. He has an experience as adjunct professor at the department of computer science - university of Moncton. He holds a Ph.D. in computer networks from the Electrical and Computer Engineering Department of Concordia University. During his Ph.D. research he was an intern at Ericsson Canada. He also holds an M.Sc. in computer networks from university of Montreal (Université de Montréal) and an engineering degree in computer science - Networking, from l’Ecole Nationale Superieure d’Informatique et d’Analyse des Systems (ENSIAS - Morocco). His research interests include end-user services, self-organizing and challenging networks, services and protocols engineering.

Dr. Belhaj ELGRAINI is a professor at the electrical department of Mohammadia School of Engineers (EMI), Rabat, Morocco, since 1988. He Received the Ing. Degree in Electrical and Electronic engineering from the Mohammadia School of Engineers (EMI), Rabat, Morocco, in 1988. He holds a Ph.D. from Liège University, Belgium.