Peaceful Coexistence of IEEE 802.11 and IEEE 802.16 Standards in 5GHz Unlicensed Bands

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***Abstract*—**Cognitive radio devices have been considered as a key technology for next-generation of wireless communication. These devices in the context of IEEE 802.11 standards and IEEE 802.16 standards, can opportunistically utilize the wireless spectrum to achieve better user performance and improve the overall spectrum-utilization efficiency, mainly in the unlicensed 5 GHz bands. However, opportunistic use of wireless spectrum creates news problems such as peaceful coexistence with other wireless technologies, such as the radiolocation systems, as well as understanding the influence of interference that each of these networks can create. In this paper, we suggest a dynamic access model that considerably reduces this interference and allows efficiency and fairness use of the wireless spectrum.

***Keywords*—**Dynamic access, exclusive access, spectrum opportunities, unlicensed band.

I. Introduction

IN recent years, the demand for spectrum access has increased substantially. Most of the last generation networks are wireless ones. So, that emphasizes the problem of need of wireless. And Wireless networks, are regulated by governmental agencies which assign the spectrum for particular applications. While spectrum is typically regarded as a scarce resource, leading to tremendous efforts to efficiently utilize the dedicated spectrum, measurements indicate that mayor parts of the spectrum are greatly underutilized as shown in Figure 1 [1]. This figure presents the example of measured spectrum occupancy between $30\ MHz$ and $3\ GHz$ at six locations. This dilemma, which is attributed to the static and exclusive allocation of dedicated frequency bands to specific systems and/or operators by regulators, has inspired a new research field of dynamic spectrum sharing [2]. So, this innovative approach is thus necessary to allow a dynamic, opportunist and controlled use of the spectrum in addition to the current static assignment of the spectrum. Besides, the software define radio (SDR) promises a big flexibility by allowing the same device to reach a wide spectrum and various technologies [3].

The concept of “cognitive radio” intends to use the possibilities offered by the software define radio to allow a more effective use of the spectrum. Cognitive radio is one approach to coexisting radio systems. Indeed, cognitive radio has attracted much attention as a key solution towards accommodating several wireless communication systems in the same frequency band [2]. Cognitive radio devices are equipped with the capability to sense the radio environment and then adaptively configure their transmission parameters, for example, carrier frequency, baud rate, and beam-forming pattern, according to the sensing results and the spectrum utilization policies [2]. In a spectrum-sharing scenario where the secondary usage of underutilized spectrum portions, that is, white space, of a primary system is allowed, secondary systems are able to acquire free spectrum by accessing the white space of the primary system. Nevertheless, a secondary cognitive user, before transmission, needs to sense the spectrum and confirm the absence of primary users in order to avoid imparting harmful interference to those users [4]. Recognition among multiple secondary systems competing for white space spectrum is also important as it may enable the setting of advanced spectrum policy such as multilevel priority or advanced access control such as maintaining fairness among secondary systems [5].

In United States, as an example consider the wireless evolution in unlicensed bands. In these bands any technology that complies with the Federal Committee for Communications (FCC) rules for band is allowed to operate [5]. A good example of such band is the “Industrial Scientific and Medical (ISM)” band in $2.4\ GHz$ [6]. There are multiple wireless technologies that operating in these band as standards IEEE 802.11 (WLAN: Wireless Local Area Network), IEEE 802.15 (WPAN: Wireless Personal Area Network) and cordless phone. Others examples of unlicensed frequency bands include the U-NII (Unlicensed National Information Infrastructure) where systems such as IEEE systems 802.11a (WLAN) and soon IEEE systems 802.11n (WLAN) [7]. While unlicensed bands have opened up avenues for the advent of new technologies, their full potential is not realizable because of the presence of interference from other technologies [8]. However the full and whole use of these new technologies cannot be realized because of the interferences

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caused by the presence of the other systems operating in these bands. Where from, the necessity of the implementation of techniques allowing a coexistence of all these technologies. Certain works focused on this question, to propose solutions of cooperation between various technologies [8]-[10].

This paper also approaches the problem of coexistence, in particular the coexistence of the standards IEEE 802.16 (WMAN) and IEEE 802.11 (WLAN) with the radiolocation systems in the 5 GHz unlicensed bands. The objective of the present paper is to propose, according to IUT-R M.1652 recommendation [11], a model of dynamic access allowing an effective cooperation of all these systems in these bands.

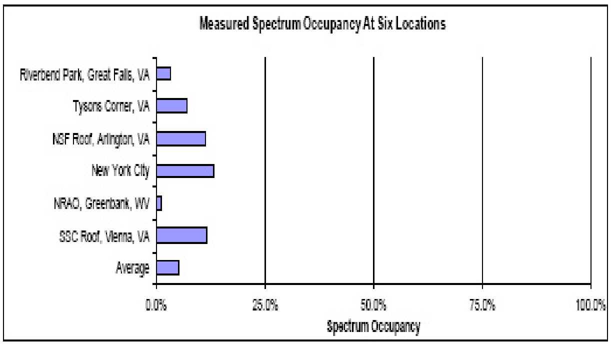

Fig. 1 Measured spectrum occupancy at six locations [1]

The rest of the paper is organized in the following way. In the section 2, the formulation of the problem is presented. The section 3 gives the model of the channel and the traffic, whereas the section 4 approaches the model of dynamic access. An analysis of the model of access is made in the section 5. Finally, the paper ends with a conclusion and perspectives in the section 6.

II. Problem Formulation

It does consider two groups of networks operating in the $5\ GHz$ unlicensed bands; mainly primary and secondary or cognitive radio networks. A primary network has exclusive access to its dedicated spectral bands; while a cognitive radio network only accesses a spectral band when this one is not used by primary network. Here, the primary networks represent the radiolocation systems, such as the radars systems and cognitive radio or secondary networks are appointed by standards IEEE 802.11 (WLAN: Wireless Local Area Network) and IEEE 802.16 (Wireless Metropolitan Area Network). The transmission systems of these standards are based on the OFDM (Orthogonal Frequency Division Multiplexing) technique. In general, the availability of spectrum is a function of *geographic area* and *time*. With the FCC pushing for more intensive and efficient use of spectrum, the next generation of wireless communication systems is being designed to use the spectrum in a dynamic manner. The term dynamic spectrum access has different connotations in different contexts [12].

This paper is mainly concerned with the scenario where a cognitive radio dynamically monitors certain bands of the $5\ GHz$ unlicensed spectrum, finds idle spectrum and uses it as needed. It is mandatory for the cognitive radios not to cause any interference to the primary users of the spectrum. This scheme of dynamic spectrum access is also known as *opportunistic spectrum access* [12]. A typical example of dynamic spectrum access scenario is shown in Figure 2. So in rest of this paper, the expression dynamic spectrum access is equivalent to opportunistic spectrum access.

To allow the opportunist access to the radio resources of the primary systems, secondary networks support spectral agility. Thus it is their responsibility to locate available radio resources in both spectral and temporal domains [2]. It's also important to precise that primary networks don't cooperate with other systems. Here, N primary networks with the same number of channels are considered. Each primary network has one dedicated channel, and has an exclusive access. M secondary networks are present in this environment existence and compete to access spectral opportunities.

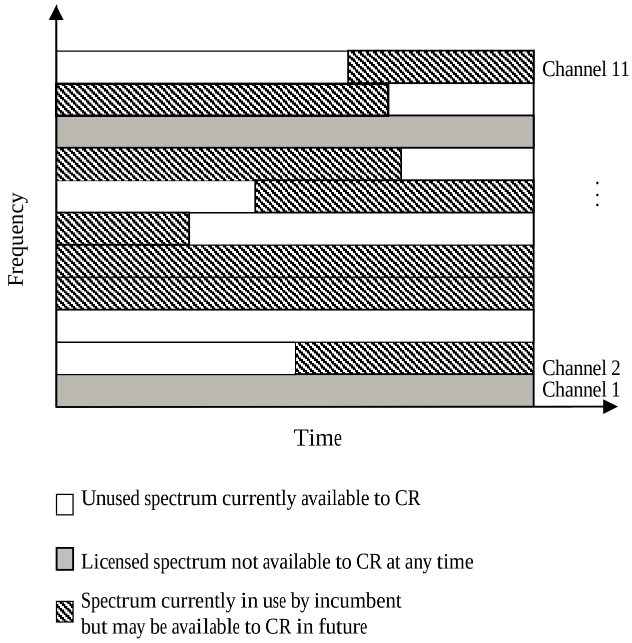

Fig. 2: A typical dynamic spectrum access model (Opportunistic spectrum access).

Each secondary network only uses a single channel for basic communication, but it can also use multiple channels for better performance. For example, the software define radio makes it possible to adopt a modulation scheme requiring higher bandwidth when several adjacent channels are available simultaneously. Moreover, it is possible to use discrete channels as sub-carriers of a multi-carrier modulation scheme such as the OFDMA (Orthogonal Frequency Division Multiplexing Access).

Besides, cognitive radio systems proceed by the principle of "Listen Before Talking (LBT)". When a system finished its communication, it releases automatically the radio resource used.

Depending on a primary network's spectrum usage pattern, the duration of a spectral opportunity can exceed hours, even days in spectral bands reserved for emergencies; or can be only few milliseconds in heavily-used spectral bands. It will be relatively easy, for the secondary network to use long-lasting opportunities. However, for short-lasting spectral opportunities, a secondary network may not be able to detect their existence and then utilize them before “expire”. Therefore, this study only focuses on the case when spectral opportunities last in the order of seconds.

In order to exploit these spectral opportunities and as said above, a secondary network has first scan the spectrum, either periodically or randomly to discover and use the idle portions of spectrum. When it has detected any activities of a primary network, it releases automatically channels used with the aim of avoiding interferences.

All nodes of a cognitive radio network use the same spectral opportunities so as to maintain their inter-connectivity all the time. Consequently, the different nodes also have to hold the same information on both spectral and temporal environment to decide switching their traffics on these spectral opportunities.

III. Channel and Traffic Model

The spectrum is divided into "channels" which represent small units of spectral bands. Every cognitive radio network uses a single channel for its basic communication, but that it has the possibility of using several neighboring channels, simultaneously available for a better quality of transmission. The software define radio allows to adopt the modulation scheme required for the use of a large bandwidth. Besides, a secondary network can use these neighboring discreet channels, as subcarrier of multi-carrier modulation scheme such as the OFDMA. The temporal usage of every channel by a primary network can be characterized by a random process. When a primary network does not use its dedicated frequency band, it leaves some idle channels which will be exploited by cognitive radio networks or secondary networks.

A. Channel model

The different channels of spectral bands are all considered perfect. That is a channel is either busy or idle. The usage pattern of the primary network, in every channel defines independent ON and OFF-periods. An ON-period indicates that the channel is busy while an OFF-period represents a spectral opportunity to be exploited by a secondary network. The distributions of ON and OFF-periods in every channel are represented by exponential distributions with the respective means $T_{ON}^{(i)}$ et $T_{OFF}^{(i)}$. The function of use of every channel i is thus : $\tau_i = \frac{T_{ON}^{(i)}}{T_{ON}^{(i)}+T_{OFF}^{(i)}}$. Therefore, the fraction of time during which, there are k free channels simultaneously is:

$$\sum_{c=1}^{\frac{N!}{k!(N-k)!}} \left[\prod_{i \in S_c^k} (1-\tau_i) \times \prod_{j \in \{1,2,\ldots,N\}-S_c^k} \tau_j \right] \quad (1)$$

Where $S_c^k = \{c, c+1, c+2, \ldots c+k-1\}$ with $c, k \in IN^*$ is the set of k idle channels among N of the spectrum, available for a secondary usage.

In the present case, $M > 1$ and M secondary networks with agile spectrum try to exploit k available spectral opportunities. Of course, if $M = k$, every cognitive radio network, obtains one channel. Otherwise, these M networks compete for the access to these channels. It is then that the other parameters return in game, which will allow an effective and fair access to the available spectrum.

It’s important to note that the interval of blocking has for the beginning, the passage of OFF-period to the ON-period and for the end, the passage of ON-period to the OFF-period. This interval notes t_{block} and calculation by the following :

$$t_{block} = min_{i=1,2,\ldots,N} \left[T_{remain}^{(i)} \right] \quad (2)$$

Where $T_{remain}^{(i)}$ is the remaining ON-period in channel i. This blocking interval means that there is no spectral opportunity for secondary networks.

B. Traffic model

In this analytical traffic model, two models per radio system are considered. For the radio system i, traffic arrives according a Poisson random process with rate λ_i, and the inter-arrival time is negative exponentially distributed with means time $\frac{1}{\lambda_i}$. The departure traffic is also characterized by another Poisson random process with rate μ_i, Thus, the radio system access duration is negative exponentially distributed with means time $\frac{1}{\mu_i}$. And the spectral scanning is performed instantaneously. So there is no scanning delay.

IV. Dynamic Access Model

The present problem of access to the $5\ Gi$ unlicensed bands is modeled by the continuous time Markov chain. The analysis of the process of dynamic access is made through a simple technique of calculation to determine the distribution of the airtime and the blocking probability.

A. Sharing airtime

In this Markov chain, K states are considered and define the steady state probability $\Pi = [\Pi_1 \quad \Pi_2 \quad \ldots \quad \Pi_K]$, where Π_i represents the probability of being in state i. An infinitesimal generator matrix A is also defined to characterize the transition of Markov chain states. So the relation linking the steady state probability and generator matrix is :

$$\Pi \times A = 0 \quad (3)$$

The generator matrix A is singular; so state probability cannot be solved directly. But with the condition that the sum of all the steady state probabilities should be one, these two conditions can be put into the following compact equation :

$$\begin{bmatrix} A^T \\ 1_{1\times K} \end{bmatrix} \times \Pi^T = \begin{bmatrix} 0_{K\times 1} \\ 1 \end{bmatrix} \quad (4)$$

Then by defining :

$$A' = \begin{bmatrix} A^T \\ 1_{1\times K} \end{bmatrix}, \qquad b = \begin{bmatrix} 0_{K\times 1} \\ 1 \end{bmatrix} \tag{5}$$

The equation becomes :

$$A' \times \Pi = b \tag{6}$$

By using minimum mean squared error (MMSE) criterion [13], the following unique solution is obtained:

$$\Pi^T = \left(A'^T \times A'\right)^{-1} \times A'^T \times b \tag{7}$$

So, after having the state probabilities, the $airtime_i$ share for radio system i is just the weighed summation of the respective states probabilities of the system.

B. Blocking probability

In addition to the fairness problem resolution between the different radio systems, it will be necessary to take into account the instant access probability or blocking probability. The present model can be considered as a finite population queuing model, and the time blocking is the proportion of time that the system spends in the blocking states. The seen state probability can be determined by an arriving traffic by the following expression :

$$\Pi_j^* = \frac{\lambda_j \times \Pi_j}{\sum_{k=0}^{s} \lambda_k \times \Pi_k} \tag{8}$$

Where $s+1$ is the total number of states. Considering a long period of time T, on the average the system spends in state j the time $\Pi_j \times T$. During this time, there are on the average $\lambda_j \times \Pi_j \times T$ call arrivals (entering traffics) which find the system in the state j. The total number of calls arriving in time T is on the average $T \times \sum_{k=0}^{s} \lambda_k \times \Pi_k$. Then the proportion of calls which finds the system in the state j, is as given by the above expression. When the random access probability is P_i the blocking experienced by the system radio i is:

$$P_{BLKi} = 1 - P_i \times \left[1 - \sum_{j\, etats\ bloques} \Pi_j^*\right] \tag{9}$$

In this equation, the access probability determination is very important. To obtain this probability, all information µ's and λ's are needed, which is not practical in a real access scenario. In this case, a more realistic scheme is chosen to allow each radio system to learn its access probability itself with only local information or measurement. The technique used here, based on the principle of the evolution in Homo Egualis society [14]-[15]. The inequality aversion property of the Homo Egualis agents can utilize to achieve fairness in spectrum access problem. In this scheme, each radio system learns the access probability P_i by itself. Here, $Onlinetime_i$ is defined as the averaged cumulative « on » spectrum time per radio system of type i. $x_i = \frac{Onlinetime_i}{L_i}$ is also defined, where L_i is a parameter proportional to the traffic load of radio system type i. The cumulative $Onlinetime_i$ is normalized by the radio system's traffic load, which makes this spectrum access scheme able to adapt to different traffic loads and hence achieve more efficiency and maintain fairness. With $P_i = 1$, each time the probability P_i is updated as follows [5], [16],

$$P_i = max\left[0, min\left\{1, P_i + \frac{\alpha_i}{n-1} \times \sum_{x_j \geq x_i} (x_j - x_i) - \frac{\beta_i}{n-1} \times \sum_{x_i > x_j} (x_i - x_j)\right\}\right] \tag{10}$$

for all $j \neq i$, where n is the number of radio system types, and $0 < \beta_i < \alpha_i$.

V. Dynamic Access Model Analysis

Unlicensed bands promote spectrum sharing (as any device can transmit while others are idle), which reduces trunking inefficiencies [2]. Unlicensed spectrum also facilitates experimentation and innovation, as it readily accessible. So the $5\ GHz$ unlicensed bands do not break it. However, for peaceful coexistence between cognitive radio networks and primary networks, three challenges must be overcome. First, there may be a mutual interference, as devices can transmit at will. Second applications using unlicensed bands may vary greatly, making it difficult to enforce efficient utilization for all applications. Third, and most difficult, there is little incentive for devices to conserve shared spectrum. Thus, a device may overuse shared spectrum to improve its own performance, even if performance degrades for other devices. If this is common, the shared resource will be of little use. This phenomenon has been referred to as a tragedy of the commons [17]. These three challenges can be resumed into three problems denoted as interference, efficiency and fairness. Indeed, efficiency and fairness are obviously the main goals of spectrum etiquette. The $5\ GHz$ unlicensed bands are one of the unlicensed bands that can be efficiently used only with the principle of spectrum etiquette. The principle of "Listen Before Talk (LBT)" is based on the spectrum etiquette [7], [18]. In reality, spectrum etiquette is all the rules for the management of the radio resources of open spectrum. These rules allow establishing certain fairness for the available radio resources access. The proposed random access scheme makes it possible to achieve the desired fairness in open spectrum access with different types of radio systems. But with the increasing number of such devices, reducing the blocking probability and increasing the airtime share become a critical issue [5]. Spectrum agility based channel access helps this cause. It reduces the problem of the ineffectiveness of spectrum access [18]-[20]. Indeed, spectrum agility decreases the blocking probability and increases the airtime share. With the advances in software defined radio, spectral agile networks become more and more tractable. Such radio devices can dynamically (in particular, opportunistically in this case) utilize idle spectrum bands. One of the interesting concerns here is, given the additional freedom of carrier frequency switching, what is the gain in efficiency for radio systems with different bandwidth requirements. There are lots of ways to take advantage of this switching. To achieve the upper bound for agile spectrum efficiency, one way is to "pack" all the radio systems tightly together in the spectral domain. Such a packing would ensure that there is no spectral hole (white space). The "LBT" feature inherently provides much better protection from interference than a system of power limits where there is no sensing. The etiquette has no restriction on the technologies that devices may use except that they must follow the etiquette, and therefore it supports more diversity. However, the etiquette has an inherent limitation that cannot distinguish between applications of low value and high value, and restricts all applications equally. The etiquette also includes many provisions to improve spectrum efficiency. This etiquette uses a (LBT) approach, which requires devices to first sense the channel for a specified time and determine whether there is a transmission underway. If the received power is sufficiently low that they are unlikely to experience or cause interference, they can transmit. All these principles help to reduce mutual interference, but not greed. If every radio system accesses the unlicensed band in a greedy manner, then the radio system requiring broader band to operate will suffer from an unacceptable low airtime share. So one way to provision more fairness to etiquette rules would be to require each radio system to work in cooperative manner. One option would be that each radio system i tries to contend for the spectrum with probability P_i. After the radio system has decided to contend for the spectrum, it accesses the spectrum compliant to etiquette rule. So the spectrum access scheme based on the Homo Egualis society principle proposed here used the inequality aversion property of the Homo Egualis agents to achieve fairness in this spectrum access problem [5]. The condition $0 < \beta_i < \alpha_i$, reflects the fact that Homo Egualis exhibits a weak urge to inequality when doing better than the others and a strong urge to reduce inequality when doing worse than the others. This forces each radio system to make an effort to efficiently use the idle spectrum while taking fairness into consideration. Here the only local information needed is the radio system's own history of the $airtime$ and the $airtime$ of the others radio system whose spectrum overlaps with its spectrum. This can be obtained by keeping a record of the busy time of the required spectrum, which can be obtained by periodically spectrum scanning. So each radio system can access the spectrum based only on its own recorded history and local measurements performed by itself. Beside, L_i can be estimated by historical usage records of radio system type i.

Generally, interferences between IEEE 802.11 system, IEEE 802.16 system and radiolocation systems will occur when devices have exploited at the same frequencies and when they will be in reach some of the others. The dynamic access model proposed here, allows not only to guarantee the system load spreading on the entire available spectrum; but also to avoid co-channel exploitation with the primary systems of radiolocation. Thus the use of this dynamic access model can be able to supply a suitable protection to the radiolocation systems in the $5\ GHz$ unlicensed bands. So cognitive radio systems avoid the usage of a busy channel, and release a channel which they occupied when radiolocation devices want to use their dedicated channel by the detection of the signals that they emit.

VI. Conclusion

Traditionally, interference protection is guaranteed through a policy of spectrum licensing, whereby wireless systems get exclusive access to spectrum. This is an effective way to prevent interference, but it leads to highly inefficient use of spectrum. The dynamic spectrum access along with cognitive radio allows spectrum sharing that would greatly improve spectral efficiency and alleviate scarcity. In this paper, a model of cooperation between the systems IEEE 802.11 and IEEE 802.16 with the systems of radio localization in the 5 GHz unlicensed bands, is proposed. This model based on the technique of dynamic access to the radio spectrum, allows an effective and fair use of the spectrum. It also creates an environment of peaceful coexistence of the various systems radio, by reducing the interferences. Besides, it contributes to the enfeeblement of the need in frequency bands for these new emergent technologies. It is clear therefore, that the cognitive radio positions as the major solution to reduce the problem of rarity of the spectrum of frequency in this new context of the wireless communications.

A next paper will approach the numeric aspect of this subject. It will accentuate the impact of the number of cognitive radio systems on the effective cooperation of all the systems working in these $5\ GHz$ unlicensed bands.

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