AN ANALYSIS OF SPECTRUM MANAGEMENT FOR COEXISTENCE OF FIXED AND COGNITIVE RADIO SYSTEMS

Kotaro WATANABE, Koji ISHIBASHI, and Ryuji KOHNO.
(Graduate School of Engineering, Division of Physics, Electrical and Computer
Engineering, Yokohama National University, Yokohama, Kanagawa, JAPAN,
kotaro@kohnolab.dnj.ynu.ac.jp)

ABSTRACT

Recently, the shortage of assignable radio spectrums becomes the serious issue because of appearance of many licensed wireless communications systems. Therefore, cognitive radio technology has gained attention around the world, which maybe aware of its environment and makes occupancy of radio spectrums more efficiently. In this paper, the frequency band between 3.4-4.8GHz is focused on. We consider a coexistence environment of a narrowband radio system, e.g. 4th generation cellular system (4G) and TV broadcasting, and wideband radio system, e.g. ultra wideband (UWB) communication systems. In the frequency band between 3.4-4.8 GHz, UWB systems are required Detect And Avoid (DAA) technology (e.g. [1]). Therefore, in our scenario, narrowband radio system is a traditionally licensed one, i.e., it uses fixed frequency bands. On the other hand, wideband radio system is one with a cognitive radio technology. We introduce two important benchmarks and analyze this communications model using continuance Markov model. Computer simulations have been performed to justify these analytical results. In addition, the design issue of cognitive radio systems is discussed based on these numerical results.

1. INTRODUCTION

The usage of the radio spectrum and the regulation of radio emissions are coordinated by national regulatory bodies. As part of radio regulation, the radio spectrum is divided into frequency band, and licenses for the usage of frequency bands are provided to operators, typically for a long time such as one or two decades. With licensed frequency bands, operators have often the exclusive right to use the radio resources of the assigned bands for providing radio services. Depending on the type of radio service and on the efficiency of the radio systems, frequency bands may be used inefficiently. Therefore many national regulatory and standards bodies such as The Federal Communications Commission (FCC)[2], IEEE802.22 WG [3], and Ministry of Internal Affairs in Japan have paid attention to the dynamic spectrum access technology. Using dynamic spectrum access technology, radio systems can dynamically use and release radio spectrum wherever and whenever they are available. Moreover, dynamic spectrum access technology helps to minimize unused radio spectrum band. This technology is also referred to as *cognitive radio technology*. Cognitive radio is defined as an intelligent wireless communication system, which may be aware of its environment and adapt to statistical variations in the input stimuli [4].

Coordination rules for radio resource management have been studied for radio systems with different channel bandwidths with focus on the 5GHz U-NII frequency band [5]. In [6], continuous-time Markov models have been considered in order to analyze dynamic spectrum access in open spectrum wireless networks.

In this paper, we consider a coexistence environment of spectrum-fixed and cognitive radio systems. Throughout the paper, spectrum-fixed radio systems such as 4th generation cellular system (4G) and TV broadcasting, are referred to as *narrowband radio systems* and cognitive radio systems such as ultra wideband (UWB) communication systems are referred to as *wideband radio systems*, respectively.

While the unlicensed spectrum allocation of Ministry of Internal Affairs in Japan is between 3.4-4.8GHz and between 7.25-10.25GHz for UWB systems, UWB technology has seen great debate over its possible interference to existing or future wireless systems using of the same and nearby spectrum bands, such as WiMAX or 4G cellular networks. Therefore, the allocation requires Detect And Avoid (DAA) technology (e.g. [1]) for the 3.4-4.8GHz bands in order to ensure a coexistence with incumbent systems and new services such as 4G . Although UWB systems with DAA technology are allowed to transmit with power level of -41.3dB/MHz, those without DAA technology must limit their emission level by -70dBm/MHz, which is lower than the noise level. Therefore, DAA technology is essential for UWB systems in order to allow them to transmit with the maximum allowed power level. Consequently, in this paper, we assume that wideband radio systems are cognitive radio systems and narrow band radio systems are spectrum-fixed radio systems. The question that may arise at this point is how to design the medium access control (MAC) layer of cognitive radio systems. Therefore, in this paper, this coexistence environment is analyzed by introducing a mathematical model and two important benchmarks and the design issue is discussed based on these results.

The rest of this paper is organized as follows. In section 2, system model considered throughout the paper is presented. Markov models are investigated in order to analyze the effect of DAA technology in section 3. Numerical results and discussion are given in section 4. Finally, the conclusions are drawn in section 5.

2. SYSTEM MODEL

2.1 Channel and Traffic Model

We omit the effect of channel errors in order to make the analysis tractable. Hence, the channel is either busy or idle. The offered traffic is modeled with two random processes per radio systems [4]. The arrival traffic is modeled as a Poisson random process with rates λ_i for radio system *i*, so the interarrival time is negative-exponentially distributed with mean time $1/\lambda_i$. The radio system access duration is also negative-exponentially distributed with mean time $1/\mu_i$, so the departure of the radio system *i* is another Poisson random process with rate μ_i.

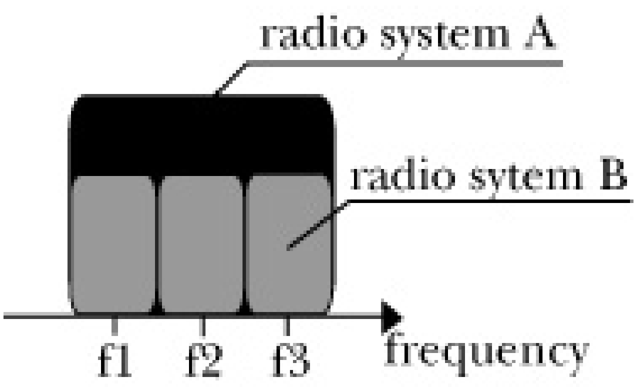

Fig. 1. Frequency channels used by two different types of radio systems (A, B)

2.2 Radio Spectrum Usage Model

The radio spectrum usage model is described, which is assumed throughout the paper. In Japan, the 3.4-4.8GHz frequency band is assigned for UWB systems, whereas this band is also including the other systems such as WiMAX, 4G, and so on. Therefore, as mentioned above, UWB systems must equip a DAA technology.

Without loss of generality, radio spectrum usage model having two different radio systems is considered to analyze this coexistence environment. Radio system A operates on one frequency channel (center frequency f_2) and radio system B operates on three frequency channels (center frequencies f_1, f_2, f_3). The frequency channels overlap with each other, as indicated in Fig. 1.

Radio system A can be considered as an UWB system with DAA technology and radio system B as a narrowband spectrum-fixed radio system. Radio system B access the channel based on the scheduling algorithm such as a time-division multiple access (TDMA). Radio system A can occupy a wideband radio resource if and only if all of the channels of radio system B are idle. Moreover, radio system A can recognize available channels without sensing error and delay.

2.3 Definitions of Benchmarks

In this paper, we employ "*airtime*" and "*interference time*" as a benchmark. "*Airtime*" means the ratio of allocation time per radio system type to the reference time (say one hour) [4][5]. Namely,

$$airtime_{type=A,B} = \frac{1}{N_{type}} \sum_{i=1}^{N_{type}} \frac{allocation\ time(i)}{reference\ time}, \tag{1}$$

where N_{type} is the number of channels belonging to $type \in \{A, B\}$ and $allocation\,time(i)$ is the total time of radio resources allocated to $type$. It characterizes the share of resources each radio system can allocate.

"*Interference time*" refers to the ratio of *interfere time* to the reference time. Hence,

$$interference\ time = \frac{1}{N_B} \sum_{i=1}^{N_B} \frac{interfere\ time\ (i)}{reference\ time}, \tag{2}$$

where $interfere\,time\,(i)$ is the total time when radio system A and radio system B use channels simultaneously.

Note that $allocation\,time(i)$ does not include $interfere\,time(i)$.

We will not show the throughput per radio system in the paper. Since the radio systems operate with different channel bandwidths, they will obtain different throughputs. This is not in the focus of discussion here. What is important is the mutual influence of the radio systems on each other.

3. MARKOV MODELLING

The model investigated in section 2 can be modeled as a continuous time Markov chain. Without loss of generality, we can model the two radio system access model illustrated in Fig. 1 as a eight state Markov chain, as shown in Fig. 2. The eight states of the Markov chain are described in Table 1. The assumption here is that for each type of the radio system, we have the same traffic load and occupation time.

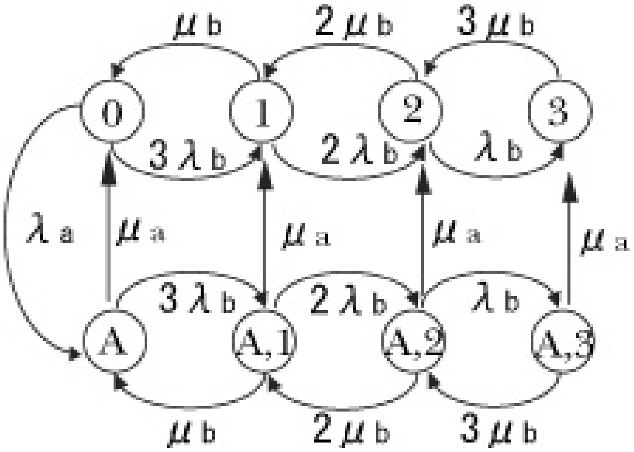

Fig. 2. Continuous time Markov chain with eight states to model the spectrum access process in section 2

Table. 1. Eight states of the Markov chain

State	Description
A	Radio system A occupies the reference spectrum range.
0	All the three frequency grids are idle.
i	Radio system B occupies *i* spectrum channels.
A,*i*	Radio system A occupies the spectrum and B also occupies *i* spectrum channels.

We define an infinitesimal generator matrix **Q** to characterize the transition of the states of the Markov chain. The infinitesimal generator matrix with the sum of each row equaling zero is given as follows:

$$\mathbf{Q} = \begin{bmatrix} \mathbf{Q}_1 \mathbf{Q}_2 \\ \mathbf{Q}_3 \mathbf{Q}_4 \end{bmatrix}, \tag{3}$$

where

$$\mathbf{Q}_1 = \begin{bmatrix} -3\lambda_b-\lambda_a & 3\lambda_b & 0 & 0 \\ \mu_b & -\mu_b-2\lambda_b & 2\lambda_b & 0 \\ 0 & 2\mu_b & -2\mu_b-\lambda_b & \lambda_b \\ 0 & 0 & 3\mu_b & -3\mu_b \end{bmatrix}, \tag{4}$$

$$\mathbf{Q}_2 = \begin{bmatrix} \lambda_a & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \tag{5}$$

$$\mathbf{Q}_3 = \begin{bmatrix} \mu_a & 0 & 0 & 0 \\ 0 & \mu_a & 0 & 0 \\ 0 & 0 & \mu_a & 0 \\ 0 & 0 & 0 & \mu_a \end{bmatrix}, \tag{6}$$

$$\mathbf{Q}_4 = \begin{bmatrix} -\mu_a-3\lambda_b & 3\lambda_b & 0 & 0 \\ \mu_b & -\mu_a-\mu_b-2\lambda_b & 2\lambda_b & 0 \\ 0 & 2\mu_b & -\mu_a-\lambda_b-2\mu_b & \lambda_b \\ 0 & 0 & 3\mu_b & -\mu_a-3\mu_b \end{bmatrix}. \tag{7}$$

Then, we have

$$\mathbf{PQ} = 0, \tag{8}$$

where $\mathbf{P} = \left[p_0, p_1, p_2, p_3, p_A, p_{A,1}, p_{A,2}, p_{A,3}\right]$ is the steady-state probability vector and p_i represents the probability of being in state *i*. We also have to consider the condition that the sum of all the steady-state probabilities should be one.

$$\sum p = 1. \tag{9}$$

Solving recursively, we can get

$$p_0 = \frac{1}{X}\mu_A\mu_B^3 Y\,, \tag{10}$$

$$p_1 = \frac{1}{X}3\lambda_B\mu_A\mu_B^2\left[Y+\lambda_A\left\{\begin{matrix}2\lambda_B^2+3\lambda_B(\mu_A+2\mu_B)+\\(\mu_A+2\mu_B)(\mu_A+3\mu_B)\end{matrix}\right\}\right], \tag{11}$$

$$p_2 = \frac{1}{X}3\lambda_B^2\mu_A\mu_B\left[Y+\lambda_A\left\{\begin{matrix}2\lambda_B^2+(\mu_A+3\mu_B)^2+\\\lambda_B(3\mu_A+7\mu_B)\end{matrix}\right\}\right], \tag{12}$$

$$p_3 = \frac{1}{X}\lambda_B^2\mu_A\left[Y+\lambda_A\left\{\begin{matrix}2\lambda_B^2+\mu_A^2+6\mu_A\mu_B\\+11\mu_B^2+\lambda_B(3\mu_A+7\mu_B)\end{matrix}\right\}\right], \tag{13}$$

$$p_A = \frac{1}{X}\lambda_B\mu_B^3 Z\,, \tag{14}$$

$$p_{A,1} = \frac{1}{X}3\lambda_A\lambda_B\mu_B^3\{\lambda_B\mu_A+(\mu_A+2\mu_B)(\mu_A+3\mu_B)\}, \tag{15}$$

$$p_{A,2} = \frac{1}{X}6\lambda_A\lambda_B^2\mu_B^3(\mu_A+3\mu_B), \tag{16}$$

$$p_{13} = \frac{1}{X}6\lambda_A\lambda_B^3\mu_B^3\,, \tag{17}$$

where

$$X = (\lambda_B+\mu_B)^3(\mu_A Y+\lambda_A Z), \tag{18}$$

$$Y = (\lambda_B+\mu_A+\mu_B)(2\lambda_B+\mu_A+2\mu_B)(3\lambda_B+\mu_A+3\mu_B), \tag{19}$$

$$\begin{aligned}Z = {}& 2\lambda_B^2\mu_A+(\mu_A+\mu_B)(\mu_A+2\mu_B)(\mu_A+3\mu_B)\\&+\lambda_B\mu_A(3\mu_A+7\mu_B)\end{aligned}. \tag{20}$$

Based on the previous Markov model, the *airtime* and *interference time* can be approximated by

$$airtime_A = p_A\,, \tag{21}$$

$$airTime_B = \frac{1}{3}p_1+\frac{2}{3}p_2+p_3\,, \tag{22}$$

$$interference\ time = \frac{1}{3}p_{A,1}+\frac{2}{3}p_{A,2}+p_{A,3}\,. \tag{23}$$

4. NUMERICAL RESULTS

We show the numerical results in this section to justify the theoretical analysis. Figure 3 and 4 show *airtime* and *interference time* versus offered traffic of radio system B or A, respectively. Also, figure 5 shows *airtime* and *interference time* versus the departure rate of radio system A. We employ that $0 \le \lambda_B \le 1$ and $\lambda_A = \mu_A = \mu_B = 0.5$ for figure 3, $0 \le \lambda_A \le 1$ and $\lambda_B = \mu_A = \mu_B = 0.5$ for figure 4 and, $0 \le \mu_A \le 1$ and $\lambda_A = \lambda_B = \mu_B = 0.5$ for figure 5.

From the figure 3, 4, and 5, every theoretical results based on Markov model exactly agree with simulation results. From the figure 3, *interference time* is approximately zero over wide range of offered traffic of radio system B because of DAA function of system A. *Airtime* of system B can achieve about 0.65 without increasing *interference time*. However, *airtime* of system A is decreased by increasing offered traffic of B. Therefore, a trade-off between *airtime* of system A and that of system B can be found.

From figure 4, *airtime* of system A may be increased by increasing its offered traffic. However, maximal *airtime* of system A cannot exceed 0.1. On the other hand, offered traffic of system A also increase *interference time*, of which maximal value is about 0.2. Therefore, if the system A require more offered traffic, then that of system A should be increased at the cost of increasing *interference time*.

From the figure 5, while *interference time* is decreased by increasing the departure rate of radio system A, *airtime* of radio system B becomes longer. However, *airtime* of system A is decreased since the occupancy time of channels becomes shorter by increasing the departure rate of system A.

Therefore, in order to minimize the *interference time*, the offered traffic of radio system A should be chosen as small and the departure rate large. The *airtime* of system B is 0.3 and *interference time* is 0.5 even if offered traffic of system A is one. On the other hand, the *airtime* of system B becomes zero and *interference time* becomes 0.5 if the departure rate of system A is zero. Therefore, the occupancy time of channels should be shortened for system A rather than decreasing offered traffic (i.e., arrival rate) since the departure rate is inverse proportion to the occupancy time.

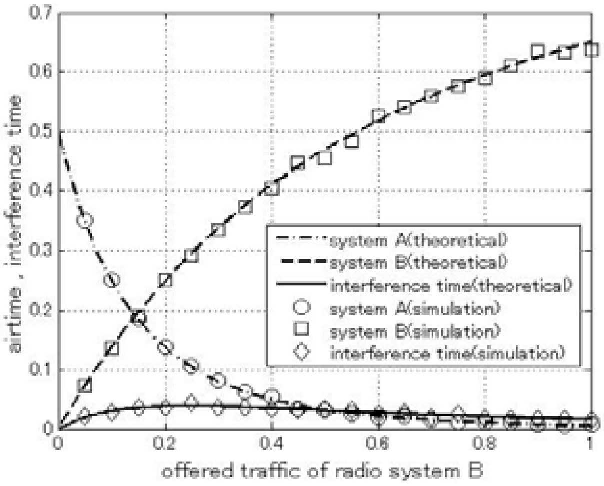

Fig. 3. Spectrum access airtime and interference time (offered traffic of radio system B)

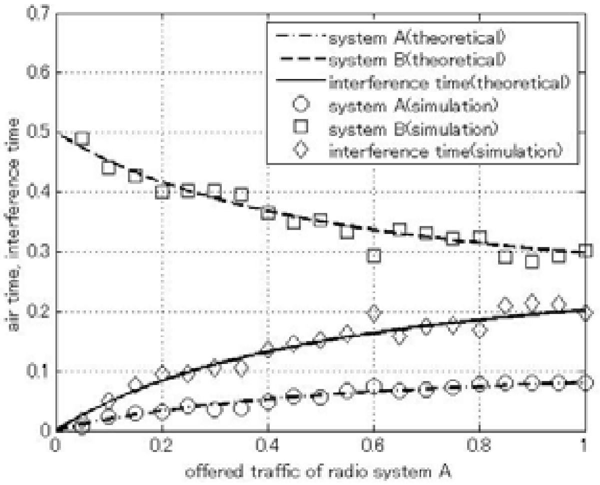

Fig. 4. Spectrum access airtime and interference time (offered traffic of radio system A)

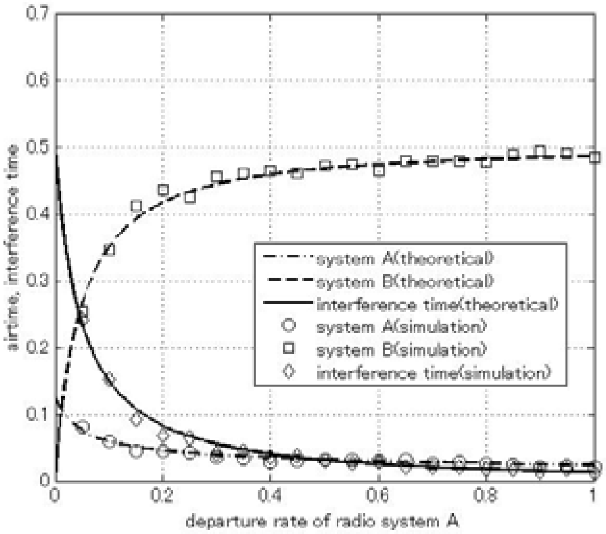

Fig. 5. Spectrum access airtime and interference time (departure rate of radio system A)

5. CONCLUSIONS

In this paper, we studied dynamic spectrum access technology in the coexistence environment of spectrum-fixed and cognitive radio systems. In order to analyze this communication model, two important benchmarks, "*airtime*" and "*interference time*," are employed. We showed some numerical results. Then, theoretical results show the good agreement with simulation results. The design guideline of MAC layer of cognitive radio systems was discussed based on these results. We can conclude that the occupancy time of channels should be shortened for cognitive radio systems rather than decreasing offered traffic.

6. REFERENCES

[1] R. Kohno, K. Takizawa, "Soft-spectrum Adaptation for Detection and Avoidance of UWB interference to Existing Radio Systems, " Frequenz, vol. 60, no. 5-6, pp. 88-91, May 2006.

[2] Federal Communications Commission, "Spectrum Policy Task Force," Rep. ET Docket no. 02-135, November. 2002.

[3] Functional Requirements for the 802.22 WRAN Standard *IEEE*.

[4] S.Haykin, “Cognitive Radio: Brain-Empowered Wireless Communications,” *IEEE* J-SAC, vol. 23, no. 2, pp. 201-220, February 2005.

[5] S.Mangold, K.Challapali, “Coexistence of Wireless Networks in Unlicensed Frequency Bands,” WWWRF#9 meeting, Zurich, Switzerland, July 1-2, 2003.

[6] Y.Xing, R.Chandramouli, S.Mangold, “Dynamic Spectrum Access in Open Spectrum Wireless Networks,” *IEEE* J-SAC, vol. 24, no. 3, pp. 626-637, March 2006.