Power Control for Time-Varying Cognitive Radio Networks

Ruifeng Duan*, Mohammed Elmusrati*, Riku Jäntti†, and Reino Virrankoski‡
*Telecommunication Engineering Group
University of Vaasa, 65101, Vaasa, Finland
Email: firstname.lastname@uwasa.fi
†Department of Communications and Networking (Comnet)
Aalto University, FIN-00076 Aalto, Finland
Email: riku.jantti@tkk.fi

Abstract—In this paper we propose a new power control scheme for cognitive radios, Distributed Power Control Algorithm for Cognitive Radios (DPCACR). As we know that in a cognitive system, the secondary users (SU) either transmit in an opportunistic way or coexist with the primary users to transmit simultaneously under the constraints that will not harm to the primary users. Previously, the interference temperature was announced to limit the transmit power of SUs. However, in 2007 the FCC has abandoned the concept which is not workable. In this paper, we consider the elastic transmission scenario for secondary system. The cognitive networks using code-division multiple access (CDMA) technology to transmit simultaneously with primary users in the same spectral band.

I. INTRODUCTION

The electromagnetic radio spectrum is a precious natural resource, which is regulated by the government agencies. Current wireless systems are characterized by command-and-control structure of frequency allocation. The Federal Communications Commission’s (FCC) frequency allocation chart indicates overlapping allocations over all of the frequency bands. However, the recent studies by the FCC’s Spectrum Policy Task Force showed that large portions of the licensed bands remain unused for as much as 90% of the time [1]. In order to utilize these spectrum ‘white spaces’, the FCC has issued a Notice of Proposed Rule Making [2] advancing Cognitive Radio (CR) technology as a candidate to implement opportunistic spectrum sharing. Coined by Mitola [3] and then promoted by FCC, Cognitive Radio technologies have the potential to provide a number of benefits that would result in increased access to spectrum and also make new and improved communication services available to the public [4], [5].

There are two spectrum sharing methodologies defined in literature, overlay and underlay [6], [5], [7]. In an overlay spectrum sharing approach, the secondary users access the network when the spectrum holes appear [4], which means that secondary users can not use the spectrum while primary system is working. Accurate spectrum sensing needs to be performed to avoid possible collision with primary users [8]. Consequently the interference caused by the secondary users to the primary system is minimized. In an underlay case, the secondary users are allowed to transmit when the interference to the primary is kept at a reasonable level. This means that the simultaneous transmission is possible in this scenario. In this paper we discuss the simultaneous transmission approach.

Power control scheme is an efficient approach to manage the interference problem, which have been extensively studied for CDMA networks. However, many new challenges exist on power control of cognitive radio networks. In [9], a scheme based on outage probability of primary systems was proposed, where the outage probability can be broadcasted to SUs who want to transmit before starting the communication. [10] proposed an efficient power control scheme based on the built-in fuzzy power controller, where the SU is able to dynamically adjust its transmission power in response to the changing interference level caused by the SUs to the PUs. In [11], an optimal power control problem is modeled as a concave minimization problem, where the authors investigate the optimal power control with and without interference temperature constraints base on Shannon capacity. However, in [10], [11] no SU is allowed to transmit before receiving authorization from the manager, thus heavy signaling is really possible. In [12], power control for Cognitive Radio Ad Hoc Networks was studied, where the genie-aided distributed power control scheme maximizes the energy efficiency of SUs and guarantees the QoS of both PUs and SUs. First, the transmission power of each SU is determined by the distributed power control algorithm. Then if the interference level caused by all opportunistic communications is so high that the PU is violated, a genie placed near by the PU informs the SUs. In [13], an fully distributed power control algorithm is presented without an additional process for CR networks. Specifically, the constraint for the sum of the interference induced by all SUs in the network is replaced by new one which limits the individual transmission power. Since each SU determines its transmission power within the range of the limit to protect the PU, the additional process required in previous works is unnecessary. The authors show that the proposed scheme never exceed the interference temperature limit of the PU. However, the authors only consider the path loss model as the one that the transmission power only attenuates with distance.

In this paper we propose a new power control scheme for cognitive radios, Distributed Power Control Algorithm for Cognitive Radios (DPCACR). The cognitive networks using
code-division multiple access (CDMA) technology to transmit simultaneously with primary users in the same spectral band. The secondary users utilize the part information of feedback channel of the primary system. This part is related to the power control command, which is sent by the PR to the PT. Our paper’s contributions are as following: the time-varying wireless channel model is considered; the primary user is protected based on the part of feedback information of primary system. The rest of this paper is organized as follows. The system model is proposed in Section II. The power control algorithms are described in Section III. Section IV shows the numerical studies. The last section concludes our paper.

II. SYSTEM MODEL

Given a primary system with a coverage radius $R_p$ and a secondary system with a coverage radius $R_s$ (see Figure 1). Without losing generality we assume that the primary receiver (PR) is located in the center of the circular region with radius $R_p$, and the primary transmitter (PT) is located uniformly in the primary region with a minimum distance $R_0$ from the PR. Also, we assume that a CR receiver (SR) is uniformly located in the same area as primary transmitter does, and a CR transmitter (ST) is located uniformly in the region with radius $R_s$ where the CR receiver is centered. The minimum distance between the CR pair is also assumed to be $R_0$.

We assume that the primary system utilizes closed power control to adjust its transmission power with the power updating step size $1$dB, for instance, the classic Foschini-Miljanic power control algorithm [14]. We assume that the secondary user can decode part of the feedback channel of the primary system. This part is related to the power control command, which is sent by the PR to the PT. In addition, the transmission power of all users is constrained by $P_{max}$. Moreover, we assume that each SR has a register with a capacity of $C$ for memorizing the update feedback commands of the primary system.

A. Channel Model

While the CR system designer can determine the transmit power, it is the propagation channel that determines how much of that power arrives as interference to primary and other CR users [6]. We assume the link gains vary during the power control process in accordance with shadow fading and multipath fading. Let $G_{ij}(t)$ be the time-varying channel gain at a particular time instant $t$ from transmitter $j$ to receiver $i$, $i, j \in (p, s)$, where $p, s$ means primary user and secondary user respectively.

Let $d_{ij}(t)$ be the distance between $j$ and $i$ at time $t$, $\alpha$ be the path loss exponent, $S_{ij}(t)$ be the dB attenuation due to shadow fading which is usually modeled as a Gaussian random variable with zero mean and standard deviation $\sigma$, and $M_{ij}(t)$ be the multipath fading, which follows exponential distribution for Rayleigh fading. $M_{ij}$ has mean value 1 in linear scale. And for convenience, $S_{ij}(t)$ and $M_{ij}(t)$ are measured to be independent of the distance.

Thus, the continuous time model for the link gain matrix is given below:

$$G_{ij}(t) = \frac{10^{-S_{ij}(t)/10} \cdot M_{ij}(t)}{d_{ij}^{\alpha}(t)}$$  \hspace{1cm} (1)

B. Shadowing Fading

According to Gudmundson [15], $S(dB)$ follows an exponential spatial correlation. Assume that a user moves at speed $v$. The spacial correlation is given by

$$R(S(t), S(t+T)) = \sigma^2 \epsilon_D^\nu T/D = \sigma^2 \rho$$  \hspace{1cm} (2)

where $\sigma^2$ is the variance of $S$ which is usually in the rage between 3 and 10dB, $T$ is sample interval of the received signal, $D$ is the reference distance, $\epsilon_D$ is the correlation between two points separated by distance $D$, and $\rho = \epsilon_D^\nu T/D$ is the correlation coefficient. For typical suburban propagation at 900MHz, it has been experimentally verified by Gudmundson that $\sigma \approx 7.5$dB with a spatial correlation of approximately 0.82 at a distance of 100m; for typical microcellular propagation at 1700MHz, $\sigma = 4.3$dB with a spatial correlation of 0.3 at a distance of 10m [15], [16]. In this paper, let $T$ be the duration of one slot for power adjustment. Then $S_{ij}(dB)$ can be represented in a discrete-time way by the following model based on a Gauss-Markov process [17], [18]

$$S(k+1) = \rho S(k) + \sqrt{1 - \rho^2}W(k)$$  \hspace{1cm} (3)

where $\rho$ is the correlation coefficient and $W(k)$ has a normal distribution with mean zero and variance $\sigma^2$. 
In this paper we assume the case that there is no line-of-sight path between the transmitter and receiver. This small-scale fading is described with accuracy statistically by Rayleigh distribution. That is, the received signal envelope $R$ is Rayleigh-distributed with the probability density function (PDF)

$$f_R(r) = \frac{r}{\sigma^2} e^{\frac{-r^2}{2\sigma^2}}, \quad r \geq 0$$

The power fading is modeled by Exponential distribution with the mean of large-scale fading caused by path loss and shadowing. It follows the PDF of

$$f_p(p) = \frac{1}{2\sigma^2} e^{\frac{-p}{2\sigma^2}}, \quad p \geq 0$$

### D. Composite Fading

According to the continuous time model in Equation (1), the discrete time model for the link gain matrix is given below:

$$G_{ij}(k) = \frac{10^{-S_{ij}(k)/10} \cdot M_{ij}(k)}{d_{ij}^\alpha}$$

In this paper, we assume that the distance will not change so much during the simulation, which means that the path loss will be constant and only the shadowing and multipath fading are considered to be time variant. In addition, flat fading is assumed in this paper.

### III. POWER CONTROL FOR CR SYSTEMS

In this section we discuss centralized and distributed power control schemes for the system given in previous section, where there are one pair of primary users and one pair of secondary users.

#### A. Centralized Power Control for CR System

In this section, we study the centralized power control algorithm for CR system. The SINR value at the primary receiver $\Gamma_p(k)$ could be represented as [19],

$$\Gamma_p(k) = \frac{P_p(k)G_{pp}(k)}{P_s(k)G_{sp}(k) + N_p} \geq \Gamma_p^T$$

where $G_{pp}$ is the channel gain between PT and PR, $P_p$ is the transmission power of PT, $P_s$ is the transmitter power of ST, $G_{sp}$ is the channel gain between PR and ST, $N_p$ is the additive noise at PR, and $\Gamma_p^T$ is the target SINR of PR.

To make the received SINR of the primary user as high as possible, the optimum solution is to switch off all secondary transmitters. Since we are seeking for any opportunity for co-existence with primary users, this switching-off approach is not attractive. To maximize the SINR for the secondary users, the transmission power follows

$$P_s(k) = \frac{P_p(k)G_{pp}(k)}{\Gamma_p^T G_{ps}(k)} - \frac{N_p}{G_{ps}(k)}$$

#### B. Distributed Power Control for CR System

In this section, we propose our new power control scheme for CR system. The secondary transmitter updates its transmission power according to the feedback commands of the primary system which are sent from primary receiver to its transmitter.

The received SINR of the secondary receiver at time slot $k$ is

$$\Gamma_s(k) = \frac{P_s(k)G_{ss}(k)}{P_p(k)G_{sp}(k) + N}$$

The transmission power at next time slot, $(k + 1)$th, of the secondary transmission power is given by (all are in dB scale)

$$P_s(k + 1) = \begin{cases} \min\{P_s(k) + \text{step}, P_{s\text{max}}\}, & \tilde{R} < 0 \\ \max\{P_s(k) - \text{step}, P_{s\text{min}}\}, & \tilde{R} > 0 \\ P_s(k), & \text{others} \end{cases}$$

where $\tilde{R}$ is the mean value of the register during the past several time slots, $P_{s\text{max}}$ is the maximum transmission power of secondary users, and $P_{s\text{min}}$ is the minimum transmission power of secondary users. $P_s(k)$ is the transmission power of secondary transmitter at time slot $k$, $G_{ss}$ is the channel power gain of the secondary pair, and $G_{sp}$ is the channel power gain from the primary transmitter to secondary receiver.

Figure 3 shows the logic how the algorithm works. If the average of the past $C$ power control commands of the primary system is positive, which means that the primary transmitter increased its transmission power in average during past $C$ time slots, the secondary transmitter will decrease its transmission power in next time slot. When the average is negative, the secondary transmitter will increase its transmission power. Otherwise, the secondary transmitter will maintain its transmission power in next time slot.

### IV. NUMERICAL STUDIES

In this section we present numerical results for the distributed power control scheme proposed in previous sections. The default parameters used in our simulation are $R_p = 500m$, $R_0 = 20m$, $R_s = 100m$, carrier frequency $f_c = 1700 MHz$. 

---

**Figure 3. Distributed Power Control Flow Chart for CR System**
the speed of users moving $v = 3.6$ km/h. For shadowing fading, the parameters are $\sigma = 6$ dB, the correlation distance $D = 10$ m and the corresponding spacial shadow correlation $\eta_D = 0.3$. Also, the register of a secondary user has a 5-bit memory, which means it could store 5 previous commands issued by the primary receiver to primary transmitter. In addition, the locations of primary transmitter and secondary users are generated randomly according to uniform distribution. The receiver thermal noise is $-120 dBw$ at all receivers. The target SINR of primary user is 10dB with a 3dB margin to mitigate the fading to some degree. The multipath fading is generated using Zheng and Xiao algorithm [20].

Figure 4 shows the four time-varying channels in dB, which are primary transmitter to primary receiver ($g_{pp}$), primary transmitter to secondary receiver ($g_{sp}$), secondary transmitter to primary receiver ($g_{ps}$), and secondary transmitter to secondary receiver ($g_{ss}$).

Figure 5 and 6 show the SINRs and transmission power of primary and secondary systems, where the secondary system has a register with a capacity of 5 bits (C=5). This means that the secondary system update its transmission power based on
the 5 previous commands of primary system. Also illustrate the optimal transmission power and achieved SINR under the condition, for comparison, that the PU transmitter uses the same transmission power for both optimal and distributed cases. We can see that because of deep fading the secondary transmitter has to switch off (23rd slot). However, the primary system can not achieve its target.

Figure 7 and 8 show the SINRs and transmission power of primary and secondary system, where the secondary system has a register with a capacity of 1 bit (C=1). This means that the secondary system update its transmission power based on the previous command of primary system. In order to compare the performance, in this case we use the same parameters as in C=5 case. Comparing this case with previous case (C=5), we could find that in this case the convergence speed of transmission power of primary transmitter is faster than previous case. However, the SINR of primary system is worse than C=5 case while the deep fading happens to the primary link. This is because in C=5 case the speed of reducing the transmission power of secondary transmitter is faster than C=1 case, which is also shown in Figure 6 and 8. Here we also illustrate corresponding the optimal transmission power and achieved SINR.

Let us take look at Figure 5 and 7. We could see that the SINR and transmission power of PU converge slightly slower in C=5 case than in C=1 case after the deep fading. This is because the SU responds slower to the change of the transmission power of primary user while C=5. However, from Figure 6 and 6 we can see that in C=1 case the PU has a higher possibility to transmit using maximum transmission power because of the deep fading.

V. CONCLUSION

In this paper, we proposed a new algorithm for spectrum shared Cognitive network based on part of the feedback channel of the primary system. This part is related to the power control command, which is sent by the PR to the PT. In Section IV, we simulate the centralized (optimal) scenario where the same transmission power of primary system and the same channel are used, and distributed algorithms, where the channels suffer path loss, shadowing and Rayleigh fading, and also compare the distributed algorithm to centralized one. The results show that the secondary system can work with primary system simultaneously with slightly harm to the primary system. Also, we could apply cross-layer optimizing schemes together with the proposed algorithms to optimize the system further. For example, the secondary user could switch off itself when it can not achieve its target SINR in order to reduce the interference to primary system.

REFERENCES