A Cognitive Beamforming Scheme for Coexistence of Incumbent and Cognitive Radios

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***Abstract* – We propose a new cognitive beamforming scheme for coexistence of IR (Incumbent Radio) CR (Cognitive Radio). The proposed cognitive beamforming scheme does not cause any interference to the IRU (IR User), while the CRU (Cognitive Radio User) is served without additional radio resource consumption. Simulation results show that when using the proposed scheme the CRU does not interfere to the IRU and there is little bit error rate performance degradation of the CRU as compared to that of the ideal beamforming system which does not consider the IR priority.**

***Index Terms* – CR (Cognitive Radio); cognitive beamforming; interference cancellation; multiple antennas**

I. INTRODUCTION

Recently, explosive advent of various wireless communication systems has led to serious deficiency of valuable frequency resources. As a solution to this problem, CR (Cognitive Radio) effectively reuses the finite radio resources by recognition of idle frequency bands via intelligent spectrum sensing. The CR is defined as a wireless transmission technology combined with awareness, learning, and adaptation capabilities[1]. For instance, the CR system actively recognizes the given channel environment at specific time using radio sensors. At this time, the recognized channel information is involved in REM (Radio Environment Map) of the CR system, and then the CR system adaptively provides the optimal transmission parameters to the CR users in the given channel environment using learning algorithms based on the REM. The CR system can improve efficiency of spectrum usage, since it reuses limited radio resources by recognizing idleness of the spectrum in time, frequency, space and region. In addition, the CR system can provide the optimal QoS (Quality of Service) even for various channel environments, since it is possible to adaptively adjust system parameters by the learning algorithms and adaptation capabilities. For these reasons, the CR system has recently drawn explosive attention as an innovative technology in wireless communications. For instances, the IEEE 802.22 WRAN (Wireless Regional Area Network) standard group was organized to develop and apply the CR techniques to practical wireless communication systems[2]. The CR working group of the SDR (Software Defined Radio) Forum[3] has been working on inter-operable CR systems with MAC (Medium Access Control) layer including policy engine and cognitive engine[4] utilizing the SDR technology. Moreover, researchers are dealing with various issues for the CR systems in next generation wireless communication systems to derive flexible and reconfigurable communication architecture that can guarantee seamless QoS.

Research areas of the CR systems are generally classified as spectrum sensing, RRM (Radio Resource Management) and wireless adaptive transmission techniques[5]. The spectrum sensing is a technique that recognizes the idle radio spectrum resources in time, frequency, space and region, in order not to cause any harmful interference to the incumbent users. The RRM is a set of MAC protocols that simultaneously inform the recognized spectrum idleness to BS (Base Station) and MS (Mobile Station), when a fixed control channel for the CR systems does not exist. The wireless adaptive transmission is a technique that optimally transmits the data by adaptively adjusting the system parameters using the given sensing information and the CSI (Channel State Information) based on the IT (Interference Temperature). Although all these three technical components are essential to develop successful CR systems, most recent CR researches have been focusing on the spectrum sensing and the RRM. On the other hand, the adaptive transmission technique is being relatively less investigated in the CR context in spite of its importance.

In this paper, we propose a new cognitive beamforming scheme for coexistence of IR (Incumbent Radio) and CR that are supposed to simultaneously occupy the same frequency band at the same time. In this paper, we consider the genie-aided CR channel[6,7] where there are one multiple-antenna CR sender, one single-antenna IR sender and two single-antenna receivers corresponding to an IRU (IR User) and a CRU (CR User). The proposed cognitive beamforming scheme does not cause any interference to the IRU, while the CRU is served without additional radio resource consumption.

II. RELATED WORKS

A. Genie-Aided Cognitive Radio Channel

In general, CR systems dynamically reuse an unused spectrum hole which is recognized by some reliable spectrum sensing process[5]. It is not possible for a CR system and an IR system to simultaneously occupy the same frequency band at the same time. For this reason, in order to simultaneously transmit data symbol at the same time in the same frequency band, N. Devroye *et al.* presented in [6,7] the genie-aided CR channel as shown in Fig. 1 which is a simplest example of 2 senders and 2 receivers. The genie-aided CR channel is defined

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as two senders (IR transmitter T_1, CR transmitter T_2) and two receivers (IR receiver R_1, CR receiver R_2) interference channel in which T_2 is noncausally given by a genie the message T_1 plans to transmit. Then, the CR transmitter T_2 may mitigate the interference such as in [6,7]. Meanwhile, what differentiates the genie-aided CR channel from a general interference channel is the message knowledge of the CR transmitter. This message knowledge is possible due to the properties of CR. If the CR transmitter T_2 is geographically close to the IR transmitter T_1, then in a fraction of the transmission time, T_2 obtains the message transmitted by T_1[6,7].

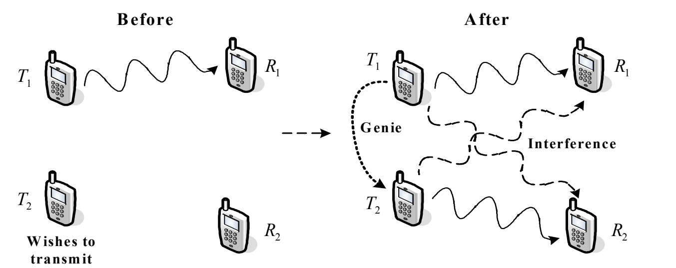

Fig. 1. An example of the genie-aided CR channel with 2 senders and 2 receivers[6,7].

B. MIMO-OFDM System Based on Feedback Information

Figure 2 shows a block diagram of a closed-loop MIMO-OFDM (Multiple Input Multiple Output-Orthogonal Frequency Division Multiplexing) system based on the Grassmannian beamforming[8]. The transmitter and the receiver preserve the same codebook which contains V beam weight vectors for the Grassmannian beamforming. In a given channel environment, the optimal beam weight vector $\mathbf{w}$ of the codebook set F at the receiver is selected as

$$\mathbf{w} = \arg\max_{\mathbf{x}_i \in F} \left\| \mathbf{H}\mathbf{x}_i \right\|^2 \tag{1}$$

where $\mathbf{H}$ and $\mathbf{x}_i$ $(i = 1, \cdots, V)$ denote the channel matrix and a beam weight vector in the codebook set F, respectively. In the Grassmannian beamforming, the index for the optimal beam weight vector $\mathbf{w}$, not the vector itself, is fed back from the receiver to the transmitter. Thus, the amount of feedback information can be reduced to $\lceil \log_2 V \rceil$ bits, and the MIMO-OFDM system using the Grassmannian beamforming provides a high spectral efficiency by maximizing the channel gain and reducing the feedback information[8].

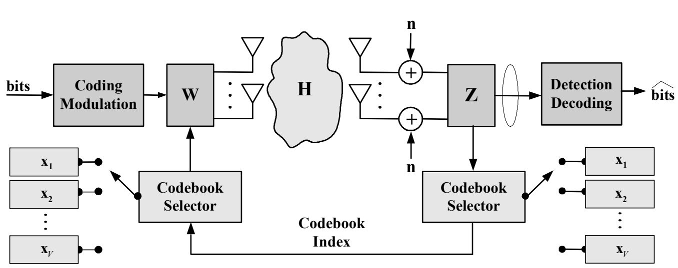

Fig. 2. Block diagram of a MIMO-OFDM system based on the Grassmannian beamforming.

III. New System Model

In this paper, we will propose a new transmission scheme for CR systems, which can transmit data symbols at the same time in the same frequency band. In order to present this transmission scheme termed "cognitive beamforming" scheme hereafter, we consider the genie-aided CR channel[6,7] where there are one multiple-antenna CR sender, one single-antenna IR sender and two single-antenna receivers corresponding to an IRU and a CRU as depicted in Fig. 3.

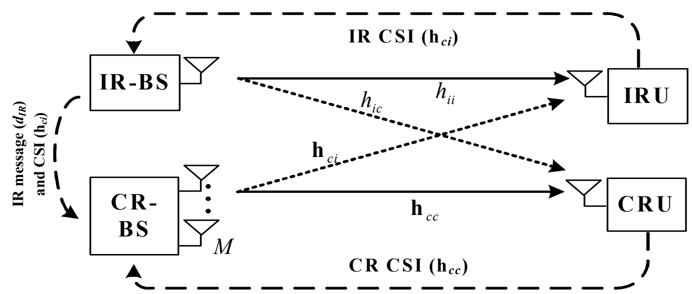

Fig. 3. System model based on the genie-aided CR channel for the proposed cognitive beamforming scheme.

Here, solid lines denote wireless channels for the signal, dotted lines are wireless channels of the interference, and dashed lines indicate the feedback channels. The system model supposes that the IR-BS (Base Station) passes on its message and CSI (Channel State Information) of the IR to the CR-BS. The IRU sends feedback on the CSI $\mathbf{h}_{ci}$ of a link between the CR-BS and the IRU to the IR-BS. Also, The CRU transmits the CSI $\mathbf{h}_{cc}$ and h_{ic} of links between the CR-BS and the CRU, between the IR-BS and the CRU to the CR-BS. Hence, the CR-BS is supposed to have all the CSIs in the channel. We also assume that the CRU and the IRU receive the signal and the interference of the same power from both IR-BS and CR-BS.

IV. Proposed Cognitive Beamforming Scheme

This section presents the proposed cognitive beamforming scheme for coexistence of IR and CR systems that are supposed to simultaneously occupy the same frequency band at the same time. In order to maintain the priority of the IR in spectrum utilization, the proposed cognitive beamforming scheme needs to have the CR not cause any interference to the IR. At the same time, the proposed scheme has to provide maximum channel gain to the CRU. In the given channel environment of the system model, the received signals y_{IR} and y_{CR} at the IRU and the CRU, respectively, are given as

$$\begin{bmatrix} y_{IR} \\ y_{CR} \end{bmatrix} = \begin{bmatrix} h_{ii} & \mathbf{h}_{ci} \\ h_{ic} & \mathbf{h}_{cc} \end{bmatrix} \begin{bmatrix} d_{IR} \\ \mathbf{w}_c d_{CR} \end{bmatrix} = \begin{bmatrix} h_{ii} d_{IR} + \mathbf{h}_{ci} \mathbf{w}_c d_{CR} \\ h_{ic} d_{IR} + \mathbf{h}_{cc} \mathbf{w}_c d_{CR} \end{bmatrix} \tag{2}$$

where d_{IR} and d_{CR} denote the signals of the IR and the CR, respectively, and M is the number of transmitted antennas of the CR-BS. Moreover, h_{ii}, h_{ic}, $\mathbf{h}_{ci} = \left[h_{ci,1} \;\; h_{ci,2} \cdots h_{ci,M} \right]$ and $\mathbf{h}_{cc} = \left[h_{cc,1} \;\; h_{cc,2} \cdots h_{cc,M} \right]$ are channel responses for the corresponding links, and $\mathbf{w}_c = \left[w_{c,1} \; w_{c,2} \cdots w_{c,M} \right]^T$ is the beamweight vector[9] of the CR-BS.

At first, the beamweight vector must satisfy the following equation to cancel interference to the IRU.

$$\mathbf{h}_{ci}\mathbf{w}_c = 0 \tag{3}$$

Hence, the beamweights $w_{c,1}$, $w_{c,2}$, ..., $w_{c,\mathrm{M}}$ of all the transmitted antennas have to maintain the following constraint to satisfy (3).

$$w_{c,1} = -\frac{1}{h_{ci,1}} \sum_{m=2}^{M} h_{ci,m} w_{c,m} \tag{4}$$

In addition, in order to maximize the channel gain of the CRU, the beamweight vector should be determined as

$$\mathbf{w}_c = \arg\max_{\mathbf{x} \in X} \left\| \mathbf{h}_{cc}\mathbf{x} \right\| \tag{5}$$

where X is a set of the beamweight vectors satisfying (3). That is, the proposed scheme may select a beamweight set which provides a maximal channel gain for the CRU among the ones satisfying (3).

$$\begin{aligned} G_{CR} &= \sum_{m=1}^{M} h_{cc,m} w_{c,m} \\ &= -\frac{h_{cc,1}}{h_{ci,1}} \sum_{m=2}^{M} h_{ci,m} w_{c,m} + \sum_{m=2}^{M} h_{cc,m} w_{c,m}. \\ &= \sum_{m=2}^{M} \left(h_{cc,m} - h_{ci,m} \frac{h_{cc,1}}{h_{ci,1}} \right) w_{c,m} \end{aligned} \tag{6}$$

In addition, we can write the received signal of the CRU with the interference from the IR-BS as

$$\begin{aligned} y_{CR} &= d_{IR} h_{ic} + d_{CR} G_{CR} \\ &= d_{IR} h_{ic} + d_{CR} \left[\sum_{m=2}^{M} \left(h_{cc,m} - h_{ci,m} \frac{h_{cc,1}}{h_{ci,1}} \right) w_{c,m} \right] \end{aligned} \tag{7}$$

Hence, the received signal of the CRU can be rewritten in a form of the ideal beamforming as

$$y_{CR} = d_{CR} w_{temp} h_{ic} + d_{CR} w_{c,2} h_{temp,2} + \cdots + d_{CR} w_{c,M} h_{temp,M} \tag{8}$$

where $w_{temp} = \dfrac{d_{IR}}{d_{CR}}$, $h_{temp,m} = h_{cc,m} - h_{ci,m} \dfrac{h_{cc,1}}{h_{ci,1}}$ $(m = 2, 3, \cdots, M)$. Equation (8) is similar to the received signal of the ideal beamfoming[9], so we can decide the cognitive beamweight vector like the ideal beamforming to achieve maximum channel gain, and its first beamweight is calculated using (3) to cancel the interference to the IRU.

V. Simulation Results

For the simulation to analyze the BER (Bit Error Rate) performance of the proposed cognitive beamforming scheme, we considered the IEEE 802.22 WRAN system parameters[10], as summarized in Table I. Note that the IEEE 802.22 WRAN system parameters considered here are only used to verify the performance of the proposed scheme, so this scheme may be applied to any other systems. Table I presents an illustrative set of the OFDM system parameters for a system occupying one 7 MHz TV band. We also considered the IEEE 802.22 WRAN multipath profile A channel model[11], where the Rayleigh fading was employed. Table II summarizes the WRAN reference multipath profile A determined by the IEEE 802.22 standard group. The cyclic prefix duration was set to 1/4 of FFT (Fast Fourier Transform) duration and the system applies QPSK (Quadrature Phase Shift Keying) modulation. We assumed that the channel state was perfectly known to the receiver, since the channel estimation and feedback procedure are not main issues of this paper. The CR system has $M = 3$ transmitted antennas and 1 received antenna configuration and the IR system has only 1 transmitted and 1 received antenna.

TABLE I
AN ILLUSTRATIVE SET OF THE OFDM SYSTEM PARAMETERS FOR THE IEEE 802.22 WRAN SYSTEM[10]

System bandwidth	7 MHz
Sub-carrier spacing	3906 Hz
FFT period	256 μsec
FFT size	2048
Number of guard sub-carriers	368 (left=184, DC=1, right=183)
Number of used sub-carriers	1680
Number of data sub-carriers	1440
Number of pilot sub-carriers	240

TABLE II
MULTIPATH PROFILES OF THE IEEE 802.22 WRAN REFERENCE CHANNEL MODELS[11]

Profile A	Path1	Path2	Path3	Path4	Path5	Path6
Excess delay [μsec]	0	3	8	11	13	21
Relative amplitude [dB]	0	-7	-15	-22	-24	-19
Doppler frequency [Hz]	0	0.10	2.5	0.13	0.17	0.37

Figure 4 compares the BER performance according to E_b / N_0 of the CRU by the proposed cognitive beamforming and the ideal beamforming. Here, the solid-circle line ("Proposed") denotes the BER curve of the CRU by the proposed cognitive beamforming scheme considering the priority of the IR in spectrum utilization. Also, the solid-triangle line ("Ideal 2Tx-1Rx") and the solid-square line ("Ideal 3Tx-1Rx") are the BER curves of conventional systems which do not take this priority of the IR into account, respectively. In the figure, we observe that the proposed scheme achieves 2 dB inferior BER performance of the ideal beamforming system that has the same number of transmitted antennas. However, we also confirm that the proposed scheme achieves about 4 dB gain over the ideal beamforming with 2 transmitted antennas which is the case of Ideal 2Tx-1Rx. These observations are explained by the fact that the proposed scheme has to select a beamweight set which provides a maximal channel gain for the CRU after satisfying (3) to cancel the interference with the IRU, as described in section 4. Figure 5 shows BER performance of the IRU with and without the proposed cognitive radio system. From the figure, we confirm that the proposed scheme does not cause any interference with the IR.

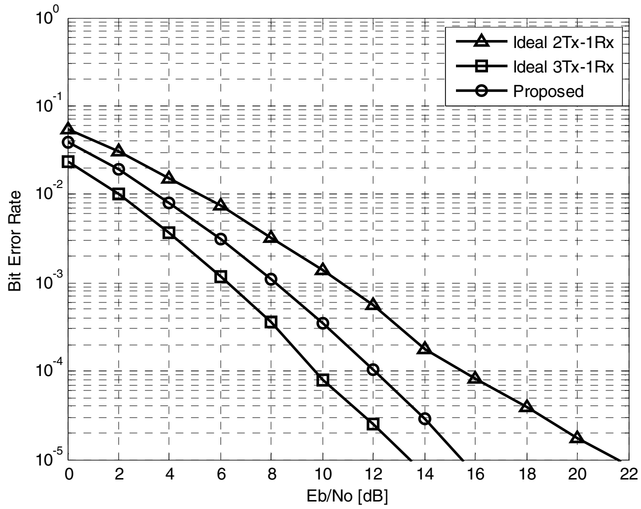

Fig. 4. BER performance of the CRU by the proposed scheme and the ideal beamforming.

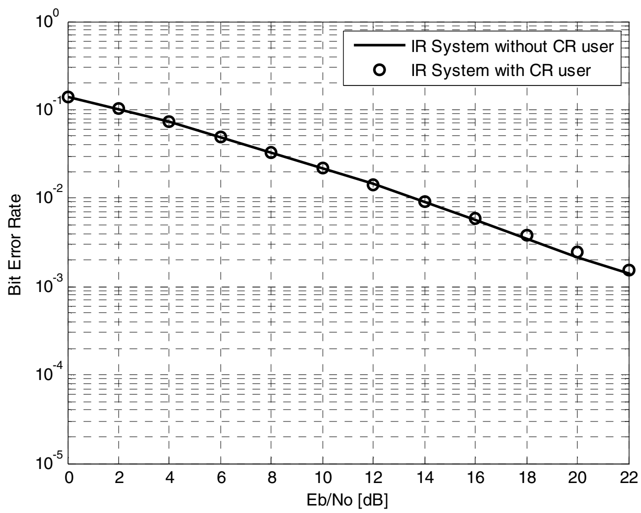

Fig. 5. Comparison of BER performance of the IR system with and without the CR system utilizing the proposed scheme.

VI. Conclusion

In this paper, we have proposed a cognitive beamforming scheme for coexistence of CR and IR at the same time in the same frequency band. We considered the genie-aided CR channel where there were one multiple-antenna CR sender, one single-antenna IR sender and two single-antenna receivers corresponding to an IRU and a CRU. The proposed cognitive beamforming does not cause any interference to the IRU, while the CRU is served without additional radio resource consumption and with maximum channel gain. Simulation results reveal that when using the proposed scheme the CRU does not interfere with the IRU and there is little BER performance degradation of the CRU as compared to that of the ideal beamforming which does not consider the IR priority.

The system model in which the proposed cognitive beamforming scheme is applied, requires the message information and CSI of the IR, and has to acquire its information through the genie-aided CR channel. Until now, there is no a clear solution for these issues in current CR context. However, most transmission techniques in next generation wireless communication systems aim to effectively increase the throughput by utilizing the closed-loop transceiver architectures based on feedback[8,12], and various methods to reduce the feedback information are well known. Moreover, many researchers studying for next generation wireless systems try to develop the heterogeneous networks[13] or the overlay networks[14], in order to improve the system capacity efficiently. We expect that the proposed scheme may be successfully applied in the next generation wireless communication systems based on the CR concept.

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