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Hybrid cognitive Gaussian two-way relay channel: Performance analysis and optimal resource allocation

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A B S T R A C T

Motivated by the deployment of hybrid cooperative cognitive radio (HCCR) based relays in cellular environments, this paper proposes the hybrid cognitive Gaussian two-way relay channel (HCGTWRC) model. Recently, the combination of licensed and cognitive radios with cooperative systems has gained popularity. These combined techniques have the potential to outperform primary network and pure cognitive network by utilizing the complementary nature of licensed and cognitive radios. In the proposed HCGTWRC model, a relay jointly utilizes both the licensed as well as the unlicensed/cognitive radio resources (RRs). Unlike conventional two-way relay channel, in this proposed model, source uses licensed resources for transmission and relay forwards this information using cognitive RRs. These licensed and unlicensed resources are not affected by total resource constraints of source and relay. Here, unlicensed RRs are not only described by bandwidth and power but also by reliability/availability parameter because of its opportunistic nature. In this paper, the proposed HCGTWRC model is studied by taking information theoretic aspect. In this respect, firstly, upper and lower bounds of performance metrics such as capacity, spectral efficiency (SE), and energy efficiency (EE) are analytically derived for the proposed HCGTWRC model. Then the optimal resource (such as power and bandwidth) allocation is derived with respect to upper and lower bounds of each performance metrics. Further, the performance comparison of the proposed HCGTWRC model is presented with the existing one. Numerical results are also presented for the optimal resource allocation to validate the analytical ones.

1. Introduction

Due to rapid growth of wireless communication systems over the past few decades, the available radio spectrum resource is draining at a higher rate and at the same time the amount of radio spectrum that has been already allocated is found to be highly underutilized. These two contradictions gave the birth of cognitive radio (CR) technology. Cognitive radio means an intelligent radio, which can automatically adjust its radio parameters according to the sensed information from the surrounding environment, in which it operates [1–3].

According to cognitive radio terminology, most commonly used terms are primary or licensed users, secondary/cognitive or unlicensed users. Both the primary and secondary users can utilize the same spectrum bands, but they are differentiated by the priorities to access these spectrum bands. Resources which are available for licensed users are called licensed resources and resources which are available for unlicensed users are called as cognitive / unlicensed resources. These two resources are characterized by transmit power, bandwidth, cost, reliability or availability, and flexibility. Licensed resources are typically featured with high transmit power, small bandwidth, expensive, reliable, and inflexible. Whereas, cognitive resources are characterized by low power, wide bandwidth, inexpensive, low reliability, and adaptable [4,5].

The complementary nature of these resources gave the birth of hybrid cognitive radio (HCR), which utilizes both licensed as well as cognitive RRs jointly [6]. For example, a mobile network operator can utilize its own spectrum and a borrowed secondary spectrum from TV white space to model a hybrid network. Exact advantages of HCR network can be seen by adopting the cooperative communication strategies. Based on this phenomena, a HCR is classified into two types, cooperative and non-cooperative. Hybrid cooperative CR (HCCR), is advantageous over non-cooperative HCR, because no separate physical layers are required in hardware designing part and also due to presence of cooperation, it can effectively utilize the radio resources (RRs). For example, for a long distance communication, it utilizes licensed RRs because it has higher transmit power, whereas, it utilizes cognitive RRs for shorter distances. Most of the literature assumes that only pure cognitive RRs are utilized, which results into a pure CR network [4,5]. But the reliability of such pure

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CR network is low, because of its opportunistic nature. Few articles studied about HCR networks and it was found that these networks outperform pure cognitive networks by joint utilization of both the licensed and cognitive RRs [6]. Further, a link level perspective of the problems of resource allocation and relay scheme combination are studied in [7] to enhance the rate performance of heterogeneous networks. Furthermore, an efficient user association scheme is proposed which optimizes the system downlink rate in cellular networks with hybrid CR relays and mainly focused on dynamic load balancing among the relays and the BS with varying accessible resources [8].

The related work in [9], proposed a relay channel called hybrid cognitive Gaussian relay channel and the two-way communication has been studied by authors from different perspective in [10]. The work in this paper, proposes a novel two-way relay channel called hybrid cognitive Gaussian two-way relay channel (HCGTWRC) model which significantly exploits the concepts of hybrid CR networks, cooperative communications, and the two-way communication. In the proposed model, the relay performs two-way communication which is not proposed earlier as per authors knowledge. By considering the information-theoretic aspect, the performance of the proposed HCGTWRC model is analyzed in terms of lower and upper bounds of capacity (C), spectral efficiency (SE), and energy efficiency (EE) metrics and analytical expressions are derived for each of the metric. Further, resources such as power and bandwidth are allocated optimally to maximize the system performance.

Rest of the paper is organized as follows. Section 2 presents motivation and system model of the proposed HCGTWRC model. Performance analysis and optimal resource allocation of the proposed HCGTWRC model are described in Section 3. Numerical results and discussion are given in Section 4. Finally, Section 5 concludes the work of this paper.

2. Motivation and system model

Fig. 1, shows an application of HCCR network (HCCRN) in cellular environments, which provides motivation to our work. In this figure, mobile station (MS) and base station (BS) are communicating through a relay, which has the hybrid cooperative cognitive capabilities. In such a scenario, each and every node can work in full-duplex fashion, which shows path for inclusion of two-way communication. Representation of two-way communication is shown by link symbol. In figures, the licensed and unlicensed/cognitive links are shown by solid and dashed lines, respectively. In such a setup, both MS and BS are using licensed RRs (e.g., licensed cellular spectrum), whereas relay is using cognitive resources (e.g., leased spectrum from TV white space) for communication. An advantage of this configuration is that there is not much modifications are needed for user devices (upgrading radios which can sense cognitive bands), the network-side upgrade of implementing CR technology is apparent to users devices. To deploy CR in cellular environments up-gradations are required (whether it is software or hardware), then only we can provide services to the mobile users according to their needs.

We model HCCRN as shown in Fig. 1 into HCGTWRC and such a scenario is illustrated in Fig. 2, where S_1 and S_2 are two sources, R is a relay, and ρ_x indicates signal-to-noise ratio (SNR) of a particular link x.

HCGTWRC model shares similar structure with the conventional Gaussian two-way relay channel [11] along with the Orthogonal Gaussian relay channel [12], but main differences are: First, the proposed HCGTWRC model considers the sources and relay which are subjected to separate resource constraints instead of assuming a total resource constraints as given in [11]. Second, the cognitive resources are opportunistic in nature, so these are characterized in the proposed work not only by bandwidth and power

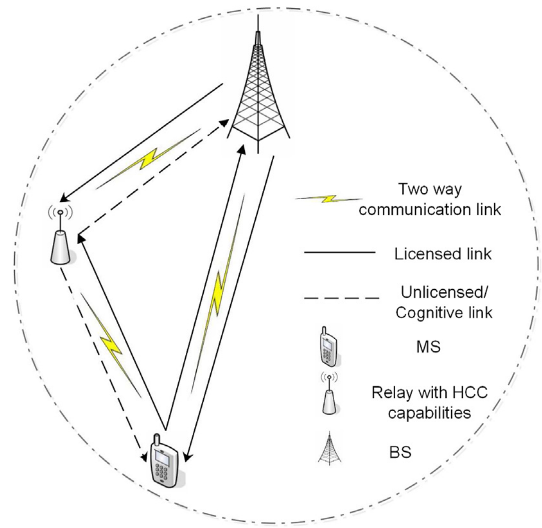

Fig. 1. An application of HCCR network in cellular environments.

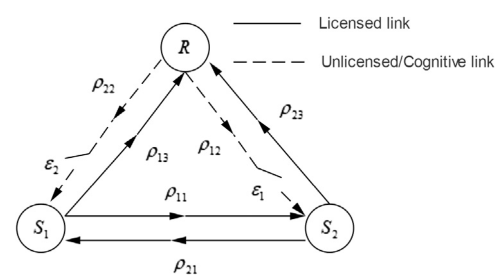

Fig. 2. Hybrid Cognitive Gaussian Two-Way Relay Channel (HCGTWRC) model.

resources, but also by the reliability parameter. For the purpose of mathematical analysis, the detailed illustration of HCGTWRC model is further shown in Fig. 3.

In Fig. 3, $(X_1,\ X_2)$ and $(Y_{11},\ Y_{12})$, $(Y_{21},\ Y_{22})$ are the transmitted and received signals of sources S_1 and S_2, respectively. $\tilde{Y}_1$ and $\tilde{Y}_2$ are the received signals at the relay from sources S_1 and S_2, respectively. $\tilde{X}_1$ and $\tilde{X}_2$ are the re-transmitted signals of the relay. P_l and P_c are transmitted powers in licensed and cognitive bands, respectively. W_l and W_c are the bandwidths allocated to licensed and cognitive bands, respectively. $h_{s_1r},\ h_{s_1s_2},\ h_{rs_2},\ h_{s_2r},\ h_{s_2s_1}$, and h_{rs_1} are the channel gains corresponding to source S_1 to relay R, source S_1 to source S_2, relay R to source S_2, source S_2 to relay R, source S_2 to source S_1, and relay R to source S_1 links, respectively. Z_{12}, $\tilde{Z}_{1R}$, Z_{R2}, Z_{21}, $\tilde{Z}_{2R}$, and Z_{R1} are the independent Gaussian noises with zero mean and N_2W_l, N_0W_l, N_2W_c, N_1W_l, N_0W_l, N_1W_c are variances, respectively. $N_1,\ N_2$, and N_0 are the noise power spectral densities at $S_1,\ S_2$, and R, respectively. ε_1 and ε_2 are binary random variables, which are equal to 1, when cognitive channel is available and equal to 0 when cognitive channel is not available. Further, assuming expectation of ε_1 and ε_2 are given as $\bar{\varepsilon}_1$ and $\bar{\varepsilon}_2$, respectively, which represent availability measure of a particular cognitive link. One of the key assumption in the paper is that ε_1 and ε_2 varies much slower than the transmit information and the capacity of such links are calculated over a long period of time.

The mathematical representation of the proposed HCGTWRC model is given as follows: First, the received signal Y_{11} at source S_2 and received signal Y_{21} at source S_1 through direct path are given