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IJSRNSC

Volume-5, Issue-2, May 2017
Research Paper

Int. J. Sc. Res. in Network Security and Communication

ISSN: 2321-3256

Performance Analysis of Hybrid Cognitive Gaussian Relay Channels

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Received 28th Feb 2017, Revised 10th Feb 2017, Accepted 21st Mar 2017, Online 30th May 2017

Abstract— Since last decade, Cognitive Radio has been the solution for the problem of underutilization of radio spectrum. Resources such as power and spectrum are very limited. Optimization of Resource Allocation (RA) is the most important problem in Cognitive Radio Network (CRN). But due to opportunistic nature of Cognitive Radio Resources(RRs), Pure Cognitive Radio Networks are unreliable in nature. To improve the performance and reliability of the network, Hybrid Cognitive Radio Network is useful.Hybrid CRN jointly utilizes both the licensed and cognitive RRs. This paperanalyses the performance of Hybrid Cognitive Relay network under AWGN and Rayleigh fading channels. The performance metrics such as Capacity, Energy efficiency and Spectral efficiency are formulated and numerical simulations are performed. This analysis is helpful in determining the Capacity for optimum usage of power and bandwidth.

Keywords— Cognitive Radio Network (CRN), Cooperative Hybrid CRN, Capacity, Spectral efficiency, Energy efficiency

I. INTRODUCTION

Wireless communication has become part of our life. There is sharp growth and rapid development of wireless communication. Due to this, available resources like spectrum are becoming scarce. On the other hand, it is found that most of the time these limited and expensive resources are remained underutilized by licensed networks [1],[2]. Since last decade, Cognitive Radio(CR) has been the solution for the problem of underutilization of radio spectrum, in which CR devices intelligently sense and exploit the part of spectrum, which is not being used by Primary Users (or licensed networks) [1],[2].

The main functions of Cognitive Radio include [3]:

1. Spectrum sensing: In this function, CR devices sense the spectrum holes, those are not being used by Primary Users(PU). CR devices analyze the spectrum band, also detect the arrival of primary users.
2. Spectrum decision: In spectrum decision, CR devices select the best spectrum bands among the sensed(detected) spectrum holes.
3. Spectrum sharing: Many Secondary Users(SU) can detect spectrum holes and access those spectrum bands. During using the same spectrum by SUs, collisions may occur. These collisions and interference among the SUs also interference to the PU can be managed in spectrum sharing.
4. Spectrum mobility: After selecting appropriate band, secondary users start communication. Meanwhile, if licensed user starts communication in same selected band, in that case, CR devices change their operations and functionalities according to the situations. This is called spectrum mobility.

These CR networks can be called pure CR networks, as only the Cognitive RR(Radio Resource) is utilized. Due to opportunistic nature of pureCognitive RRs [3],

- Pure Cognitive Radio Networks are unreliable.
- Power level is limited to avoid interference with Primary User (PU).
- Also, there are possibilities of delay in data transmission.

To increase the reliability, functionality of the network, the “Hybrid Cognitive Radio Network” is useful. The Hybrid CRN integrates both dedicated licensed spectrum as well as secondary spectrum to serve the users that is Hybrid CRN jointly utilizes both the licensed and cognitive Radio Resources (RRs). Hybrid CRN combines and uses the nature ofboth licensed RRs and pure Cognitive RRs, so that Hybrid CRN can perform much better than licensed as well as pure Cognitive Radio Network [4].

Two basic architectures are there for Hybrid CRN, non-cooperative and cooperative [4]. In non-cooperative hybrid CRN, users are served by either the licensed or secondary bands. This architecture creates two separate radio interfaces which are operating at licensed RRs and Cognitive RRs. In cooperative Hybrid CRN, users cooperate with each other, so system performance improves through cooperative communication. In this architecture both RRs make single integrated physical layer to form cooperative communications. In this paper, the focus is on Hybrid cooperative CR systems. There is lot of work done on link level studies in pure CRN, but not in Hybrid CRN. In this paper performance analysis of Hybrid Cognitive Gaussian relay channel is performed. The model considers the Gaussian channel along with relays. Relay increases the coverage of network. Use of both licensed and cognitive resources make the system Hybrid Cognitive Gaussian Relay system. Hence the name is Hybrid Cognitive Gaussian Relay Channel (HCGRC) [4], [5], [6], [8].

HCGRC has same structure like the conventional Gaussian relay channel and Orthogonal Gaussian channel [4], [8], but this model is somewhat different from them. In HCGRC, source and relay utilize different RRs. Source broadcasts through licensed link, while relay sends information through cognitive link, also due to opportunistic nature of pure cognitive RRs, HCGRC model is characterized by not only power and bandwidth but also by availability and reliability.

In section II System model of Hybrid cooperative CRN is discussed. A simple three node HCGRC model is considered for study of performance analysis, followed by signalling procedure of HCGRC model.In section III performance metrics of HCGRC model are formulated. Section IV covers performance analysis and simulation results. In last section results of this paper are concluded.

II. SYSTEM MODEL

The system model of Hybrid cooperative CR network in cellular system is shown in Fig. 1. Two scenarios are considered. In Scenario 1, a Cognitive relay is placed to increase the coverage area. This Relay communicates with the Base Station using licensed RR and provides a local coverage using the cognitive RR.In scenario 2, a cognitive relay uses the Cognitive RR for backhaul and licensed RR for local coverage. We consider scenario 2, as Cognitive RR are used in backhaul, there will not be requirement of change of handset. A simple three node model having source,destination and relay is considered. Source sends the information to both destination and relay using licensed RRs, while relay sends the data to the destination using Cognitive RRs. As licensed and Cognitive RRs are used on different frequency bands, relay node works in duplex fashion, that is, it transmits and receives atthe same time.

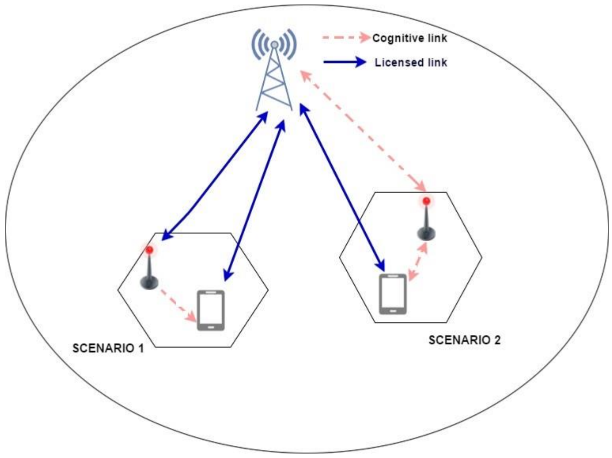

Fig. 1 Cooperative Hybrid CRN model

The signalling procedure of the HCGRC is shown in Fig.2 which takes following steps:

1) As soon as the source initiates a connection, bandwidth W_1 and power $P_1$are allocated to the source, using licensed RRs Source sends the information to destination through licensed link
2) When the source communicates to the destination in the licensed band, at the same time, a CR relay also receives the user's transmitted signal through licensed band and stores the information.
3) Meanwhile, the CR relay senses the cognitive band for secondary access. When this band is available $\varepsilon = 1$), the CR relay decides a bandwidth W_2 and power P_2 to relay information to the destination. Otherwise the CR relay transmits nothing. Here ε is the binary random variable, represents the opportunistic nature of CR channel. If Cognitive band is unavailable, $\varepsilon = 0$, both CR transmitter and receiver stop working and they do not consume any extra power. If cognitive band is available $\varepsilon = 1$ CR relay decides to relay the information.
4) The destination receives both the continuous signal from the licensed band and the irregular signal from the cognitive band, and joint decoding is performed at the destination.

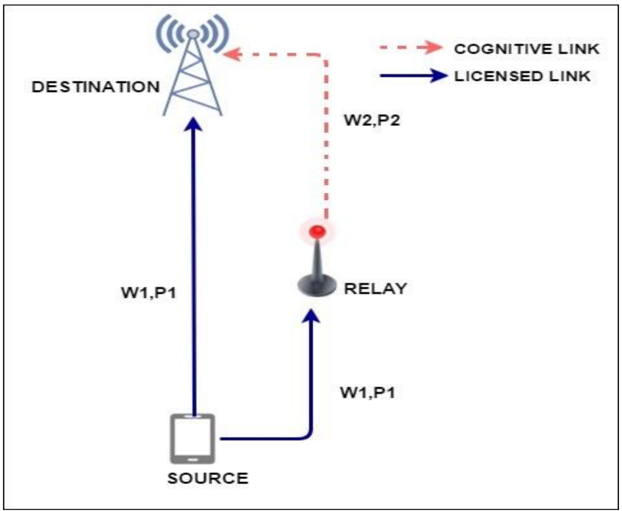

Fig. 2Signalling procedure

The transmitted power in licensed and Cognitive RR is denoted by P_1 and P_2 respectively. Also, the bandwidth of licensed and Cognitive RR denotes W_1 and W_2respectively. We define bandwidth ratio and power ratio as [4],

$$\Theta = W_2/W_1, \quad Ø = P_2/P_1 \quad (1)$$

Let's consider h_{sr}, $\mathrm{h_{rd}}$ and h_{sd} are channel gains from source-to-relay, relay-to-destination and source-to-destination, respectively. Moreover, Z_1, Z_2, and $\tilde{Z}$ are zero-mean independent white Gaussian noises, whose variances are given by W_1N_0, $W_2 N_0$, and $\bar{N}_0 W_1$, respectively. Where, N_0 and $\bar{N}_0$are the noise power spectrum densities at the destination and relay, respectively. The transmit signal-to-noise ratios of the source to destinationρ_1, source to relay link ρ_2 and relay to destination linkρ_3 can be written as [4],

$$\rho_1 = \frac{P_1}{N_0 W_1} \quad (2)$$

$$\rho_2 = \frac{\rho_1 Ø}{\Theta} \quad (3)$$

$$\rho_3 = \frac{P_1}{\bar{N}_0 W_1} \quad (4)$$

It is also assumed that is taken that the relay lies on the line between the source and destination for simplicity.

III. METRICS FOR HCGRC MODEL

In this section the focus is on the performance analysis of HCGRC under three different metrics: Capacity, SE, and EE. For each metric, first theoretical upper and lower bounds are obtained, followed by the derivation of the optimal bandwidth and power allocation in the Cognitive band. The corresponding optimal (Θ, Ø) curves are obtained by numerical methods and highlighted in simulation results.

A. Capacity

The capacity is most important metric because main purpose of using CR is for capacity enhancement. Capacity is calculated by its upper and lower bounds.HCGRC model is similar to Gaussian orthogonal relay model. Using standard formulas, capacity bounds of HCGRC are given by [4], [5], [7]

$$C_{lower} = \min\{C_{1,low}(\theta, \emptyset), C_{2,low}) \quad (5)$$

$$C_{upper} = \min\{C_{1,up}(\theta, \emptyset), C_{2,up}) \quad (6)$$

Respectively, where

$$C_{1,low} = W_1 \log(1 + \rho_1 h_{sd}) + W_1 \Theta\acute{\epsilon} \log\left(1 + \frac{\rho_1 Ø \mathrm{h_{rd}}}{\Theta}\right) \quad (7)$$

$$C_{2,low} = W_1 \log(1 + \rho_3 h_{sr}) (8)$$

$$C_{1,up} = C_{1,low} (9)$$

$$C_{2,up} = W_1 \log(1 + \rho_3 h_{sr} + \rho_1 h_{sd}) \quad (10)$$

In HCGRC model, the source and relay node are not limited by total bandwidth. Channel capacity is calculated in its upper and lower bound. $C_{lower}$and $C_{upper}$are the capacity bounds, where lower capacity bound lies between $C_{1,low}$ and $C_{2,low}$. Similarly, upper capacity bound lies between $C_{1,up}$ and $C_{2,up}$. Here$C_{1,low}$ is lower bound capacity related to the licensed and Cognitive link. The $C_{2,low}$ is a capacity bound between source and relay.It is calculated without Cognitive link. $C_{2,up}$ is calculated through licensed link.

B. Spectral Efficiency (SE)

Spectral efficiency is the average number of bits per Hertz. SE indicates how efficiently bandwidth is utilized by the network.InHCGRC model, Cognitive bandwidth is available only for a fraction of time $\acute{\epsilon}$. So, the effective bandwidth of the total system will be $W_1 + \acute{\epsilon} W_2$. The lower and upper bounds of SE are calculated in[4]

$$S_{1,lower} = \frac{C_{lower}}{(W_1 + \acute{\epsilon} W_2)} \quad (11)$$

$$S_{1upper} = \frac{C_{upper}}{(W_1 + \acute{\epsilon} W_2)} \quad (12)$$

$$S_{lower} = \min\{S_{1,low}(\theta, \emptyset), S_{2,low}(\theta)) \quad (13)$$

$$S_{upper} = \min\{S_{1,up}(\theta, \emptyset), S_{2,up}(\theta)) \quad (14)$$

Where

$$S_{1,low} = \frac{\log(1 + \rho 1 \mathrm{h_{sd}}) + \Theta\acute{\epsilon} \log\left(1 + \frac{\rho 1 Ø \mathrm{h_{rd}}}{\Theta}\right)}{(\Theta\acute{\epsilon} + 1)} \quad (15)$$

$$S_{2,low} = \frac{\log(1+\rho_3 h_{sr})}{(\Theta\acute{\varepsilon}+1)} \quad (16)$$

$S_{1,up}$ $S_{1,low}$ (17)

$$S_{2,up} = \frac{\log(1+\rho_3 h_{sr}+\rho_1 h_{sd})}{(\Theta\acute{\varepsilon}+1)} \quad (18)$$

Where, $S_{1,lower}$ and S_{1upper} are the lower and upper bounds for Spectral Efficiency. And by using Eq. 7 – 10, we can formulate the values for lower and upper bounds of SE. Here $S_{1,low}$ is calculated when both links are available. $S_{2,low}$ is calculated when licensed link is unavailable. Upper bound of SE lies between $S_{1,up}$ and $S_{2,up}$.

C. Energy Efficiency

The EE metric evaluates the average number of bits per Joule spent. In this section, we consider the total energy consumption of the source and relay. When the Cognitive spectrum is unavailable (ε = 0), the relay consumes no power. Similar to the Capacity and SE, E_{lower} and E_{upper} are the lower bounds of Energy Efficiency. The corresponding lower and upper bounds of EE are given as [4]

$$E_{lower}(\theta,\emptyset) = \min\{E_{1,low}(\theta,\emptyset), E_{2,low}(\emptyset)) \quad (19)$$

$$E_{upper}(\theta,\emptyset) = \min\{E_{1,up}(\theta,\emptyset), E_{2,up}(\emptyset)) \quad (20)$$

Where

$$E_{1low} = \frac{W1(\log(1+\rho 1 h_{sd})+\theta\acute{\varepsilon}\log\left(1+\frac{\rho 1 \emptyset h_{rd}}{\theta}\right)}{(P1+P\emptyset 1\acute{\varepsilon})} \quad (21)$$

$$E_{2,low} = \frac{W_1\log(1+\rho_3 h_{sr})}{(P1+P\emptyset 1\acute{\varepsilon})} \quad (22)$$

$$E_{1,up} = E_{1,low} \quad (23)$$

$$E_{2,up} = \frac{W_1\log(1+\rho_3 h_{sr}+\rho_1 h_{sd})}{(P1+P\emptyset 1\acute{\varepsilon})} \quad (24)$$

Like lower and upper bounds of Capacity and SE, bounds for EE are calculated. Availability of Cognitive link is considered whilecalculating E_{1low}, $E_{2,low}$ and $E_{2,up}$.

IV. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

In this section, numerical simulation results are presented. We consider system under AWGN and Rayleigh fading environments. Without loss of generality we can set W_1=1,$P_1 = 1$, r_{sd}=1 where $r_{sd}$is the distance between source to destination and path loss exponent α = 4. Figure 3 illustrates the variations of lower bound capacity with bandwidth ratio (Θ)and power ratio(Ø). It is observed that as bandwidth and power ratio increases lower bound Capacity also increases and reaches to its maximum value, and gets saturated as illustrated in Fig. 3.

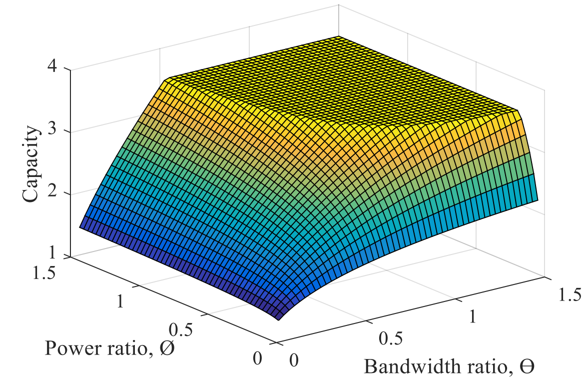

Fig. 3 Capacity lower bound as function of Θ and Ø

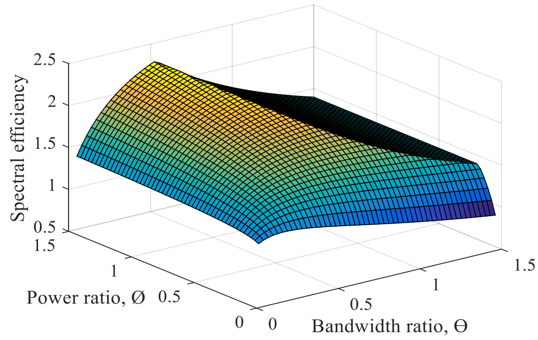

Fig. 4SE lower bound as a function of Θ and Ø

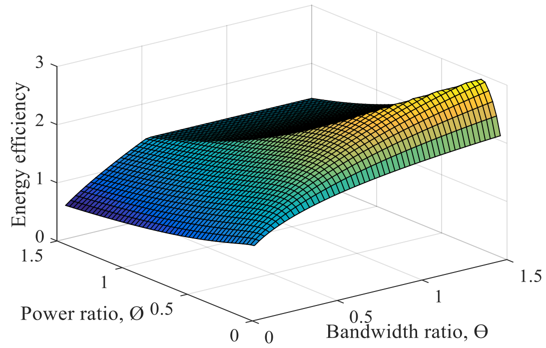

Fig. 5 EE lower bound as a function of Θ and Ø

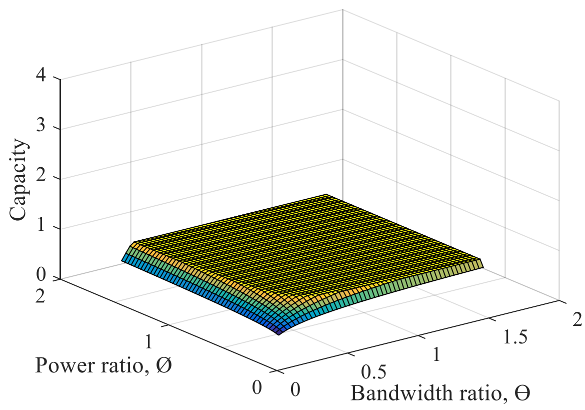

Fig. 6 Capacity lower bound as function of Θ and Ø, with fading

Fig. 4 illustrates the variation of SE with power ratio. This is simulated using Eq. 11 – 18. We observe that as power ratio increases SE also increases and there is one optimum value of bandwidth ratio, where SE maximizes. For HCGRC model lower bound EE also simulated as shown in Fig. 5. It is observed that EE increase continuously with bandwidth ratio and there is one optimum value of power ratio ratio at which EE maximizes. Numerical results for Capacity, SE and EE are shown in Table I, II and III respectively.

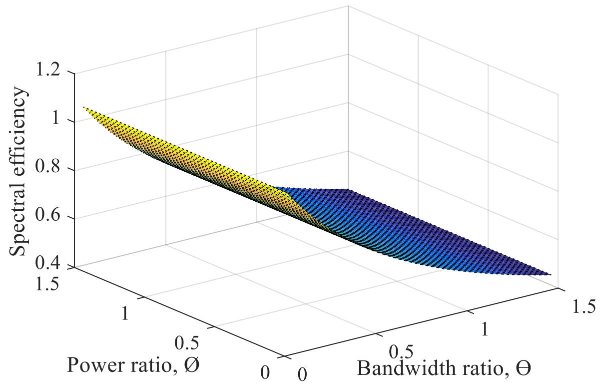

Fig. 7 SE lower bound as function of Θ and Ø, with fading

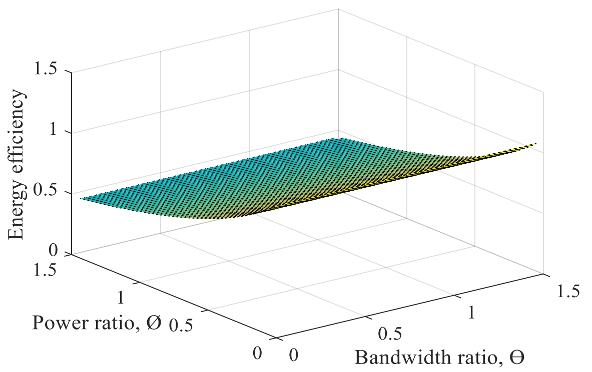

Fig. 8SE lower bound as a function of Θ and Ø, with fading

Numerical simulations are also performed for HCGRC network under Rayleigh fading channel environment. It is observed that fading affects the performance metrics drastically. If we compare Fig. 3 and Fig. 6 it is observed that capacity is decreased under Rayleigh fading. As illustrated in Table I, II and III, more bandwidth and power are required in order to achieve same Capacity, SE, and EE.

TABLE I: LOWER BOUND CAPACITY

Sr. No.	Types of channel	Lower bound capacity	Bandwidth ratio(Θ)	Power ratio(Ø)
1	AWGN	3.497	0.7036	0.6418
2	Rayleigh	1.107	0.26	0.257

TABLE II: LOWER BOUND SE

Sr. No.	Type of channel	Lower bound Spectral Efficiency	Bandwidth ratio(Θ)	Power ratio(Ø)
1	AWGN	2.155	0.6122	0.908
2	Rayleigh	1.05	0.079	0.612

TABLE III: LOWER BOUND EE

Sr. No.	Type of channel	Lower bound Energy Efficiency	Bandwidth ratio(Θ)	Power ratio(Ø)
1	AWGN	2.514	0.876	0.375
2	Rayleigh Fading	1.05	0.93	0.05

V.CONCLUSION

We formulated the HCGRC system model and perform the analysis under AWGN and Rayleigh fading environments. The performance metrics calculated are Capacity, SE and EE. From the simulation analysis and results we can say that, Capacity continuously increases with bandwidth ratio and power ratio, up to its maximum value. SE increases with power ratio and EE monotonically increases with bandwidth ratio. These results are also compared with Rayleigh fading channel. It is found that, Rayleigh fading decreases the overall performance of the system and more power and bandwidth are required as compared to AWGN channel.

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