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Performance Analysis of Hybrid Cognitive Relay Network under AWGN and Rayleigh Fading Channels

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Abstract – The underutilization of radio spectrum is a major problem in the field of communication engineering. Since last decade, Cognitive Radio has been proved to be an efficient and reliable solution for the problem of spectrum underutilization. The limited availability of spectrum and power demands the optimal allocation of resources which is the most Challenging problem in the Cognitive Radio Network (CRN). Pure cognitive Radio Networks are unreliable in nature due to their opportunistic nature. So as a step towards the improvement of efficiency, reliability and performance of the network. Hybrid Cognitive Radio networks are proposed. These networks utilize the properties of both the licensed and cognitive RRs[3],[4]. they can be programmed and dynamically configured to use the best wireless channels available to avoid user interference and Congestion. This paper analyses the performance of Hybrid Cognitive Relay Network (HCRN) under Additive White Gaussian Noise (AWGN) and Rayleigh fading channels. The typical performance measures Such as Capacity, Energy Efficiency (EE) and spectral efficiency (SE) are formulated and numerical simulations are performed taking into Consideration different scenarios. The analysis and one of results will be helpful in determining the fundamental performance metric i.e. capacity for optimum usage of power and bandwidth.

Index Terms – Cognitive radio, capacity, energy efficiency, spectral efficiency.

1. INTRODUCTION

Due to sharp growth in wireless communication, the availability of spectrum is becoming scarce. contrary to this, it is found that large portion of allocated spectrum goes underutilized most of the time by the licensed radio Networks. The solution for this problem demands a cooperative network which is Intelligent to sense and use the part of the system which is not being used by the licensed users. Cognitive radio is the one which exactly does the same. It is capable of dynamically Configuring the parameters of the radio network.

The main functions of cognitive radio include[4],[6]

1.Sensing of spectrum: The main function of CR device is to sense the spectrum holes[3]. The spectrum holes are the bands of Spectrum that Can be used by unlicensed or Secondary users. These Spectrum holes from a basic resource for the CR systems. The main challenge of CR systems is to effectively sense when they are with in such spectrum holes. the CR devices should also analyze the Spectrum band to detect the arrival of licensed users.

2.Spectrum choosing: In this step the CR devices Select the best available spectrum among the detected spectrum holes.

3.Spectrum sharing: The spectrum holes can be detected and accessed by many secondary users. In this process a same spectrum hole can be detected by different secondary users and as a result collision may occur. These collisions not only cause interference among the secondly users but also to primary users. This problem can be managed by spectrum sharing.

4. Spectrum dynamics: The secondly users can start communication as soon as they find a spectrum hole. If a primary user starts communication in the same selected band, the CR devices should be robust to change their priorities according to the situations. This is called spectrum dynamics.

The CR networks are also called pure CR networks when only the Cognitive Radio resource is utilized. But there are few disadvantages of pure CR networks.

1. Pure CR networks are opportunistic in nature[5] so they are unreliable.

2. The power level of pure CR networks is limited as to avoid the interference with the licensed users.

3. Due to their unreliable nature, there will be difficulties and possible delays in data transmission.

To overcome these difficulties and also to increase efficiency and robustness of CR networks, the "Hybrid cognitive Radio Network" is proposed. This exploits the properties of both dedicated licensed spectrum and secondary Spectrum and integrate them in such a way to serve the customers with better performance and reliability. It performs much better than pure Cognitive Radio networks. The hybrid CR networks Can be studied with two basic architectures: non-cooperative and cooperative.

The non-cooperative architecture aims to create two separate radio interfaces which will operate at licensed and cognitive radio RRs. They are designed to perform joint scheduling. on the other hand, the cooperative architecture exploits the principles of cooperative communications to utilize both licensed and unreliable cognitive radio resources to design a single integrated physical layer. The resulting network is also called hybrid cooperative cognitive Radio network. The performance results of hybrid CR networks are better than non-cooperative networks when they are carefully designed taking into account of the problem of matching of heterogeneous RRs created by cooperative communication schemes. As an example for short range communication applications cognitive RR is used because of low transmit power and for long range communications, licensed RR can be used because of high power. There is a lot of literature work done for link level studies in pure CR network but not in the HCRN. This paper focuses on the performance analysis of hybrid cognitive Gaussian relay channel[5]. Relays are considered in the Gaussian channel because they increase the coverage of network by relaying the information. Since both the licensed and Cognitive resources are used in the system, it is called Hybrid Cognitive Gaussian Relay channel. (HCGRC).

A relay channel is a mathematical model of a channel for analyzing the different performance metrics from the information theory point of view. HCGRC has the same structure like the other Channels like Gaussian relay channel and orthogonal Gaussian channel, but this model has some differences from them. the main difference is that in HCGRC, the source and relay utilize different radio resources. Source uses licensed link, while relay broadcasts though cognitive link. Also due to opportunistic nature at pure cognitive RRs, the HCGRC model is Characterized by availability and reliability [8]in addition to power and bandwidth.

The system model of hybrid Cooperative CRN is discussed in section II .This model is a simple three node model. The model is used for signaling procedure and performance analysis. In section III the performance metrics of HCGRC are formulated. The performance analysis and simulation results are discussed in section IV. The results of this paper are presented in the last section.

2. SYSTEM MODEL

There are two scenarios considered under the system model of the hybrid cooperative CR network[4] shown in Fig.1.In scenario 1, cognitive relay communicates with the BS using licensed RR and aims to provide a local area coverage using the opportunistic cognitive RR. In scenario 2 the cognitive relay uses the cognitive RR for backhaul and licensed RR for coverage of local area. This model is represented by a simple three node source, destination and relay considered. Using licensed RRs, the source sends the information. The relay node works in full duplex fashion as the licensed and cognitive RRs are used on different frequency bands. So the relay node transmit and receive at the same time.

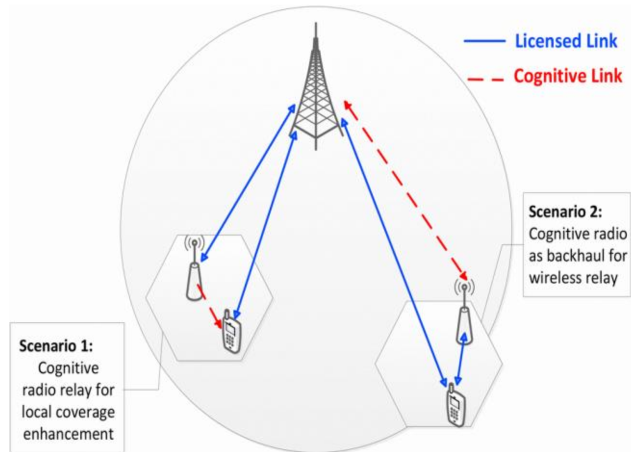

Fig. 1 Cooperative Hybrid CRN model

The signaling procedure of HCGRC shown in Fig.2 takes the following steps.

1.First, the source initiates the connection, bandwidth

W_1 and power P_1 are allocated to the source. By using licensed RRs. Source sends the information to destination Via a licensed link.

2. After the source communicates to the destination in the licensed band, a CR relay recieves the transmitted user signal through licensed radio resource and stores the information.

3.The cognitive relay senses the cognitive band for secondary access. When there is availability of band(□=1) the CR relay allocates a bandwidth W_2 and power P_2 for relaying the information to the destination. If the cognitive relay does not sense a spectrum hole, the relay transmits nothing. This can be characterized by a binary random variable □.□ represents the opportunistic nature of CR channel. If the cognitive band is unavailable, □=0, the CR transmitter do not consume any extra power as they stop working. The CR relay decides to relay the information if the cognitive band is available i.e. □=1.

4.The joint decoding is performed at the destination after receiving both the signals from the licensed and cognitive bands.

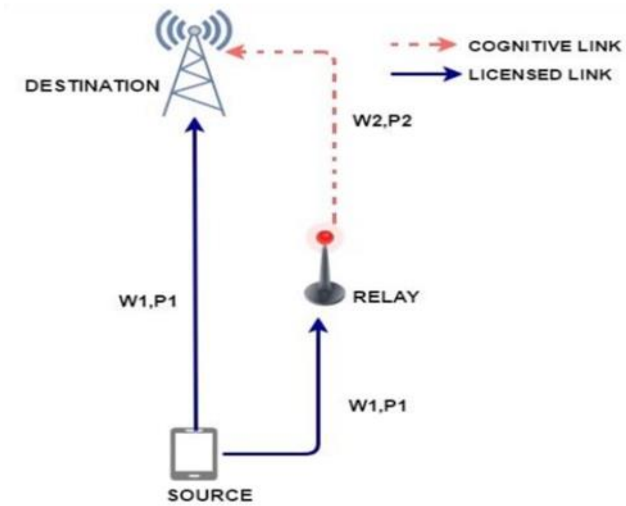

Fig. 2 Signaling procedure

The transmitted power in the licensed and cognitive RR is denoted by P_1 and P_2 respectively. The bandwidth of licensed and cognitive RRs are denoted by W_1 and W_2 respectively. We define two terms the bandwidth and power ratio.

$$\theta = \frac{W_1}{W_2}, \quad \phi = \frac{P_1}{P_2} \qquad (1)$$

h_{rd} , h_{sr} and h_{sd} are the channel gains from relay to destination, source to relay and source to destination respectively. We define Z_1 , Z_2 and $\tilde{Z}$ are zero mean independent white Gaussian noises whose variances are given by N_0W_1 N_0W_2 and $\tilde{N}_o W_1$ respectively where $\tilde{N}_o$ and N_0 are the power spectral densities of noise at the destination respectively. To reflect the potential difference in the receiver noise figures at the destination and relay, $\tilde{N}_o$ and N_0 are treated different. The transmit signal to noise ratios of the source to destination ρ_1 , source to relay link ρ2 and relay to destination link ρ3 can be written as

$$\rho_1 = \frac{P_1}{N_0 W_1} \qquad (1)$$

$$\rho_2 = \frac{P_2 \phi}{\theta} \qquad (2)$$

$$\rho_3 = \frac{P_1}{\tilde{N}_o W_1} \qquad (3)$$

For simplicity, it is assumed the relay lies in between the source and destination. Furthermore it is assumed that the variation of □ is at a much lower rate than the transmit symbols and the channel is observed for a very long time in the calculation for its capacity so as to make □ statistically independent[7].

3. METRICS FOR HCGRC MODEL

The three different metrics for the performance analysis of HCGRC are capacity, spectral efficiency(SE) and energy efficiency(EE).For each metric, in the information theoretic point of view, the upper and lower bounds are obtained followed by allocation in the cognitive band, the corresponding optimal(θ, ϕ) curves are obtained with the help of numerical methods and highlighted in simulation results.

A. Capacity

The main purpose of using CR is for capacity enhancement. It is the most important metric in assessing the performance of a CR system. There are upper and lower bounds of capacity calculated from a mathematical perspective using the concepts of information theory. The HCGRC model is similar to Gaussian orthogonal relay model [4],[2]. Using the standard results, capacity bounds of HCGRC model are given by

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

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

$$C_{1,low} = W_1 \log(1+\rho_1 h_{sd}) + W_1 \theta \varepsilon \log(1+\frac{\rho_1 \phi h_{rd}}{\theta}) \qquad (7)$$

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

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

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

There is no total bandwidth constraint for the source and relay in the HCGRC model. C_{lower} and C_{upper} are the capacity bounds, where lower capacity bound lies between $C_{1,low}$ and C_{2low} .similarly upper bound of capacity lies in between $C_{1,up}$ and $C_{2,up}$ .Here $C_{1,low}$ is lower bound capacity related to licensed and cognitive link. C_{2low} is a capacity bound between source and relay calculated without cognitive link. $C_{2,up}$ is calculated through licensed link.

B. Spectral efficiency:

Spectral efficiency is an important performance metric for the CR systems. It is the average number of bits per hertz. The efficient utilization of bandwidth in the network is indicated by spectral efficiency. Since the cognitive bandwidth in HCGRC is available only for a fraction of time □, the effective bandwidth of the total system depends on □. The lower and upper bounds of SE are calculated in [4]

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

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

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

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

$$S_{1,low} = \frac{\log(1+\rho_1 h_{sd}) + \theta\varepsilon \log(1+\frac{\rho_1 \phi h_{rd}}{\theta})}{(\theta\varepsilon + 1)} \quad (15)$$

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

$$S_{1,up} = S_{1,low} \quad (17)$$

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

where $S_{1,low}$ and $S_{1,up}$ are the lower and upper bounds for spectral efficiency. $S_{1,low}$ is calculated when both links are available, $S_{2,low}$ is calculated when there is availability of licensed link. Upper bound of SE lies between $S_{1,up}$ and $S_{2,up}$.

C. Energy Efficiency

The energy efficiency is defined as the average number of bits per joule spent[8]. The overall energy consumption of the source and relay is considered in this section. When there is availability of cognitive spectrum, the relay consumes no power. Similar to the discussions in the capacity and spectral efficiency sections, E_{lower} and E_{upper} are the lower bounds of energy efficiency.

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

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

$$E_{1,low} = \frac{W_1 \log(1+\rho_1 h_{sd}) + \theta\varepsilon \log(1+\frac{\rho_1 \phi h_{rd}}{\theta})}{P_1 + P_1 \phi\varepsilon} \quad (21)$$

$$E_{2,low} = \frac{W_1 \log(1+\rho_3 h_{sr})}{P_1 + P_1 \phi\varepsilon} \quad (22)$$

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

$$E_{2,up} = \frac{W_1 \log(1+\rho_3 h_{sr} + \rho_1 h_{sd})}{P_1 + P_1 \phi\varepsilon} \quad (24)$$

As discussed in the capacity and SE sections, the upper and lower bounds of EE are calculated. The availability of cognitive link is considered while calculating the above.

4. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

This section presents the numerical simulation results. The system is considered under AWGN and Rayleigh fading environments. Without loss of generality, we can set $W_1 = 1$, $P_1 = 1$, $r_{sd} = 1$ where the distance between source to destination is denoted by r_{sd}. The path loss component is set to α =5. Fig.3 illustrates the variations of lower bound of capacity with bandwidth ratio, the lower bound of capacity also increases and approaches a peak value and gets saturated. Fig 4 illustrates the variation of SE with power ratio. The observation is that as power ratio increases SE also increases but there is one optimum value of bandwidth ratio where the value of spectral efficiency gets maximized[1]. In Fig.5 shows the curve of power ratio vs bandwidth ratio. Numerical results for capacity, SE and EE are tabulated in tables I, II and III respectively.

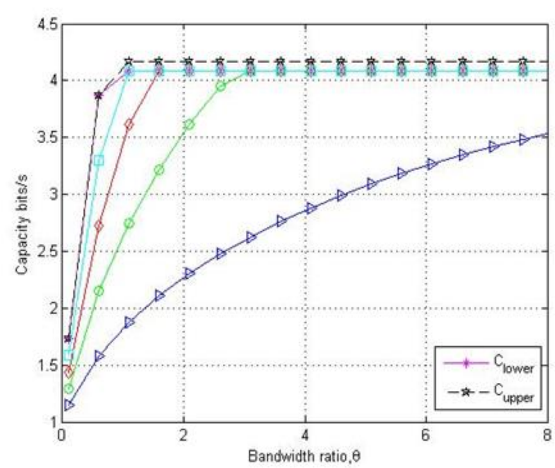

Fig.3 Capacity as a function of Bandwidth ratio

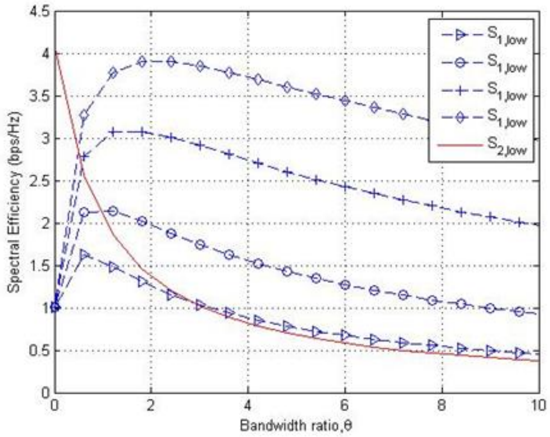

Fig.4 Spectral efficiency as a function of Bandwidth ratio

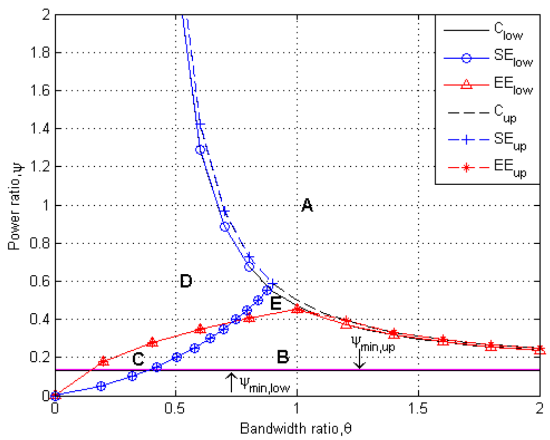

Fig.5 Power ratio vs Bandwidth ratio

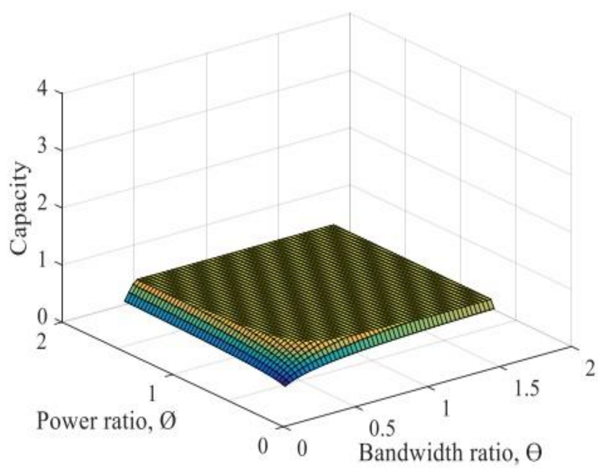

Fig. 6 Capacity lower bound as function of Θ and Ø, with fading

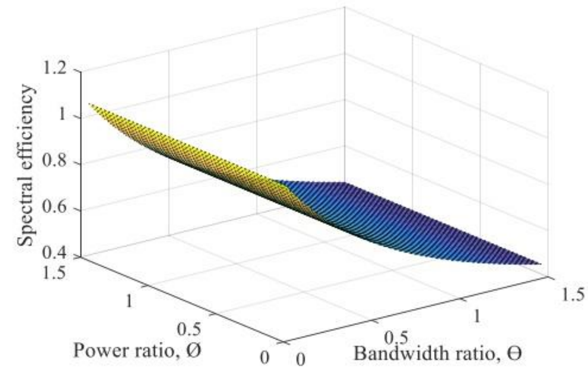

Fig. 7 SE lower bound as function of Θ and Ø, with fading

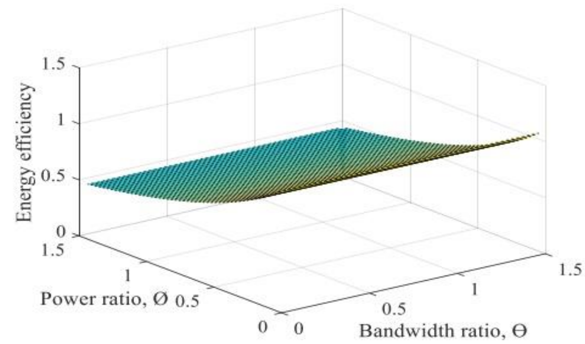

Fig. 8 SE lower bound as a function of Θ and Ø, with fading

The numerical simulations under rayleigh fading channels are performed for HCGRC network.The observation is that the performance metrics are drastically affected by fading. As illustrated in table I, II and III there is a requirement of more bandwidth and power in order to achieve same performance metrics i.e. capacity, SE and EE.

TABLE I: LOWER BOUND CAPACITY

S.No	Type of channel	Lower bound capacity	Bandwidth ratio (Θ)	Power ratio(Ø)
1	AWGN	3.728	0.8237	0.6901
2	Rayliegh	1.302	0.47	0.358

TABLE II: LOWER BOUND SE

S.No	Type of channel	Lower bou spectral efficiency	Bandwidth ratio (Θ)	Power ratio(Ø)
1	AWGN	2.375	0.718	0.912
2	Rayliegh	1.26	0.091	0.783

TABLE III: LOWER BOUND EE

S.No	Type of channel	Lower bou Energy efficiency	Bandwidth ratio (ϴ)	Power ratio(Ø)
1	AWGN	2.812	0.913	0.421
2	Rayliegh	1.172	0.957	0.071

5. CONCLUSION

We formulated the model for HCGRC and performed the mathematical analysis under AWGN and Rayleigh fading environments. Using the concepts of information theory, the performance metrics of HCGRC i.e. capacity, SE and EE are calculated. From the analysis of simulation results, it is concluded that the capacity increases continuously with bandwidth ratio and power ratio up to its peak value. The spectral efficiency SE increases with power ratio and energy efficiency EE monotonically increases with bandwidth ratio. The multi-objective power, bandwidth allocation in HCGRC. These results are also compared with another type of channel called Rayleigh fading channel. Once the bandwidth and power is limited, the important factor that limits the feasible ranges of EE and SE is the reliability. It is found that the overall performance of the system is decreased by Rayleigh fading and more power and bandwidth is required compared to AWGN channel. Future work can seek to extend the results to MIMO, multi-user multi relay and multi-antenna scenarios

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