Hybrid CR Network: An Approach Based on Interweave- and Underlay-Type CR Network

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Abstract Increased usage of mobile devices has surged demand for RF spectrum considerably. Cognitive radios (CR) hold tremendous promise for improving spectral efficiency in the wireless system. It provides a fair solution for the dynamic allocation of frequencies between the primary user (PU) and secondary user (SU). Efficient techniques for spectrum holes' estimation in available band maximize the system capacity, but in the limited band, it is tough to provide an unutilized band for SU. Since the secondary network is established where the licensed band is underutilized but if the licensed band is over-utilized, SU may still communicate if interference is lower than I_{th} to the primary user. This paper investigates the capacity of a secondary user with the variation of the power of SU in interweave and underlay network. It provides the novel solution for the performance of SU in hybrid network mode, where SU requires larger bandwidth but the availability of spectrum to the cognitive user is less.

Keywords Cognitive radio · Interweave network · Underlay network · Hybrid spectrum access · CFO

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1 Introduction

Increased usage of wireless technology has created a huge demand for high data rate in the wireless scenario. Additionally, a significant number of users in the limited available spectrum have created a scarcity in licensed band. It is expected that nearly 20 billion wireless devices will be utilized over the globe for various application by 2023 [1–3]. Demand for spectral efficiency (SE) along with energy efficiency (EE) is a major challenge in wireless research. Support for high data rate at low power has led to the wireless network densification and also increases the operational cost. From Shannon's channel capacity theorem, system throughput directly depends on SNR or transmitted power which implies that supporting high data rate in limited power is a big problem in wireless communication research. In the other side, optimal resource (time, frequency, power, space, code) allocation in multiple access scenario for uplink (UL) and downlink (DL) also be one of the emerging challenges. Cognitive radio (CR) is one of the possible areas in the field of resource allocation which utilizes the wireless resources opportunistically. CR-based network searches the underutilized license band support for high user density. CR system provides a fair solution for dynamic allocation of frequencies between the primary user (PU) and secondary user (SU) [4]. There are three type of cognitive radio network mode [5]. In the first mode called as interweave networks where spectrum, holes present in the licensed band are allocated to the SU for increasing the overall system capacity. Second mode corresponds, due to unavailability of spectrum in licensed band, the cognitive user utilizes that band in such a way that it produces interference below the threshold limit, called as underlay network. Using the same sub-carrier by the different user, interference could be nullified through intelligent signal processing which is termed as overlay mode for CR system.

1.1 Prior Research, Motivation, and Contribution

In [6], authors describe the interweave CR network with cooperative sensing, considering separate PU decoding for the closest PU receiver. The information observed by secondary base station (SBS) for all closely located SU is highly correlated in cooperative sensing environment. Hence, through soft combination, algorithm for user selection at SBS improvises the overall performance [7]. A solution for an achievable rate under an average transmit power and interference outage constraints has been derived for underlay network [8]. After spectrum sensing, a perfect decision requires based on optimal power. Deterministic and probabilistic model [9] in CR network helps to the optimal allocation of the power between PU and SU, which maximize the overall system capacity. Different literature covers the aspect of optimal power control under various regime. Mung-Chiang et al. worked on the power resource, where they discussed the optimal power allocation among user and base station (BS) through geometrical programming [10, 11] to enhance the capacity. Simultaneously optimal power allocation among BS and user equipment (UE) solves the problem of high power requirement in uplink and downlink scenario and also maximizes the desired SNR at low power condition [12]. The adaptive deactivation of adjacent sub-carrier provides flexible guard bands between PU and SU and causes mutual interference cancelation in OFDM-based CR system [13].

Above literature mainly covers (1) spectrum sensing, (2) OFDM-based CR network, (3) different optimal power control regime, and (4) different modes (interweave, underlay) for CR system. This paper integrates these various aspects and presents a comprehensive solution for hybrid spectrum access for SU, considering interweave and underlay scenario. Chu et al. have described the hybrid spectrum access in cooperative cognitive network [14] but our work is based on OFDM-enabled single base station (BS) supporting multiple users-based CR system. Interweave and underlay are the two separate aspects for utilizing the frequency resource. Interweave mode requires full spectrum slot, and a lot of work were based on the sensing and allocation of sub-carrier to the cognitive user in this mode. Like interweave, sensing and sub-carrier allocation for underlay mode have also been addressed in the above literature. No paper address these two modes jointly for performance analysis of cognitive user. The numerical result validates the scenario under different real-time constraints with suitable assumption. Performance analysis in interweave, underlay, and hybrid mode has been carried out by an adaptive number of sub-carrier allocation to the SU. This paper investigates the capacity performance enhancement in cognitive radio through hybrid network approach which includes the benefits of interweave and underlay mode.

In summary, major contributions of this paper can be stated as follows:

- Based on spectrum sensing and average information about the interference of PU, we maximize the overall throughput for cognitive user.
- On the basis of two decision threshold, hybrid spectrum access has been implemented. It depends on the channel condition of licensed sub-carrier in OFDMA-based user access mechanism.
- Some other effects like carrier frequency offset which degrade the performance of PU as well as SU have been jointly analyzed.

This paper has been organized as follows, where Sect. 2 covers the related work about conventional CR mode like interweave and underlay. Section 3 describes the system model for proposed method along with classical one. Numerical results have been analyzed in Sect. 4 carried out by the conclusion in Sect. 5.

2 Related Work Based on Interweave and Underlay Toward Achievable Rate

Based on the intuition framed for interweave and underlay mode [5], its extension for cognitive network in OFDM system [15] gives the background of this research.

So OFDM-based interweave and underlay performance analysis has been discussed through two cases.

Case 1: Performance of SU in Interweave Network Generalized frequency response of received wireless signal for OFDM-based system can be expressed as

$$Y_{m,n}(f) = H_{m,n}(f)X_{m,n}(f) + W_{m,n} \tag{1}$$

where $Y_{m,n}(f)$, $H_{m,n}(f)$, $X_{m,n}(f)$, $W_{m,n}$ are the received signal frequency response, transfer function of wireless channel, transmitted symbol, and additive white Gaussian noise of n_{th} sub-carrier for m_{th} time domain sampling index, respectively. Transmitted symbol of n_{th} sub-carrier for m_{th} time domain sampling index can be expressed as

$$X_{m,n}(f) = \left|X_{m,n}(f)\right| e^{\frac{j2\pi mn}{N}} \tag{2}$$

where N is the total number of sub-carrier.

In interweave network, PU does not influence the SU. It is mainly affected due to system noise and carrier frequency offset (loss of orthogonality between consecutive sub-carrier). The received power of n_{th} sub-carrier can be expressed as

$$P_{(n)} = \int_{-B_k/2}^{B_k/2} \rho_0(n) \left(\frac{\sin(\pi\left(f - \frac{n}{T_s}\right)T_s}{(\pi\left(f - \frac{n}{T_s}\right)T_s} \right)^2 df \tag{3}$$

where $P_{(n)}$, $\rho_0(n)$, $T_s = \frac{1}{\Delta f}$, B_k are the power allocation of nth sub-carrier, peak power spectral density of n_{th} sub-carrier, symbol duration, and allocated bandwidth, respectively. At constant bandwidth, if power level of user terminal increases then the power spectral density (PSD) also increases. PSD should not exceed from the maximum limit in such a scenario. In the practical scenario, the upper bound capacity obtained by Jensen's inequality gives the maximum achievable observed capacity. The maximum achievable observed capacity of any random SU in interweave scenario without (CFO) can be expressed as [16].

$$\begin{aligned} C_{k_s} &= \log_2\left(1 + \frac{\alpha k_{s,n}}{N_{fk_s} - N_{sk_s}} \sum_{n=N_{sk_s}}^{N_{fk_s}} \frac{p_{k_{s,n}}\left|h_{k_{s,n}}\right|^2}{\sigma_n^2}\right) \\ \alpha k_{s,n} &= 1 \forall N_{sk_s} \le n \le N_{fk_s} \\ \alpha k_{s,n} &= 0 \text{ elsewhere} \end{aligned} \tag{4}$$

where C_{k_s} is the expected capacity of any k_s^{th} cognitive user. N_{sk_s} and N_{fk_s} are the starting and last sub-carrier number allotted to respective user. It is also expected that all these sub-carriers have not been allocated to any PU or other secondary user. N, B, σ_n^2 are total number of available sub-carriers, total system bandwidth, and noise variance in license band, respectively. $h_{k_{\mathrm{s},n}}$ is the channel gain of n_{th} sub-carrier for $k_{\mathrm{s}}^{\mathrm{th}}$ SU also $h_{k_{\mathrm{s},n}} = g_{k_{\mathrm{s},n}}\sqrt{\beta_{k_{\mathrm{s}}}}$ where $g_{k_{\mathrm{s},n}}$ and $\beta_{k_{\mathrm{s}}}$ are the fast fading and slow-fading coefficient and $E\left[\left|g_{k_{\mathrm{s},n}}\right|^2\right] = 1$. In interweave network, there is no inter-user interference, but the performance of cognitive user is suppressed by only through system noise and CFO.

CFO in SU Sub-carrier

Inter-carrier interference arises mainly due to incorrect (CFO). It occurs due to improper sampling. When l_{th} sub-carrier suffers with CFO ε, then the received l_{th} sub-carrier can be expressed as

$$Y_l = \frac{1}{N}\sum_{n}\sum_{K=-N/2}^{N/2} X_K H_K \mathrm{e}^{-j2\pi(k-l+\varepsilon)n/N} \tag{5}$$

The closed-form equation for observed *SINR* of SU can be expressed as

$$\gamma_1 = \frac{P_{k_{\mathrm{s},n}}\left|h_{k_{\mathrm{s},n}}\right|^2\left(\frac{\sin(\pi\varepsilon)}{(\pi\varepsilon)}\right)^2}{0.822P_{k_{\mathrm{s},n}}\left|h_{k_{\mathrm{s},n}}\right|^2\sin(\pi\varepsilon)^2 + \sigma_n^2} \tag{6}$$

Case 2: Performance of SU for underlay network When spectrum holes are unavailable in the licensed band, SU utilizes the licensed band in such a way that power level of SU could not exceed the threshold limit. Adaptive power controlling mechanism can limit excess power transmission from the secondary base station (SBS). Mathematically, the power distribution through the SBS for SU can be expressed as

$$P_{k_{\mathrm{s},n}} = min\{I_{\mathrm{th}}, P_{\mathrm{sbs}}\} \tag{7}$$

where $P_{k_{\mathrm{s},n}}$, I_{th}, P_{sbs} are the optimal power for $k_{\mathrm{s}}^{\mathrm{th}}$ SU, interference threshold to PU and transmitted power through SBS respectively. Since in underlay scenario PU is the strong interferer to the secondary, observed achievable capacity in such a scenario can be expressed as

$$C_{k_{\mathrm{s}}} = \log_2\left(1 + \frac{\frac{1}{N_{fk_{\mathrm{s}}} - N_{sk_{\mathrm{s}}}}\sum_{n=N_{sk_{\mathrm{s}}}}^{N_{fk_{\mathrm{s}}}} P_{k_{\mathrm{s},n}}\left|h_{k_{\mathrm{s},n}}\right|^2}{\frac{1}{N_{fk_{\mathrm{s}}} - N_{sk_{\mathrm{s}}}}\sum_{n=N_{sk_{\mathrm{s}}}}^{N_{fk_{\mathrm{s}}}} P_{j_{p,n}}\left|h_{j_{p,n}}\right|^2 + \sigma_n^2}\right) \tag{8}$$

where $P_{j_{p,n}}$ is the power of j_{th} PU, whose few sub-carrier starting from $n = N_{sk_{\mathrm{s}}}$ to $n = N_{fk_{\mathrm{s}}}$ has been allotted to a random SU where $P_{j_{p,n|N_{sk_{\mathrm{s}}}\dots N_{fk_{\mathrm{s}}}}} > P_{k_{\mathrm{s},n|N_{sk_{\mathrm{s}}}\dots N_{fk_{\mathrm{s}}}}}$ and power level of SU should not cross the interference threshold limit. In worst case, scenario achievable capacity in underlay network is jointly influenced by interference and CFO.

When SU and PU suffer with CFO

Under such scenario, the SU performance significantly degrade and observed SINR can be expressed as

$$\gamma_1 = \frac{P_{k_{s,n}} \left|h_{k_s}\right|^2 \left(\frac{\sin(\pi\varepsilon)}{(\pi\varepsilon)}\right)^2}{0.822 P_{k_s} \left|h_{k_s}\right|^2 \sin(\pi\varepsilon)^2 + P\left|h_{j_p}\right|^2 + \sigma_n^2} \tag{9}$$

If CFO arises in PU band then observed SINR can be expressed as

$$\gamma_2 = \frac{P_s |h_s|^2 \left(1 + \frac{0.822 P_p (\sin(\pi\varepsilon))^2}{\sigma_n^2}\right)}{\sigma_n^2 + 0.822 P_p \left|h_p\right|^2 (\sin(\pi\varepsilon))^2 + P_p \left|h_p\right|^2 \left(\frac{\sin(\pi\varepsilon)}{(\pi\varepsilon)}\right)^2} \tag{10}$$

3 Hybrid Network

Composite network comprises the coexistence of the primary and secondary network in a certain geographical bound. Primary network consists primary base station (PBS) and PU, whereas secondary network is framed by SBS or SU. Here, system model includes the following constraints.

1. Bandwidth allocation for SU should not be greater than B_s Hz for preventing the unauthorized access of large spectrum from the security point of view.
2. Primary users (PU) are assumed to be not very far from the SBS as well as secondary users (SU) such that false alarming issues did not come into the picture.
3. Among the SU, there are no spatial correlation.
4. Expected power level across allocated sub-carriers to the PU remain same.

Hybrid spectrum allocation for SU based on interweave/underlay scenario has been categorized into three steps.

1. Spectrum sensing
2. Decision based on activation threshold
3. Performance analysis for PU and SU.

3.1 Spectrum Sensing Across SBS

In this section, we consider that M_p number of PUs are active in the particular geographical bound and PBS/SBS both receive the signals. PBS remains unaffected, but SBS acquires the information from the PU. During sensing, no uplink and downlink data transmission occur by secondary network till sensing time slot. Only SBS receives the signal and SU remains inactive during sensing. Within sensing time interval, N_{sub} number of data samples are acquired by SBS. Received data sample is passed through the FFT block across the SBS. For such a system $N_{\text{sub}} > N$ and $\Delta f = B/N$, where Δf is the sub-carrier bandwidth. Two scenarios may be considered for the received signal

$$y_1(t) = \begin{cases} n_1(t) & A_0 \\ s_l(t) + n_l(t) & A_1 \\ \forall & 0 < t < \dfrac{N_{\text{sub}}}{B} \end{cases} \tag{11}$$

From above equation, $y_l(t)$ is a normal distributed random variable (RV) with mean 0 for hypotheses A_0 implies the absence of PU, whereas for hypotheses A_1, replicate the presence of PU; the received symbol $y_1(t)$ is a normal distributed RV with mean μ_s. The received power across the SBS can be modeled as

$$P_y(j) = \sum_{i=1}^{M_p} \left|y_{ij}\right|^2 = \sum_{i=1}^{M_p} \left|s_{ij}\right|^2 + \left|n_j\right|^2 \tag{12}$$

where $\left|s_{ij}\right|^2$ is the signal power of i_{th} user for j_{th} sample. From above equation, if $i = 0$ (All primary users are inactive), $s_{ij} = 0$; only noise power is considered to be received power. Statistical analysis gives an idea about the power level of different PU whose signals are received across the SBS.

4 Numerical Results

In this section, analytical results have been numerically verified. In multiple access scenario, we have chosen the OFDM-based frequency resource allocation for different users. These users may be PU or SU. We also consider the availability of perfect channel state information CSI between PBS to PU and SBS to SU. Cognitive users also know CSI between itself and PBS/PU. The expected channel variance across each sub-carrier either for SU has been taken unity, i.e., $E\left[\left|h_{k_{s,n}}\right|^2\right] = 1$. In three different scenarios, SU performance variation has been observed due to nearest reference PU. In LTE-TDD standard, to access multiple users, minimum one resource block (RB) is transferred to any user, where one RB is 0.5 ms and 180 kHz wide in time–frequency frame. One-time slot carries 7 OFDM symbol. In normal cyclic prefix condition, 12 sub-carriers are carried by one resource block. So sub-carrier spacing _f is equal to 15 kHz. Total number of available sub-carrier, i.e., $N = 512$. For simplicity, let $B_{\text{p}}= 1.5$ MHz bandwidth has been allocated to the PU and the maximum permissible bandwidth for SU is $B_{\text{s}} = 300$ kHz. In such a wireless network, 5 PU are active and for each PU 100, sub-carriers are allocated. In this assumption, maximum permissible sub-carrier for SU is 20. As per OFDM-based system constraints, the minimum BW allocation to the cognitive user is 180 kHz and maximum allocated bandwidth is 300 kHz for preventing the unauthorized access of larger licensed band. According to dynamic allocation of the frequency band, the wireless network may allocate the band to SU in three different modes termed as interweave, underlay, and hybrid mode. Figure 1 shows the capacity performance in offset scenario. Under such condition, three modes have shown. In interweave mode, one sub-carrier suffers from 10% CFO due to incorrect sampling, so the achievable rate degrades. In underlay scenario, two cases have been taken. In the first case, 10% CFO arises in one sub-carrier and at same sub-carrier PU acts as an interferer, while in the second case, PU sub-carrier suffers with 10% CFO. Under no CFO and PU as an interfering agent, the performance degradation in such scenario has been shown in Fig. 1. Since power control mechanism in underlay is applied in such a way that SBS did not transmit power more than I_{th} irrespective of maximum power transmit limit by SBS, power constraints from (9) and taking 5 dB as (I_{th}) all curve remain to go to the saturation in underlay scenario. In proposed hybrid spectrum access methodology, 10% CFO has been considered for those sub-carrier which utilizes the PU band and same amount of CFO in the unused band. If all signals are perfectly sampled, then the achievable rate for three modes can be observed from Fig. 2. In the joint scenario, two decision thresholds γ_l and γ_{avg} are used for correct justification about the interweave and underlay band. Here, γ_l and γ_{avg} have been taken 0 dB and 10 dB, respectively, for PU. Out of 500 allocated sub-carrier of PU, best 8 sub-carriers are selected from the PU band. As per assumption, 12 sub-carriers are unused and free from inter-user interference. Eight sub-carriers of PU band having $\gamma_l > \gamma_{\text{avg}}$ are aggregated with twelve unused sub-carriers, which fulfill the BW greed for SU. Based on proportionality average, SNR for hybrid spectrum access methodology is formulated. In such a

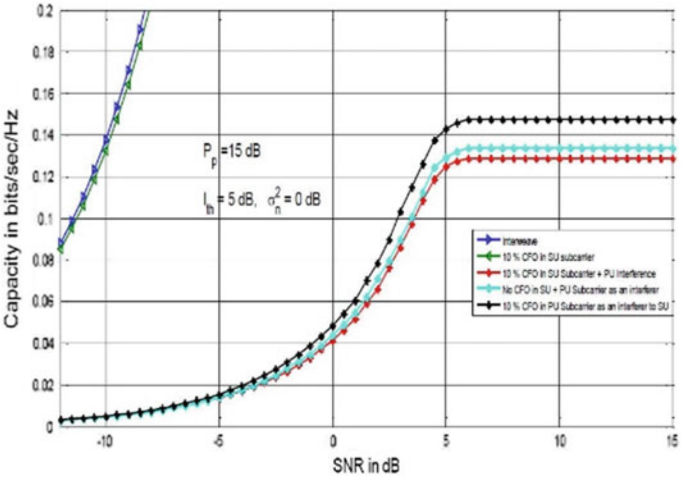

Fig. 1 Observed capacity of cognitive user in offset scenario

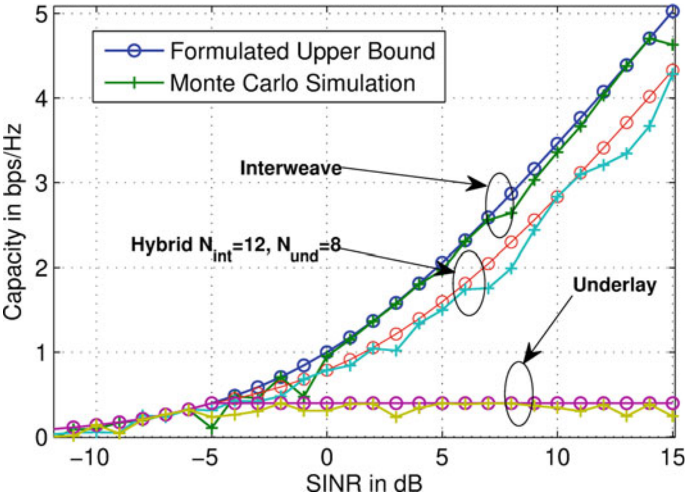

Fig. 2 Capacity in three modes of CR system

condition, I_{agg} be the transmit power and 5 dB is taken for numerical simulation. The analytical curve for the upper bound of a closed-form solution to average achievable rate is obtained from (5), (10) and (13), which are tightly matched to the exact Monte Carlo simulation. Depending on sub-carrier availability in interweave and underlay mode, Fig. 3 depicts the achievable rate performance under different proportionality. In this figure, only upper bound close form expression has been used. Due to increase in the number of unused sub-carrier, the capacity increases with greater extent. Neglecting the impact on statistics for frequency selective at channel, it is

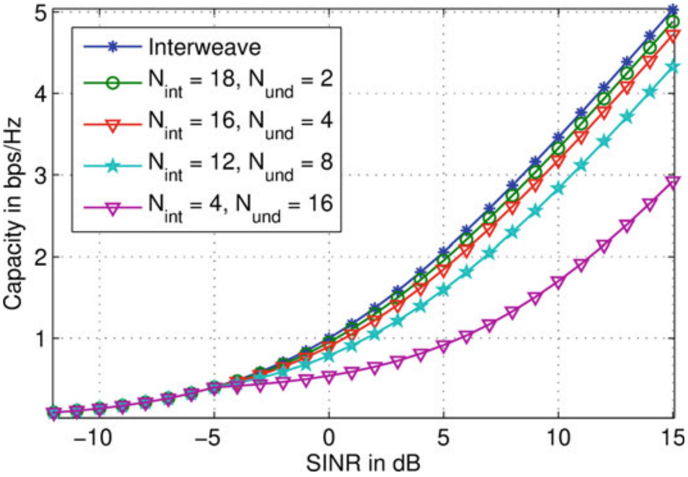

Fig. 3 Capacity in mixed networks for different value of N_{und} and N_{int}

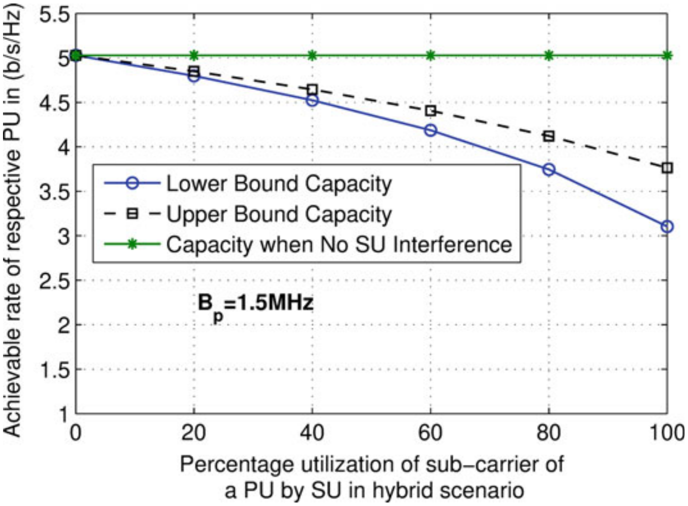

Fig. 4 Achievable rate of PU vs percentage utilization of sub-carrier in hybrid spectrum access methodology where D_{th}= 1:25 dB and I_{th}= 5 dB

assumed that all selective channels for PU have unit variance $E\left[\left|h_{(j_{p,n})}\right|^2\right] = 1$ for PU.

$$\text{Selective Channel} = \frac{B_p}{B_c} = \frac{N_P \Delta f}{B_c} \tag{13}$$

Figure 4 shows the impact of SU on PU. Multiple cognitive users degrade the performance of PU in the nonlinear fashion. For numerical computation, detection and interference threshold have been taken 1.25 and 5 dB, respectively, in underlay scenario. Since 1.5 MHz and 300 kHz bandwidth have been assigned to PU and SU, in this practice, the permissible cognitive users are five where all SU consume maximum bandwidth. Figure 5 depicts two independent scenarios. In the first, when the cognitive user receives power level up to detection threshold than such situation causes less interference to the PU gets upper bound capacity. In the second scenario, when the cognitive user receives the power level up to I_{th}, the PU suffers from more interference and lower bound capacity can be observed if $P_{\text{SU}}= I_{\text{th}}$.

5 Conclusion

In this paper, a detailed analysis has been carried out for SU capacity performance in different CR network mode. In the case of limited BW availability, hybrid spectrum access mode gives moderate solution among another mode like, interweave and underlay. For maintaining fairness among multiple SU, hybrid spectrum access methodology is more helpful in comparison to interweave and underlay scenario. This technique improvises the cognitive user density providing fairness at the cost of hardware complexity. This paper analyzes the OFDM-based three-mode performance comparison for a single cognitive user. Multiple users' achievable rate performance and their fairness can be an extension of this paper.

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