
INTERFERENCE MITIGATION OF UNDERLAY SECONDARY USERS USING INTERFERENCE ALIGNMENT

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

As the number of wireless devices and services grows exponentially, the Radio Frequency (RF) spectrum is becoming increasingly a scarce resource. Again, the current fixed spectrum-licensing policy has made the RF spectrum underutilized. Cognitive Radio (CR) seeks to provide solution to address the imbalance between spectrum scarcity and spectrum underutilisation by allowing cognitive users, called Secondary Users (SUs), to share the spectrum with the licensed users called Primary Users (PUs) in a manner that the PUs do not suffer harmful interference. This work is aimed at mitigating underlay cognitive intra-network interference with a view to enhancing the effective sum capacity of the SUs. The PU is protected through Interference Temperature (IT) model. Interference Alignment (IA) scheme under the IT constraints is developed for mitigating the mutual interference among the SUs. A closed form expression for the sum capacity of three-user underlay cognitive channel is derived. Applying the ergodic IA with IT constraints enhances the sum capacity of the SUs thereby achieving 23.54% and 24.77% gain in the channel sum capacity under maximum and average IT limits respectively. This gain is with respect to time-division scheme at signal-to-noise-ratio of 19dB. By utilizing the long delay time associated with ergodic IA to send more bits in time-division scheme, 3.0094 bps/Hz and 3.1741 bps/Hz gains in spectral efficiency were achieved under maximum and average IT limits over a full time-division scheme at SNR of 19dB.

Keywords: Cognitive Radio; Interference Alignment; Underlay; Spectral Efficiency; SNR

1. INTRODUCTION

The rapid growth of wireless broadband, multimedia, mobile computing, and emerging wireless services has resulted in an increasing demand for radio-frequency spectrum. At the same time, conventional fixed spectrum allocation has resulted in significant underutilization of portions of the licensed spectrum. Out of the imbalance between scarcity of preferred spectrum and underutilisation was born the idea of Cognitive Radio (CR) to improve spectrum utilization (Mitola, 2009). CR uses advanced radio and signal processing technology along with novel spectrum allocation policies to share the spectrum as a Secondary User (SU) in a manner that the Primary (licensed) Users (PUs) are as unaffected as possible. CR provides a means of improving spectrum utilization by allowing unlicensed or SUs to opportunistically access spectrum assigned to PUs, subject to appropriate interference constraints (Xu *et. al.*, 2025).

Three principal spectrum-sharing paradigms are commonly considered in cognitive radio networks: interweave, overlay, and underlay as illustrated in figure 1.

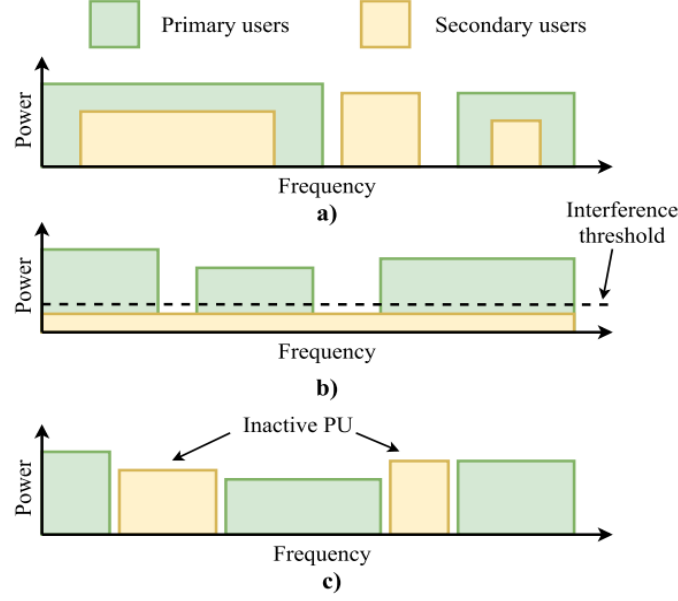


Figure 1: Spectrum sharing in CR. a) overlay, b) underlay, c) interweave (Briones *et. al.*, 2020)

In the underlay paradigm, an SU is allowed to transmit concurrently with a PU provided that the interference received by the PU remains below a prescribed threshold. The interference-temperature (IT) concept provides a convenient means of specifying this interference constraint (Yau *et. al.*, 2025).

Although the underlay approach allows simultaneous transmission, the requirement to protect the PU imposes a restriction on the transmit power of the SUs. The problem becomes significant when multiple SUs share the spectrum. In addition to SU-to-PU interference, there is mutual SU-to-SU interference. Consequently, a reduction in SU transmit power does not by itself solve the interference problem; rather, the mutual interference may become a dominant limitation on the achievable secondary-network capacity (Yang, *et. al.*, 2024).

Interference Alignment (IA) is a transmission strategy that combines transmitter precoding and receiver interference suppression to achieve optimal network degrees of freedom. The idea of IA has challenged most of conventional wisdom about the sum capacity limit of wireless channels (Abdulkadir *et. al.*, 2024). IA is an interference-management technique that exploits the dimensions of a time-varying interference channel to arrange interfering signals in a manner that permits their suppression at the intended receivers. Ergodic Interference Alignment (EIA) uses appropriately selected channel realizations to align and cancel interfering signals. The work of Yau *et. al.*, (2025) evaluated the ergodic capacity of multiple underlay cognitive users under maximum interference constraints. This paper investigates interference mitigation of multiple underlay SUs using ergodic interference alignment under interference-temperature constraints with the following novel contributions:

- i. Modelling the interference in a 3-SU underlay cognitive-radio in the presence of a single PU.
- ii. Incorporating EIA into the underlay system for mitigating interference among the SUs while satisfying both maximum and average IT constraints.
- iii. Obtaining a closed-form sum-capacity expressions for the three-user system.
- iv. Evaluating the performance of EIA against an equal time-division benchmark
- v. Utilizing the EIA to send delay insensitive bits for significant spectral efficiency gains.

2. METHODOLOGY

A spectrum sharing model is considered as illustrated in Figure 2 where three Secondary Users (SUs) underlay their transmissions in the same narrow-band frequency as the Primary User (PU). The IT metric is used as measure of the interference power. The channel coefficient between transmitter j to receiver i is denoted as h_{ij} . All the channel coefficients are assumed to be independent and identically distributed (i.i.d) random variable following Rayleigh distribution (Ren *et. al.*, 2026).

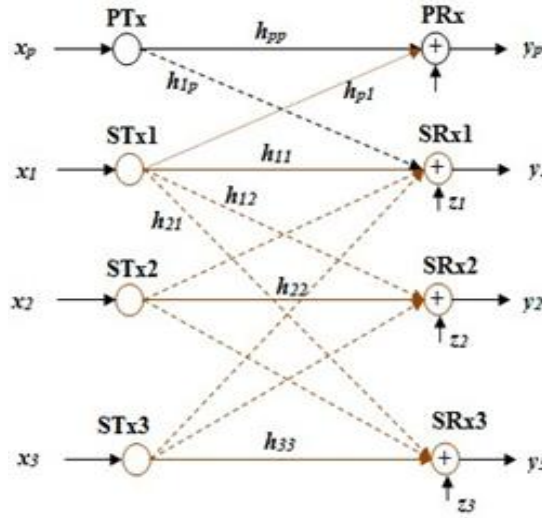


Figure 2: System Model: 3 SUs Coexisting with a Single PU

The received signal at the primary receiver, y_p , is a noisy linear combination of the signals from the intended primary transmitter and unintended secondary transmitters which can be modelled as:

$$y_p = h_{pp}x_p + \sum_{k=1}^3 h_{pk}x_k + z_p \quad (1)$$

where:

h_{pp} and h_{pk} are the channel coefficient between the PU transmitter and PU receiver and the channel coefficient between the k th SU transmitter and the PU receiver respectively; x_p and x_k are the signals transmitted by the PU transmitter and the k th SU transmitter respectively; z_p is an additive white Gaussian noise with zero mean and unit variance at the primary receiver.

Similarly, the channel model for the j th SU receiver is as follows

$$y_j = h_{jp}x_p + \sum_{k=1}^3 h_{jk}x_k + z_j \quad (2)$$

where, $j = 1, 2, 3$

For a given bandwidth, B , the SU determines its transmit power, P , subject to interference constraint given by.

$$P \leq \frac{k \cdot B(T_L - T_I)}{L} \quad (3)$$

Thus,

$$E[|x_k|^2] = P \leq \frac{k \cdot B(T_L - T_I)}{L} \quad (4)$$

Equation (4) ensures that the total power in the terms $\sum_{k=1}^3 h_{pk}x_k$ of equation (1) do not cause harmful interference to the PU receiver.

2.1 ERGODIC INTERFERENCE ALIGNMENT UNDER IT CONSTRAINTS

For a time varying interference channel, the achievable capacity per user, C_{SU_EIA} , using ergodic interference alignment is given by

$$C_{SU_EIA} = \frac{1}{2} E[\log(1 + 2|h_{kk}|^2 P)] \quad (5)$$

where, P is the transmit power of the user.

The sum capacity achieved for fully connected 3 underlay CR users under the IT constraints is formulated as follows:

A. ERGODIC IA UNDER MAXIMUM IT LIMITS

The sum capacity, C_{Σ}^{EIA} , achieved for a fully connected 3-users is solution to the following optimization problem.

$$C_{\Sigma}^{EIA} = \max_{P \geq 0} \frac{3}{2} E[\log(1 + 2g_{ss}P)] \quad (6)$$

Subject to

$$\sum_{k=1}^3 g_{pk} P \leq kBT_L \quad (7)$$

The optimal power, P^* , is just given by

$$P^* = \frac{kBT_L}{\sum_{k=1}^3 g_{pk}} \quad (8)$$

Putting equation (8) into equation (6) gives

$$C_{\Sigma}^{EIA} = \max_{P \geq 0} \frac{3}{2} E \left[\log \left(1 + 2 \frac{g_{ss}}{\sum_{k=1}^3 g_{pk}} \psi \right) \right] \quad (9)$$

$$C_{\Sigma}^{EIA} = 1.44 \times \frac{24\psi^3 \log 2\psi - 36\psi^3 + 24\psi^2 - 3\psi}{2(2\psi - 1)^3} \quad (10)$$

B. ERGODIC IA UNDER AVERAGE IT CONSTRAINT

The sum capacity, C_{Σ}^{EIA} , achieved is solution to the following optimization problem.

$$C_{\Sigma}^{EIA} = \max_{P_{su} \geq 0} \frac{3}{2} E[\log(1 + 2g_{ss}P)] \quad (11)$$

Subject to

$$E \left[\sum_{k=1}^3 g_{pk} P \right] \leq kBT_L \quad (12)$$

The optimal power, P^* , is obtain using Lagrange method as

$$P^* = \left(\frac{1}{\lambda \sum_{k=1}^3 g_{pk}} - \frac{1}{2g_{ss}} \right)^+ \quad (13)$$

Hence, the sum capacity, C_{Σ}^{EIA} , in bpcu is obtained as

$$C_{\Sigma}^{EIA} = 1.44 \left[\frac{3}{2} \log(1 + \gamma(\psi)) - \frac{3\gamma(\psi)(2 + 3\gamma(\psi))}{4(1 + \gamma(\psi))^2} + \frac{3\gamma(\psi)^3 \log 2}{2(1 + \gamma(\psi))^3} \right] \quad (14)$$

2.2 UTILIZING THE EXPECTED DELAY OF ERGODIC ALIGNMENT

A major drawback of ergodic alignment scheme is a very long delay incurred to attain half the interference-free rate. This limits the scheme to applications where high rates are far more valuable than low delays. Thus, the spectral efficiency of the ergodic alignment becomes very low due to the long delay time during which the users have to stay quite waiting for the realization of the complimentary channel matrix. To better the spectral efficiency of the proposed ergodic IA under IT constraints, the waiting time (expected delay) can be exploited by the SUs for sending delay-sensitive messages. The spectral efficiency gain is obtained as follows.

Let τ be the expected delay time slots between the two transmissions to achieve ergodic alignment. If the SUs utilize the expected delay time slots in a time-division scheme, the spectral efficiency is given by

$$\eta_{EIA} = 2 \times \frac{3}{2} E[\log(1 + 2g_{ss}P^*)] + \tau \times E[\log(1 + g_{ss}P^*)] \quad (15)$$

For a full time-division SUs, the spectral efficiency, η is

$$\eta = (2 + \tau) E[\log(1 + g_{ss}P^*)] \quad (16)$$

Subtracting equation (16) from equation (15), the gain in spectral efficiency, η' , is obtained as

$$\eta' = 3E[\log(1 + 2g_{ss}P^*)] - 2E[\log(1 + g_{ss}P^*)] \quad (17)$$

3. RESULTS AND DISCUSSION

This section describes the performance of the proposed ergodic interference-alignment (EIA) scheme was evaluated for the 3-SU underlay cognitive-radio system. Table 1 shows the simulation parameters.

Table 1: Simulation Parameters

S/N	Parameter	Value/Setting
1	Boltzmann constant (K)	1.38×10^{-23} J/K
2	Background IT	290 K
3	SNR range, ψ	0 – 20 dB
4	Channel model	i.i.d Rayleigh fading
5	Channel knowledge	Perfect CSI
6	Channel bandwidth , B	Normalised
7	SU time allocation	1/3
8	EIA time factor	$\frac{1}{2}$

Comparison of the sum capacities of the SUs under maximum IT limit and average IT limit for the same SNR is done in Figure 3. The capacities in the former case are generally lower than those of the latter which results due to the more restrictive nature of the maximum (as opposed to the average) IT constraint.

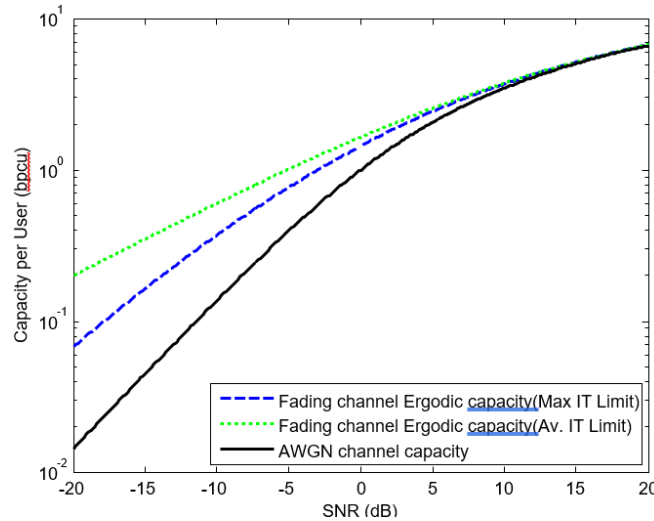


Figure 3: Sum Capacity through Time Division

A. ACHIEVABLE SUM CAPACITY THROUGH EIA UNDER IT LIMITS

Figures 4 (a) and (b) show the sum capacity achieved through ergodic IA under maximum and average interference temperature limits using equations (10) and (14). For all values of SNR under average IT limit, the achievable sum capacity through ergodic IA is higher than that obtained through time-division. But in the case of Max. IT limit below 6.2dB, the capacity achieved through ergodic IA is below that of time-division. This due to the more restrictive nature of the maximum (as opposed to the average) IT constraint.

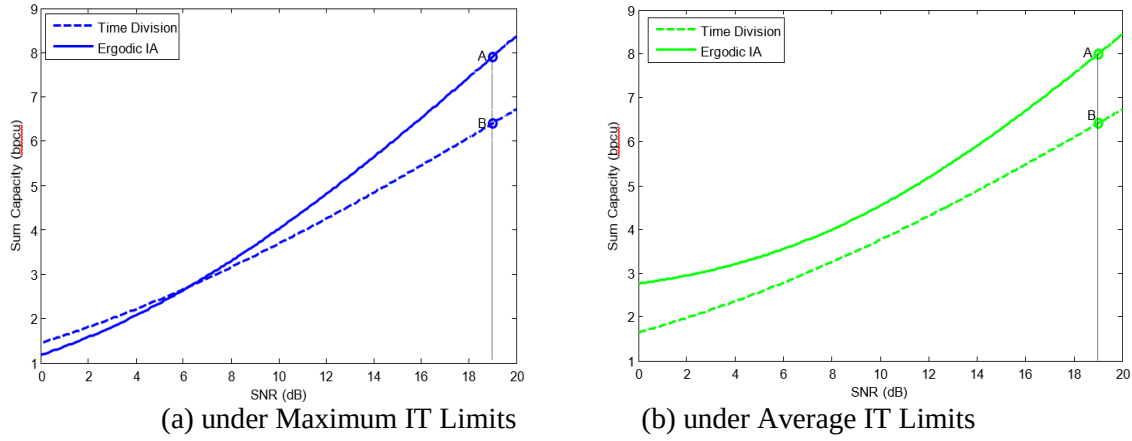


Figure 4: Sum Capacity

The typical values of SNR of UWB (an underlay communication) applications are around 19 dB (Nelson *et. al.*, 2025). Thus, the performance of the developed model is evaluated at 19 dB under maximum and average IT limits as follows:

Maximum IT Limit

The sum capacities achieved through the developed ergodic IA under IT limits and the time division scheme are given by the coordinates A(19 dB, 7.8968 bpcu) and B(19 dB, 6.3921 bpcu) respectively in Figure 4 (a).

The capacity gain = $7.8968 - 6.3921 = 1.5047$ bpcu

The capacity gain

$$= \frac{1.5047}{6.3921} \times 100 \% = 23.54 \%$$

Average IT Limit

The sum capacities achieved through the developed ergodic IA under IT limits and the time division scheme are given by the coordinates A(19 dB, 7.9943 bpcu) and B(19 dB, 6.4073 bpcu) respectively in Figure 4 (b).

The capacity gain = $7.9943 - 6.4073 = 1.5870$ bpcu

$$= \frac{1.5870}{6.4073} \times 100 \% = 24.77 \%$$

The capacity gain

Comparison of the achievable capacity under IT constraints with that of the time-division scheme is shown in Figure 5. It also gives an upper bound to the capacity which corresponds to capacity achievable by non-interfering cognitive users.

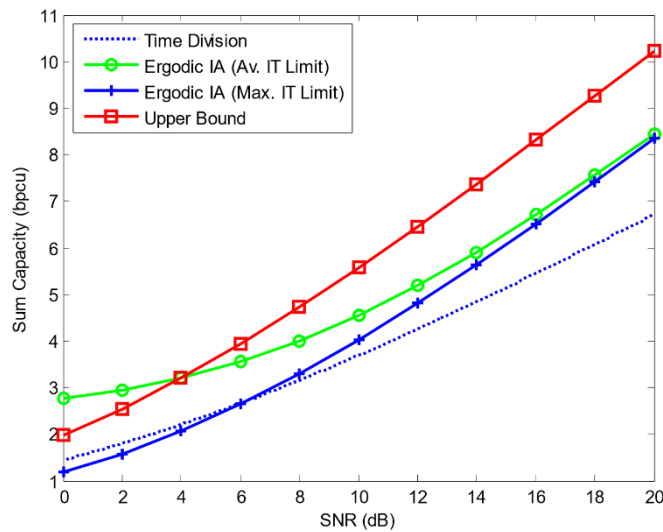


Figure 5: Sum Capacity Comparison

B. SPECTRAL EFFICIENCY GAIN

Spectral efficiency gain was achieved through exploiting the long delay necessary for the ergodic alignment. By utilizing the waiting time slot to send delay insensitive bits in time division scheme, 3.0094 bps/Hz and 3.1741 bps/Hz gains in spectral efficiency were achieved under maximum and average IT limits over a full time-division scheme at SNR of 19dB.

4. CONCLUSION

This research work proposed to mitigate the mutual interference among multiple Secondary Users (SUs) in underlay cognitive radio network aimed at enhancing the sum capacity the SU. Mitigating interference and improving spectrum efficiency are essential for rapid and sustainable growth of telecommunications industry in Nigeria. Ergodic interference alignment scheme under the IT constraints is developed for mitigating the mutual interference among the SUs. To provide a benchmark to gauge the performance of the developed model, the sum capacity through time-division scheme is first obtained. A closed form expression for the sum capacity of three-user underlay cognitive channel is derived. The ergodic IA has a major drawback of a very long delay in order to achieve half the interference-free rate. This was utilized to send delay insensitive bits which give significant percentage improvements of 23.54% and 24.77% in the channel sum capacity under maximum and average IT limits respectively. Since the network sum capacity with EIA increases linearly with the number of users, successful implementation of IA for higher number of SUs will render the capacity of wireless channels interference unlimited. A Rayleigh fading environment is assumed to demonstrate the performance of the developed model. For further work, more generalized fading distributions such as Nakagami-m and α - μ distributions could be considered so that the model can be adapted to suit different environment.

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