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Comparative Analysis of Reactive and Proactive Spectrum Handoff Techniques in a Cognitive Radio System

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ABSTRACT

Spectrum Handoff (SH) is an important concept in Cognitive Radio Networks (CRN) in which a cognitive user vacates the spectrum and re-establishes new communication links through other idle spectrums to avoid interference. However, reactive and proactive methods, which are the two major techniques used for SH, have their strength and weaknesses. Hence, in this paper, a performance analysis of the two techniques in a CRN was carried out to evaluate the performance of the SH technique. MATLAB was used for the analysis by generating random data using a random integer generator and a Primary User (PU) signal. An Energy Detector (ED) was used to detect the presence of idle spectrum. SH technique was then carried out using reactive and proactive methods. Handoff Delay (HD), Collision Rates (CR) and Average Throughput (AT) were the metrics used to analyse the effectiveness of each SH technique in CRN. Simulation results demonstrated that the proactive spectrum handoff scheme exhibited lower latency, fewer collisions, and higher throughput compared to other schemes, especially in dynamic spectrum environments. It indicates its potential as an effective mechanism for cognitive radio user handoff management.

INTRODUCTION

The field of wireless systems has shaped world communications as it tends to be more important in terms of technological advances. The need for wireless data services has been seen in applications such as 5G technology, public safety communications (Faruk *et al.*, 2018), e-health, and virtual clinics (Salami *et al.*, 2019; Faruk *et al.*, 2017). Unfortunately, this spectacular development of wireless technologies is threatened as most of the spectrum, which represents the physical media for wireless transmission, has already been allocated to existing systems (Spavins, 2016). This has given rise to a great need for more spectrum, resulting in spectrum scarcity (Samrat and Ajitsinh, 2016; Hyun-Seo *et al*., 2024). However, this spectrum scarcity is artificial as it is possible to find frequencies not used by its owner when browsing through the full spectrum, which suggests that the issue can be regulated by the introduction of a policy for bandwidth and spectrum management. Therefore, a fixed spectrum access policy is no longer a viable approach to meet the rapidly growing demand for frequency spectrum to support emerging wireless applications (Jayanta *et al.*, 2014; Saeid *et al*., 2013; Ojo *et al*., 2021; Samrat and Ajitsinh, 2016; Josip *et al*., 2022). Cognitive Radio (CR) is a promising Spectrum Sharing (SS) technique that aims to improve spectrum efficiency by dynamically accessing underutilized spectrum bands, as enabled by Dynamic Spectrum Access (DSA).

DSA is a technology that improves spectrum efficiency by allowing unlicensed devices (secondary users) to temporarily access unused spectrum bands assigned to licensed users (primary users). This is achieved through a technique called Spectrum Sharing (SS), where devices scan the spectrum to identify available frequency bands, known as white spaces or spectrum holes (Nikhil and Rita, 2017; Meenakshi *et al*., 2016; Pawel *et al*., 2022). For smooth operation, SUs must relinquish the spectrum when the PU needs to transmit. This process, known as spectrum handoff, can be triggered by several factors, including PU return, SU Mobility and decreasing signal strength. PU return is when the PU returns to a channel currently occupied by an SU, and the SU must vacate the channel, while SU mobility occurs when the SU moves to a location with poor signal quality, it may need to switch to a different channel. A decline in signal strength can degrade the SU's connection, prompting a handoff. While spectrum handoff is essential for maintaining spectrum order, it can also increase the time it takes for SUs to transmit data, potentially impacting their overall performance (Ojo *et al*., 2020; Runze *et al*., 2019; Nurul *et al*., 2025).

During SH, SU needs to search for another available spectrum, which causes temporary interruptions to the communication line. The process whereby SU vacates the current spectrum due to the availability of PU to avoid interference is known as the Spectrum Handoff (SH) technique. This technique allows SU to switch to other spectrums without interrupting their transmission. The major commonly used SH techniques in CRN are proactive and reactive handoff techniques (Christian *et al*., 2012; Kumar *et al.*, 2016). In the proactive handoff, cognitive users carry out spectrum sensing to identify the backup spectrum before actual handoff is required, that is, before PU is active. In this technique, the handoff delay is very short because everything is planned. However, the technique suffered from high interference by cognitive users to the PU due to the information about the backup target spectrum that is obsolete. On the other hand, in reactive handoff, the cognitive user performs sensing to identify the backup spectrum when handoff triggering occurs, that is, when the PU is active. This technique addressed the problem of proactive interference, which is mainly due to the obsoletion of the target backup spectrum. However, the technique suffered from very high handoff delay due to cognitive users that first carry out sensing to identify another idle spectrum to move to another idle spectrum before vacating the current spectrum to active PU (Jayant *et al*., 2018).

There have been several existing works on the comparison between the reactive and proactive techniques in CRN. Wang and Wang (2008) examined the SH techniques used in CRN, that is Proactive Handoff (PH) and Reactive Handoff (RH). The results of the findings reveal that the PH technique suffered from high interference by cognitive users to the PU or another SU due to information about the backup target spectrum being obsolete. On the other hand, the RH technique is characterized by high handoff delay due to cognitive users that firstly carry out sensing to identify another idle spectrum to migrate to before vacating the current spectrum to active PU

However, in-depth analysis of the major performance metrics in CRN, such as average throughput and collision rate, was not considered. Also, Kumar *et al*. (2016) carried out a comparative study on different SH techniques that highlighted the advantages and disadvantages of each technique. The results showed that the proactive handoff can improve channel utilization by 6% and reduce the perturbation rate by 40% compared to the reactive handoff. However, an in-depth analysis of the collision rate and handoff delay, which were the major metrics to evaluate CRN was not carried out. Furthermore, Thomas and Menon (2017) specified a fundamental difference between these two handoff methods where the authors have specified a fundamental difference between handoff methods. However, in-depth analysis of the major performance metrics in CRN, such as average throughput and collision rate, was not considered. In summary, previous works on SH failed to provide an in-depth analysis of average throughput, handoff delay and collision rate on the active and proactive SH that determined the best technique. Therefore, in this paper comparative analysis of reactive and active SH techniques in a CRN was considered.

METHODOLOGY

This model focuses on a scenario where Secondary Users (SUs) perform spectrum handoff (SH) in anticipation of Primary User (PU) activity. By analyzing channel usage patterns, SUs aimed to predict when a PU will return to a channel, thus avoiding potential interference. A channel can be either active (ON) or inactive (OFF). PU data transmissions indicate an active channel, while the absence of transmissions signifies an inactive channel. In this model, SUs competed for access to the available spectrum. A channel selection system was employed to facilitate SH and improve SU throughput. Both PUs and SUs were assumed to follow a Poisson arrival process, meaning the number of arrivals in a given time slot follows a Poisson distribution. To simplify the model, it was assumed that PUs and SUs shared the same channels and had equal access to channel availability information. When selecting a channel for SH, SUs prioritized two factors, which are, Maximum Channel Vacancy Time.$(\gamma\tau)^k$'and Minimum Service Time '$e^{-\gamma\tau}$' as depicted in Equation (1)

$$P_k(\tau) = \frac{(\gamma\tau)^k}{k} e^{-\gamma\tau} \quad (1)$$

Scenarios Illustrating the Mechanism of Spectrum Mobility

In CRN, SUs do not own the frequency band and the appearance of the owner (that is the PUs) on a frequency band forces the SU to cede the given band. The SU will attempt by another means to access another available frequency band to continue transmission following one of the following three actions. Firstly, until the PU finishes its transmission, the SU will remain in the original channel and set its transmission. Secondly, SU selects a spectrum from a list of previously detected spectra. Finally, SU switches to a certain spectrum immediately and if the SU fails to regain the spectrum, it is obliged to terminate its session.

Reactive-handoff spectrum decision scheme

In this spectrum handoff scheme, when a user's transmission is interrupted, a wide range of frequencies will be scanned for some time (Tse) to find another available spectrum. If multiple idle frequencies are found, the user will randomly select one to continue their transmission. However, if no idle spectrum is available, the user must wait in a queue until the original channel becomes free again. The time it takes to scan for available spectrum (sensing delay) increases with the number of channels being scanned. If it takes 'c' units of time to scan one channel, then scanning 'n' channels will take 'nc' units of time. While scanning fewer channels can reduce the total service time, it may also make it harder to find an available frequency, leading to longer handoff delays and increased overall service time.

To address this, the handshaking time (Tha) should also be considered. This is the time it takes for devices to establish communication on the new channel. The total processing time, which includes sensing, handshaking, and switching times, can be divided into two categories: $T_{pr\text{-}stay,}$ which is the processing time when the user remains on the original channel and $T_{pr\text{-}change}$, which is the processing time when the user switches to a new channel. The mathematical expressions for $T_{pr\text{-}stay}$ and $T_{pr\text{-}change}$ are given in equations (2) and (3), respectively.

$$T_{pr\text{ - }stay} = T_{se} + T_{ha} \tag{2}$$

$$T_{pr-change} = T_{se} + T_{ha} + T_{sw} \tag{3}$$

From equation (2), switching time describes the interrupted SU changes operating spectrum. Therefore, if the switching time is assumed to be zero, then the total processing time *(T_{pr})* is obtained as

$$T_{pr} = T_{pr\text{ - }stay} = T_{pr\ change} \tag{4}$$

In the reactive technique, the prioritized principle is not applicable because the interrupted user will only change its operating channel to an idle target channel. For the other type of spectrum handoff scheme, which is a proactive handoff, the handshaking time does not exist because the target channel for spectrum handoff is already determined before the communication starts between the intended secondary users.

Proactive handoff spectrum decision scheme

In this technique, Secondary Users (SUs) predict when a Primary User (PU) might return to a channel by analyzing channel usage patterns. Based on this prediction, the SU can decide to either stay on the current channel, switch to a different channel, or even pause the current data transmission. Figure 1 illustrates a channel (channel i) where PU handoff occurs. The time between the arrival of two consecutive PU data packets is denoted by U^k_i, and the arrival time of the kth packet is P^k_i. The arrival of these packets follows a Poisson process with an average arrival rate of γi packets per second. The size of PU data packets is described by a Probability Density Function (PDF) gHi(h). To calculate the probability of a channel being idle, it is necessary to understand the duration of both active and inactive periods of transmission.

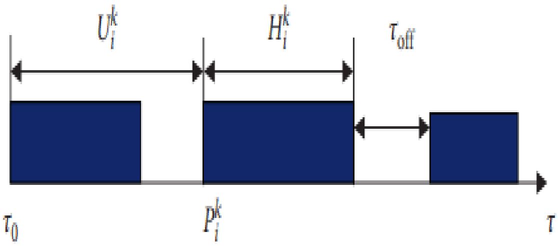

Figure 1. Illustration of the handoff mechanism of PU on the channel.

Based on Figure 1, the probability *(Pb)* of channel *i* to be inactive or active for a certain time τ is formulated as follows.

$$P_b(M_i(\tau) = 1)\ ,\ P_i^k > t, P_i^k + H_i^k \geq \tau, k \geq 1,$$

$$P_b(M_i(\tau) = 0)\ ,\ P_i^k + H_i^k < \tau, P_i^{k+1} \geq \tau, k \geq 1,$$

$$P_i^k \geq \tau,\ \ k = 0,$$

where $H^k{}_i$ denotes the *k*th information packet dimension of the PU on channel *i*. Thus, the probability at any point interval of time τ where the channel *i* is inactive is formulated by (Wu *et al.*, 2016) as

$$P_b(M_1(\tau) = 1) = \int_0^\infty \lfloor \sum_{k=1}^{\infty} P_b\ \left(P_i^k + H_i < \frac{\tau}{k}\right)\ P_b(k) + P_b\ (p_i^1 < \tau)\ x$$

$$P_b(k = 0)\rfloor x g H_i(h) dh,$$

$$\mathrm{P_b(M_1(\tau) = 1)} = \int_0^\infty \{ \sum_{k=1}^{\infty} \left[\frac{(\gamma(\tau\text{-}H_i))^k}{k!} e^{-\gamma_i(\tau\text{-}H_i)}\right] \left[\frac{(\gamma_i\tau)}{k!} e^{-\gamma_i\tau}\right] x \frac{(\gamma_i\tau)}{k!} e^{-\gamma_i\tau} + e^{-2\gamma_i\tau} \}$$

Using the previous predictions, the condition giving the possibility for an SU to pass on another channel is obtained as

$P_b(M_i(\tau) = 0) < \tau_H$,

where τ_H represents the probability limit below which a channel is considered active and the SU must perform an SH, for the current channel cannot be considered active at the end of the transmission of information packets. Moreover, the measures by which a potential channel j can become a promising channel at the next time τ is given as

$$\begin{cases} P_b\big(M_j(\tau) = 0\big) < t_L, \\ P_b\big(\tau_{j,off} > \mu\big) \geq \varphi, \end{cases}$$

where t_L is the probability limit that the channel should be considered inactive, $\mu = \zeta + \alpha$ is considered as the period of an information packet and a time interval; and φ is the probability limit that the channel is considered inactive.

Collision Rate

The collision rate is the rate at which PU interferes with SU whenever a licensed user arrives on the channel used by the cognitive user, that is, during the handoff period. The collision rate is the probability of having a collision between PU and SU during the handoff period. For efficient spectrum usage and smooth handoff, this value must be less than one. Collision rate 'σ' is given as

$$\sigma = \frac{Volume\ of\ Collision}{Time} \tag{5}$$

Average Throughput

Average throughput describes the average amount of data that is successfully transferred between the transmitter and receiver. Average Throughput (AT) is the rate at which messages are delivered successfully over a fading channel. The average Throughput 'S' is given by Mohamad *et al*. (2019) as

$$S = \frac{P_{str}L}{(1-P_{str})\tau + P_{str}\delta + \varphi} \tag{6}$$

where P_{str} is the probability of successful handoff in this paper, L is the packet length, τ is the SU slot time, δ is the average successful handoff time

φ is the collision time

Simulation Results and Discussion

The simulations for this research were conducted using MATLAB R2024a discrete event simulator. Three key performance metrics were analyzed for both reactive and proactive SH techniques: average throughput (AT), handoff delay (HD), and collision rate (CR). To simplify the analysis, a random channel selection system was used, where SUs randomly chose a channel from available options. Figures 2 and 3 compare the collision rates of reactive and proactive SH techniques for different numbers of PUs and different channel numbers. The number of channels of 100 and 300 was chosen to check the effect of some channels on the collision rate. The results show that the proactive technique reduces collision rates by up to 40%. This improvement is attributed to the proactive approach's ability to predict future channel availability, minimizing the risk of collisions with PUs. Also, the results obtained revealed that the collision rate reduces as the number of channels increases.

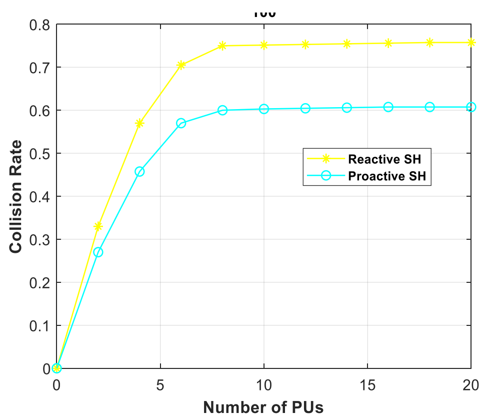

Figure 2: Collision rate against number of PUs at number of channels = 100

Figures 4 and 5 present handoff delay against some PUs for the two techniques at some channels from 100 to 300, respectively. It can be deduced from the graph that, the handoff delay for the proactive technique is 10% which proves that the proactive technique gives better performance than its reactive counterpart. Also, the reactive technique has a very high latency because the technique allows the SU to remain on the target channel until the channel is available again before continuing to retransmit the information packets.

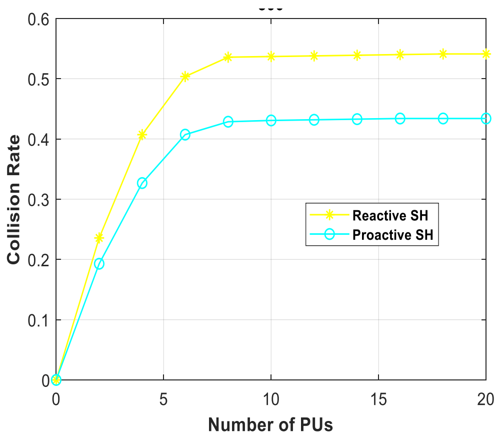

Figure 3: Collision rate against number of PUs at number of channels = 300

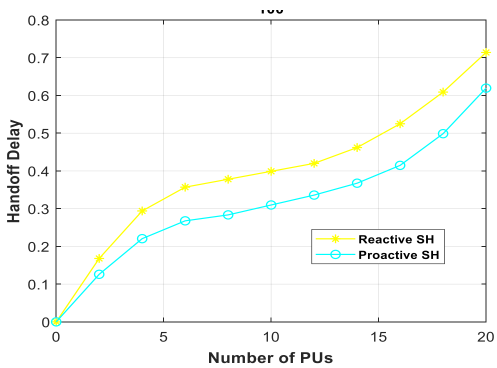

Figure 4: Collision rate against the number of PUs, 100 channels

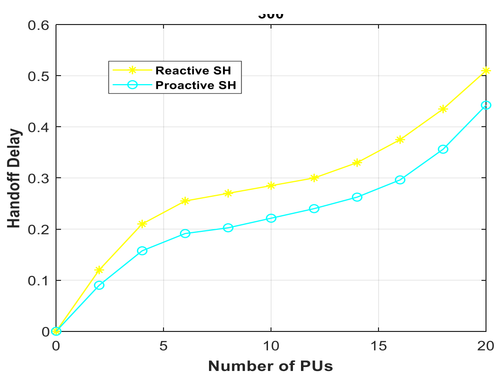

Figure 5: Collision rate against number of PUs with 300 channels number

Figures 6 and 7 illustrate the average throughput of Secondary Users (SUs) as the number of Primary Users (PUs) increases, considering 100 to 300 channels. The transmission rate of SU packets ranges from 50 to 200 packets per second, while PU packets vary from 10 to 80 packets per second, with 20 SUs in the network. The average throughput of SUs increases with the number of available channels. Conversely, as the number of channels decreases, the average throughput of SUs also decreases due to fewer available channels. The proactive handoff technique outperforms the reactive approach, achieving a 40.5% increase in average throughput.

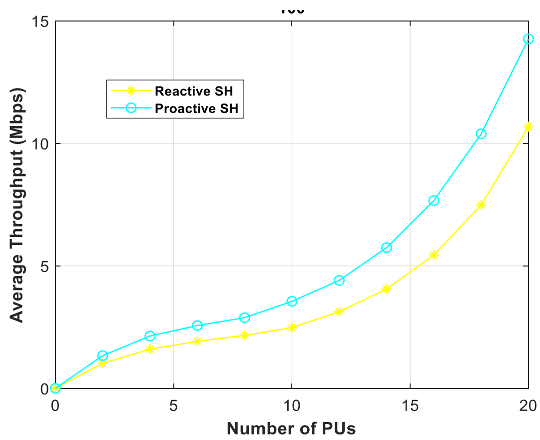

Figure 6: Average Throughput against the number of PUs 100 channels

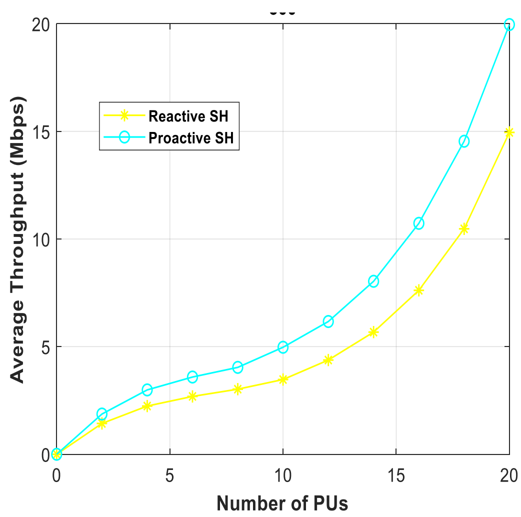

Figure 7: Average Throughput against number of PUs 300 channels number

CONCLUSION

Cognitive radio is a promising technology that can significantly improve the efficiency of wireless spectrum usage. Spectrum Handoff (SH) is a key feature of CR networks, but multiple handoffs can degrade the performance of secondary users (SUs) by increasing service time and handoff delays. This paper compared reactive and proactive SH techniques to address the uncertainty of PU behavior. Proactive handoff offers a significant advantage by allowing SUs to resume interrupted transmissions on new channels. This mobility management strategy prioritizes two factors: the duration of channel inactivity and the predicted probability of PU activity. By improving mobility and connection management, proactive handoff reduces information loss and latency during handoffs. Numerical results show that the proactive scheme reduces collision rates between SUs and between PUs and SUs, leading to decreased handoff latency and improved SU throughput. Future research should focus on developing advanced channel selection algorithms and exploring additional performance metrics for evaluation. The contributions of this paper include an in-depth analysis of average throughput, handoff delay and collision rate on proactive and reactive SH techniques, to reveal the appropriate technique that gives higher AT, lower HD and CR. Furthermore, the effect of different numbers of PU and channels on the performance of each of the techniques is to reveal the appropriate SH technique when a particular number of channels is to be considered.

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