Dynamic Power Control Strategy for Overlay Multi-Secondary User in Cognitive Radio Environment

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Received: 31.07.2020 Accepted:25.09.2020

Abstract- Current scarcity of radio spectrum availability for new wireless services and applications has made dynamic spectrum access a rich research area across the world. However, one of the problems confronting dynamic spectrum access via cognitive radio technology is optimal spectrum resource allocation in a cognitive radio environment (CRE). In proffering solution to this problem, the study presented in this paper applies the inherent capability of iterative water filling (IWF) algorithm to develop resource allocation strategies in an overlay CRE. The developed IWF algorithm in this study was designed for multi-secondary user, consisting of two- and three-secondary users, in a CRE with an idle primary user. The developed algorithm was simulated in MATLAB® environment. Results obtained when the developed IWF multi-secondary user algorithms were tested show that while the two-secondary user requires signal-to-noise ratio of 1.7 dB to achieve data transmit rate convergence, the three-secondary user requires signal-to-noise ratio of 0.5 dB to achieve data transmit rate convergence. In addition, the performance evaluation results show that while users in the 2-SUs CRE have a maximum transmision rate of 1.12 Mbps, the users in the 3-SUs CRE have a maximum rate of 0.6 Mbps. Also, the tests conducted on the developed resource allocation algorithms show that the number of the secondary users is inversely related to the data rate convergence potential. Furthermore, the overall result of this study shows that effective and efficient dynamic radio spectrum access and radio spectrum resource allocation are feasible in an overlay multi-secondary user cognitive radio envornment.

Keywords- Dynamic spectrum access, cognitive radio, access models, dynamic resource allocation, iterative water filling.

Özet- Yeni kablosuz hizmetler ve uygulamalar için mevcut radyo spektrumu yetersizliği, dinamik spektrum erişimini dünya çapında zengin bir araştırma alanı haline getirmiştir. Bununla birlikte, bilişsel radyo teknolojisi aracılığıyla dinamik spektrum erişiminin karşılaştığı sorunlardan biri, bilişsel radyo ortamında (CRE) optimal spektrum kaynak tahsisidir. Bu soruna çözüm sunarken, bu yazıda sunulan çalışma, bir örtüşmeli CRE'de kaynak tahsis stratejileri geliştirmek için yinelemeli su doldurma (IWF) algoritmasının doğal yeteneğini uygular. Bu çalışmada geliştirilen IWF algoritması, boşta bir birincil kullanıcı olan bir CRE'de iki ve üç ikincil kullanıcılardan oluşan çok ikincil kullanıcı için tasarlanmıştır. Geliştirilen algoritma MATLAB® ortamında simüle edilmiştir. Geliştirilen IWF çok ikincil kullanıcı algoritmaları test edildiğinde elde edilen sonuçlar, iki ikincil kullanıcının veri iletim hızı yakınsaması elde etmek için 1,7 dB sinyal-gürültü oranına ihtiyaç duyarken, üç ikincil kullanıcının sinyal-gürültü oranına ihtiyaç duyduğunu göstermektedir. Veri iletim hızı yakınsaması elde etmek için 0,5 dB. Ek olarak, performans değerlendirme sonuçları, 2-SU CRE'deki kullanıcıların maksimum 1.12 Mbps iletim hızına sahipken, 3-SU CRE'deki kullanıcıların maksimum 0.6 Mbps hızına sahip olduğunu göstermektedir. Ayrıca, geliştirilen kaynak tahsis algoritmaları üzerinde yapılan testler, ikincil kullanıcı sayısının veri hızı yakınsama potansiyeli ile ters orantılı olduğunu göstermektedir. Ayrıca, bu çalışmanın genel sonucu, etkili ve verimli dinamik radyo spektrumu erişiminin ve radyo spektrumu kaynak tahsisinin, bir üst üste bindirilmiş çok ikincil kullanıcı bilişsel radyo ortamında uygulanabilir olduğunu göstermektedir.

Anahtar Kelimeler - Dinamik spektrum erişimi, bilişsel radyo, erişim modelleri, dinamik kaynak tahsisi, yinelemeli su dolumu.

1. Introduction

Over the last two decades, observations have shown that demand for and use of radio-based services and applications have grown rapidly. This stemmed from the fact that radio-based or wireless-based services and applications are capable of providing access to right information anytime and anywhere. Furthermore, its inherent capabilities in overcoming series of geographically limitations coupled with mobility advantage have made it a preferred choice of everybody. These inherent capabilities and other advantages that wireless-based services and applications have over wire-based services and applications have led to a shortage of radio spectrum because majority of the radio-based services and applications are bandwidth hungry-based devices. However, literature surveyed have shown clearly that there is no actual shortage of radio spectrum only that most of the allocated radio spectrum are underutilized. In overcoming the problem of radio spectrum scarcity and underutilization, there is need for an enabling technology to access and use un-used portions of licensed spectrum in an opportunistic manner. This access strategy that permits usage of radio spectrum in an opportunistic manner is referred to as dynamic spectrum access or opportunistic spectrum access.

According to [1], the radio technology endowed with the capability to exploit the un-used portions of already licensed spectrum being referred to as spectrum holes is cognitive radio (CR). CR is a type of radio technology, which allows unlicensed user, also known as secondary user (SU), to use unused portions of licensed spectrum, which is not being used by the licensed owners or primary user (PU) in an opportunistic manner. The basic goal of the dynamic spectrum access (DSA) is to alleviate the current problem of radio spectrum scarcity and under-utilization. The strategies for DSA as reported in [2] can take place in three different access models namely dynamic exclusive use model, open share model, and hierarchical access model. The hierarchical access model, which is a hybrid of the first two radio spectrum access models, permits transmission of PU and SU as long as SU transmission will not interfere with the PU. The importance of hierarchical spectrum access model is primarily to increase radio spectrum utilization efficiency, which can be either through spectrum underlay approach or spectrum overlay approach [3].

In hierarchical access model through underlay approach, parallel transmission of both PU and SU is allowed. However, the PU is protected by enforcing a special mask on the signal of the SU so that the interference generated by the SU is below an acceptable noise floor for the PU. This implies that DSA through underlay approach works by imposing constraints on the transmission power of the secondary users [2, 4]. On the other hand, DSA strategy using overlay spectrum sharing approach does not allow concurrent transmission by both PU and SU. In this hierarchical access model, the secondary users (SUs) only access the idle channel of the licensed spectrum whenever the PU is inactive and leave the channel before PU reappears. Critical analysis of these two DSA models indeed shows that the two access models have the potential to enhance efficiency of spectrum access and utilization. However, the introduction of DSA has ushered in a new challenge on how the spectral resources such as transmit power, bandwidth and bit-rate to mention but a few can be evenly distribution in order to ensure interference-free communication in CRE consisting of more than one multi-secondary users.

Thus, towards achieving interference-free communication as well as ensuring effective sharing of radio resources in CRE, dynamic resource allocation (DRA) is crucial based on the channel state information. In addition, dynamic allocation of spectral resources is a crucial issue in multi-users radio environment because of the of time varying characteristic of wireless channel and its interference effect. Thus, in ensuring interference free communication as well as sharing of radio resources in multi-user communication system, power control is very essential [5]. This is because in multi-user communication system, each user's performance does not only depend on its own power but equally depends on the power allocation of all other users. Therefore, when there is effective power control in CRE, according to [6], there will be significant improvement in SU communication subject to appropriate setting of PU interference threshold level.

However, one of the greatest problems of DRA in CRE consisting of multiple secondary users, is how to carry out power control of secondary users (SUs) while maintaining the required quality of service for both the licensed and unlicensed users [7]. This is because majority of power control algorithms in surveyed literature only consider interference constraints of a single user without considering interference among multiple users in the CRE. Therefore, the aim of the study reported in this paper is to solve the problem of power allocation amongst multiple secondary users in CRE. One of the prominent technologies currently being employed in solving resource allocation problem for CR system according to [8] is distributed power control algorithm (DPCA). In making DPCA for this study to be suitable for practical CRE, an overlay spectrum sharing approach, which does not allow concurrent transmission by both PU and SU, was assumed. Thus, eliminating interference power from PU to SUs and vice versa, and limiting interference between or among SUs as case may be, which can be solved through appropriate resource allocation (RA) strategy.

Basically, resource allocation (RA) in wireless communication system defines how limited resources in communication network can be optimized. It is not a new peculiar problem to the cognitive radio technology (CRT), but also a problem common to wireless communication system. However, as a result of the potential CR has in solving the imbalance between radio spectrum scarcity and underutilization, RA has recently become an active research area in radio spectrum sharing systems using underlay sharing model. According to [9], sizable amount of research work in surveyed literature on RA problems in CRE were solved using the traditional mathematical optimization methods [7, 10-11]. For instance, in [7], a convex optimization DPCA developed without user cooperation for multi-user underlay CR satisfies the constraints optimization problem.

Likewise, in [12], a robust second order cone programming approximation method optimization algorithm was employed to optimize the network sum rate under inference constraints. The simulation result shows that the robust algorithm is effective in optimizing the performance of both the multiple primary and secondary users. Similarly, [13] employed optimization method to maximize the total transmission rate of multi-user cognitive orthogonal frequency division multiplexing radio network power allocation. Despite the results obtained, [14] observed that solutions of RA problems through optimization approaches are usually computational complex and time consuming. Another very popular method recently used to obtain solutions to RA problems in CRE is the development of either heuristics or meta-heuristics [9]. Examples of heuristics developed and employed to solve RA problems in CRE in literature are greedy algorithm [15-17], water filling schemes [5, 18] and recursive-based and/or iterative-based heuristics [14].

Furthermore, the study undertaken by [13] showed that the PA-Jaya algorithm improved the convergence speed with optimal total transmission rate amongst SUs in orthogonal frequency division multiplexing radio network. Similarly, a hybrid of multi-objective particle swarm optimization and iterative water filling algorithms for solving the problem of maximum energy optimization and minimum energy efficiency in CRE was proposed in [18]. These authors showed that the hybrid algorithm outperformed most algorithms existing in literature at the time.

However, from the surveyed literature, it is obvious that there is no information on RA based on overlay spectrum sharing model. This become the basis of the study presented in this paper. Thus, the primary contribution of this paper is development of heuristics RA algorithm using IWF algorithm in an overlay hierarchical access model. Furthermore, another major contribution of this paper to knowledge is that while vast majority of the related studies in surveyed literature considered two secondary users in CRE, the study presented in this paper considered both two seondary users (2 SUs) and three seondary users (3 SUs) in CRE. In addition, the study presented in this paper explored the inherent capability of transmit power control in overlay CRE with two and three secondary users, that enhanced effective spectral resources sharing with interference free data tranmission. Detailed information on the step-by-step approach used in conducting the study is presented in the next section of this paper.

2. System Design

The spectrum-sharing model assumed in this study is an overlay spectrum access model that will ensure no concurrent/parallel transmission of data between SUs and the PU. The system design consists of two scenarios: 2 SUs and 3 SUs in the midst of an idle PU. Hence, this section is divided into two subsections. In the first subsection, 2 SUs CRE was considered with the assumption that the primary/licensed user is idle for a given period. Likewise, in the second subsection, 3 SUs CRE was considered with the same assumption that the associated PU is idle for a given period.

2.1. Two Secondary Users Design

In this subsection, the transmit power control for a CRE consists of two SUs that are constantly sharing information, while avoiding interference with the idle primary user was explored. This implies that the 2 SUs are now sharing the unoccupied available spectral band, also known as white space. For the sake of simpicity, notations were used to describe the parameters that concerns the secondary and primary users. As shown in Figure 1, the 2 SUs transmit and receive data concurrently in the white space created by a segregated PU.

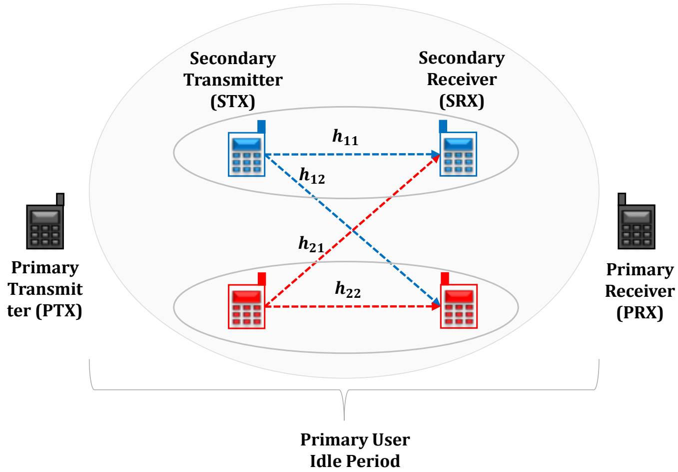


Fig. 1. CRE with two secondary users and an idle primary user.

In Figure 1, STXs and SRXs are the 2 secondary users' transmitters and receivers, respectively. The blue band is the first secondary user (SU_1), while the red band is the second secondary user (SU_2). The idle primary user (PU) is situated outside the white space since it is not transmitting. During PU's idle period there is communication between STXs and SRXs, with the main goal of ensuring that the two SUs transmit power control reach a point of equilibrium such that none of the SU is starved. In ensuring this goal or desire, recursive/iterative water filling algorithm (IWF) was employed because it has been proven to be efficient in solving optimal resource allocations problem in linear Gaussian Multiple Access and also capable of preventing power wastage [5, 19]. Its acclaimed efficiency in RA in CRE formed the basis for its adoption in computing both the transmit rate and transmit power in this study. The channel gains, which results from the communication between the SUs are denoted by h_{11}, h_{12}, h_{21} and h_{22}, h_{11} and h_{22}, which are respectively the path losses resulting from the communication between each secondary user's transmitter and its corresponding receiver, while h_{21} and h_{12} are the channel losses resulting from the interaction between each secondary user's transmitter and the adjacent secondary user's receiver. Using the concept described in [20], the CRE shown in Figure 1 was modelled mathematically as;

$$y_1 = h_{11}x_1 + h_{12}x_1 + n_1 \quad (1)$$

$$y_2 = h_{22}x_2 + h_{21}x_2 + n_2 \quad (2)$$

Where h_{11}, h_{22}, h_{12}, and h_{21} are the path losses of the channel between the transmitters and receivers, n_1 and n_2 are respectively the additive white Gaussian noises (AWGNs) introduced by the channels, and y_1 and y_2 are the respective communication output for each user. In this study, a flat-fading communication channel is assumed, with absence of channel noise. Thus, in the implementation of the IWF algorithm for this study, n_1 and n_2 were assumed to be equal to zero.

The IWF algorithm is a convex optimization solution to multiple-access channel (MAC) rate sum maximization problem in wireless communication [21]. Hence, in implementating the IWF algorithm, each SU determines a water-filled spectra, while the other users' spectra are presumably held constant [22]. Several cycles of this activities were carried out for each user until it converges and a solution was reached. Since the success of one SU is determined by the condition of the adjacent SU, this problem was further modelled using the notion of game theory consisting of two players—transmitter 1 (STX_1) and transmitter 2 (STX_2). The game strategies consists of the actions taken by the SUs, which are represented by the noise floor of STX_1 and STX_2—$N_1(f)$ and $N_2(f)$—respectively. The utility of the players are defined by the data transmit rates, R_1 and $R_2(f)$, respectively for STX_1 and STX_2. There is also the presence of a cross-coupling effect between two users, which is expressed in [23] as;

$$\alpha_1 = \frac{\gamma|h_{12}|^2}{|h_{22}|^2} \quad (3)$$

$$\alpha_2 = \frac{\gamma|h_{21}|^2}{|h_{11}|^2} \quad (4)$$

where γ is the signal to noise ratio (SNR). The presence of interference was assumed irrespective of the signal strength propagated from any of the users. The data transmission rate for each user as expressed in [5] are stated mathematically in (5) and (6) as;

$$R_1 = \int \log_2\left(1 + \frac{P_1(f)}{N_1(f) + \alpha_2 P_2(f)}\right) df \quad (5)$$

$$R_2 = \int \log_2\left(1 + \frac{P_2(f)}{N_2(f) + \alpha_1 P_1(f)}\right) df \quad (6)$$

where $P_1(f)$ and $P_2(f)$ are the power spectra densities (PSDs) of transmitter 1 and transmitter 2 respectively. Also, the noise terms $N_1(f)$ and $N_2(f)$are mathematically expressed in (7) and (8):

$$N_1 = \frac{\gamma\sigma(f)}{|h_{11}|} \quad (7)$$

$$N_2 = \frac{\gamma\sigma(f)}{|h_{22}|} \quad (8)$$

where σ is the channel noise density. Algorithm 1 presents the overall implementation of the 2-SUs IWF algorithm using the above defined parameters.

Algorithm 1: IWF Algorithm for 2 SU CRE

1. **for** $i = 1$ **to** 2
2. $P_i(f) = P;\ T_i = T$ %% Initial power spectra densities
3. **end**
4. **for** $i = 1$ **to** 2
5. Set $P_i(f)$ to the water-filling spectrum with noise $N_i(f)$
6. Calculate:
7. $R_1 = \int \log_2\left(1 + \frac{P_1(f)}{N_1(f) + \alpha_2 P_2(f)}\right) df$ %% Determine the target data rate for the SU1
8. $R_2 = \int \log_2\left(1 + \frac{P_2(f)}{N_2(f) + \alpha_1 P_1(f)}\right) df$ %% Determine the target data rate for the SU2
9. **end**
10. **for** $i = 1$ **to** 2
11. **if** $(R_i - T_i) > \tau$ **then** $P_i(f) = P_i(f) - \partial$ %% Decrement $P_i(f)$ with ∂ and τ is a threshold
12. **else**
13. $P_i(f) = P_i(f) + \partial$ %% Increment $P_i(f)$ with ∂
14. **end**
15. **End**

The SUs were initialized with equal target data rates T_1 and T_2 of 0.512 Mbps. In Algorithm 1, the power spectra densities, $P_1(f)$ and $P_2(f)$, were respectively initialized to a value of "0". In the inner loop, R_1 and R_2 were determined using (1) to (8). In the outer loop, which was done for N number of iterations for each user, if the difference between the transmit rate and target data rate is greater than a threshold, τ, then the spectra density $P_i(f)$ is decremented by a factor ∂ .

2.2. Three Secondary Design

In this subsection, the transmit power control for overlay CRE with 3 SUs that are constantly sharing information was explored. Figure 2 illustrates the CRE and the transmission and reception between the 3 SUs and a segregated primary user that is inactive in the spectral band prior to the secondary users (SU_1, SU_2 and SU_3) sharing the unoccupied white space.

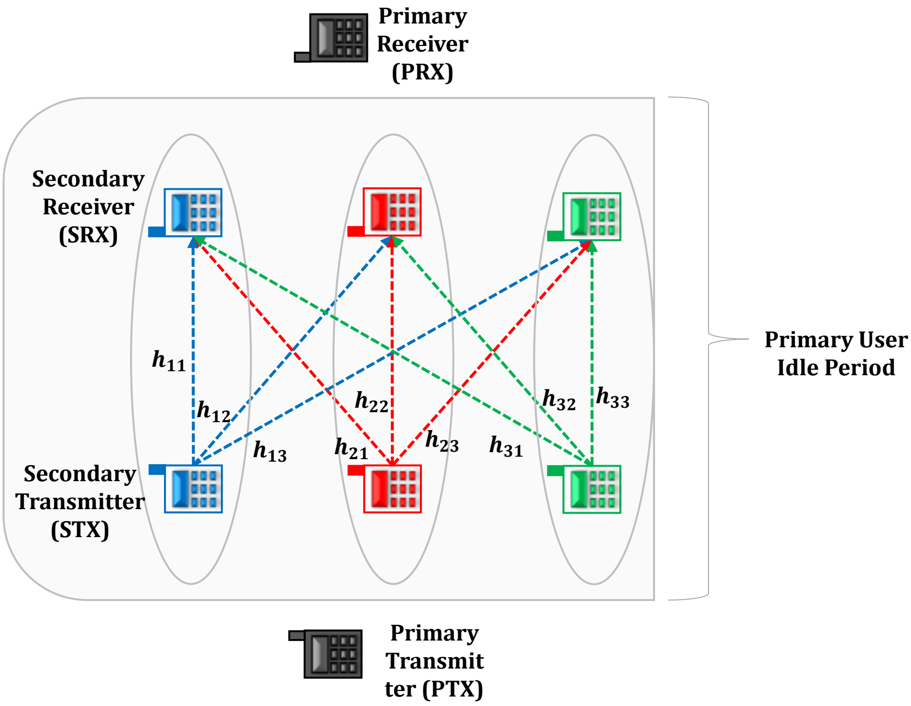


Fig. 2. CRE with three secondary users and an idle primary user.

In Figure 2, the CRE consists of the 3-secondary transmitters (STXs) and 3 secondary receivers (SRXs) in the presence of a primary user that is currently inactive in the spectrum band, thus creating a white space. The 3 SUs occupy the white space and its resource is shared by the 3 SUs. The blue STX and SRX is the first secondary user (SU_1), the red is the second secondary user (SU_2), and the green is the third secondary user (SU_3). As described in the previous subsection, h_{ij} are the channel losses. The system was thus modelled using the method describe in [20]. Hence, if the transmitted data are: x_1, x_2 and x_3 respectively, for SU_1 SU_2, and SU_3 the received data y_1, y_2 and y_3 are expressed respectively as;

$$y_1 = h_{11}x_1 + h_{12}x_1 + h_{12} + n_1 \tag{9}$$

$$y_2 = h_{22}x_2 + h_{21}x_2 + h_{22} + n_2 \tag{10}$$

$$y_3 = h_{33}x_3 + h_{31}x_3 + h_{32} + n_3 \tag{11}$$

With the assumption of a flat fading channel for 2 SUs; n_1, n_2 and n_3, are all equaled to a value of "0". In a similar way with 2 -SUs CRE, the cross coupling effect due to i^{th} and j^{th} SUs was mathematically expressed as;

$$\alpha_{ij} = \frac{(SNR)|h_{ij}|^2}{|h_{jj}|^2} \tag{12}$$

where indices i and j are the i^{th} and j^{th} SUs, α_{ij} is the cross-coupling effect contributed by the i^{th} and j^{th} SU with the constraint that $i \neq j$. Also, the i^{th} secondary user noise term can be expressed as;

$$N_i = \frac{(SNR)\sigma(f)}{|h_{ii}|^2} \tag{13}$$

where i is the ith secondary user. The data transmission rates for STX_1, STX_2 and STX_3 are respectively expressed in quations (14), (15) and (16) as;

$$R_1 = \int \log_2\left(1+\frac{P_1(f)}{N_1(f)+\alpha_{12}P_2(f)+\alpha_{13}P_3(f)+\alpha_{23}P_3(f)+\alpha_{32}P_2(f)}\right)df \quad (14)$$

$$R_2 = \int \log_2\left(1+\frac{P_2(f)}{N_2(f)+\alpha_{13}P_2(f)+\alpha_{21}P_1(f)+\alpha_{23}P_3(f)+\alpha_{31}P_1(f)}\right)df \quad (15)$$

$$R_3 = \int \log_2\left(1+\frac{P_1(f)}{N_3(f)+\alpha_{12}P_2(f)+\alpha_{21}P_1(f)+\alpha_{31}P_1(f)+\alpha_{32}P_2(f)}\right)df \quad (16)$$

Algorithm 1 was modified in the context of the cross-coupling effects and data transmission rates in order to achieve the 3-SUs scenario. The implemented steps to achieve the 3-SUs scenario are depicted in Algorithm 2

Algorithm 2: IWF Algorithm for 3 SU CRE

1. **for** $i = 1$ **to** 3
2. $P_i(f) = P;\ T_i = T$ %% Initial power spectra densities
3. **end**
4. **for** $i = 1$ **to** 3
   Set $P_i(f)$ to the water-filling spectrum with noise $N_i(f)$
5. Calculate:
6. $R_1 = \int \log_2\left(1 + \frac{P_1(f)}{N_1(f) + \alpha_{12}P_2(f) + \alpha_{13}P_3(f) + \alpha_{23}P_3(f) + \alpha_{32}P_2(f)}\right) df$ %% Determine the target data rate for the SU 1
7. $R_2 = \int \log_2\left(1 + \frac{P_2(f)}{N_2(f) + \alpha_{13}P_3(f) + \alpha_{21}P_1(f) + \alpha_{23}P_3(f) + \alpha_{31}P_1(f)}\right) df$ %% Determine the target data rate for the SU 2
8. $R_3 = \int \log_2\left(1 + \frac{P_3(f)}{N_3(f) + \alpha_{12}P_2(f) + \alpha_{21}P_1(f) + \alpha_{31}P_1(f) + \alpha_{32}P_2(f)}\right) df$ %% Determine the target data rate for the SU 3
9. **end**
10. **for** $i = 1$ **to** N %% N is the number of iterations
11. **if** $(R_i - T_i) > \tau$ **then** $P_i(f) = P_i(f) - \partial$ %% Decrement $P_i(f)$ with ∂ and τ is a threshold
12. **else** %% ∂ is the increase factor
13. $P_i(f) = P_i(f) + \partial$
14. **end**
15. **End**

2.3. Simulation Parameters

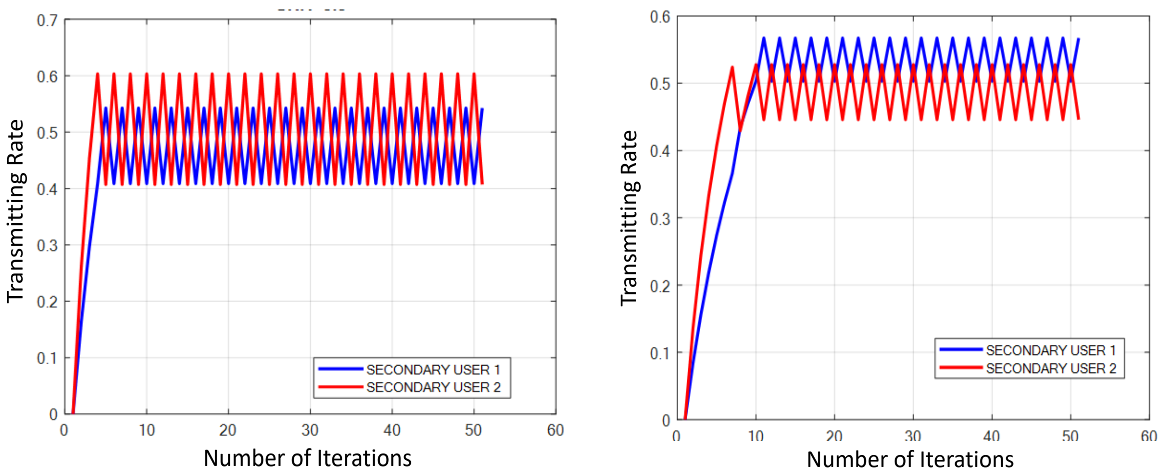
Experiments were conducted on the developed IWF algorithms for both the 2-SUs and 3-SUs scenarios with an idle PU in MATLAB® environment. For the 2-SUs scenario, a parametric sweep of the SNR, γ was carried out between the value of 0.5 and 2.1 in steps of 0.1, while for the 3-SUs scenario, the simulation was done for γ with values ranging from 0.1 and 2.0 in steps of 0.1. The target rates, T_1, T_2 and T_3 were initialized to 0.512 Mbps, while the i^{th} power spectra density, $P_i(f)$ was initially set to 0. For the 2-SUs scenario, the channel losses, h_{11}, h_{12}, h_{21} and h_{22} were set to very small or negligible values of 1×10^{-6}, 1.1×10^{-6}, 0.9×10^{-6} and 1.3×10^{-6} respectively according to [22], since there is no free-space loss, refraction, diffraction, reflection and absorption in the flat fading communication channel adopted. For the 3-SUs scenario, the channel losses, h_{11}, $h_{12}, h_{13}, h_{21}, h_{22}, h_{23}, h_{31}, h_{32}$ and h_{33} were set to negligible values of 1×10^{-6}, 1.1×10^{-6}, 0.9×10^{-6}, 0.9×10^{-6}, 1.3×10^{-6}, 1.4×10^{-6}, 1×10^{-6}, 1.1×10^{-6} and 0.9×10^{-6} respectively based on the same stated condition for 2-SUs scenario. The noise density, σ was set to a value of 2×10^{-11}. The increase/decrease factor, ∂ was set to a value of one-half of 3 dB, the threshold, τ was set to 0.0005 while 50 was used as the number of iterations, N. Graphical results of transmit rates against the number of iterations for each value of γ were generated. The graphical results obtained were presented, analyzed and discussed in the following section

3. Results and Discussion

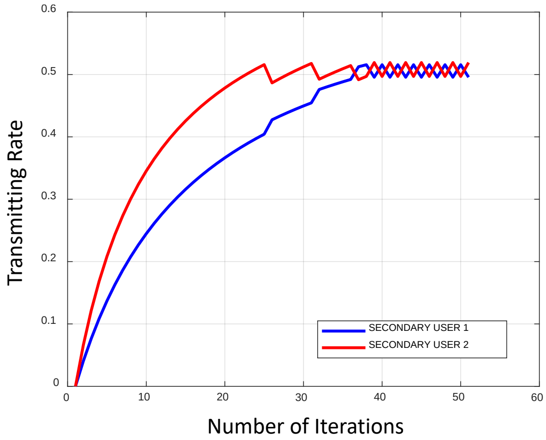
The results obtained when the developed IWF algorithms for the 2-SUs and 3-SUs scenarios were evaluated are presented in this section. Actually, the section is divided into two subsections. In the first subsection, the obtained graphical results of the transmit rates for the developed 2-SUs IWF algorithm were presented and discussed. Similarly, in the second subsection, the obtained graphical results obtained when the transmit rates for the developed 3-SUs IWF algorithm were presented and discussed. The obtained results in each scenario are presented and discussed in the following subsections

3.1. Results and Discussion for 2-SU Scenario

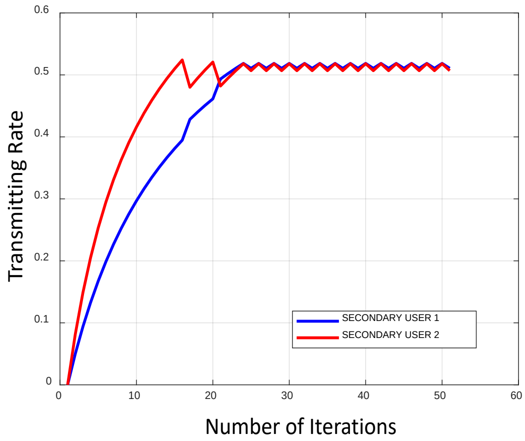
In this subsection, the graphical results obtained for transmit power rate against number of iterations for the 2-SUs scenario are shown in Figure 3(a) – (d). A parametric sweep was carried out by varying SNR (γ) from 0.1 to 2.1 in steps of 0.1. However, only four out of the twenty graphical results obtained are presented in Figure 3(a) – 3(d) due to limited space. Figure 3(a) shows the achieved transmit rate after 50 iterations when γ was set to 0.5. The overall maximum achievable transmission rate for 2 SUs CRE is approximately 1.12 Mbps. After five iterations, the transmit rate of SU_1 oscillates between a value of 0.54 Mbps and 0.40 Mbps. On the other hand, SU_2 required a slightly smaller number of iterations to reach a transmit rate of 0.6 Mbps before it starts oscillating between 0.4 Mbps and 0.6 Mbps. This trend continues over the period of the 50 iterations without convergence. This non-convergence in the data transmit rates of the secondary users at a SNR of 0.5 dB shows that there is no even distribution of spectrum resources between the two secondary users. In addition, the non-convergence of the transmit rates of the two secondary users at a SNR of 0.5 dB show that there is no mutual interference between the two secondary users, thus parallel transmission of the two secondary users is infeasible. Similarly, when the SNR was set to 1.0 dB, the transmit rates of the two secondary users were oscillating between two values but at a slightly higher rate. The numerical result obtained shows that the two secondary users only have about 14% increase in transmit rates compared to when the SNR was set to 0.5 dB. However, the transmit rates was unstable throughout the 50 iterations, which implies that there is no interference free communication between the two secondary users.



(a) (b)



(c)



(d)

Fig. 3. Simulation results for two-users CRE at different SNR of (a) 0.5 dB, (b) 1 dB, (c) 1.7 dB, and (d) 2.1 dB

However, when the SNR was set to 1.7 dB, as shown in Figure 3(c), the 2-SUs converged with a transmit rate of 0.51 Mbps after 24 iterations and maintains the convergence until the end of the 50 iterations. This implies that at SNR of 1.7 dB, there is even distribution of the spectrum resource between the two secondary users. The convergence equally indicates interference free communication between the two secondary users, which indeed implies efficient utilization of the white space underutilized by the licensed user. On the other hand, when the SNR value was increased to 2.1 dB, convergence was hardly achieved as shown in Figure 3(d). The results show that before and after SNR value of 1.7 dB where the convergence occurred, there were oscillations, which implies unequal resource allocation in the CRE. However, at the convergence point, both SUs transmitted simultaneously at the same rate whilst the primary user remains idle. This implies that at the convergence point, the SUs do not starve each other. The results also indicate that at the convergence point, the idle channel was optimally utilized with equal distribution of the radio spectrum resources.

3.2. Results and Discussion for 3-SU Scenario

In this subsection, the graphical results obtained for transmit power rate against number of iterations for the 3-SUs scenario are shown in Figure 4(a) – (d). Like in 2-SUs scenario, only four out of the twenty graphical results obtained are presented in Figure 4(a) – 4(d) due to limited space. In Figure 4(a), when the SNR value was set to 0.1 dB, the graphical result obtained for transmit power rates against number of iterations shows continuous oscillation. The oscillation occurs from the beginning to the end from the lowest value of 0.52 Mbps to the highest value of 0.75 Mbps without convergence. This shows that there is no interference free communication and even sharing of spectral resources among the three secondary users. However, when the SNR was set to 0.3 dB as shown in Figure 4(b), the response obtained was somewhat different from Figure 4(a) as the oscillation has gradually reduced. At the initial stage, SU_1 and SU_2 attain a maximum transmit rate of 0.60 Mbps which is 0.08 Mbps faster than SU_3, which attained a maximum transmit rate of almost 0.52 Mbps till the end of the whole iteration but without convergence,

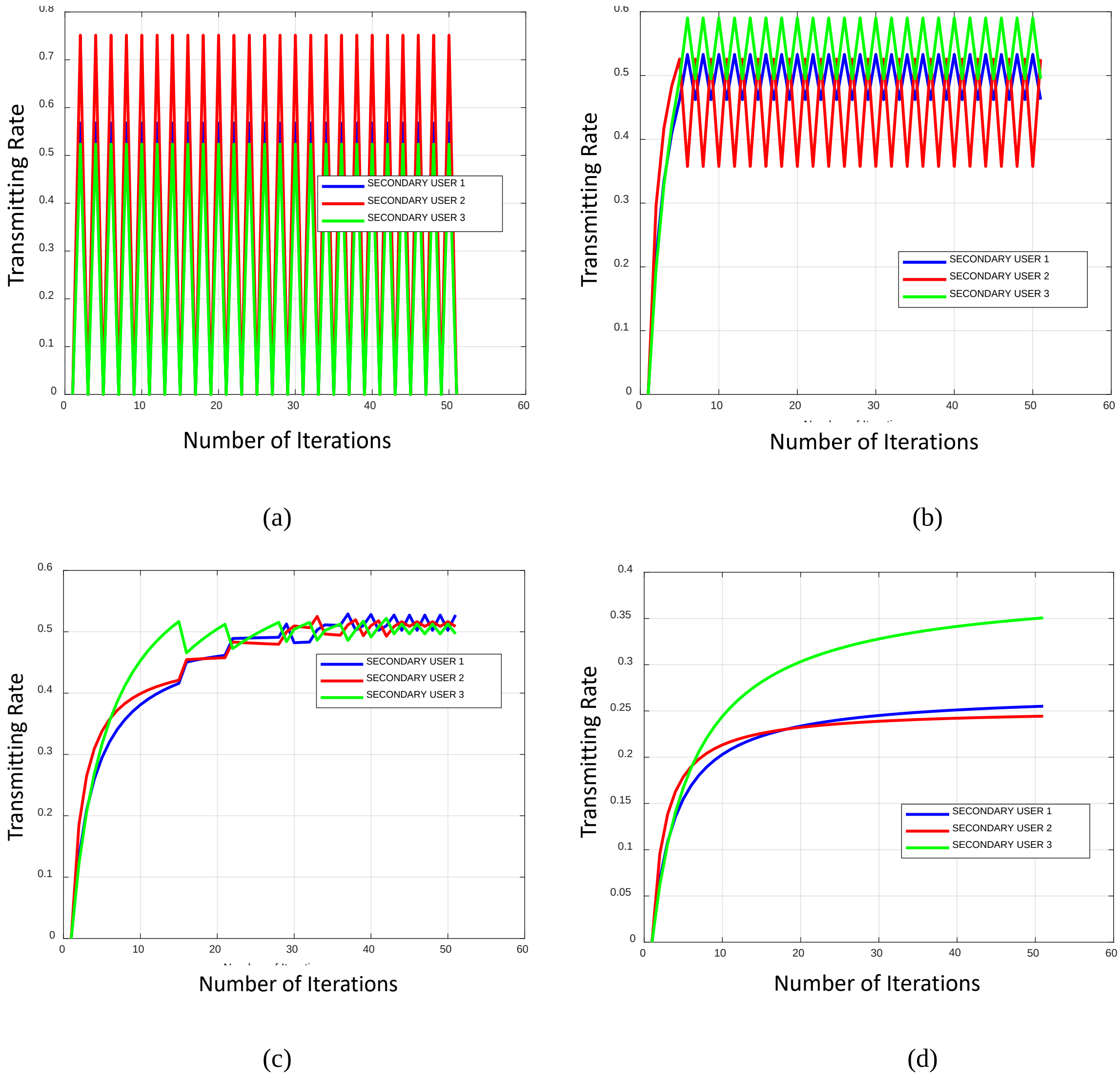


Fig. 4. Simulation results for three-users CRE at different SNR of (a) 0.1 dB, (b) 0.3 dB, (c) 0.3 dB, and (d) 1 dB.

However, when γ was set to 0.5 dB, the transmit rates of the three secondary users started to converged after about 15 iterations as shown in Figure 4(c). Perfect convergence was achieved around 30 iterations till the end of the maximum number of set iterations . This means that even sharing of the spectral resource as well as interference free communication for the 3-SUs scenario was achieved at SNR value of 0.5 dB. Similarly, critical observation of Figure 4(c), shows clearly that the oscillations in terms of the transmit rate did not exceed 0.5 ± 0.03 Mbps, which is an acceptable threshold. At this SNR value of 0.5 dB, the three SUs transmit data are at about the same rate, which implies that there was no starving amongst the 3-SUs. On the contrary, severe divergence in the transmit rate set in when the value of γ was increased to 1 dB as shown in Figure 4(d). At this new value of γ, all the 3-SUs start data transmission at different rates. For instance, SU_3 transmits data at a rate that is 1.4 times the transmit rates of both SU_1 and SU_2, which implies that convergence was altered above 0.5 dB. These results show that the convergence transmit data rates for the 2-SUs and 3-SUs scenarios considered are not the same. Similarly, the results obtained in the two scenarios show that the higher the number of secondary users in CRE the higher the noise level.

Furthermore, the overall results for the two scenarios as shown in Figure 3(a) – (d) and Figure 4(a)-(d), show that the maximum number of iterations are reached. This implies that the models controls are satisfied. In addition, the overall results obtained for the two scenarios buttress the finding in [5] that IWF algorithm has inherent capability to negotiate the optimal use of spectrum resources. Furthermore, with variation in convergence potential of the two scenarios at different SNR, the results of this study agrees with finding in [24] that performance of wireless communication systems is a function of SNR. Similarly, the convergence at lower SNR of 3-SUs scenario compared with that of 2-SUs conforms to finding in [3] that increase in secondary users leads to reduction in SNR due to interference from other computing secondary users. More so, the feasible convergence potentials of the two scenarios investigated in this study show that parallel communications of multi-secondary users in CRE is achievable in improving efficient and effective radio spectrum access and utilization.

4. Conclusion and Future Work

In this study, distributed power control algorithm for a CRE was implemented using overlay spectrum sharing approach, which disallowed concurrent transmission of both primary and secondary users. Two different scenarios of multi-secondary users CRE were considered based on the number of SUs involved: 2-SUs and 3-SUs with the PU assumed being idle in the two scenarios. Based on concurrent transmission of the secondary users, CRE were simulated for both scenarios with the notion of transmit power control using the generic iterative water filling algorithm for spectrum resource allocation. It was observed that for a CRE consisting of two secondary users, a SNR of 1.7 dB was required to achieve data transmit rate convergence, while for the 3-SUs CRE, a SNR of 0.5 dB was required for transmit data rate convergence to be established. However, it was observed that in the 3-SUs scenario, some oscillations were included in the process of data rate convergence as opposed to the 2-SUs scenario. Hence, it can be hypothesized that increasing the number of secondary users in a CRE leads to instability in data transmit rate convergence. This result buttresses the finding in [25] that there is an ideal number of SUs that can cooperately operate in CRE for optimal sensing accuracy and optimal transmission efficiency to be achieved. In future work, we plan to extend this study to multi-secondary users where the target rates of the SUs will at some point, be compromised to allow for exigencies and emergency data transmission.

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