

OFDM-CR based Power Allocation Algorithm for Radio Systems

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Abstract. As a matter of fact, both local and foreign academics have focused on the efficient power allocation method for discussion in recent years. With this in mind, the system power distribution method of cognitive radio combined with orthogonal frequency division technology is the subject of this paper's research aims. At the same time, the theoretical foundations of OFDM-CR will serve as the beginning point for this research, which will then focus on three existing power allocation algorithms. To be specific, they are water-filling algorithm, convex optimization algorithm as well as game theory algorithm. Based on the analysis, the paper then uses a table to compare various power allocation methods. Finally, according to the analysis, it makes logical recommendations based on the issues and considers how OFDM-CR technology may develop in the future. Overall, these results shed light on guiding further exploration of wireless communication of OFDM-CR based power allocation algorithms.

Keywords: Wireless communication, power allocation, algorithm implementation.

1. Introduction

Radio spectrum resources are become more restricted as the number of communication devices rises, but they are not being used to their full potential. The creation of new dynamic frequency allocation systems is crucial in this time period from a practical standpoint. In a report, the Federal Communication Commissions (FCC) noted that only around 70% of the available spectrum resources are being used to their full potential [1]. The FCC reserves a finite amount of spectrum resources for primary users, whereas secondary users without licenses are prohibited from using those resources [2]. This has led researchers both domestically and internationally to concentrate on finding ways to attain the full utilization of spectrum. Orthogonal frequency division multiplexing uses a multi-carrier-based transmission method. The method is a multi-carrier (MC) innovation. Chang first proposed the idea of MC in 1966, which refers to the parallel transmission of data using a number of subcarriers in a single frequency band [3]. In 1971, Weinstein and Ebert put forth a differential phase modulation technology that is today referred to as the OFDM methodology [4]. The idea of Cognitive Radio (CR) was put forth by Mitola, who also noted that CR can balance spectrum use between main users and secondary users [5]. Another important feature of CR is the device's capacity to adapt its parameters of operation in response to modifications in the radio environment [6]. While OFDM alleviates the load of primary user state analysis, CR approaches facilitate access between users and the spectrum resources that are accessible. As a result, the system performance can be further enhanced by combining the CR method and OFDM [7].

The definition of "non-orthogonal multiple access" (NOMA) refers to two different types of multiple access technology: code domain and frequency domain. In 2018, Xue Li proposed a NOMA-OFDM cognitive system for frequency domain NOMA to improve the effectiveness of power allocation [7]. This system makes use of the NOMA approach to multiplex the difference in channel gain between users. Algorithms for NOMA-OFDM cognitive systems have been the subject of extensive research by many academics. In 2023, Alayu introduced an Arctangent LMS algorithm, which reduces BER and hence boosts spectral efficiency and system capacity [8].

Because water-filling algorithms produce simulation results that are close to the optimum and considerably simplify the design of the devices at both the transmitter and receiver, researchers frequently utilize them for power allocation [9]. Mishra developed a geometric water-filling (GWF)

Peak power method in 2020, which requires less time and space because conventional water-filling algorithms cannot be directly used to OFDM-CR systems [10]. Therefore, the transmission capacity can be effectively increased by applying the GWF Peak power algorithm to the OFDM-CR system.

A lot of academics have recently applied genetic algorithms (GA) to signal processing in an effort to find the best solution. GA is a mathematical model created and developed based on the principles of biological evolution. Yilmazel suggested using GA in 2021 to get the best channel allocation outcomes in OFDM-CR networks, and simulated findings demonstrate that GA can significantly increase accuracy [11]. In recent years, particle swarm optimization methods have drawn a lot of interest. In 2019, Hongzhi Wang proposed the genetic particle swarm optimization (GPSO) algorithm, which incorporates genetic ideas into particle swarm optimization algorithms [12].

This paper begins by outlining the fundamentals of OFDM-CR power allocation, follows with a description of its theoretical foundations, compares application objects, research scenarios, methodological features, and the benefits and drawbacks of various OFDM-CR power allocation techniques, and concludes by looking ahead to the future of OFDM-CR technology. Following the sequential logic, three optimization algorithms (i.e., the water-filling algorithm, the convex optimization algorithm, and the game theory algorithm) are described in this paper for the selection of OFDM-CR power allocation and are contrasted using tables. These three alternative power allocation algorithms have all been used in practice, but they all need to take power limitations and system performance into account. Later in the paper, the theoretical foundations of the three power allocation algorithms and the contexts in which they are used will be discussed.

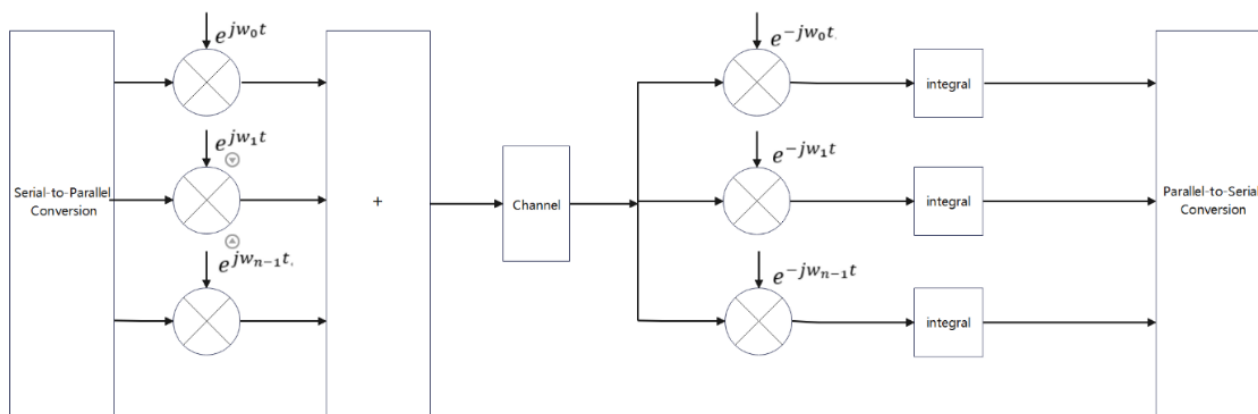


Figure 1. OFDM Schematic

2. Principle

When considering performance loss, OFDM technique makes the multiple subcarriers orthogonal to one another to reduce inter-symbol interference. The fast speeds stream of information is split up into several low-speed data streams, which are then sent simultaneously on several subcarriers [13]. The fulfillment of this orthogonality condition allows the spectral resources to be used effectively from a spectral point of view, because when the frequency spacing of multiple subcarriers satisfies certain requirements, the remaining subcarriers won't interfere with the sampled carrier during the process of sampling the peak of one subcarrier [14]. The basic concept behind the OFDM technique is to judiciously distribute the power in order to maximize link capacity while paying respect to the limits, namely that the system's transmitter has the maximum transmit power [15]. The usage of OFDM technology offers the following benefits: it can increase spectrum utilization, and it has a powerful anti-interference capability. However, there are significant drawbacks to OFDM technology as well, including high peak-to-average power ratio and highly power peaks [13]. There is a significant increase in transmission efficiency with OFDM's flexibility [16]. Here, N is the number of subcarriers, and an OFDM signal can be created by superimposing sub-signals that have been modulated by N orthogonal subcarriers, as shown in Fig. 1. If d_i is defined as the data symbol

assigned to the i th channel, f_i is defined as the wave frequency of the i th channel, and signifies time period of an orthogonal frequency division multiplexing symbol [17]. The output signal is as follows:

$$s(t) = \sum_{i=0}^{N-1} d_i \cdot \text{rect}\left(t - \frac{T}{2}\right) \cdot \exp(j2\pi f_i t) \quad 0 \leq t \leq T \quad (1)$$

With limitations

$$\text{rect}(t) = 1, |t| \leq \frac{\pi}{2} \quad (2)$$

Since the subcarriers are arranged in a period in a mutually orthogonal pattern, they must satisfy:

$$\frac{1}{T} \int_0^T \exp(j2\pi m \Delta f t) \cdot \exp(-j2\pi n \Delta f t) dt = \begin{cases} 1, m = n \\ 0, m \neq n \end{cases} \quad (3)$$

The frequency of the subcarrier can be derived from equation (2) as $f_i = \frac{i}{T}, (i = 0, 1, \dots, N - 1)$. Then further the relevant equation for demodulating the k th subcarrier can be derived:

$$d'_k = \frac{1}{T} \sum_{i=0}^{N-1} d_i \cdot \int_0^T \exp\left(j2\pi \frac{i-k}{T} t\right) dt = d_k \quad (4)$$

From Eq. (3), it is clear that while the integration of the other subcarriers provides 0, demodulation of the k th subcarrier produces a signal. One of the most crucial elements of the OFDM principle is the ability to segregate the sub-signals of each path, and this orthogonality makes this possible. The principle of the CR technique states that the cognitive user actively scans the target spectrum to obtain information, i.e., to determine whether it is an available band or not. The temporarily available band is known as a spectrum holes, and the cognitive user then dynamically accesses the holes to complete the communication [17], as shown in the Fig. 2.

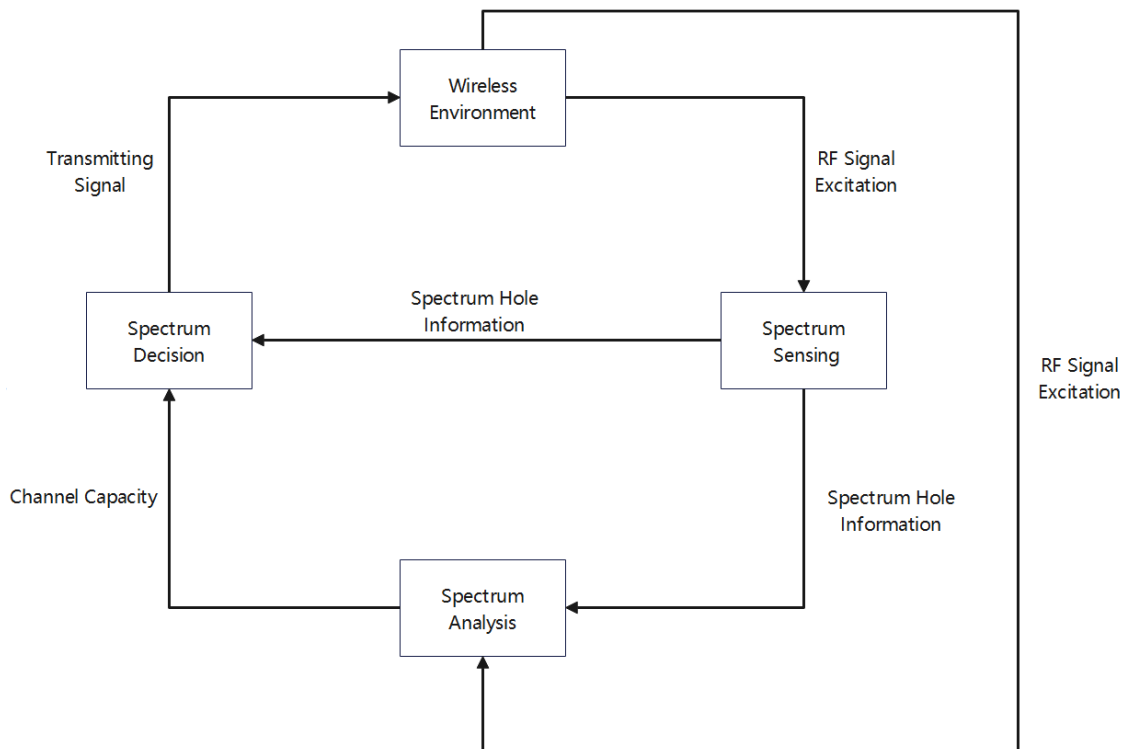


Figure 2. Cognitive Radio Schematic

The four main CR technology concerns are spectrum sensing, dynamic spectrum management, spectrum transform, and power control. This paper will focus on power allocation, which is closely related to power control module, as one of the four main CR technology concerns. We use the model as an illustration of the principle of OFDM-CR technology, which is specifically reflected in the suppression of interference between main user system and cognitive user system, to maintain main user system functioning normally, while causing the cognitive user system performance to reach the maximum [18]. The theoretical foundations of the three various power allocation methods in this work must be examined before analyzing them. Since it outperforms the typical power distribution algorithm, the water-filling algorithm is recognized as the best power distribution technique to maximize system throughput [19]. In 2007, Iterative partitioning water-filling and power distribution algorithms that allow for the updating of the water surface value were proposed [20]. In the case of finding the best power allocation scheme about CR, the selection of appropriate convex function along with power and interference limitations is transformed into a convex optimization [21]. In the 20th century, John von Neumann developed the idea of game theory. The general definition of game theory is the decision-making when the decision-makers' behaviors interact and the equilibrium problem of decision-making. In the game theory model, the gamers' primary motivation is to seek the greatest benefit while minimizing loss; the two behaviors involved can be described by the utility function and the cost function, respectively. As a result, power control can also be viewed as a game process [22]. Game theory is built on the basis of multi-users by creating a game model, creating various power allocation schemes based on various performance requirements, and designing various utility functions to satisfy the Nash Equilibrium [21]. This differs from allocation algorithms that target the overall system performance.

3. Three Optimized Power Allocation Algorithms

Systems based on OFDM-CR radio are divided into single user and multi user categories according to the water-filling algorithm. All sub-channels in single-user OFDM-CR radio systems are subject to power constraints [20]. Peng Wang noted in his paper from 2007 that for the single-user case, a new iterative segmentation water-filling algorithm needs to be proposed in the case of maximize capacity of secondary users while power allocation is optimized. This algorithm constrains both the total power and each sub-channel [23]. The iterative segmentation water-filling algorithm does have some limitations, such as the requirement to recalculate the water surface value when using it for subcarrier power allocation, which adds to the complexity of the power distribution process. To address problem of high complexity, a low-complexity power distribution algorithm for multiuser systems has been proposed in this paper [24], but this algorithm performs power distribution without considering the constraints of peak power, and thus suffers from significant deficiencies. The linear water-filling PI method can be used to provide a high channel capacity with minimal complexity. However, the cognitive system is more disruptive to the primary system. The resulting PIA method is an optimization of the PI algorithm that uses two rounds to take advantage of the power limits, making it less disruptive and complex than the PI algorithm [18]. In order to distribute resources to users with the most optimal channel state information, a unique power distribution technique for multiuser OFDM-CR systems for the uplink was suggested in 2010. This algorithm determines whether each assigned subcarrier exceeds the maximum power limitation [25].

The technique effectively raises spectral efficiency while reducing the complexity of power distribution. It is significant to note that influence of channel gain on the power allocation process of the OFDM-CR system has not been adequately considered in many research. In order to achieve this, Bepari proposed a "n-adjacent" strategy in 2015, in which the minimum number of adjacent subcarriers is used to determine the various water levels of the adjacent groups. The algorithm achieves a certain level of capacity while satisfying the constraints, and if the value of n is high enough, it permits CR users to share spectrum with main users with a low interference tolerance [26]. According to Bansal's research, the conventional water-filling algorithm based on OFDM-CR is

subpar [27]. In light of this, many academics have dedicated time and resources to the study of convex optimization theory. The Lagrange multiplier method, which dates back to the seventeenth century, was the precursor to convex optimization. Later, the Bellman dynamic programming, the linear programming problem, the interior point method, and the extended Kamaka algorithm were developed. Without going into great detail about the underlying mathematical reasoning, this paper concentrates on how to construct convex optimization algorithms, including the ladder allocation method and the RC allocation method. The overall goal of the ladder power allocation method, which is based on the Lagrangian algorithm is to lessen interference to the main user by converting cognitive user's power on the subcarrier into a ladder distribution within limitations of main user's tolerance for interference. It is possible that users with poor channel quality receive greater power due to algorithmic restrictions, such as the algorithm's inability to take into account anything other than the frequency band's distance [28]. This was done in consideration of the significant impact this problem has on power allocation. Chunnian Zhu proposed a suboptimal method based on ladder power allocation, which realizes the allocation of less power on subcarriers with higher interference and more power on subcarriers with lower interference, taking into account the different step sizes [29].

Additionally, utilizing the KKT condition, the literature also offers optimal power allocation plans for various models [21]. For multiuser OFDM-CR systems, Qin Tao devised the RC allocation algorithm in 2007 to increase the system throughput for secondary users in contrast to the ladder power allocation technique [30]. By considering both the power increase and the interference increment and finding a balance between the interference limit and the current value of power, the RC allocation algorithm optimizes the algorithm. However, the overall computational cost is significantly raised by the RC algorithm's inclusion of both MP and MI algorithms [28]. Bingham also proposed to maximize downlink capacity under power constraints, which is accomplished by allocating sub-carriers to users with the greatest channel conditions. This optimal power distribution scheme can be found by applying Lagrangian dyadic theory to the power distribution problem for multiple cognitive users [31]. Hasan proposed a power distribution scheme based on Risk-Return model and three suboptimal schemes in 2009, which defines an average rate loss function to include channel reliability. By comparing performances of different schemes, Hasan came to the conclusion that the water-filling algorithm has the worst performance [32].

Table 1. Comparison of different power allocation algorithms

	Characteristics	Vantage	Disadvantaged
Water-filling algorithm	Power allocation based on channel status	Maximizes system throughput	Interference between users need to be addressed additionally
Convex Optimization algorithm	Iterative computation to find the unique optimal solution can effectively solve large-scale problems	Efficient, mathematical modeling to find optimal solutions	High computational complexity
Game Theory algorithm	The game process is characterized by two properties: finiteness and fairness.	Flexibility of methodology, which can be selected on a system-by-system basis	There are difficulties in finding Nash equilibrium points

The introduction of game theory can meet the performance needs of various systems due to the differences between OFDM-CR systems, and taking into account the various practical settings, different utility functions are frequently utilized. The two fundamental ideas in game theory are Pareto optimality and Nash equilibrium. Nash equilibrium is a non-cooperative game model that assesses the game's stability and examines its result. On the contrary, Pareto optimality denotes a condition of resource allocation that maximizes the interests of at least one player while protecting the interests of all other players [33]. Zhang noted that there are four steps in creating a CR system model based on game theory: designing a stable algorithm first; identifying all Nash equilibriums in the game process; screening the Nash equilibriums [34]; and figuring out the convergence conditions. Given that only past secondary user information can be used in a cognitive wireless network environment, an iterative

algorithm is needed for the secondary users to reach the Nash equilibrium. In addition, iterative algorithms should converge to the Nash equilibrium quickly in the case of rapid changes in network topology in order to minimize delay in power allocation as much as possible [35]. The optimized conjugate gradient algorithm might be taken into consideration during the algorithm selection because of the requirement for quick convergence. Contrary to conventional conjugate gradient algorithms, Lasdon presents a stable, less computationally demanding, and faster-converging optimized conjugate gradient algorithm [36]. The method, however, is obviously no longer applicable to the current network structure, which is why Zhou proposes an improved distributed allocation iterative algorithm based on game theory. This algorithm not only optimizes the conjugate gradient algorithm but also improves the utility function in the game process. Experimental findings show that our enhanced distributed allocation iterative method converges swiftly and reaches the Nash equilibrium point after a number of iterations [35]. In 2020, Ma proposed a model to maximize the cognitive user's satisfaction and the main user's profit. This model is a Bertrand game to reach a Nash equilibrium on the price of main user's transmitter power in order to energy harvesting, specifically divided into two parts: price competition at the level of main user and energy harvesting at level of cognitive user [37]. The Bertrand game can lead the model's cognitive user and main user to Nash equilibrium, according to an analysis of the simulation data. In 2018, Dachun Feng proposed a power allocation algorithm based on a non-uniform pricing mechanism with the goal of determining a distinct power allocation scheme in response to the need to focus the research's direction and the issue of multiple equilibrium points in underlay CR networks [38]. The technique can effectively increase network capacity, according to simulation results. And next paper will compare the advantages and disadvantages of three different power distribution algorithms based on their characteristics, as shown in the Table 1.

4. Conclusion

This paper begins by pointing out that the radio spectrum resource tension is the starting point, then analyzes and summarizes the findings of the prior research, discusses the fundamentals of the water-filling algorithm, the convex optimization algorithm, and the game theory algorithm, and finally describes in detail how the three different types of power allocation methods are implemented. Despite the fact that power allocation approaches based on OFDM-CR are continuously evolving, there are still certain issues in related sectors. The depth of research for these issues in this work is insufficient, and many techniques still require more investigation. Because numerous primary users and cognitive users may coexist in practical applications, further research on this model's power allocation method is necessary. It is necessary to research power allocation methods when only performance criteria are rate and bit error rate .

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