Research for Modern Spectrum Allocation Algorithms and Their Applications in Communication Systems

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Abstract. In the context of the digital age and the growing prevalence of the Internet, spectrum resources assume a pivotal role in the field of communication technology. This paper examines the potential of modern spectrum allocation algorithms in communication systems, particularly in the context of limited and scarce spectrum resources. This paper compares and evaluates the application of graph coloring theoretical models, game theory-based allocation algorithms, and distributed greedy algorithms in cognitive radio (CR) networks. It reveals the advantages and disadvantages of different algorithms in improving spectrum utilization efficiency and communication performance. Moreover, these algorithms have a broad range of applications in the fields of 5G communication systems, the Internet of Things (IoT), and satellite communications. In particular, the novel model integrating diverse algorithms offers novel insights into enhancing network performance in cognitive radio networks (CRN). In addition, a series of challenges and potential research avenues are proposed for the development trend of future communication systems, including intelligent spectrum sensing and allocation techniques, optimized communication system algorithms, and new techniques for integration. The findings of this research will serve as invaluable references and guidance for the advancement of future communication technology, thereby facilitating the evolution of communication systems toward greater efficiency, reliability, and intelligence.

Keywords: Communication technology, Dynamic spectrum allocation, Cognitive radio, Spectrum allocation algorithms.

1 Introduction

In this era of digitization and internet penetration, communication technology plays a vital role in all walks of life. Spectrum resources are one of the cores of carrying communication technology. Recent studies have shown that with the rapid development of mobile communications, the IoT, and various other fields such as industrial, medical, aviation, radar, and satellite technologies, the demand for wireless spectrum resources is growing exponentially. The finiteness and scarcity of spectrum

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resources make effective spectrum allocation algorithms one of the most pressing issues in the future development of communication systems [1].

According to a recent study by the Federal Communications Commission (FCC), some commonly used frequency bands are heavily utilized, often resulting in congestion, while a few other bands are partially occupied or unutilized. For example, only 5.2% of the frequency bands below 3 GHz are being utilized, which is a great waste of precious spectrum resources [1]. The traditional Fixed Spectrum Allocation (FSA) strategy supports different uses for the user experience not to be interfered with, each portion of the spectrum is licensed to a single user. However, in this method, only the allocated spectrum is allowed to be used by the licensed user, which leads to inefficiency and underutilization of the spectrum [2].

To improve spectrum efficiency, a new strategy Dynamic Spectrum Allocation (DSA) is proposed. In DSA, the allocation of spectrum is no longer fixed. The primary user (PU) is assigned a portion of the spectrum, while other users can use the spectrum temporarily or use the low-priority spectrum when the PU is not occupying it [2]. Among them CR has emerged as a much-talked-about technology for DSA, CR improves the inefficient utilization of the available radio spectrum and improves the pass-through of dynamic access to idle bands through cognitive capabilities. In CR users other than PUs called secondary users (SUs) can automatically sense the spectrum conditions and adaptively access and utilize the spectrum not used by PUs [3]. CRN is considered by many in the communication industry, academia, and policymakers as a solution for the next generation of communication networks as it is believed to have the ability to handle future traffic due to the adaptive nature of spectrum allocation [4]. CR networks in which unauthorized and authorized users coexist and share the same frequency band with the PUs without affecting the normal operation of the PUs and can withstand high traffic loads during abnormal effects such as sudden disasters because it overcomes the lack of network capacity [3, 4].

The main objective of the CR algorithm is to satisfy the quality of service (QoS) requirements of the SUs in the context of protecting the PUs from unfavorable interference from the SUs, this transmission strategy is called spectrum sharing [5]. Since many opposing objectives may arise in the design and implementation of CR used for spectrum allocation in CRN, which requires algorithmic optimization, several different technical attributes and objectives need to be considered to optimize the spectrum allocation and to achieve the properties of CR when performing spectrum allocation incorporating CR techniques [3]. Since the concept of CR was proposed, numerous scholars have developed corresponding CR algorithmic models to solve the spectrum allocation problem. These models are based on various algorithms and draw inspiration from classical mathematical and microeconomic theories, such as graph theoretic algorithms and game theoretic algorithms [6]. These classical and effective algorithms based on other domains are once again playing an important role and becoming a research hotspot in the context of spectrum management.

However, there is a research gap in the comparison and cross-sectional evaluation of the application of the three more effective and typical algorithms with different theoretical frameworks, namely, graph-theory-based allocation algorithm, game-theory-based allocation algorithm, and greedy algorithm in CR communication systems. These algorithms are chosen for their good scalability, applicability, and more different characteristics from each other, which can cover part of the algorithm characteristics to some extent.

The objective of this thesis is to conduct a comparative and evaluative analysis of three contemporary frequency allocation algorithms in communication systems. By examining the relative merits and demerits of these algorithms, their performance, and the circumstances in which they are applicable, this study aims to provide new insights and methodologies for improving spectrum resource management.

2 Introduction to Algorithms

2.1 Graph Coloring Theoretical Model

The graph coloring theoretical model is a classical graph-theory-based allocation algorithm in CR. The coloring algorithm in graph theory is widely used by resource planning and management in communications [6]. In this algorithm, the available spectrum is divided into multiple non-overlapping channels, and the analog spectrum planning for the cell is combined into a list coloring problem. Here, the spectrum available to the users in the CR is equivalent to the number of colors in the coloring algorithm, and the interference between CR users can be analogized to edges [6, 7]. These coloring algorithms are divided into two main types: distributed greedy algorithms and distributed fair algorithms. Distributed greedy algorithms emphasize maximizing channel utilization, while distributed fair algorithms emphasize fairness [6].

The graph coloring theoretical model has the advantage of being among the more mature schemes. It offers many function optimization schemes to compress the complexity and time cost, as well as good applicability [6, 7].

However, it does not give enough consideration to the heterogeneity factor of spectral efficiency and spectral interference in the allocation and its impact on the utility matrix [6]. Only the interference constraints between SUs are considered and the total interference generated by SUs to co-channel PUs is not analyzed in many graph-coloring-based allocation algorithms [7].

The graph coloring theoretical model focuses on the availability and fairness of spectrum allocation. It is suitable for scenarios that require a bias towards these two properties, and different function optimization directions can reflect the different properties emphasized [6, 7].

2.2 Game-Theory-Based Allocation Algorithm

Game-theory-based allocation algorithm is another effective CR algorithm. It achieves this by simulating a non-cooperative game process among multiple users to find the Nash equilibrium, which serves as the optimal spectrum allocation strategy [8]. In game theory, Nash equilibrium means that in a game process, each participant chooses the optimal strategy and has no incentive to change their strategy again, thus forming a stable state. For the spectrum allocation problem, game theory can describe the competition and cooperation between users, analyze the conflict of interests between different users, and find the spectrum allocation scheme that achieves the optimal effect.

The application of game theory can optimize spectrum allocation in different scenarios, such as multi-user shared channels, power control, and interference management [8]. By establishing appropriate game models, thus achieving efficient utilization of spectrum resources and improving system performance and user experience [8].

However, there are some limitations of game theory-based spectrum allocation algorithms. For example, the computational complexity is high, especially in large-scale networks, and the effectiveness of the algorithm is affected by the channel conditions, interference conditions, and user behavior. In addition, game theory can only find the Nash equilibrium point as a local optimal solution and cannot guarantee the global optimal solution [8].

Probabilistic-based spectrum allocation algorithms are suitable for scenarios such as small cell networks, heterogeneous networks, and self-organized networks, and can optimize spectrum utilization efficiency and system performance [9].

2.3 Distributed Greedy Algorithm

The third and more effective one is the CR algorithm of the distributed greedy algorithm. It requires initialization first to generate a list of free spectrum resources and set the initial allocation scheme. Then, the strategy of the greedy algorithm enables each selection of the optimal spectrum resource that minimizes the interference index, channel leakage rate, and interference to PUs [4]. Next, based on the selected spectrum resources, the state information such as interference index and channel leakage rate of other nodes is updated and the list of free spectrum resources is updated. Subsequently, leveraging the updated state information, a suitable power allocation scheme is computed to assign the selected spectrum resources to the corresponding SUs. This iterative process is repeated to maximize the capacity of the entire CRN [4].

The algorithm achieves coordination between CR user mobility and network density and can be applied to various CR applications and purposes. By considering the factor coefficients, it can dynamically select the optimal spectrum resources and power allocation scheme to maximize the overall capacity of the CRN [4].

Since the whole distributed algorithm is based on a greedy algorithm, it may have some limitations. For example, it tends to favor local optimal solutions, is susceptible to overfitting, and the computational complexity may be too large when dealing with large-scale problems. Also in the worst case, the algorithm may stop in a finite number of steps [10].

A distributed greedy algorithm for spectrum allocation is suitable for large-scale network environments, PUs protection, and high-traffic load scenarios. As in the case of community-wide cellular network models, the effectiveness of the algorithm in different scenarios can be further optimized by reasonably adjusting the algorithm parameters and weights [4].

3 Application of Algorithms in Communication Systems

3.1 5G

Sustainable spectrum allocation in future mobile networks is a promising research area [11]. Algorithms have many applications in communication networks.

In 5G communication systems, CR and its related algorithms are seen as potential technologies to drive future developments. In the study by Ahmad et al., is mentioned that Bairagi et al. conducted a study on spectrum resources and proposed a scheme called LTE over unlicensed bands, which utilizes a virtual coalition formation game and Q-learning algorithms to improve the QoE [1].CR technology has the cognitive potential to adjust transmission parameters according to environmental characteristics and utilizes algorithms such as Q-learning to perform resource allocation [1, 11]. The switching process of CRNs involves a fractional protected channel allocation method which improves the throughput of unauthorized users by forcibly terminating SUs [1]. The most promising CR algorithmic models are exclusive-use models with spectrum trading solutions, such as algorithms from game theory and market equilibrium [1]. Improvements and applications of these algorithms may drive the development of 5G technologies and provide the opportunity to bring more efficient, reliable, and intelligent 5G-based communication services.

3.2 IoT

In the IoT, non-equivalent spectrum allocation methods are based on the user's knowledge of unused spatial spectrum and the utilization of that band for communication, providing a viable solution for CR [12]. In IoT environments, effective management of spectrum is especially critical due to the large number of devices and dynamically changing communication demands. Therefore, e.g., fuzzy logic, neural networks, Hidden Markov Models, genetic algorithms, and classification algorithms are widely used in CR networks to improve the capacity and the dynamics of spectrum access to meet the communication demands of IoT devices [12]. The DSA algorithm plays an important role in CR. It can not only ensure high reliability of communication but also meet the relatively high mobility requirements of IoT nodes [12]. At the same time, it can effectively solve the problem of low utilization of existing spectrum resources. This provides a reliable guarantee for IoT nodes transmitting large amounts of data on a large scale and provides a solid foundation for the development of IoT communications.

3.3 Wireless Communication

It is mentioned in the study by Liu et al. that with the development of wireless communication technology and the increase in business demand, the competition between satellite communication and terrestrial mobile communication in spectrum resources is becoming more and more intense. Shortage of spectrum resources leads to spectrum congestion and interference becomes one of the main factors limiting the development of satellite communications [13]. Spectrum allocation has become a key issue, and the commonly used solution is based on game-theoretic modeling. The Cooperative Nash bargaining game and Colonel Blotto game are common non-cooperative game models, while the Stackelberg game and Cournot game are commonly used for spectrum allocation [13]. However, these models also have certain limitations, such as too many constraints or static games. To solve these problems, evolutionary game algorithms are usually used to allocate spectrum resources. This model can more accurately reflect the dynamic behavior of the system and use less user information to reach the equilibrium state under the same conditions, which is more suitable for the application scenarios of satellite communication networks [13].

In summary, with the continuous progress of communication technology, the application of algorithms in spectrum allocation will increasingly shape the future of mobile networks, offering a robust foundation for their sustainable development.

4 Algorithm Performance Analysis

In a study by Xu et al., a distributed greedy algorithm a distributed fairness algorithm based on graph coloring theory, and a new algorithm combining these two algorithms were tested in a cognitive satellite network [14]. The MSAABGCT algorithm proposed in the paper combines the advantages of DGA and DFA [14]. The gains of cognitive satellite networks using DGA, DFA, and MSAABGCT algorithms were evaluated. For the same available spectrum and the same number of secondary satellites, the MSAABGCT algorithm exhibited the highest gains of cognitive satellite networks, the DGA algorithm ranked second, and the DFA algorithm exhibited the lowest gains. The difference between the gains of all three algorithms is approximately 0.5, for example, the MSAABGCT gain is 8.5, DGA is 8, and DFA is 7.5 under the same conditions. Additionally, the gain of a cognitive satellite network increases with the increase in the number of available spectrums. Consequently, the gain increases as the number of available spectrums increases, particularly when there are few secondary satellites.

The DFA algorithm exhibits the most balanced fairness among the three algorithms. In contrast, the DGA algorithm exhibits the least balanced fairness, as it solely considers the gain of the cognitive satellite network. Among the three algorithms, the MSAABGCT algorithm is the most balanced in terms of fairness.

The traditional DGA and DFA algorithms demonstrate superior specialization performance for specific fairness requirement scenarios. In contrast, the MSAABGCT algorithm achieves the highest cognitive satellite network gain while maintaining a high degree of fairness.

Algorithms based on graph coloring theory may be more advantageous in multi-user environments such as satellite and IoT.

Teng et al. conducted a study comparing a game theory-based potential game algorithm with a randomized game algorithm and a classical SIR balancing algorithm. A simulation experiment was conducted, which included 10 cognitive users. Each user had access to five data channels, and they shared a common control channel to transmit control information.

The algorithm demonstrated significant efficacy in reducing congestion and optimizing spectrum utilization, with notable improvements in channel occupancy and user distribution compared to the random game algorithm and the SIR balancing algorithm [8]. Concurrently, the algorithm addresses the issue of channel distribution imbalance and reduces user interference, thereby enhancing spectrum utilization and communication quality. Moreover, the algorithm significantly enhances the signal-to-noise ratio for users on each channel, facilitating rapid convergence towards the Nash equilibrium and optimal values [8]. In scenarios requiring effective management and optimization, such as communication networks and intelligent transportation systems, game theory-based spectrum allocation algorithms offer a more advantageous approach.

The study by Ranjan et al. tests the efficacy of a greedy algorithm for spectrum allocation with the introduction of an interference index. The capacity of the CRN of the improved algorithm was found to be significantly improved by 60% compared to the normal greedy algorithm. The efficacy of this algorithm lies in its capacity to effectively mitigate interference between secondary nodes, thereby enhancing network capacity while accounting for potential interference from PUs. Moreover, it is capable of adapting to diverse network environments and fluctuating traffic demands by meticulously adjusting the interference index and channel leakage rate [4].

The introduction of the interference index effectively reduces interference between secondary nodes, thereby improving the overall performance of the network. Nevertheless, the algorithm is not without limitations. One such limitation is the potential for high computational complexity when dealing with large-scale networks. Additionally, parameter tuning for specific network environments may require further optimization.

In conclusion, the algorithm may be suitable for scenarios where CRN capacity and performance need to be increased and for scenarios where flexibility is required to cope with different network environments and traffic demands. This includes instances where the capacity of the wireless network is insufficient to support more users and traffic or when optimization of network performance is required.

5 Discussion

A critical analysis of the aforementioned studies reveals the paramount importance of optimizing spectrum allocation algorithms in cognitive satellite networks and wireless communication systems to enhance spectrum utilization efficiency and communication performance. Researchers have made progress by introducing and optimizing techniques such as graph coloring theory, game theory, and greedy algorithms. Nevertheless, there are still some challenges and potential avenues for future innovation research.

Firstly, to further enhance the efficacy of spectrum utilization, a range of spectrum-sharing mechanisms may be investigated, including those that facilitate precise dynamic spectrum sharing and spatio-temporal spectrum sharing. The implementation of intelligent spectrum sensing and allocation techniques enables more flexible and efficient spectrum utilization, thereby meeting the diverse needs of users and application scenarios. For instance, the study by Ranjan et al. introduced interference coefficients to facilitate more precise simulations, thereby enhancing spectrum utilization [4].

Secondly, for the optimization of communication performance, suitable algorithms and optimization algorithms can be selected to design intelligent communication systems. By predicting and optimizing communication links, channel states, and user demands, it is possible to achieve more reliable, low-latency, and high-throughput communications. In addition, further research is required to develop more accurate scheduling algorithms to enhance the performance and adaptability of communication systems [12].

For future research directions, it would be beneficial to consider the integration and optimization of cognitive satellite networks and wireless communication systems. For instance, network optimization algorithms that incorporate additional layers can be developed to optimize global performance by concurrently addressing optimization issues at the physical, link, and network layers. Furthermore, novel technologies such as artificial intelligence, blockchain, and edge computing can be integrated to develop intelligent, highly reliable, and low-energy communication systems.

The enhancement of spectrum utilization efficiency and communication performance represents a pivotal objective and challenge for future research on cognitive satellite networks and wireless communication systems. Through continuous innovation and technological breakthroughs, it is possible to create a more efficient, reliable, and intelligent communication network, which will in turn facilitate the development of the digital society and the progress of the intelligent industry.

6 Conclusion

This paper examines the significance of spectrum resource allocation in communication systems. This study compares the efficacy of graph coloring theory algorithms, game theory-based algorithms, and distributed greedy algorithms in CRNs. By evaluating the characteristics of different algorithms in improving spectrum utilization efficiency and communication quality, the following conclusions can be drawn: Firstly, the optimization of spectrum resource allocation algorithms is of paramount importance for the enhancement of communication system performance. Different algorithms apply to varying scenarios and possess distinct advantages. Secondly, it is anticipated that future developments in communication systems will increasingly rely on intelligent technology to select and optimize algorithms. This will achieve more efficient and intelligent resource allocation, thereby maximizing resource utilization efficiency. In conclusion, spectrum allocation algorithms have made significant contributions to the widespread deployment of 5G communication systems, the IoT, and other fields. They also play a pivotal role in satellite communications and other domains. As technology continues to advance, these contemporary spectrum allocation algorithms will continue to evolve, driving further advances in communication technology.

The paper elucidates the application of graph coloring theory, game theory, and greedy algorithms in communication systems. It emphasizes their significance in enhancing the efficiency of spectrum utilization, optimizing the quality of communication, and fostering the advancement of intelligence.

Currently, these modern spectrum allocation algorithms have a wide range of applications in the fields of 5G communication systems, the IoT, and satellite communications. For instance, in 5G communication systems, these algorithms can be employed to optimize the allocation of spectrum resources and enhance the performance and coverage of communication systems. In the field of IoT, these algorithms can be employed for spectrum sharing and dynamic allocation between smart devices, thereby facilitating efficient communication between IoT devices. In satellite communication, these algorithms can be employed to optimize the allocation of satellite resources and enhance the coverage and transmission efficiency of the communication system.

As communication technology continues to evolve, the research field of spectrum resource allocation algorithms will continue to expand. These algorithms will be combined with high-tech solutions such as artificial intelligence to increase cross-layer optimization and collaborative optimization. This will bring about further innovation and development in the communication system. This will facilitate the advancement of communication technology in the direction of enhanced efficiency, reliability, and intelligence.

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