Frequency allocation algorithm

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Abstract. Wireless communication technology's quick advancement has facilitated the ongoing formation of numerous new communication business scenarios and the thorough connectivity of man-machine-object-space. The conflict between few channel resources and high demand is becoming more and more obvious, which adds to the stress on the entire network. In order to enhance communication quality with constrained frequency resources, more optimal channel allocation techniques are urgently required. This paper discusses the increasing demand for frequency resources due to the exponential growth of data traffic, which has necessitated more efficient channel allocation methods to optimize communication quality with limited frequency resources. The evolution of mobile wireless cellular communication systems from the first generation to the current fifth generation, and the imminent emergence of the sixth generation, are also discussed. The paper highlights the importance of ultra-dense networks and device-to-device communication in meeting the capacity and coverage requirements of 5G networks. The advantages and disadvantages of different frequency reuse methods, specifically Fractional Frequency Reuse (FFR) and water injection algorithm, are analyzed. The paper summarizes these methods' principles and application effects in specific situations, emphasizing the need for appropriate frequency reuse methods to achieve optimal channel allocation and communication quality.

Keywords: frequency reuse, ultra-dense networks, device-to-device communication.

1. Introduction

Today, the demand for frequency resources is increasing substantially[1]. It is estimated that the level of data traffic will increase 1000 times over 2010 levels in the sustained decade after 2020 [2]. Therefore, in order to make full use of the available frequency resources, researchers need to use more optimal channel allocation methods to improve communication quality with limited frequency resources [3].

Bell Laboratories first introduced the concept of cellular networks in the 1970s. Some important parts, such as frequency reuse and plot fission, are the basis of mobile communication technology. To date, there have been five generations of mobile wireless cellular communication systems, with the most recent generation being the fifth generation (5G) wireless networks. A new generation of wireless cellular communication has been released roughly every ten years since 1980, including the first generation of analog FM cellular systems in 1981, the second generation (2G) in 1992, the third

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generation (3G) in 2001, and the fourth generation (4G) in 2011 (a process known as long-term evolution [LTE]). [4].

As mobile communication networks are updated and iterated, their complexity is also increasing. 5G technology has been gaining ground in a lot of fields including the recent advances focusing on promising techniques such as ultra-dense networks (UDN), device to device(D2D), and other optimization and heuristic techniques. The global upsurge in linked devices and multimedia services requires an expansion of communication networks' capacity and coverage. Deploying several tiny cells to build ultra-dense networks (UDN) is one strategy for dealing with the enormous surge in capacity and coverage requirements [5]. The emerging needs of fifth-generation (5G) networks are met by D2D communication. In a cellular structure, D2D establishes direct communication with improved licensed band spectrum usage between nearby devices or users without information relay through the base station (BS)[6]. The sixth generation (6G) of wireless communication networks is anticipated to offer global coverage, improved spectral/energy/cost efficiency, better intelligence level and security, among other things. 5G, however, will not be able to meet all of the demands of the future in 2030 and beyond. 6G networks will depend on new enabling technologies to satisfy these needs, i. e. Air interface and transmission technologies and novel network architecture include waveform design, multiple access, channel coding schemes, multi-antenna technologies, network slicing, cell-free architecture, and cloud/fog/edge computing[7].

This paper analyzes various frequency reuse methods and explores the advantages and disadvantages of FFR and water injection algorithm for frequency reuse. Summarize how to choose the correct frequency reuse method in certain specific situations through their principles and application effects.

2. The basic principle of frequency reuse

With the advent of the 5G era, mobile Internet and IoT development has posed new challenges to traditional technologies. Among them, the limited frequency of resources is a major obstacle to the development of communication speed. Therefore, the technology of reusing the same frequency, called Frequency Division Multiplexing (FDM), has emerged.

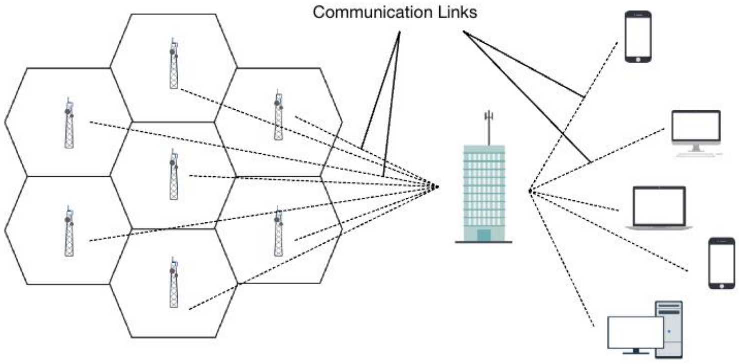

Figure 1. The wireless cellular communication system.

As Figure 1, a wireless cellular communication system consists of a base station, a user terminal, and a core network. Base stations include base station controllers, RF transmitting equipment, and user terminals include cell phones and data terminals. The core network connects each base station and provides user account management and traffic control services.

Frequency reuse is one of the most important means to improve the system's spectral efficiency. Integer frequency reuse (IFR) allocates all cells according to integer frequency multiples, with different frequencies for adjacent cells to avoid interference and for each area within the same cell to reduce noise and enhance the signal-to-noise ratio. Fractional frequency reuse (FFR) uses different subcarrier bandwidths and power allocation strategies for different areas within the same cell based on integer frequency reuse to further improve data transmission requirements in different areas. Frequency reuse is based on integer frequency reuse and uses different subcarrier bandwidth and power allocation strategies for different areas in the same cell to adapt to the data transmission needs of different areas and further improve the spectrum utilization of the cell.

Water-filling Algorithm is an optimization algorithm used to determine the subcarrier bandwidth allocation between different cells or regions in the spectrum allocation process. The water-filling algorithm dynamically allocates subcarrier bandwidth to achieve the highest possible spectrum efficiency, taking into account the interference around each cell and based on the channel state information between cells.

The water injection algorithm is the key scheduling and resource allocation module responsible for deciding the subcarrier bandwidth and power allocation strategy between different cells or regions to optimize the system's spectrum utilization and signal quality.

2.1. Frequency multiplexing

Frequency multiplexing is a scheme that divides the entire area into multiple cellular sub-regions and then allocates and reuses channels in the sub-regions. A cellular base station is set up in each subregion, and each base station is assigned multiple channels with different frequencies, which are reused in each subregion as a group. A frequency division multiplexing system divides the overall bandwidth into various sub-bands that are used by the cells. The shape of the cells is usually hexagonal, which allows for maximum coverage of the entire area while maximizing efficiency and thus consuming less bandwidth. Selecting frequency groups and allocating power to all cellular base stations in a system is called frequency division multiplexing or frequency planning. Frequency division multiplexing can improve spectral efficiency and signal quality.

2.2. Integer Frequency Reuse (IFR)

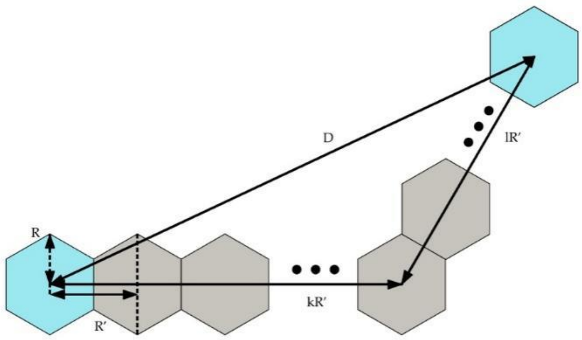

Figure 2. Frequency reuse factor calculation.

The number of different frequency channels in Figure 2 contained in a cluster is called the reuse factor. The number of times a frequency can be reused usually depends on the interference caused by adjacent channels of the same frequency. If the channel is resistant to interference, the frequency is reused more often and the reuse factor is smaller. The reuse factor N can be determined from the distance of adjacent channels of the same frequency:

$$N^2 = k^2 + kl + l^2 \tag{1}$$

When the reuse factor N is 1, which is IFR1, the frequency range in each cell is the same, containing all Nc channels, so the interference between the same frequencies is the closest and most severe. When N is 3, the number of channels in each cell becomes Nc/3, and the interference between channels is significantly reduced. The following equation can determine the channel capacity

$$C_n = log_2\left(1 + \frac{\left|h_{m,n}\right|^2 P_n}{\sum_{m\neq n}\left|h_{m,n}\right|^2 P_m + \sigma^2}\right) \quad (2)$$

Hm, n is the channel's Interfering factor between Base Station m and User n, Pn is the Base Station n's Transmit power, Pm is the Base Station m's Transmit power, σ is the noise power. The key parameter for calculating channel capacity in integer frequency reuse is the Signal-to-Interference-plus-Noise Ratio (SINR). Channel capacity calculation helps determine the maximum data rate reliably transmitted over a communication channel. This is important in optimizing available frequency bands and ensuring efficient communication.

2.3. Fractional Frequency Reuse (FFR)

Another technique to reduce inter-channel interference is fractional frequency reuse (FFR), which involves employing various reuse factors for the frequency partitions in various cells during a set period of downlink and uplink transmission. FFR is often combined with other schemes such as power control or automatic control and joint optimization of Multi-BS MIMO, and Multi-Base Station Multiple Input Multiple Output (MIMO). The subcarriers across the full transmission bandwidth are organized into frequency partitions with various reuse factors during transmission over the entire region. Mobile stations close to cell edges or those experiencing severe inter-cell interference reduce interference between channels and aid in improving the quality of the received signal because mobile base stations can typically be assigned to frequency partitions with higher frequency reuse coefficients due to the low inter-cell interference level. At the same time, the base station can adopt a lower frequency reuse factor for some mobile stations with less serious inter-cell interference, and apply different reuse factors for different mobile stations, thus improving the spectrum efficiency. The resource allocation in the FFR scheme needs to consider several factors, such as how to allocate the reuse factor among different cells, the power of each cell, and the number of users for each cell.

Fractional frequency reuse (FFR) is also a method to mitigate inter-channel interference by using different reuse factors for frequency partitions in different cells during a certain interval of transmission in the downlink and uplink. FFR is often combined with other schemes such as power control or automatic control and joint optimization of Multi-BS MIMO, and Multi-Base Station Multiple Input Multiple Output (MIMO). The subcarriers across the full transmission bandwidth are organized into frequency partitions with various reuse factors during transmission over the entire region. Mobile stations close to cell edges or those experiencing severe inter-cell interference reduce interference between channels and aid in improving the quality of the received signal because mobile base stations can typically be assigned to frequency partitions with higher frequency reuse coefficients due to the low inter-cell interference level. At the same time, the base station can adopt a lower frequency reuse factor for some mobile stations with less serious inter-cell interference, and apply different reuse factors for different mobile stations, thus improving the spectrum efficiency. The resource allocation in the FFR scheme needs to consider several factors, such as how to allocate the reuse factor among different cells, the power of each cell, and the number of users for each cell.

The allocation of resources in the FFR scheme needs to consider several factors, such as how the reuse factor is distributed among different cells, the power and multiple antenna patterns of each cell, and how the co-channel interference is measured quantified at the mobile station.

2.4. Water-filling solution

With the rapid development of user requirements, self-optimizing algorithms or distributed intelligent sensing systems are attracting more and more attention to further improve channel utilization by selecting frequencies based on the characteristics of different users. Water injection algorithms can provide multiple frequency channels for a user to maximize its capacity. The following equation can calculate the channel capacity of each user under the water injection algorithm.

$$C = max\{P_f\} \sum_{f=1}^{N} \left(1 + \frac{P_f |H[f]|^2}{\sigma^2}\right) \tag{3}$$

H[f] is the transmit power at frequency f, σ is the noise power, Pf is the transmit power for each frequency channel. The larger the channel-to-noise power ratiohe worse the frefrequency quality is the total number of frequency channels.

For a general system, the target signal and the noise are present at the same time. In practical applications, the energy of the target signal is limited. The water injection algorithm can be imagined as filling a container with water. Let the width of the kth step be ak, the height (from the bottom) be Lk/ak, and the corresponding area be Lk. The process of power distribution is like filling a water tank with water. If the step is too high (i. e., the transmission quality of the channel is too low), no water will be allocated to the step, i. e. , no power will be allocated to this channel. In the simple unweighted case, each step is set to the same width, and weighting is changing the step width.

3. Several methods of frequency allocation

3.1. IFR

Within a certain area, the coverage range of a base station can be approximated as an equilateral hexagon with a side length of R. In contrast, the areas covered by multiple base stations are connected in a honeycomb like shape, as shown in Figure 2. Among them, k represents the distance between two base stations, while k and l represent the number of base stations that differ in a certain direction. And each base station is assigned channels with different frequencies, which form different groups for each area. Frequency multiplexing (also known as frequency planning) allocates power to all regional base stations and select groups composed of different signals. The number of channels with different frequencies included in a channel group is considered N, the frequency multiplexing factor. The size of N is determined by the distance (k, l) between adjacent co frequency channels. And IFR, also known as integer channel multiplexing, refers to the value of N being an integer, such as 1, 3, 9, and so on. When N is set to 1, the frequency range of each cell in IFR1 is consistent, including a total of Nc channels. Therefore, interference at the same frequency is the most significant and the communication effect is the worst. The following formula is the channel capacity calculation of IFR1.

$$C_{total} = \sum_{n} log_2 \left(1 + \frac{\left|h_{m,n}\right|^2 P_n}{\sum_{m \neq n} \left|h_{m,n}\right|^2 P_m + \sigma^2}\right) \tag{4}$$

When the value of N is 3, the number of channels in each cell of IFR3 decreases to Nc/3, resulting in a decrease in interference between channels and a significant improvement in communication performance. The following formula is the channel capacity calculation of IFR3.

$$C_{total} = \sum_{n} log_2 \left(1 + \frac{\left|h_{m,n}\right|^2 P_n}{\sum_{m \neq n} \left|h_{m,n}\right|^2 P_m + \sigma^2}\right) \tag{5}$$

However, its reuse method has low frequency utilization and cannot meet the requirements of expanding network capacity in areas with high business volume. Therefore, it has long been banned by other reuse methods, and as a relatively basic reuse method, it has evolved many other reuse methods based on IFR.

3.2. FFR

Place six Relay Stations (RS) near the vertices of the hexagonal shape of the cellular network unit. The radius between the sector sandwiched between two RSs and the Base Station (BS) is only 2/3 units. Mobile Stations (MS) can communicate directly with BS or communicate with BS through RS, as shown

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in Figure 3 [8].

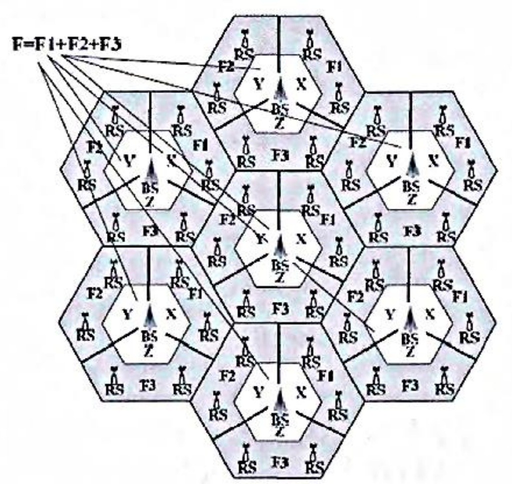

Figure 3. The Network Structure of FFR.

FFR, also known as fractional channel multiplexing, reduces channel interference and improves communication quality. It differs from IFR because its frequency multiplexing factor N is not an integer. When the interference within the community can be eliminated, use Shannon's theorem

$$C=\sum_{f=1}^{N} C_f = \sum_{f=1}^{N} log_2\left(1+\frac{P_f * |H[f]|^2}{\sigma^2}\right) \tag{6}$$

It can be seen that when the value of N is 3, the cell edge capacity is the maximum value. The use of FFR will decrease the available frequency bands within the cell, but it will also significantly improve the SINR or signal-to-noise ratio. Due to the large SINR inside the cell, co frequency multiplexing is adopted, where the N value is 1. And we can also simulate and verify under certain parameters [9].

Table 1. Parameters used in the computation.

Parameter	Value
Total bandwidth/Mhz	20
Transmission power/dBm	45
White noise power/dBm	-96
Cell radius/km	1. 0
Path loss	137. 3+35. 2*lg(d)(The unit of d is taken as km)

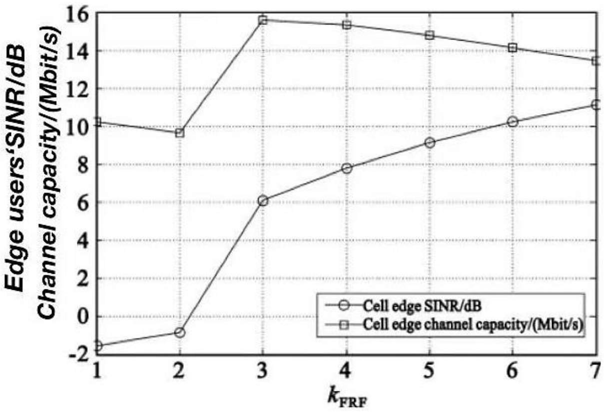

Figure 4. SINR and channel capacity with different k FRF.

Table 1 and Figure 4 show that when the value of N is 3, the cell edge capacity is the maximum value. The use of FFR will decrease the available frequency bands within the cell, but it will also significantly improve the SINR or signal-to-noise ratio. Due to the large SINR inside the cell, co frequency multiplexing is adopted, where the N value inside the cell is 1 [8].

3.3. Optimal water-filling solution

The total user capacity is , the transmission power of each user in frequency f is , the gain obtained by each user in frequency f is H[f], is the noise power, and there are N channels. According to Shannon's theorem, convert it to a Lagrangian function with constraints of:

$$L = \sum_{f=1}^{N} log_2\left(1 + \frac{P_f * |H[f]|^2}{\sigma^2}\right) + \lambda\left(\sum_{f=1}^{N} P - P_t\right) \tag{7}$$

Seeking partial derivatives to obtain the optimal solution

$$\begin{cases} P_f = \frac{1}{\lambda} - \frac{\sigma^2}{|H[f]|^2} & P_f \geq 0 \\ P_f = 0 & P_f < 0 \end{cases} \tag{8}$$

The optimal water-filling solution for obtaining partial derivatives can adjust the transmitter's power to improve channel transmission performance. When a certain frequency has a high signal-to-noise ratio, the water-filling solution will allocate higher power to the channel in order to transmit more information; When a certain frequency has a low signal-to-noise ratio, the water-filling solution allocates less power to it. The total power of the transmitting end is fixed, in other words, channels with high signal-to-noise ratio and good communication effects will obtain higher power. As shown in Figures 5-6, the power allocation for each channel by the water-filling solution is inversely proportional to the 'water level' (i. e. 1/SNR, the channel's severity) to some extent. Once the water level of the channel exceeds the water level calculated by the water-filling solution, the transmitter will not allocate power to the channel. As shown in Figures 5-6, the water levels of channels 1, 6, 12, and 16 exceed the water level given by the algorithm, so the power provided by the transmitting end to these four channels is 0 [10].

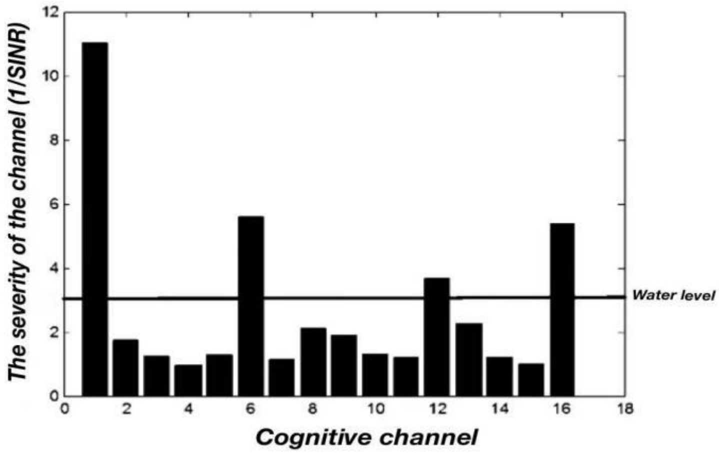

Figure 5. Water level line of water filling solution.

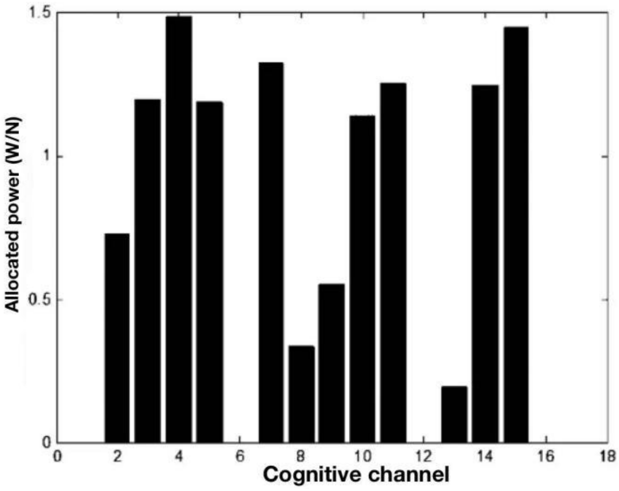

Figure 6. Water-filling solution power allocation.

As a benchmark for determining whether power should be allocated to a certain channel, the water level is iteratively searched for by the user's covariance matrix. represents the water injection covariance matrix of the i-th user, and represents the time-varying channel matrix of the i-th user. The following is the process of the iterative water injection algorithm. After the initialization process of the above equation, the calculation of the loop process is:

$$S_z^* = \sum_{j=1, j\neq i}^{K} T_j S_j T_i^T + S_z \tag{9}$$

When the total rate converges to the total capacity, each user's set of covariance matrices is converged to the optimal set of input covariance matrices, and the total target rate is bounded. Finally, the algorithm converges to a finite value, called the "water mark".

However, this algorithm is greatly affected in some cases. Taking the MDPB-30 high-power mobile phone signal blocker/mobile phone signal jammer as an example, the simulation scenario is set as follows: assuming the interference radius D=500 m and the attenuation coefficient α = 0. 2. There are a total of 4 illegal transmitters with transmission powers of =20, =30, =40, and =50. The experimental simulation also considers different noise levels, set as:=1, =5, =10. Consider three interference signal methods to interfere with the analog speech frequency modulation communication system: noise frequency modulation, speech frequency modulation, and radio frequency noise interference. The carrier frequency of the communication transmitter is 100MHz, and the frequency modulation index is

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20V/MHz. The carrier frequency of the noise frequency modulation jammer is 100MHz, with a frequency modulation index of 60V/MHz. The carrier frequency of the speech frequency modulation jammer is 100MHz, with a frequency modulation index of 60V/Hz. The carrier frequency of the radio frequency noise jammer is 100MHz, and the bandwidth is 3000Hz. Assuming that the power of all three types of jammers is 160W. The lower limit values of β under different suppression coefficient conditions can be calculated as follows: 2. 87, 3. 28, and 3. 46. [11]

Table 2. Traditional filling power allocation algorithm under different noise level.

σ_e^2	Signal			
	1	2	3	4
1	42	41	40	43
5	39	35	32	58
10	37	30	40	39
Actual required exploit	20	30	40	50

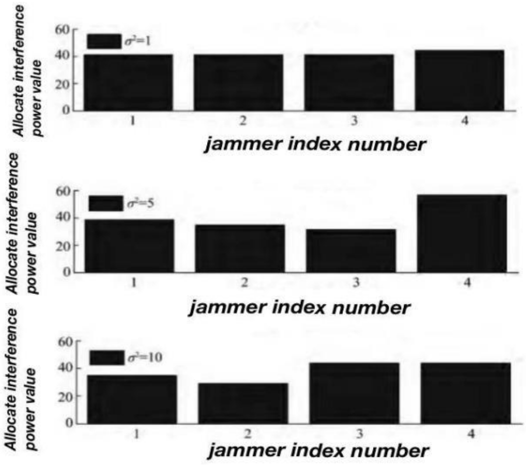

Figure 7. Power allocation of water filling algorithm under different SNR.

From Table 2 and Figure 7, it can be seen that the fourth illegal signal under =1W cannot be suppressed, the third illegal signal under =5W cannot be suppressed, and the fourth illegal signal under =10W cannot be suppressed. Although the first illegal signal can be suppressed successfully, the suppressing power is too large, causing unnecessary power waste. At low noise level, the water filling algorithm distributes power more evenly, so that all illegal transmitters can get good interference effect, but at the same time it causes a certain amount of power waste. When the noise level increases, such as the situation under =10W, some illegal transmitters do not get good interference at this time. For example, when the power allocated by the illegal transmitter with 40 W power is less than 40 W, the interference fails and the suppression of the illegal signal cannot be achieved. Therefore, it can be concluded that when the traditional water filling algorithm distributes power to deal with large differences in the transmission power of interference targets, it wastes a lot of power to distribute a large power to a low power signal, while the low power to distribute a high-power transmission signal cannot successfully suppress the interference signal. Therefore, the robustness of the traditional water filling algorithm needs to be further improved under high noise conditions.

4. Conclusion

In conclusion, the comparison between the FFR and water injection algorithms indicates that each algorithm has its own set of advantages and disadvantages that make them suitable for specific applications in different environments. The FFR algorithm is particularly useful in scenarios where interference between communication units needs to be minimized. In such cases, the algorithm can ensure efficient utilization of radio resources and reduce interference among adjacent cells. On the other hand, the water injection algorithm is useful in situations where the communication environment has a relatively low level of noise, such as in cognitive networks. However, in high noise environments, this algorithm may not be appropriate as it may lead to unstable and inefficient communication.

Overall, the selection of the appropriate algorithm for a given situation depends on various factors such as the nature of the communication environment, the level of noise, and the communication requirements. A careful evaluation of these factors is necessary to ensure that the algorithm used is suitable for the specific requirements of the communication system. Ultimately, a suitable algorithm can help to improve the performance and efficiency of wireless communication systems, leading to better user experiences and increased overall system reliability.

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