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Self-Optimizing Water-Filling Power Allocation: A Hybrid Fractional Frequency Reuse Way

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***Abstract*—Due to the development of 5G networks, wireless data traffic is accelerating at an unprecedented rate. To increase a cellular network's spectral efficiency (SE), the fundamental approach is handling the power allocation (PA). First, we proposed a SE-optimal self-optimizing water-filling (SOWF) power allocation method that considers each user's channel signal-to-interference-plus-noise ratio (SINR) while determining the power allocation scheme for all OFDMA subchannels of each user. A near-optimal forward-looking water-filling (FLWF) method was then devised to decrease computing complexity. The proposed algorithm enhanced the SE for sFFR and SFR situations compared to the simultaneous water-filling (SWF), and the integer frequency reuse (IFR) approaches. We eventually validate that the proposed algorithms surpass conventional techniques in diverse conditions with Monte-Carlo simulations. The numerical results indicate that the SOWF + IFR3 achieves the maximum SE, which is 53% higher than the conventional IFR1 + IFR3 and 29% higher than the traditional SWF in the sFFR scenario. In addition, by implementing the proposed SOWF + IFR3 algorithm in the SFR scenario, the network SE is comparable to that of the FLWF + IFR3 and SWF + IFR3 algorithms in the sFFR situation.**

***Index Terms*—Fractional Frequency Reuse, Soft Frequency Reuse, Water-Filling, Power Allocation**

I. Introduction

With the increasing demand for mobile data traffic and enhanced quality of services (QoS), it would be crucial to optimize spectrum resources and update the present power distribution method in a future wireless network to improve energy efficiency and expand spectral efficiency. With a variety of ways, the fifth-generation (5G) wireless technologies alleviate the growing load of existing data services [1]. Future 5G/6G wireless networks mainly aim at providing higher data rates, increasing the base station (BS) SE, and reducing the overall energy consumption [2].

Among all these wireless networks, the basic structure is the hexagonal cellular network for the BS. In addition, by using frequency reuse techniques, spectrum resources will be used more efficiently and across a greater geographical region. While frequency reuse approaches allow a wireless communication network to assign the same frequency channels to several cells, the integer frequency reuse (IFR) strategy developed for GSM systems reduces intercell interference compared to the traditional IFR method [3]. Only one-third of these spectral resources are now allocated to each cell when the reuse factor equals 3. And even if we apply the IFR1 in which all spectrum are utilized for each cell, there may still be severe co-channel interference at the cell boundary [4].

In OFDMA-based mobile cellular networks, inter-cell interference is a significant concern [5]. If the frequency resource is uniformly reused in every cell of the system, with no macro diversity and no quick power allocation scheme, users at the cell boundary would experience severe inter-cell interference and, thus, poor signal strength.

Fractional Frequency Reuse (FFR) and Soft Frequency Reuse (SFR) [6] have been evaluated as inter-cell interference (ICI) mitigation methods in an Orthogonal Frequency Division Multiple Access (OFDMA) based multi-cell deployed next generation wireless network [7], and the objective is to improve the spectral efficiency of wireless networks by distributing each cell's spectral resources such that the ICI in the multi-cell OFDMA network is decreased. [8]. OFDMA is a highly promising radio access technique that has been selected for the uplink and downlink air interfaces of the WiMAX fixed and mobile standards, IEEE802.16d and IEEE802.16e, respectively [9], [10].

As for FFR, sFFR [11] and SFR are the most common FFR deployment methods. While FFR may be used in both the uplink and the downlink, this research mainly concentrates on the downlink scenario.

Furthermore, power optimization of wireless networks has become a hot topic among 3GPP members as well as users. The next generation of networks will necessitate unrestricted access to data, resulting in higher energy consumption applications [12]. Resource management challenges include power allocation algorithms, relay selection, and interference reduction. As a result, power-constrained devices need to be supported with smarter power allocation schemes.

In this paper, we address the problem of maximizing the network SE at SFR and sFFR scenarios. To this end, we develop a novel, self-optimized power allocation algorithm for a multi-cell network that enables the BS to determine the best possible transmit power for each frequency channel. The major contributions of this paper are summarized as follows:

- We first analysis the overall spectral efficiency of the multi-cell network applying different power allocation algorithm in two different frequency reuse scenarios given the perfect channel state information (CSI).
- We then develop two hybrid power allocation algorithms, the SOWF is to reach the optimal SE, and the FLWF is to reduce the complexity in computing the network SE. First, we define a self-optimized water-filling (SOWF) power allocation algorithm with a flexible power thresh-

old that contributes to a higher SE than the traditional SWF [17]. Our second approach, namely FLWF, adopts the framework of the Nash game with forward-looking players [13], which acquire network-wide information to negotiate spectrum resources among themselves via a series of calculated competitions, thereby reducing convergence iteration times compared with SOWF and [14], [15].

- We also evaluate the complexity of the proposed algorithms compared to [17], [19], which validate the efficient equilibrium of the FLWF. The network SE in sFFR and SFR of different algorithms are compared based on the generated analytical equations and then confirmed using Monte-Carlo simulations. The comparison is performed by evaluating alternative algorithm combinations for the cell center and cell edge.

The rest of this paper is organized as follows. The system model and the mathematical derivations are presented in Section II. The analysis of the state-of-the-art and proposed algorithms are presented in Section III and IV. The numerical results for network SE are presented in Section V. Section VI concludes the work in this paper.

II. System Model with perfect CSI

In this paper, we consider a downlink OFDM model for an M-cell network, each equipped with a hybrid FFR power allocation, as shown in Fig. 1, where the direct link from the BS to the users in the same cell is the signal channels are indicated by green solid lines and interference channels from other BS are indicated by red dotted lines. Here, we define a set $m = \{1, 2, \ldots, M\}, i, j \in m, i \neq j$. And $\mathbf{h}_{i,i}$ is the channel matrix from the BS i to its user i, $\mathbf{h}_{j,i}$ is regarded as the channel matrix from the BS j to the user served by another BS i, which share the same frequency channels as BS j, which is the interference channel coefficient.

The same transmit power, p_1, is assumed for all users in the cell center, and the same transmit power, p_2, is assumed for user equipment (UE) at the cell edge. In this paper, the transmit power is from each base station (BS) to the user equipments (UEs). In addition, we assume that each user has access to all frequency channels provided by the cell's central base station. Due to the low transmit power and relatively great distance between cells that share the same frequency channels, we assume that there is no interference power across different frequency channels when OFDMA is used by users in each cell center. For general trade-off analysis of communication system designs, a simplified path-loss model that captures the majority of signal propagation's essence is helpful. Consequently, it will be used for the analysis that follows. This article examined the statistical performance of network SE under sFFR and SFR scenarios.

Owing to the fact that the transmit power of each BS is limited, the received power of each user within the same cell is subject to a threshold. Motivated by work [14], we also consider the following assumptions and constraints.

Assumption. 1. Each channel changes slowly enough that it can be considered fixed for the transmission duratione, making the information-theoretic results meaningful.

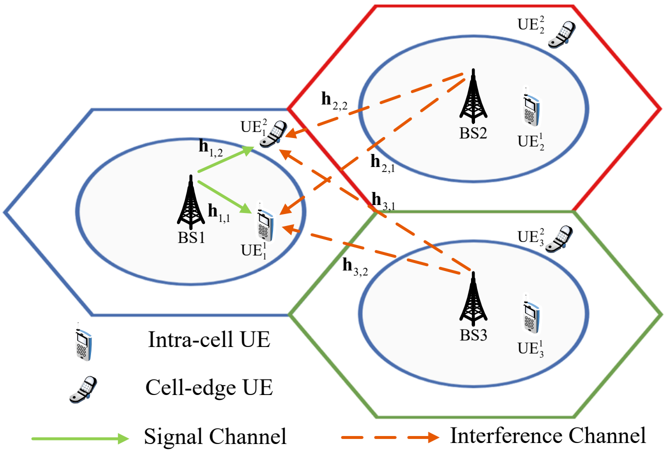

Fig. 1. A FFR based downlink network model.

Assumption. 2. All users are block-synchronized with a maximum degree of uncertainty equal to the length of the cyclic prefix. This enforces a minimum length for the cyclic prefix, which is dependent on the maximum channel delay spread.

Constraint. 1. The maximum received power threshold for the user in the specific cell is given by

$$\sum_{f=1}^{N_i} p^f \leq p_{\max}, \tag{1}$$

where p^f is the transmit power for the frequency channel f, and $p_{\max}$ is the threshold of one specific user, N_i is the frequency channel number of cell i.

Constraint. 2. The maximum transmit power threshold for a BS is given by

$$\sum_{u=1}^{U_i} \sum_{f=1}^{N_i} p^{u,f} \leq P_{\max}, \tag{2}$$

where $u = \{1, 2, \ldots, U_c\}$, $f = \{1, 2, \ldots, N_i\}$, U_i is the user number of cell i, and $P_{\max}$ is the BS's power threshold.

Path loss increases with distance, and the strength of the received signal or co-channel interference may be illustrated as

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2}, \tag{3}$$

where P_t represents the transmit power; $G_t(G_r)$ represents the transmit (receive) antenna gain; λ represents the wavelength, and d represents the distance.

More generally,

$$P_r = P_0 d^{-\alpha}, \tag{4}$$

where P_r denotes the UE's received power; P_0 denotes the BS's source power; d denotes the distance between the user and the BS; and α denotes the path loss exponent, which varies corresponding to the environment. In the following simulation, this simplified path loss model is adopted. Besides, we assume the channel state information of the system model is perfect, $\rho_{j,i}$ is the path loss parameter that adjusts the interference from

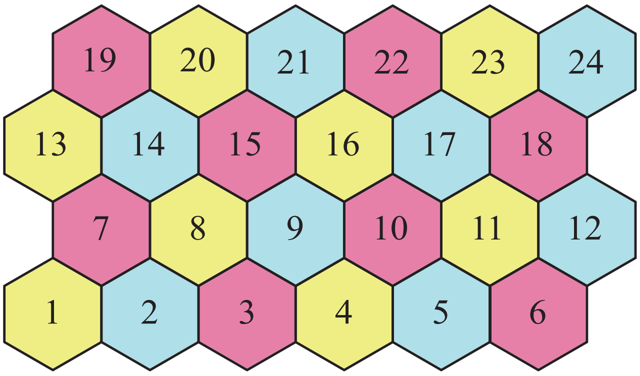

Fig. 2. Frequency allocation scheme for IFR3 in a 30-cell network.

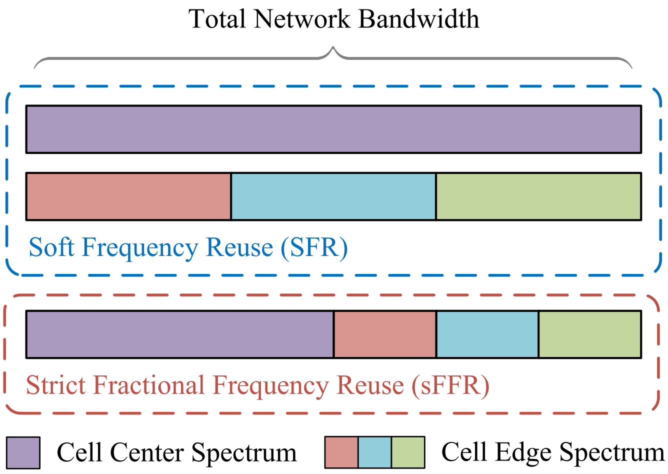

Fig. 3. Frequency reuse patterns for sFFR and SFR.

cell j to cell i, which can be calculated by $\rho_{j,i} = D_{j,i}^{-\alpha}$, $D_{j,i}$ is the distance between the BS in cell j and the i user in cell i.

III. The state-of-the-art algorithms

A. Spectral efficiency of integer frequency reuse

Regarding the cellular network, frequency reuse is an essential technology, and the majority of frequency allocation techniques are adapted from the classic frequency reuse for hexagonal cells. Therefore, it would be required to determine how frequency reuse works. Frequency Reuse Factor (FRF) is an important metric for IFR, and this component is always represented by N for all FRF that contribute to distinct frequency reuse patterns. The frequency reuse patterns are demonstrated by work [15]. After selection, cells within the same group will be assigned the same frequency batch. Then, to describe the frequency with various FRF, Fig. 2 uses different colors to represent distinct groups to show the frequency allocation schematic for a 24-cell network with FRF equals to 3. The IFR3 distributes the system's bandwidth into three subband groupings. Each cell is assigned different frequency channels from the sub-bands assigned to its neighbors.

Then, we analyse an M-cell network, the SE for the frequency channel f in the cell i can be calculated by

$$S_f^{i,u} = \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{|h_{i,i}|^2 p_i^u}{\sum_{j=1}^{M} \rho_{j,i} |h_{j,i}|^2 p_j + \sigma^2} \right) (i \neq j), \quad (5)$$

where $h_{i,i}$ is the channel coefficient from the BS i to its user, and $h_{j,i}$ is regarded as the channel coefficient from the BS j to the users served by another BS i, which share the same frequency channels; p_i^u is the transmit power from the BS i to the user u; p_j denotes the interference power from another BS j; σ^2 is the noise power, and in the following system, the noise is all considered as the zero-mean white Gaussian noise; Thus, the SE of a network using IFR can be derived as

$$S_{\text{IFR}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i} S_f^{i,u}, \quad (6)$$

As the FRF grows, each cell will suffer less interference because fewer channels will be allocated to each cell. Due to the sacrifice of spectrum resources, there will be less interference between cells using the same frequency channel, and the SE will increase. However, this strategy lacks sufficient flexibility, and the only option to get a high SINR is to employ a larger FRF, limiting the number of usable channels per cell. Moreover, it would be unbearable if there were an excessive number of unaddressable UEs per cell.

B. Spectral efficiency of FFR in sFFR and SFR scenario

Fractional Frequency Reuse (FFR) is a flexible method based on applying different frequency reuse methods for the cell center and cell edge. Each cell uses OFDMA technology at the cell center, so there is minor interference between users accessing orthogonal subcarriers [16].

Fig. 3 demonstrates the sFFR and SFR scenarios in the frequency reuse patterns. Each colour represents a defined group of the frequency channel, and the frequency channel varies in each cell center and edge. P_1 and P_2 denote the average power allocation for each user at cell center and cell edge. As for sFFR, there is no overlap between the cell center and the cell edge in this case.

The SE of all cell centers in a M-cell network is given by

$$S_{\text{center}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i^1} \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{|h_{i,i}|^2 p_1^f}{\sum_{j=1}^{M} \rho_1^{j,i} |h_{j,i}|^2 p_1^f + \sigma^2} \right), \quad (7)$$

The SE of all cell edges in a M-cell network is given by

$$S_{\text{edge}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i^2} \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{|h_{i,i}|^2 p_2^{u,f}}{\sum_{j=1}^{M} \rho_2^{j,i} |h_{j,i}|^2 p_2^{u,f} + \sigma^2} \right), \quad (8)$$

where U_i^1 denotes the number of users at the cell center of cell i and U_i^2denotes the number of users at the cell edge of cell i. Because the cell edge uses the IFR3 and will not have co-channel interference with the neighboring cell, $\rho_1^{j,i}$ and $\rho_2^{j,i}$ are path loss parameter matrices with the same dimension.

And for the entire network, the SE can be derived as

$$S_{\text{FFR}} = S_{\text{center}} + S_{\text{edge}}. \tag{9}$$

As the SE for the sFFR scenario is already defined, the frequency channel may be utilized more efficiently by applying SFR, which allows the same set of frequencies to be distributed to both the cell center and cell edge inside the same cell.

Then, for the SFR scenario, we have

$$\begin{aligned} S_{\text{SFR}} &= \sum_{i=1}^{M}\sum_{u=1}^{U_i}\sum_{f=1}^{N_i}\log_2\left(1+\frac{|h_{i,i}|^2 p_i^{u,f}}{I_1+I_2+\sigma^2}\right), \\ I_1 &= \sum_{j=1}^{M}\rho_1^{j,i}|h_{j,i}|^2 p_1, I_2 = \sum_{j=1}^{M}\rho_2^{j,i}|h_{j,i}|^2 p_2^{u,f}, \end{aligned} \tag{10}$$

where $p_t^{i,u}$ denotes the transmit power from cell i's BS to its user u, when the user is at cell center, p_t equals to p_1, for those at the cell edge, p_t equals to p_2^u. Besides, I_1 is the interference power from all cell centers, I_2 is the interference power from the cell edges where they share the same frequency channels.

Although the FFR and SFR mitigate the inadequacy of frequency channels for the cell center, it is not flexible enough to accommodate the growing data demands. To significantly minimize the interference in each cell center. Therefore, it is vital to employ other strategies to reduce the interference and increase network SE simultaneously.

C. Classical simultaneous water-filling power allocation

Considering a multi-user frequency allocation scenario, we can use Simultaneous Water-Filling power allocation to allocate each frequency channel's power for each user intelligently in OFDMA, and here we suppose $H_i^{u,f}$ is the channel coefficient from BS i for user u at frequency channel f. Then, the SE of user u in cell i is given by

$$S_i^u = \sum_{f=1}^{N_i}\log_2\left(1+\frac{p_i^{u,f}|H_i^{u,f}|^2}{\sigma^2}\right), \tag{11}$$

where $p_i^{u,f}$ denotes the power allocated for one specific frequency channel f in cell i for user u. And the maximization problem of SE with power constraints for user u is given by

$$\begin{aligned} \max_{\{p_i^{u,f}\}} S_{\text{SWF}}^u &= \sum_{f=1}^{N_i}\log_2\left(1+\frac{p_i^{u,f}|H_i^{u,f}|^2}{\sigma^2}\right), \\ \text{s.t.} \sum_{f=1}^{N_i} p_i^{u,f} &\le P_{\max}. \end{aligned} \tag{12}$$

Using the Lagrange multiplier method in [17] can help solve the maximization problem in (12)

$$\mathcal{L} = \sum_{f=1}^{N_i}\log_2\left(1+\frac{p_i^{u,f}|H_i^{u,f}|^2}{\sigma^2}\right) + \lambda\left(\sum_{f=1}^{N_i} p_i^{u,f} - P_{\max}\right), \tag{13}$$

where λ represents the Lagrange multiplier param.

For $\forall f$, set $\frac{\partial\mathcal{L}}{\partial p_i^{u,f}} = 0$, $\frac{\partial\mathcal{L}}{\partial\lambda} = 0$, we have

$$p_i^{u,f} = \left(\frac{1}{\lambda} - \frac{\sigma^2}{|H_i^{u,f}|^2}\right)^+. \tag{14}$$

Using the Karush-Kuhn-Tucker (KKT) conditions [18], classical water-filling's water-level $\frac{1}{\lambda}$ is the solution that satisfies

$$\sum_{f=1}^{N_i}\left(\frac{1}{\lambda} - \frac{\sigma^2}{|H_i^{u,f}|^2}\right)^+ = P_{\max}, \tag{15}$$

where $(x)^+ = \max\{0, x\}$.

Above is the explanation and derivation of the classical simultaneous water-filling power allocation scheme. In this algorithm, the water-level is static at each iteration, and it may result in excessive employment of the frequency channel, resulting in undesired co-channel interference. The computational complexity of SWF is decided by the SE calculation, especially the SINR calculation. Since the error tolerance δ and the maximum iteration number T_{max} are determined, the computational complexity is $\mathcal{O}(n^3)$. Therefore, the algorithm complexity needs to be mitigated to achieve a faster equilibrium.

IV. The Proposed Algorithms

A. Forward-looking water-filling power allocation

In this section, two power allocation algorithms, namely SOWF and FLWF, are used to utilize the frequency channel more efficiently and lower the complexity. Forward-looking Water-filling constructs a self-optimizing OFDMA cognitive radio network that approaches forward-looking equilibrium(FE) [19], which has no co-channel interference because the channels are orthogonal.The power allocation for user u at time t is updated by (16) using the previous power allocation information,

$$\begin{aligned} p_u^f[t] &= \left(w_u[t] - \frac{\left(c_u^f[t]\right)^2 + \varphi_u^f[t]\left(p_u^f[t-1]\right)^2}{c_u^f[t] - \varphi_u^f[t]p_u^f[t-1]}\right)^+, \\ \varphi_u^f[t] &= -\sqrt{\frac{c_u^f[t]}{2c_u^f[t] + p_u^f[t-1]}} \quad \forall u, \end{aligned} \tag{16}$$

where $w_u[t]$ is regarded as the water-level that meets the equality of the power constraint, $c_u^f[t] \triangleq \sigma_u^f[t] + I_u^f[t]$ corresponds to the overall noise on the frequency channel f for user u. And the power allocation is based on the forward-looking ability of each user. In instance, a cognitive transmitter may choose to allocate more power on its excellent subcarriers to enhance its SE but this may cause more interference with other users on these subcarriers. The SE maximization problem of user u is

$$\begin{aligned} \max_{\{p_i^{u,f}\}} S_{\text{FLWF}}^u &= \sum_{f=1}^{N_i}\log_2\left(1+\frac{p_u^f[t]|H_i^{u,f}|^2}{\sigma^2}\right), \\ \text{s.t.} \sum_{f=1}^{N_i} p_i^{u,f} &\le P_{\max}. \end{aligned} \tag{17}$$

Algorithm 1 Iterative-Based FLWF/SOWF PA algorithm

1: Initialize parameters M, $P_{\max}$, N, U, $p_{\max}$, ρ, h, σ^2, w
2: Set the maximum iteration times $T_{\max}$ and the convergence accuracy δ, set the initial iteration index $t = 0$.
3: **while** $\sum_{u=1}^{U_i} \sum_{k=1}^{N_i} \left|p_u^{t+1}[k] - p_u^t[k]\right| \geq \delta$ and $t \leq T_{\max}$ **do**
4: Calculate $p_u^t[k]$ using (16) or (19) for all the cell center.
5: Calculate the SE for all the cell center using (7) or (9).
6: Calculate the SE for all the cell edge using (8).
7: $t = t + 1$.
8: **end while**
9: Calculate the overall network SE: $S_{\text{FFR}} = S_{\text{center}} + S_{\text{edge}}$.

As for the entire network, the SE maximization problem can be formulated as

$$\begin{aligned} &\max_{\{p_i^{u,f}\}} S_{\text{FLWF}} = \sum_{i=1}^{M}\sum_{u=1}^{U_i} C_{\text{FLWF}}^{u}, \\ &\text{s.t.} \sum_{f=1}^{N_i} p_i^{u,f} \leq P_{\max}. \end{aligned} \tag{18}$$

In this paper, we first design an iterative-based FLWF (SOWF) hybrid power allocation algorithm, as shown in Algorithm 1, to solve the maximization problem in (18).

First, this algorithm aims to find the optimal values of all variables of (16) in each iteration. The network SE can then be determined using the power allocation technique. And to determine the greatest SE, we enter the subsequent iteration using previous data till convergence.

B. Iterative-based SOWF power allocation algorithm

When it comes to SFR scenarios, the classical SWF can hardly satisfy many users for its utilizing some intermediate frequency channel and introduce a strong co-channel interference. To be more specific, we introduce a self-optimizing parameter ξ that helps manage the level of interference. On this basis, the power updating scheme can be derived as

$$\begin{aligned} &p_i^{u,f} = \begin{cases} \left(w_u^t - \gamma_i^{u,f}\right)^+ & \text{if } \gamma_i^{u,f} \leq \xi_i^{u,f} \\ 0 & \text{if } \gamma_i^{u,f} > \xi_i^{u,f} \end{cases}, \\ &\sum_{f=1}^{N_i} \left(w_u^t - \gamma_i^{u,f}\right)^+ = P_{\max}, \end{aligned} \tag{19}$$

where $\gamma_i^{u,f} = \frac{\sigma^2}{|H_i^{u,f}|^2}$, and the self-optimizing $\xi_i^{u,f}$ can be calculated by

$$\tilde{\xi}_i^{u,f} = \max\left(\xi_i^{u,f}, \frac{\sum_{u=1}^{U_i} c_u^f \text{sgn}\left(p_i^{u,f}\right)}{\sum_{u=1}^{U_i} \text{sgn}\left(p_i^{u,f}\right)}\right). \tag{20}$$

In this way, the UE only uses the frequency channels with the small amount of interference. Therefore, the spectral efficiency of the system has been further improved.

According to Algorithm 1, the computational complexity of SWF is decided by the SE calculation. When the error tolerance and the maximum iteration number T_{max} are determined, the computational complexity for these three algorithms is $\mathcal{O}(n^3)$. However as for SOWF, we sacrifice 35% of the complexity for mitigating co-channel interference. Besides, for the sFFR scenario, the FLWF affords savings in numerically computing the optimal power allocation for each user as the number of terms in the power updating drops from 105.249 to 59.422 in sFFR scenario.

TABLE I
AVERAGE NUMBER OF ITERATIONS FOR CONVERGENCE

Scenario \ Algorithm	SWF	FLWF	SOWF
sFFR	105.249	59.422	140.353
SFR	150.672	92.342	207.426

V. SIMULATION RESULTS

In this section, simulation results are shown to verify the performance of the proposed method. The system SE will be used to assess the performance of different power allocation algorithms requiring full network CSI. We evaluate a multi-cell network and assume a 6-subcarrier OFDMA system to the cell center and 6 for the cell edge, utilizing the Poisson distribution to determine the number of users in each cell and the Poisson point process to determine the location of each user. The cell center and cell edge radius are 150 m and 200 m, respectively, since the 200 m cell radius often has less interference but lower spectral efficiency [20]. Other simulation parameters are presented as follows: $U_c = 12$, $p_{\max} = 35$ dBm, $P_{\max} = 46$ dBm (with 12 UEs) [21], $\alpha = 3$, $T_{\max} = 300$, $\delta = 10^{-3}$.

Fig. 4 provides a numerical comparison between SOWF + IFR3, FLWF + IFR3 and SWF + IFR3 of many independent runs for various SNR in the sFFR scenario. As the plot indicates, the hybrid power allocation using SOWF + IFR3 has the highest SE for both the 20 and 30 cell configurations. Besides, the proposed SOWF algorithm improves the SE by 26% and 29% compared to the FLWF method and the SWF approach, respectively. Also, the simulation results of FLWF + IFR3 reduce the computational complexity and reach a slightly 3% growth of SE.

To provide a complete comparison between SOWF, FLWF , SWF and IFR, in Fig. 5, we present the average system SE for a 30-cell network under sFFR and SFR scenarios. The plot shows the SOWF + IFR3 has reached the highest SE in sFFR. The SOWF + IFR3 is 53% higher than the traditional IFR1 +IFR3 algorithm and nearly 30% higher than SWF + IFR3, the same is true in SFR with stronger intra-cell interference.And even in the SFR, the SE of SOWF + IFR3 is approximate to the other two algorithms in sFFR scenario.

Besides, since the sFFR has a better SE performance than SFR in SE as it has less co-channel interference, the SOWF can offset the co-channel interference to a large extent and help the BS determine a flexible overall power allocation scheme.

VI. CONCLUSION

In this paper, we first proposed a SE-optimal SOWF power allocation algorithm, which incorporates each user's channel

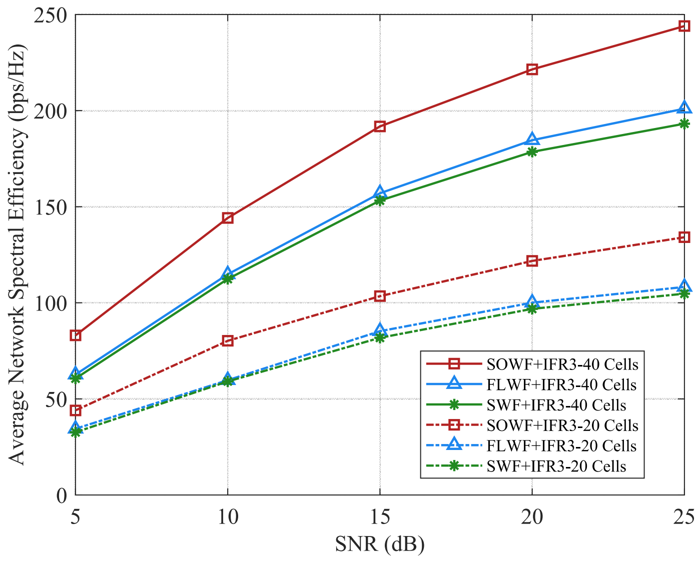

Fig. 4. Network SE in sFFR scenario with differnt cell settings.

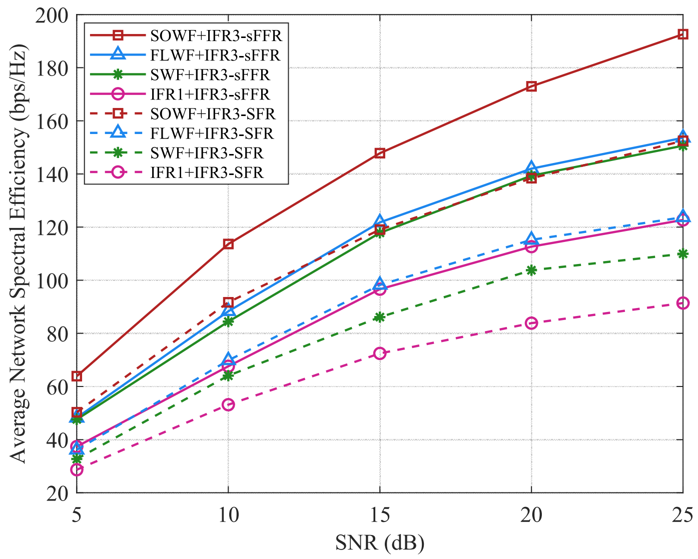

Fig. 5. SE comparison between sFFR and SFR with different algorithms.

SINR correlation to determine the power allocation scheme for all the subchannels of each user for OFDMA subchannels. After that, a near-optimal FLWF approach was proposed to reduce the complexity of computing the optimal power allocation scheme. The SOWF is found to outperform the other two methods, but it has a slightly higher complexity in both sFFR and SFR scenario.

Numerical results indicate that the SOWF + IFR3 obtain the supreme SE, and it is 53% higher than the traditional IFR1 + IFR3, nearly 30% higher than the classical SWF in sFFR scenario. Besides, by applying the proposed SOWF+IFR3 algorithm in SFR scenario, the network SE is found to be approximate to the FLWF+IFR3 and SWF+IFR3 in sFFR scenario but still greater than applying a conventional IFR1+IFR3 algorithm for both scenarios.

Future work involves developing more intelligent power allocation schemes with lower computational complexity. Analyzing system SE with imperfect CSI and incorporating additional energy efficiency or outage probability constraints at the UE or BS are other interesting avenues for future work.

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