A New Cellular-Automata-Based Fractional Frequency Reuse Scheme

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***Abstract*—A fundamental challenge in orthogonal-frequency-division-multiple-access (OFDMA)-based cellular networks is intercell interference coordination, and to meet this challenge, various solutions using fractional frequency reuse (FFR) have been proposed in the literature. However, most of these schemes are either static in nature, dynamic on a large time scale, or require frequent reconfiguration for event-driven changes in the environment. The significant operational cost involved can be minimized with the added functionality that self-organizing networks bring. In this paper, we propose a solution based on the center of gravity of users in each sector. This enables us to have a distributed and adaptive solution for interference coordination. We further enhance our adaptive distributed FFR scheme by employing cellular automata as a step toward achieving an emergent self-organized solution. Our proposed scheme achieves a close performance with strict FFR and better performance than SFR in terms of the edge user's sum rate.**

***Index Terms*—Author, please supply index terms/keywords for your paper. To download the IEEE Taxonomy go to http://www.ieee.org/documents/taxonomy_v101.pdf.** AQ1

I. Introduction

ONE of the key challenges in orthogonal frequency-division multiple access (OFDMA)-based cellular networks is intercell interference (ICI). Various interference management schemes (averaging, avoidance, and coordination) have been proposed to mitigate ICI. Coordination of ICI is often adopted due to its improved performance and spectral efficiency compared with interference averaging and avoidance [1]. To achieve intercell interference coordination (ICIC), variants of the fractional frequency reuse (FFR) scheme in [2] and [3] have been proposed in the literature, which reduce the amount of ICI received by cell-edge users and give good performance based on their target performance metrics such as signal-to-interference-plus-noise ratio (SINR), spectral efficiency, outage probability, and system throughput. All of these schemes exploit either frequency or power or both to achieve ICIC. However, these schemes do not give due consideration to the fact that in real networks, user distribution is nonuniform as it varies with seasons and the occurrence of major events. This is an important challenge and has also been identified in [4], where the introduction of liquid radio, which combines heterogeneous networks, coordinated multipoint transmission, and a self-organizing network is described to break the rigid architecture of today's network to a flexible, adaptive, and intelligent network.

In this paper, we focus on the fact that in FFR schemes, modeling a fixed region of cell edge and cell center in all cells irrespective of user positions is not optimum for a dynamic cellular system. There is thus an opportunity to simultaneously exploit power, frequency, and space (user location) to self-organize ICIC. With accurate knowledge of user positions (which is feasible with smartphones), a more dynamic and adaptive scheme can be developed, which adapts to medium- and long-time-scale user position variations. We thus propose a solution that directly correlates the geographical position of users to their available resources (bandwidth and power). A majority of users at the cell borders have their SINR below the desired SINR threshold and are thus referred to as cell-edge users, whereas the other users above this threshold (usually closer to the serving eNodeB) are referred to as cell-center users.

In general, any resource allocation procedure has two steps: first, the allocation of resources to the geographical regions or cells and second, the allocation of resources to the users in that region or cell. Our focus in this paper is on the first step in the resource allocation.

A novel FFR scheme based on cellular automata (CA) for ICIC is presented. To achieve this, we characterize the user distribution in each sector by its center of gravity (CoG). This helps classify each sector in different configuration states. Next, we employ an evolutionary algorithm called *cellular automata* to demonstrate its self-organizing functionality in the wireless cellular networks. In this paper, we compare the performance of various FFR schemes showing how system performance varies with the classification of users in the cell-edge or cell-center region. This classification, which we will show later, is based on the ratio of the radius of the cell-center region to the radius of the cell sector. We further present a distributed and adaptive FFR scheme that is dependent on the user distribution in each sector of a cell site. The regions of cell edge and cell center are not fixed across the entire network or a particular site but vary on a medium time scale (seasonal change in user distribution)

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in each sector. Thus, based on the user distribution, the system can autonomously adapt the region of cell edge and cell center and thus the resource allocation to users. This adaptive scheme provides a significant improvement in system performance.

A. Emergent Patterns in Cellular Networks

The concept of emergence is an integral part of self-organizing systems in nature. Emergence can be understood as resultant behavior at a macrolevel based on interactions of a system's constituent parts at a microlevel [5].

In the specific context of self-organization in wireless cellular networks, various definitions, design principles, and methodologies have been outlined in [6]. One interesting finding is how self-organized systems in nature follow simple rules that result in an emergent pattern. Dynamical systems with an emergent pattern have a global behavior due to interactions among local neighbors. These global patterns can neither be traced back taking the individual components in isolation nor can the process be easily modeled analytically due to their increased statistical complexity. Important characteristics of self-organized systems include system adaptability, autonomy, scalability, and stability. In designing such self-organized systems, any emergent patterns that result from localized interactions among the system components should also be adaptive to variations of its operating environment.

In this paper, we apply CA theory, which is an efficient method in modeling biological complex systems, to combine adaptive emergent patterns as a first step in achieving a self-organized system by modeling an interference coordination scheme among neighboring cells. The key concept here is that the power allocation for cell-edge and cell-center users is dependent not only on the user distribution in a sector but on the cell-edge area, power allocation, and user distribution of neighboring sectors as well. We have interestingly discovered from our results that using simple localized rules among a defined neighborhood results in an emergent pattern that meets the desired system objective.

B. New CA-Based FFR Scheme

For a cloverleaf cellular system model [7], each sector has two regions, namely, an inner region close to the serving eNodeB referred to as the cell center and the remaining outer region referred to as the cell edge. These regions can be varied, and we first show that the ratio of the cell-edge area to the cell-center area influences the system performance. This ratio is one of the major factors that determine the power amplification factor for cell-edge users in soft frequency reuse (SFR). We also vary the ratio of power transmitted to cell-edge and cell-center users in accordance with the variation in user distribution among neighboring sectors. We are able to provide an analysis of the relationship between the ratio of the cell-edge area to the cell-center area and power amplification factor.

Our major contribution is in proposing an adaptive and autonomous FFR scheme by applying CA theory whose motivation is from nature where self-organization can result as an emergent pattern. This is based on applying simple rules in a defined local neighborhood, which we also apply for ICIC via FFR.

C. Paper Outline

The rest of this paper is organized as follows: In Section II, we give an overview of OFDMA-based cellular networks and then provide the fundamentals of frequency reuse schemes deployed in such networks. We expand on interference analysis in FFR schemes and on resource sharing between cell-edge and cell-center users. In Section III, we introduce CA theory, providing fundamental definitions and properties. We also mention previous attempts in the literature aimed at applying CA in wireless cellular networks. Section IV describes our system model, and we formulate our problem based on determining an optimum resource allocation characteristic for each individual cell with the objective of applying a more distributed, adaptive, and autonomous FFR scheme. Section V describes our proposed solutions based on CoG and an enhancement of this using CA to show an emergent behavior. We discuss the simulation results obtained in Section VI and conclude in Section VII with a summary of findings and contributions. We also highlight limitations of the proposed scheme and suggest potential areas for future research.

II. Overview of Resource Allocation Schemes in an Orthogonal Frequency-Division Multiple Access-Based Cellular Network

An interesting fact that governs cellular system design is that the signal power falls off with distance. It allows frequency resource to be reused at a spatially separated location such that signal power diminishes to the extent that it does not cause any significant interference. The distance at which the frequency resource can be reused is known as the *reuse distance*. This concept of *frequency reuse*[8] helps in increasing the system capacity, while making the system interference limited. The interference due to frequency reuse is known as *intercell interference* (ICI). Here, we give an overview of an OFDMA-based cellular network, the preferred solutions to reduce ICI, and the various static and dynamic resource allocation schemes deployed therein. Our emphasis is on determining the resource partitions and transmit power for dynamic reuse schemes. We also illustrate the metrics used for performance evaluation and comparison of the different reuse schemes.

A. OFDMA-Based Cellular Network

The ability of orthogonal frequency-division multiplexing (OFDM) to combat frequency-selective fading for downlink data transmission justifies its use in current and future cellular networks. OFDM transforms the wideband frequency-selective channel into several narrowband channels, which are known as *subcarriers*. It transmits the digital symbols over a group of subcarriers for a user, with certain transmit power and modulation and coding scheme (MCS). Due to the narrowband subcarriers, each transmission undergoes flat fading. This makes the system robust to multipath fading and narrowband interference [8]. In a multiuser environment, each subcarrier may exhibit different fading characteristics to different users at different time instants. This is due to the time-variant wireless channel and the variation in the user's location. This feature can be advantageous by assigning subcarriers to those users who can use them in the best possible way at that particular time instant. Such an OFDM-based multiple-access scheme is known as OFDMA. In OFDMA, a contiguous or noncontiguous set of subcarriers[1] are allocated to a user for a predetermined time interval. This is known as a physical resource block (PRB) as per the Third Generation Partnership Project Long-Term Evolution (3GPP-LTE) specifications [9]. Thus, PRBs have both time and frequency dimension, and it is the minimum resource that can be allocated to a user. In addition to PRB allocation, the transmit power and MCS can be varied based on the channel condition at the level of the subcarrier group assigned to a user. Thus, OFDMA facilitates flexible resource planning due to the granularity of the resources available for allocation.

To maximize spectral efficiency, next-generation systems recommend frequency reuse of 1, i.e., each neighboring cell uses the same resources. In such a case, different users in the neighboring cells may use the same PRB, and if the signals are strong enough, users (particularly the cell-edge users) are likely to suffer from severe ICI. Various interference management (averaging, avoidance, and coordination) schemes have been proposed to combat ICI [3]. ICIC is often adopted due to its improved performance and spectral efficiency compared with other schemes [7]. To achieve ICIC, different variants of FFR schemes have been proposed in the literature, which essentially allocates different resources to the interfering areas of neighboring cells. Such schemes reduce the amount of ICI experienced by the cell-edge users. The different variants of FFR schemes are illustrated in the following section.

B. *Variants of FFR Schemes*

To illustrate and compare the different variants of FFR schemes, we have used the cloverleaf cellular system model in this paper, where each cell site comprises three hexagonal sectors with one eNB (base station is known as eNodeB (eNB) in the LTE standard) located at the common vertex of these three sectors. The hexagonal geometry of sectors is used as an approximation for irregular or sometimes circular shape of a cell coverage area. The motivation for the cloverleaf model is that it appropriately demarcates the radiation pattern of a cell site utilizing three sector antennas, as shown in Fig. 1. We give an overview of the widely used static and dynamic reuse schemes in the following sections.

1) Static Reuse Schemes: Due to the fact that cell-edge users are more prone to ICI compared with cell-center users, the cell-edge users are usually allocated a distinct frequency resource. The users are classified as cell center or cell edge based on either their geographical location in the cell or their experienced signal-to-interference-plus-noise ratio (SINR) from the eNodeB (which is indicative of the ICI they experience), and then, different reuse patterns can be applied. When the resources allocated for cell-center and cell-edge users are fixed, the scheme is said to be *Static*. Static ICIC schemes exhibit lower implementation complexity and less overheads. When the fixed resource partitions are integer in number, it is known as *integer frequency reuse scheme*. For example, *Frequency Reuse 1* (FR1) is typically deployed in an OFDMA-based cellular network, where all cells in the system are allowed to use the same resources without any restrictions, as shown in Fig. 2(a). All resources are available in all cells, and the resource utilization efficiency is high and gives good performance during low traffic conditions. When the traffic load (i.e., user density) increases, the interference effects cannot be neglected, and significant ICI is experienced by the cell-edge users.

[1]It is known as a subchannel in OFDMA. However, we will not differentiate between the terms subcarrier and subchannel in this paper.

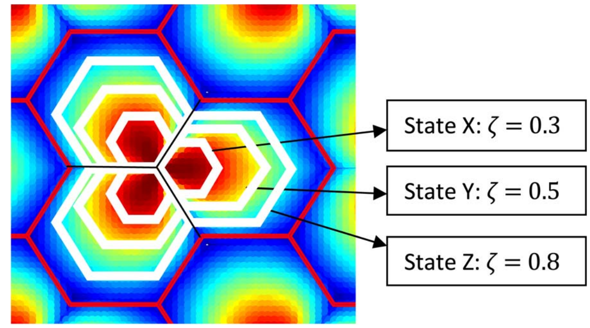

Fig. 1. Defining cell sector states.

To alleviate this problem of ICI at the cell edge, a frequency reuse scheme with a higher reuse factor (frequency reuse 3) can be deployed. In *Frequency Reuse 3* (FR3), adjacent sectors operate on three different subbands, which, in total, constitute the available number of subbands [see Fig. 2(b)]. Due to the use of distinct subbands in neighboring cells, the problem of ICI is mitigated to a large extent. However, with this subband partitioning, the available number of resources in each sector is reduced to one third. This penalty in terms of reduced resource utilization efficiency is paid to achieve improved edge user's performance.

With *FFR schemes*, it is possible to have a tradeoff between achieving high resource utilization efficiency as in FR1 and improved edge user's performance as in FR3. It is clear that resource partitioning is beneficial in improving edge user's performance. However, the cell-center users do not suffer from ICI, and therefore, resource partitioning is not a key factor in characterizing their performance. FFR schemes exploit these facts and use a combination of the two integer frequency reuse schemes previously mentioned to achieve this tradeoff. The key concept of all FFR schemes is that the cell is geographically divided into two regions: cell center and cell edge with FR1 deployed for cell-center users and FR3 for the cell-edge users.

There are different variants of FFR in the literature. One of the most predominant is *strict FFR (S-FFR)*, in which the cell-center region deploys FR1, and the edge region deploys FR3. Thus, cell-center users do not share the spectrum with the edge users, as shown in Fig. 2(c). This scheme improves the cell-edge performance substantially but compromises on the system throughput and resource utilization due to the availability of only a quarter of the total resources in the cell-center and cell-edge region.

Another approach to improving the resource utilization efficiency and system performance is to exploit the two dimensions

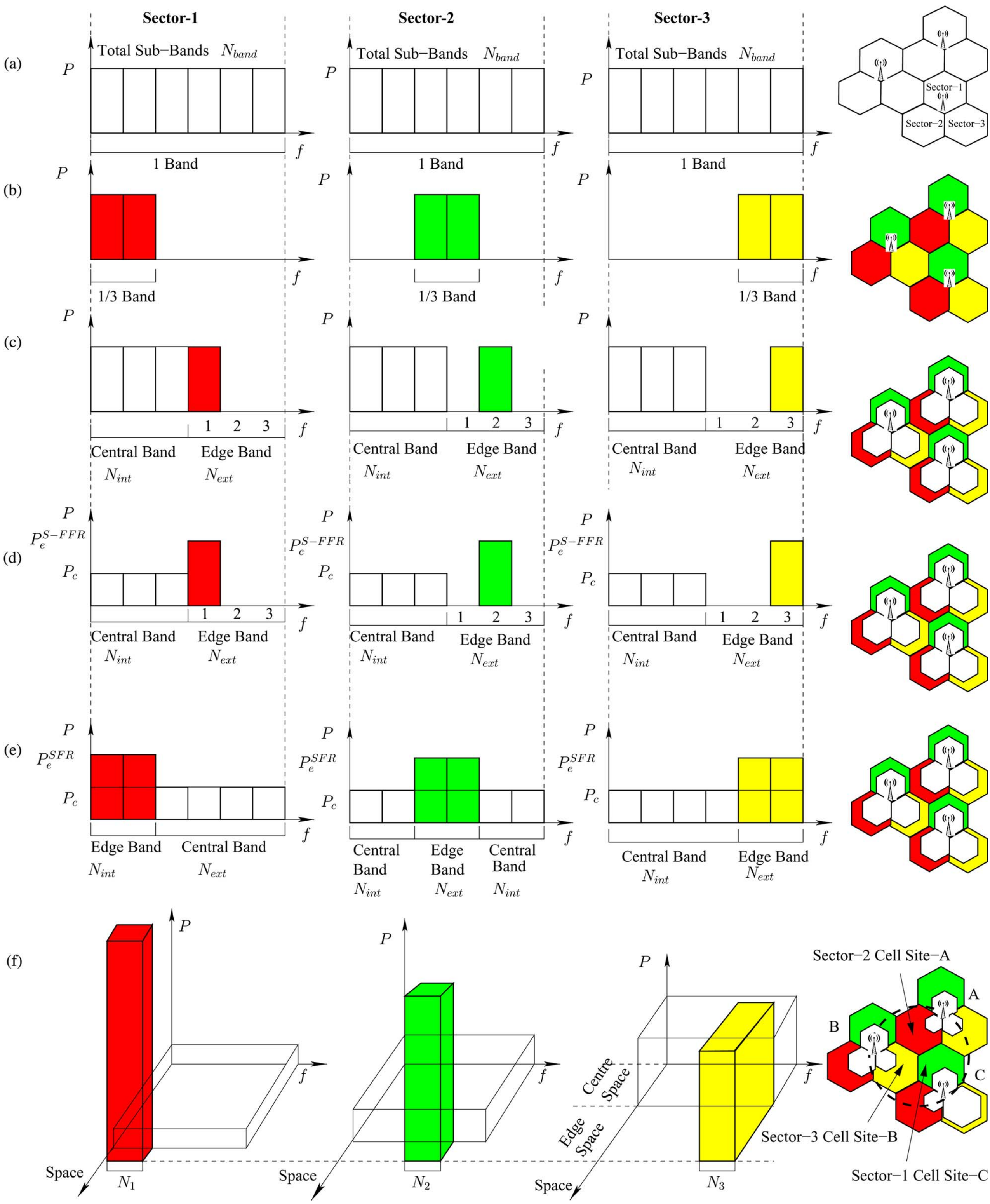

Fig. 2. Different reuse schemes for OFDMA-based cellular networks. (a) FR-1. (b) FR-3. (c) Strict FFR. (d) Partial reuse. (e) SFR. (f) Proposed FFR.

of resources available: spectrum and power. *Partial reuse* [10] and *SFR*[2] are two such schemes widely reported in the literature. They involve power control along with applying different reuse factors to the cell center and cell edge. Partial reuse employs the same resource partitioning strategy as S-FFR, with the only difference being the resources reserved for cell-center users are utilized with a lower power level, whereas a reuse factor of 3 with a higher power level is deployed for the cell-edge users [see Fig. 2(d)].

SFR [3], [11] is one of the FFR schemes that efficiently exploits the power and spectrum resources. It employs the same

[2]Throughout this paper, our reference to SFR is in accordance to the original scheme proposed in [3] and [11]

resource partitioning and power allocation strategy as the partial reuse scheme; however, in SFR, all resources are available for the cell-center users if they are unused by the users at the cell edge of the same sector. However, the resources used by cell-center users are at a lower power level and can also be used by cell-edge users in neighboring cells. This is achieved by employing power control for users that use the same band (low power for users in the center region and high power for users in the edge region of the neighboring cell). This is also shown in Fig. 2(e).

2) Dynamic Reuse Schemes: All the static reuse schemes implement fixed resource partitioning and, therefore, hard limits the achievable user throughput. In dynamic reuse schemes, a flexible resource partitioning is performed between the cell-center and cell-edge users, which can be based on factors such as the amount of interference power experienced by users and the traffic density. Such schemes have the potential of achieving efficient resource utilization and improved system throughput.

A dynamic reuse scheme has been proposed in [12], which the authors refer to as "softer" frequency reuse (SerFR). Here, the reuse factor for both cell-center and cell-edge users is 1, and a modified proportional fair scheduler is used, which gives preference to edge users over cell-center users and ensures fairness among them as well. It is thus essential for resource management algorithms to adapt to system dynamics while keeping the flexibility of using the entire spectrum resource in every region. The idea is to keep the resource planning adaptive with no inherent constraints from a design perspective.

In general, dynamic resource plans for interference mitigation are proposed in [13] and [14] and tend to perform better than their static counterparts due to the fact that they provide the flexibility of using all the available resources. The generation of soft-FFR patterns in a self-organized manner is featured in [15] and [16], where resource allocation (i.e., determining the number of subcarriers and power assignment) is performed by dynamically adapting to the traffic dynamics for a constant bit rate and best-effort traffic. They have compared the performance for two cases, i.e., with and without eNBs coordination, and showed that performance is better with coordination.

Mehta *et al.* in [17] have proposed one variant of dynamic FFR specifically tailored for a relay-assisted cellular network, which performs an intelligent allocation of resources such that no two neighboring edge regions are allocated the same channels. Such a scheme based on the interfering neighbor set gives improved edge user's throughput and area spectral efficiency (ASE) compared with all other variants of reuse schemes. However, in the case of nonuniform traffic density, the resource allocation policy does not perform very well. Thus, we observe that no particular reuse policy works for all possible scenarios. If a policy is optimal for a given scenario and improves one performance metric, then it compromises on other metrics. Moreover, the variation in user traffic density affects the performance of the reuse policy, which needs to be taken into account.

An illustration of determining the transmit power and interference calculation for the different reuse schemes is given in the following section.

C. Resource Partitions and Transmit Power Levels for Dynamic Reuse Schemes

The maximum transmit power available in the cell is influenced by the reuse scheme because different fractions of resources are available for cell-center and cell-edge regions of the cell for different reuse schemes. We illustrate the concept further as follows.

Let P_T be the maximum transmit power budget in the cell.
Let P_{PRB} be the transmit power per PRB.
Let N_{band} be the total number of PRBs available in the system.
Let N_{int} be the number of PRBs used by center users in a sector.
Let N_{ext} be the number of PRBs used by edge users in a sector.

Assuming equal power allocation, the transmit power per PRB for FR1 in each sector will be

$$P_{\mathrm{PRB}} = \frac{P_T}{N_{\mathrm{band}}}. \tag{1}$$

For S-FFR, the number of PRBs available in the cell-center and cell-edge region will depend on the ratio of cell-center area to cell-edge area [18]. Let s_{int} represent the radius of the cell-center region and s_{ext} the radius of the entire sector. For cell-center users

$$N_{\mathrm{int}} = N_{\mathrm{band}} \times (s_{\mathrm{int}}/s_{\mathrm{ext}})^2 \tag{2}$$

and resources for cell-edge users will thus be

$$N_{\mathrm{ext}} = (N_{\mathrm{band}} - N_{\mathrm{int}})/3. \tag{3}$$

The factor 3 is due to the minimum number of nonoverlapping sector edges. This is synonymous to the chromatic index in graph coloring [19].

The power transmitted to cell-center users and cell-edge users will be

$$P_c = P_{\mathrm{PRB}} \times N_{\mathrm{int}} \tag{4}$$

$$P_e^{(\mathrm{S-FFR})} = P_{\mathrm{PRB}} \times N_{\mathrm{ext}}. \tag{5}$$

In SFR, the calculation of N_{ext} changes as the users in the cell-edge area have their received power boosted by the power amplification factor β_s. The amount of PRBs used in the cell edge is not dependent on that used in the cell center as was in the case of S-FFR. Cell-center users can use a maximum number of PRBs available irrespective of the allocation to cell-edge users. Thus N_{int} can be obtained using (2), whereas the number of PRBs available to cell-edge users is

$$N_{\mathrm{ext}} = \max[N_{\mathrm{band}}/3, N_{\mathrm{band}} - N_{\mathrm{int}}]. \tag{6}$$

The power transmitted to cell-center users will be the same as in the case of S-FFR given in (4), and the power transmitted to cell-edge users will be

$$P_e^{(\mathrm{SFR})} = \beta_s \times P_{\mathrm{PRB}} \times N_{\mathrm{ext}}. \tag{7}$$

D. System Performance Metrics

1) SINR and Sum Rate: The SINR performance of users gives a good indication of their received signal strength and the amount of interference. Other metrics to characterize system performance are also usually a function of SINR. One such metric is the sum rate, which represents the available rate achieved by all users. In the results presented later in Section VI, we show the sum rate of cell-edge users for different frequency reuse schemes and the total system sum rate. However, a tradeoff is expected between achieving a high sum rate and maximum resource utilization.

2) Outage Probability: We also consider outage probability as one of the performance metrics in our analysis. We consider a user to be in outage if it experiences SINR below a predefined threshold, i.e.,

$$\text{Prob}(\text{outage}) = \text{Prob}(SINR > SINR_{\text{threshold}}). \quad (8)$$

As the cell-edge users are more prone to ICI, they are likely to experience low SINR and, hence, remain in outage. The outage probability comparison for cell-edge users is therefore significant when comparing different reuse schemes.

Outage probability is expected to be higher in systems using frequency reuse of 1 compared with systems employing FFR schemes. In SFR, as the power allocated to edge users is increased, the lower the probability of users having their SINR below the required threshold.

3) ASE: The spectral efficiency is measured as the maximum achievable throughput (bits per second) per unit of bandwidth. Its unit is bits/sec/Hz and is evaluated as

$$\eta_{\text{SE}} = \frac{1}{\mathcal{B}} \sum_{k \in \mathcal{K}} \mathcal{B}_k \log_2(1 + SINR_k) \quad (9)$$

where $\mathcal{K}$ is the set of users in the system, $\mathcal{B}$ is the total system bandwidth, $\mathcal{B}_k$ is the bandwidth of the PRBs used by each user, and $SINR_k$ is the $SINR$ of user k.

As compared with spectral efficiency, ASE is the measured throughput per hertz per unit area for a given cell resource [20]. This gives a practical representation of the improvement in capacity achieved relative to cell size (and reuse distance) with available resources. This is one of the significant performance metrics used to compare different frequency planning schemes, which greatly impacts cellular system design. This determines achievable system throughput per unit frequency per unit area (bits/sec/Hz/km^2). It is computed as

$$\eta_{\text{ASE}} = \sum_{r \in \mathcal{R}} \frac{\frac{1}{\mathcal{B}} \sum_{k \in \mathcal{K}} \mathcal{B}_k \log_2(1 + SINR_k)}{A_r}. \quad (10)$$

$\mathcal{R}$ is the set of all nonoverlapping regions, and A_r is the area of any region r.

III. Cellular Automata

CA is a *new kind of science* that can be used to model complex dynamic systems [21]. They are large decentralized systems made up of simple identical components with defined localized neighbor relations. The state of individual simple components (usually referred to as cells) synchronously changes and is triggered by state updates in neighboring cells. These updates are based on local rules and previous states of neighbors. CA is suitable for modeling autonomous systems, as the fundamental concepts use inspiration from complex biological systems. These natural systems are autonomous and made up of large numbers of small cells. The basic idea is that a system that needs to be automated is modeled as an aggregation of a large number of small cells. Each cell follows simple rules and updates its individual states based on its current state and that of the neighboring cells [21]. Detailed studies on modeling dynamic systems using CA can be found in [22]. Emergence and self-organized systems in nature have similar operational principles to CA. It is thus inferred from the literature that CA is one of the most extant natural approaches toward designing self-organized networks [23].

In applying CA algorithms, a neighborhood function must be clearly defined. This determines the cell states that affect the future states of the reference cell. Various types of neighborhoods can be defined, but the most common are the Von Neumann, Moore, and Hexagonal [22]. We adopt a hexagonal neighborhood as it is analogous to our system model for wireless cellular communication networks where we consider the coverage of each eNodeB's sector to be hexagonal in shape.

A 2-D CA can be represented as a five tuple $(\mathcal{W}, N, \psi, \zeta, t)$, where the following statements hold.

- $\mathcal{W}$ is the lattice 2-D cell represented by hexagons at position (x, y), $\mathcal{W} = \{\mathcal{W}_n, n = 1, 2, \ldots, \mathcal{N}\}$.
- N is the neighborhood set, a finite subset of $\mathcal{W}$, $N \subset \mathcal{W}$, $N = \{\boldsymbol{n_1}, \boldsymbol{n_2}, \ldots, \mathbf{n}_{\boldsymbol{\mathcal{N}}}\}$.
- ζ is a finite set of configuration states of each cell, $\zeta_i^{t+1} = f(\zeta_{i-\mathcal{N}}^t, \ldots, \zeta_{i-1}^t, \zeta_i^t, \zeta_{i+1}^t, \ldots, \zeta_{i+\mathcal{N}}^t)$, where ζ_i^t is the state of cell i in time t.
- ψ is the localized rule that triggers the state transition. The local rule is a function $f : \zeta^{\mathcal{N}} \to \zeta$, where $\mathcal{N}$ is the size of the neighborhood.
- t is the transition time of a cell moving from its current state to its final state.

The neighborhood vector N determines the neighborhood relationship or better described as the neighbor cell list. We give more insights into the neighborhood relation we use in our proposed solution in Section V. The transition time is important to prevent frequent change of states, which may lead to instability and increased system convergence time.

CA have many diverse properties, but we highlight relevant properties for our work as follows.

- CA systems are complex systems but consist of a large number of simple objects.
- Evolution of each component is based on interactions with their localized neighborhood.
- They follow simple rules and result in an emergent pattern.
- All components synchronously operate in parallel.

In wireless cellular communication systems, it has been established that adaptive and autonomous systems depend on local interactions with their neighbors, which results in an emergent pattern. In simulating such large dynamic complex systems, CA is a viable approach.

Some attempts have been made to apply CA in wireless cellular systems in general. In [24], we provide an introduction to CA as a viable tool for self-organizing solutions in wireless cellular systems, proposing potential use cases in addressing ICIC and energy efficiency challenges. In [25], a self-organized channel assignment scheme using CA theory with distributed control has been presented. Therein, Beigy and Meybodi used learning automata to adjust the state transition probabilities. The most significant application of CA is the work by Ho *et al.* in [26], where a CA-based approach toward coverage optimization has been developed. They describe how each base station updates its neighbor cell list (NCL) when a new node is deployed. This is determined by calculating the distance from other nodes and setting its cell size by adjusting its power levels. However, to the best of our knowledge, no one has applied CA to address ICI via FFR for ICIC in OFDMA-based cellular networks. We address this problem by first proposing a novel distributed and adaptive FFR scheme that determines the CoG of user distribution in each sector and then applying the CA algorithm for its autonomous reconfiguration.

IV. System Model

Fig. 2(a)–(e) shows the current frequency reuse and FFR models, whereas Fig. 2(f) shows our proposed model. Consider a sector in Fig. 2(f), the white block indicates the band being used by central users. It is observed that they have the flexibility of using any part of the complete band but at low power (shown by the height of the white block). The colored blocks highlighted by the circle in Fig. 2(f) indicate the bands used by edge users in the neighboring cell sites. Note that the central users of a sector do not use those PRBs that are already used by the edge users of the same sector. In the neighboring cell site, central users can however reuse these PRBs at an acceptable power level (determined based on the user density in the cell-edge and cell-center region of that sector).

The power varies for each sector as the area of the edge region (along the space axis) varies. We observe that for a fixed amount of bandwidth in each sector, the amount of transmit power for cell center P_c and cell edge P_e users varies according to the area of concentration of majority of the users. The area of these two regions and their power level varies for every sector in each cell site. We thus seek to first estimate a parameter that uniquely characterizes the user distribution in each sector and then determine the optimum power allocation to cell-edge and cell-center users for both the reference cell site and its neighboring sites.

Consider a real network where user distribution is nonuniform, the ratio of the radius of cell-center area to the radius of cell-edge area ζ would vary for each sector depending on the user distribution. In determining the classification of users as either cell edge or cell center, a given SINR threshold is usually used, and users whose SINR is below this value are regarded as cell-edge users. However, for easy analysis, we can approximate the region where such users would be located with a hexagon, as shown in Fig. 1. This approximation is

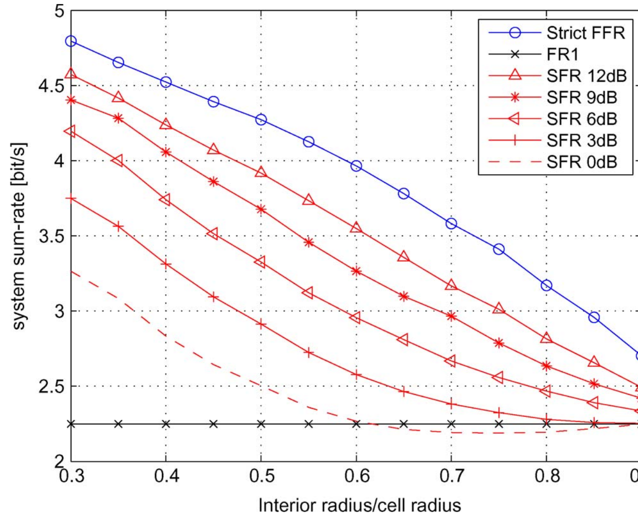

Fig. 3. Effect of $s_{\text{int}}/s_{\text{ext}}$ on various FFR schemes.

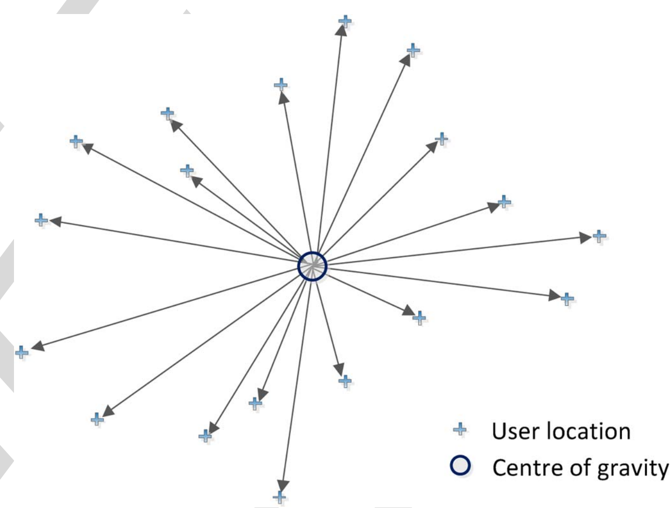

Fig. 4. Estimating central point (CoG) in each sector.

based on an SINR surface plot for a trisector antenna. This cell-edge region is variable, depending on the eNodeBs transmit power and downtilt, which invariably affects the user's SINR. The presence of hotspots at various locations further requires reconfiguration in such sectors to meet the desired system performance. Fig. 3 shows the performance of various frequency reuse schemes and SFR with different amplification factors β_s. We can infer that having a fixed ratio ζ for all sectors in all cell sites is not optimum. We demonstrate that the cell-edge and cell-center region would vary for each site and should be dependent on the user distribution, transmit power, and configuration of neighboring sites. We proceed by first determining a central point in each sector that has the shortest distance from the majority of user positions (see Fig. 4). We formulate a quadratic subproblem and, using the interior-point method, locate a unique point referred to as CoG within each sector. Second, we calculate the distance between the CoG and their serving eNodeB. We define three possible states for each sector as State X: $\zeta = 0.3$, State Y: $\zeta = 0.5$, and State Z: $\zeta = 0.8$. Each sector would assume any of these predetermined states, depending on the distance of the CoG to the eNodeB location.

Let $\mathcal{K}$ be the set of all users and $\mathcal{N}$ be the set of all sectors in the system for a cloverleaf model with three hexagonal sectors per cell site. Consider a user $k \in \mathcal{K}$ located at the cell edge, with sector $n \in \mathcal{N}$ as its serving sector. Given that the total transmit power budget is P_T, the power transmitted to users in the cell-edge area is P_e, and to users in the cell-center area as P_c, we have a constraint on power usage in each sector as

$$P_T = P_e + P_c. \tag{11}$$

Given that $P_e = \beta_s P_c$, the maximum transmit power can now be expressed as

$$P_T = \beta_s P_c + P_c \tag{12}$$

$$P_T = P_c(\beta_s + 1) \tag{13}$$

where β_s is the amplification factor of each sector. To ensure that P_T is preserved, we have

$$P_c \leq \frac{P_T}{\beta_s + 1} \tag{14}$$

and similarly

$$P_e \leq \frac{\beta_s}{\beta_s + 1} P_T. \tag{15}$$

Current solutions in the literature use values of β_s within the range of 1–20 and are usually selected using heuristics [18]. In current systems also, β_s is constant for all sectors. In our formulation however, we let β_s be dependent on the distribution of users in each sector, the ratio of users in cell edge to cell center (μ), and the value of ζ in the reference sector and its neighboring sectors. We thus aim to provide a utility function that determines β_s. This is used to determine the amount of power transmitted to users in the edge and center regions.

Let us characterize the unique distribution of users in each sector by its CoG ($CoG(x, y)$). This is a point $\boldsymbol{x} = [x, y]^T$ within the sector such that the sum of distance between this point and all user positions is minimum.

The distance is given by

$$d_k(\boldsymbol{x}) = \|\boldsymbol{x}_k - \boldsymbol{x}\|_2 = \sqrt{(x_k - x)^2 + (y_k - y)^2} \tag{16}$$

for $k = 1, 2, \ldots, K$ users in each sector. The objective is to find a unique point $\boldsymbol{x}$ that minimizes the objective function

$$CoG(x, y) = \hat{\boldsymbol{x}_n} = \arg\min_{(\boldsymbol{x})} \sum_{k=1}^{K} d_k(\boldsymbol{x}) \tag{17}$$

with inequality constraints described in Section V that specify the upper and lower bounds of possible values of $\boldsymbol{x}$. The constraints are expressed as any point within the geometrical coordinates of the hexagonal sector.

V. Proposed Solution

Our proposed solution involves two stages: The first stage is to determine the CoG of each sector and its corresponding "state." The next stage is to apply CA theory to obtain a global emergent state for all sectors.

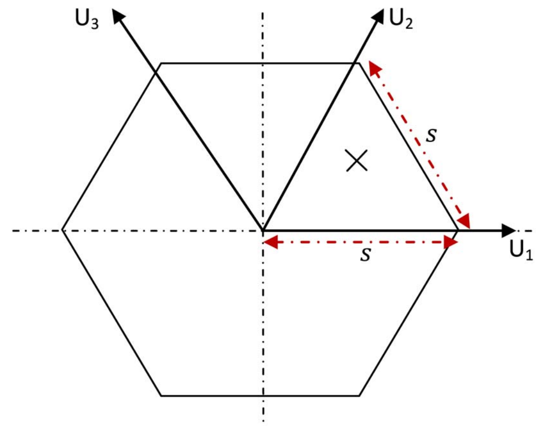

Fig. 5. Reference vectors.

A. CoG

To define a unique characteristic state for each sector based on its user distribution, we solve (17) via an iterative process. Consider three reference vectors ($\boldsymbol{u}_1$, $\boldsymbol{u}_2$, and $\boldsymbol{u}_3$) with the three orientations of the hexagon 0°, 60°, and 120° as shown in Fig. 5. The position vector $\boldsymbol{x_i}$ of any point chosen satisfies the constraints

$$\boldsymbol{x_i}.\boldsymbol{u_1} \leq s;\ \boldsymbol{x_i}.\boldsymbol{u_2} \leq s;\ \boldsymbol{x_i}.\boldsymbol{u_3} \leq s;\ \text{where } \boldsymbol{u}_1 = u_1\angle 0,\quad \boldsymbol{u}_2 = u_1\angle + \frac{\pi}{3}, \text{ and } \boldsymbol{u}_3 = u_1\angle + \frac{2\pi}{3}.$$

If $u_1 = 1$, scalar s represents the length of the side of the hexagon and $\boldsymbol{x}_i$ the position vector of any point within the hexagon. Any random point $\boldsymbol{x}_i$ can be chosen as our initial starting point for the iterative solution. The position vector can also be expressed as

$$\begin{bmatrix} 1 & 0 \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} - s \leq 0. \tag{18}$$

We denote the objective function in (17) as $f(\boldsymbol{x})$ and the inequality constraint in (18) as $g_k(\boldsymbol{x}) \leq 0$ and that they are both continuously differentiable in the whole region of $\mathbb{R}^n$. Equation (17) is a nonlinear 2-D optimization problem and can thus be solved using an iterative process.

In each iteration k, we linearize the inequality constraints and approximate the Lagrangian function, i.e.,

$$\mathcal{L}(\boldsymbol{x}, \lambda) = f(\boldsymbol{x}) - \lambda^T g_k(\boldsymbol{x}) \tag{19}$$

where $\boldsymbol{x}$ is our primal variable, and λ is the Lagrangian multiplier.

We thus form a quadratic subproblem assuming that in each iteration, $\boldsymbol{x}_k \in \mathbb{R}^n$ is an approximation to the solution, $v_k \in \mathbb{R}^n$ is an approximation of the multiplier, and $\boldsymbol{H}_k \in \mathbb{R}^{nxn}$ is an approximate Hessian of the Lagrangian function.

TABLE I
LIST OF NOTATIONS

Symbol	Description
N_{band}	Total number of PRBs in the system
N_{int}	Number of PRBs used by center users in a sector
N_{ext}	Number of PRBs used by edge users in a sector
P_T	Maximum transmit power budget in the cell
P_{PRB}	Transmit power per PRB
P_c	Transmit Power for cell-center users
P_e^{S-FFR}	Transmit Power for cell-edge users (Strict FFR)
P_e^{SFR}	Transmit Power for cell-edge users (SFR)
η_{SE}	Spectral Efficiency
η_{ASE}	Area Spectral Efficiency
$\mathcal{K}$	Set of all users in the system
$SINR_k$	SINR of user k
A_r	Area of any region r
A_c	Area of cell-centre region
A_e	Area of cell-edge region
A_{sector}	Area of a sector
R	Set of all regions
β_s	Power amplification factor (SFR)
$\mathcal{N}$	Set of all sectors in the system
N	Neighbourhood function of $\mathcal{N}$ sectors
(x_o, y_o)	Coordinates of BS
(x, y)	Coordinates of any point in a sector
$d_k(\boldsymbol{x})$	distance between k^{th} user coordinates and point $\boldsymbol{x}$
$CoG(x, y)$	Locus of points from serving BS
d_m	Distance of $CoG(x, y)$ from BS
s	Length of side of a hexagon
r_{int}	Cell radius of inner cell
R_{ext}	Cell radius of outer cell
ζ	Ratio of cell-edge area to cell-centre area
ψ	Localized Rule

The quadratic subproblem is thus

$$\min_{\boldsymbol{\omega}} \quad \frac{1}{2}\boldsymbol{\omega}^T \boldsymbol{H_k}\boldsymbol{\omega} + \bigtriangledown f(\boldsymbol{x})^T\boldsymbol{\omega}$$
$$\text{subject to} \quad \bigtriangledown g_k(\boldsymbol{x})^T\boldsymbol{\omega} + g_k(\boldsymbol{x}_k) \leq 0 \tag{20}$$

where $\boldsymbol{\omega} \in \mathbb{R}^n$, and $\boldsymbol{H}$ is the Hessian.

Using sequential quadratic programming, we solve (20) by updating the Hessian matrix H in each iteration to obtain a quadratic programming problem that we solve by using the interior-point method [27].

This solution gives us the location of the CoG of the central point of all user positions in each sector. Based on the arguments previously presented, point $CoG(x, y)$ can define a locus of points from the serving eNodeB. We can thus estimate the distance of $CoG(x, y)$ from the eNodeB as

$$d_m = \|CoG(x, y) - \text{BS}(x_o, y_o)\|_2 . \tag{21}$$

For the sake of simplicity, we partition each sector into three portions representing three states X,Y, and Z. Table I shows this classification, and depending on the distance of $CG(x, y)$ from the eNodeB d_m, the sector state ζ is chosen.

B. Neighborhood Function and Localized Rule

In the following, we define the neighborhood function and localized rule used herein.

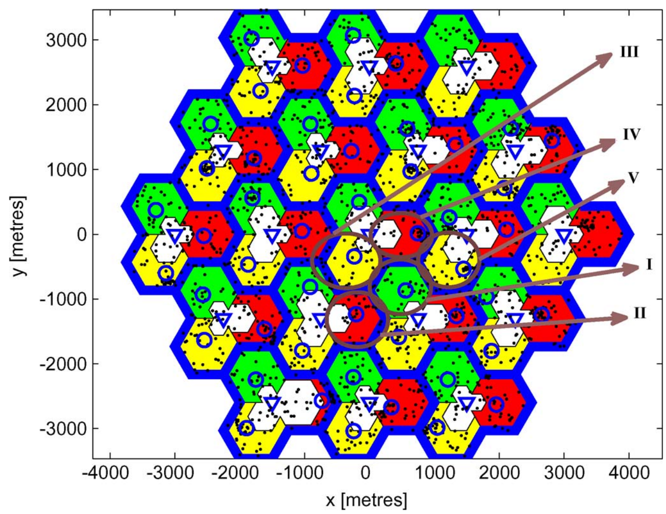

Fig. 6. System layout showing CoG of each sector.

Neighborhood Function (N)*:* Any two sectors n_1 and n_2 are said to be neighbors *iff*

$$n_1 \in N(n_2) \Longleftrightarrow n_2 \in N(n_1) \qquad \forall n_1, n_2 \in \mathcal{W}.$$

This hexagonal neighborhood relation N is a set of adjacent sectors of other cell sites with the exception that hexagonal sectors of the same cell site are not regarded as neighbors. This is due to the fact that in an OFDMA-based system, we are concerned with mitigating ICI only. The sector IDs of neighboring sectors are stored in the NCL. In the event that a sector hibernates, experiences a fault, or has been decommissioned, the NCL is updated via local communication over the X2 interface. Consider Fig. 6, where sector I has sectors II, III, IV, and V in its NCL, and the configuration settings of these sectors determine the next state of sector I.

Localized Rule (ψ)*:* Given four neighboring sectors with a set of three finite states ζ_i, the next state of sector n is the least used configuration state among its neighbors. If all states are evenly used, cell n's state remains unchanged.

In implementing this rule, we first evaluate the modal state among the neighboring sectors and eliminate it from the set of possible new states. For example, in Fig. 6, if sector II has state Y, sector III has state X, sector IV has state Y, and sector V has state Y, the next state of sector I would be state X, which is the least used state among its neighboring sectors. The localized rule is chosen based on the fact that when a new node joins a network, having too low power would make it prone to interference from other sectors, whereas a power level that is too high would cause interference to other sectors. When two or more neighboring sectors need to change their state at the same time, priority is given to sectors based on their hierarchy in the NCL. It is reasoned that if a majority are on a "low," it is tolerable to change state to a "high" provided at least one neighbor is already operating at that level, which shows that it is tolerable among its neighbors. It is important that the new state change is limited to a level already experienced by other neighbors. Thus, the rule is limited to the least used state among its neighbors.

TABLE II
MAPPING $CoG\ (x, y)$ TO ζ

$CoG(x, y)$	ζ
$d_m < s$	0.3
$s \leq d_m \leq 1.5s$	0.5
$d_m > 1.5$s	0.8

C. Cell-Edge Power Amplification β_s

In SFR, the power amplification factor β_s has to be carefully chosen as it determines the performance of cell-edge users and the amount of interference to other neighboring cells. We propose a utility function that determines the amplification factor β_s, based on the "state" of each sector, the ratio of users located in cell edge to cell center, and the current state of neighboring sectors. The state of each sector is dependent on the user distribution, which we characterize by its CoG (see Table II). We relate this system state ζ to the power amplification factor β_s, which varies for each sector.

Considering each sector represented as a hexagonal shape, the area of the sector is given as

$$A_{\text{sector}} = \frac{3\sqrt{3}}{2} \times s^2 \tag{22}$$

where $s =$ length of a side of hexagon (or half the diameter of the sector). The area of the center region can be expressed as

$$A_c = \frac{3\sqrt{3}}{2} \times (\zeta s)^2 \tag{23}$$

where the factor ζ scales the original hexagonal sector size to the center region. The area of the edge area is thus given by

$$A_e = \frac{3\sqrt{3}}{2} \times s^2(1 - \zeta^2). \tag{24}$$

We can thus obtain the ratio of edge area to center area as

$$\frac{A_e}{A_c} = \frac{1 - \zeta^2}{\zeta^2}. \tag{25}$$

The number of center and edge users is directly proportional to the area of center and edge regions assuming a uniform user distribution. If the user density (the number of users per unit area) is ρ and transmit power per user is P_k, we have

$$\mu = \rho \times P_k. \tag{26}$$

Equation (26) simplifies to give μ as the power per unit area. Thus, the transmit power to users in the edge region can be expressed as

$$P_e = \mu_e A_e. \tag{27}$$

Similarly, the power transmitted to the center region is

$$P_c = \mu_c A_c \tag{28}$$

with subscripts c referring to center and e referring to edge. In SFR, $P_e = \beta_s P_c$. Substituting this in (27) and dividing by (28), we obtain

$$\beta_s = \mu_r \frac{A_e}{A_c} \tag{29}$$

which can also be expressed as

$$\beta_s = \mu_r \frac{1 - \zeta^2}{\zeta^2}. \tag{30}$$

Having obtained this, we can now express the signal-to-noise-plus-interference ratio for any cell-edge users k as

$$\gamma_{\text{edge}} = \frac{\beta_s P_c \times G_k}{N + \sum_{n \in \mathcal{F}} \beta_s P_c \times G_k + \sum_{n = \mathcal{C}} P_c \times G_k}. \tag{31}$$

P_c is the transmitted power in sector n, G_k is the channel gain, N is noise power, $\mathcal{F}$ is the set of all sectors transmitting on the same frequency subband for cell-edge users, and $\mathcal{C}$ is a set of sectors using the same subband to serve cell-center users.

However, to ensure that our proposed scheme can autonomously adapt to spatiotemporal dynamics of the system, we need to consider the effect of these settings on neighboring cells in a defined neighborhood. We thus propose a method that would select an optimum value of ζ based on the $CoG(x, y)$ of its serving sector, the ratio of cell-edge to cell-center users μ, and the value of ζ in neighboring sectors. As the user distribution in a neighboring site changes, its power allocation for cell-edge user also varies. Thus, the sector has to adopt a new optimum power setting. This adaptive and autonomous scheme does not cause instability as the changes are restricted to a defined local neighborhood, and changes are triggered from user distribution patterns over a medium time scale that is usually hours to days [6]. We summarize steps in our proposed solution based on CA.

- Step 1) Based on user distribution and presence of hotspots at cell center or cell edge, calculate the CoG for each sector.
- Step 2) Classify each sector into states X, Y, or Z based on the distance of CoG from the serving eNodeB using Table II.
- Step 3) Apply the CA algorithm to obtain a new converged state for each sector and update NCL with new sector states.
- Step 4) Classify users as cell-edge and cell-center users based on new sector states and determine the power amplification factor β_s for each sector using (30).
- Step 5) Evaluate system performance, and if the average $SINR$ of each sector is less than the $SINR$ threshold, a new state change is triggered, thus going back to step 3.

VI. RESULTS

A system-level simulator has been used to validate our proposed scheme. All results presented are for the downlink, and the results presented in Figs. 3, 7, and 8 are obtained from Monte Carlo simulations. This is repeated for various user positions, which are randomly generated, and the average value of the performance metric is used. We also validated this scheme for different network sizes, employing a cloverleaf model that consists of three hexagonal sectors amalgamated together as one cell site. Three sector antennas were used, and simulation was performed for various random user distributions

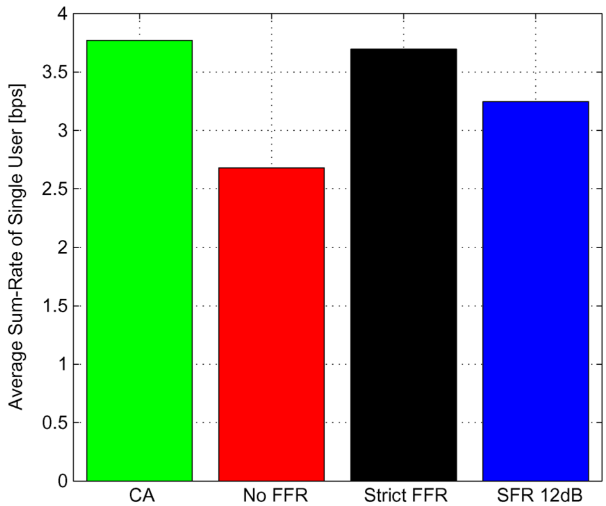

Fig. 7. Comparison of average sum rate of a user using various FFR schemes.

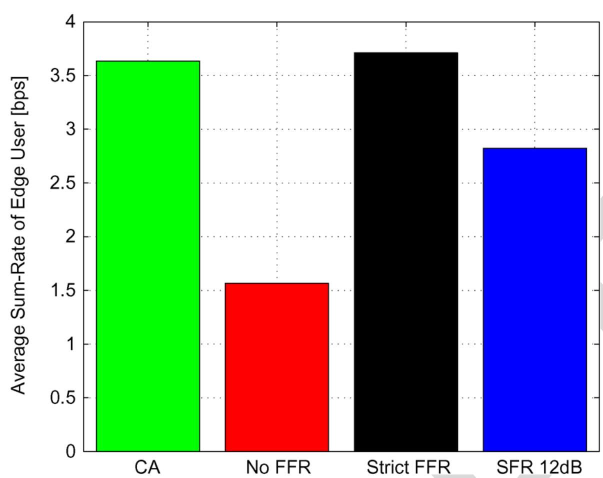

Fig. 8. Average sum rate of cell-edge users.

TABLE III
MAIN SIMULATION PARAMETERS USED

Parameter	Value
Total Bandwidth	5MHz
Inter Site Distance	1500m
eNodeB height	50m
UE height	1.5m
Transmit power	40dBm
Antenna Model	berger
Path loss Model	L = 128.1 + 37.6log D

and random hotspot locations. Other simulation parameters used are listed in Table III. Results were consistent for 21 and 57 sectors. We present results for discussion for 57 sectors. We use $N_{\text{band}} = 48$ in each sector.

Fig. 6 shows the system layout and user distribution of 150 users randomly placed in each sector. The CoG of user distribution is marked by blue circles, and as can be observed, their locations vary in each sector. Based on the classifications in Table II and illustration in Fig. 2, users located in the center white region are cell-center users and use any portion of the system bandwidth with a low power restriction. Fig. 7 shows the average user sum rate of the total system when FR1 (frequency reuse of 1 in all regions), S-FFR, SFR with optimum power

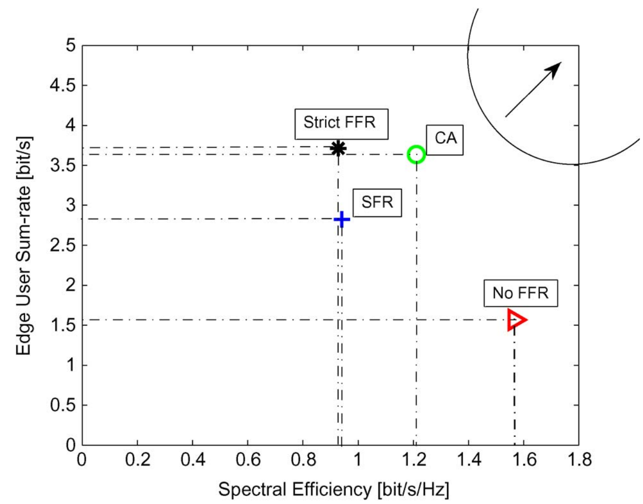

Fig. 9. Cell-edge sum rate and spectral efficiency tradeoff.

amplification of 12 dB, and our proposed scheme based on CA. This is obtained by calculating the sum rate of all users in the system (both cell-edge and cell-center users) and dividing by the total number of users. S-FFR is expected to show better performance and avoidance of ICI due to its limitation of frequency allocations to cell regions. This is the classic ICI avoidance scheme and is not spectrally efficient.

S-FFR, as expected, shows the best cell-edge user sum rate but has a fundamental tradeoff between achieving this improvement and the spectral efficiency. Thus, S-FFR achieves the highest edge user sum rate but at the expense of having lower resource utilization [28], [29]. However, our proposed scheme achieves a close performance with S-FFR and better performance than SFR in terms of the edge user's sum rate. This is also achieved at a better utilization of resources than S-FFR.

Focusing on the performance of the CA-based scheme for cell-edge users, Fig. 8 reveals an interesting result. As expected, the sum rate for cell-edge users employing frequency reuse of 1 experiences larger ICI; thus, its low sum rate for edge users. SFR also shows this effect, but due to transmission of higher power to cell-edge users, the interference is minimized. In the CA-based scheme, cell-edge users maintain a high performance better than SFR and comparable to S-FFR but with better spectrum utilization. We can thus see that CA helps serve as a tradeoff between S-FFR performance and high spectrum utilization of SFR.

Fig. 9 shows the tradeoff between the cell edge sum rate and the spectral efficiency of the schemes discussed. The objective is to design a scheme whose operating point lies in the upper-right half of the solution space (indicated by the arc and arrow). From this plot, we can see that the proposed scheme achieves higher spectral efficiency for a slightly lower performance in terms of sum rate than S-FFR.

In terms of cell-edge sum rate, S-FFR has a 4.8% better performance than the CA scheme. For its spectral efficiency, however, CA has an 18.1% better performance than S-FFR with "no FFR" as the reference. Maintaining good resource utilization is important as reduction in resource utilization can

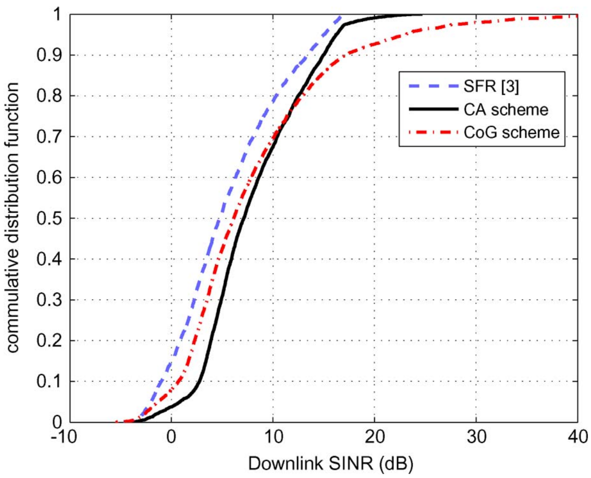

Fig. 10. System performance with CA and without (CoG).

lead to a dip in the peak data rate of the cell. This occurs when users with high rate requirements have restrictions from being allocated with sufficient number of PRBs they may require [18].

Finally, we consider the comparative performance of the proposed CA-based scheme with the simple adaptive scheme based on CoG. Fig. 10 shows the system performance using the downlink SINR as the performance metric. Two deductions can be made from this result. First is the improved performance of both proposed schemes (CoG and CA) over the SFR scheme proposed in [3] due to the distributed nature of our solution. Second is that with the CA-based solution, 75% of the users experience higher SINR than the CoG scheme. In the simple adaptive scheme (CoG), only 25% of the users experience higher SINR than the proposed solution. We can thus conclude that in employing CA, an optimal point is reached between improvements in cell-edge user performance at an acceptable decrease in performance of cell-center users.

The underlying reason behind the better performance of the CA-based approach is its distributed nature where different user locations would have different cell-edge and cell-center regions. Thus, an optimum power allocation is used in each sector. This reduces the power allocation of sectors based on their effect on neighboring sectors. The CA scheme dynamically changes its power allocation for different regions, thus showing even better performance compared with S-FFR but with better subband utilization than S-FFR.

VII. Conclusion and Future Work

In this paper, we have addressed a fundamental problem of OFDMA-based cellular networks, i.e., ICI. We have proposed a variant to the conventional FFR scheme that exploits the knowledge of user positions to determine the power ratio between cell-edge and cell-center users in individual sectors of a cell site. This scheme is based on the CoG of users in each sector. Our distributed and adaptive solution based on FFR was further enhanced by employing CA theory to achieve an emergent and adaptive solution. This is done to ensure that the distributed FFR scheme becomes autonomous via continuous reconfiguration in accordance with the configuration settings of neighboring sectors.

This proposed FFR scheme not only provides better sum rate for cell-edge users, which is comparable to the performance of the S-FFR scheme, but achieves this with higher resource utilization as well. We have also shown that our scheme outperforms the well-established SFR scheme in terms of its cell-edge user sum rate. Based on the information provided and results presented, we have thus initiated an important contribution on the relevance of emergence in adaptive and autonomous solutions for wireless cellular networks.

Despite the huge potential of applying CA in wireless cellular networks, more research still needs to be done to provide analysis of the stability and convergence of this technique. In addition to this, we would investigate applying these principles in heterogenous networks with defined localized rules for indoor base stations and well-defined neighborhood for effective interference coordination among macrocells and femtocells.

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A New Cellular-Automata-Based Fractional Frequency Reuse Scheme

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***Abstract*—A fundamental challenge in orthogonal-frequency-division-multiple-access (OFDMA)-based cellular networks is intercell interference coordination, and to meet this challenge, various solutions using fractional frequency reuse (FFR) have been proposed in the literature. However, most of these schemes are either static in nature, dynamic on a large time scale, or require frequent reconfiguration for event-driven changes in the environment. The significant operational cost involved can be minimized with the added functionality that self-organizing networks bring. In this paper, we propose a solution based on the center of gravity of users in each sector. This enables us to have a distributed and adaptive solution for interference coordination. We further enhance our adaptive distributed FFR scheme by employing cellular automata as a step toward achieving an emergent self-organized solution. Our proposed scheme achieves a close performance with strict FFR and better performance than SFR in terms of the edge user's sum rate.**

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I. Introduction

One of the key challenges in orthogonal frequency-division multiple access (OFDMA)-based cellular networks is intercell interference (ICI). Various interference management schemes (averaging, avoidance, and coordination) have been proposed to mitigate ICI. Coordination of ICI is often adopted due to its improved performance and spectral efficiency compared with interference averaging and avoidance [1]. To achieve intercell interference coordination (ICIC), variants of the fractional frequency reuse (FFR) scheme in [2] and [3] have been proposed in the literature, which reduce the amount of ICI received by cell-edge users and give good performance based on their target performance metrics such as signal-to-interference-plus-noise ratio (SINR), spectral efficiency, outage probability, and system throughput. All of these schemes exploit either frequency or power or both to achieve ICIC. However, these schemes do not give due consideration to the fact that in real networks, user distribution is nonuniform as it varies with seasons and the occurrence of major events. This is an important challenge and has also been identified in [4], where the introduction of liquid radio, which combines heterogeneous networks, coordinated multipoint transmission, and a self-organizing network is described to break the rigid architecture of today's network to a flexible, adaptive, and intelligent network.

In this paper, we focus on the fact that in FFR schemes, modeling a fixed region of cell edge and cell center in all cells irrespective of user positions is not optimum for a dynamic cellular system. There is thus an opportunity to simultaneously exploit power, frequency, and space (user location) to self-organize ICIC. With accurate knowledge of user positions (which is feasible with smartphones), a more dynamic and adaptive scheme can be developed, which adapts to medium- and long-time-scale user position variations. We thus propose a solution that directly correlates the geographical position of users to their available resources (bandwidth and power). A majority of users at the cell borders have their SINR below the desired SINR threshold and are thus referred to as cell-edge users, whereas the other users above this threshold (usually closer to the serving eNodeB) are referred to as cell-center users.

In general, any resource allocation procedure has two steps: first, the allocation of resources to the geographical regions or cells and second, the allocation of resources to the users in that region or cell. Our focus in this paper is on the first step in the resource allocation.

A novel FFR scheme based on cellular automata (CA) for ICIC is presented. To achieve this, we characterize the user distribution in each sector by its center of gravity (CoG). This helps classify each sector in different configuration states. Next, we employ an evolutionary algorithm called *cellular automata* to demonstrate its self-organizing functionality in the wireless cellular networks. In this paper, we compare the performance of various FFR schemes showing how system performance varies with the classification of users in the cell-edge or cell-center region. This classification, which we will show later, is based on the ratio of the radius of the cell-center region to the radius of the cell sector. We further present a distributed and adaptive FFR scheme that is dependent on the user distribution in each sector of a cell site. The regions of cell edge and cell center are not fixed across the entire network or a particular site but vary on a medium time scale (seasonal change in user distribution)

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in each sector. Thus, based on the user distribution, the system can autonomously adapt the region of cell edge and cell center and thus the resource allocation to users. This adaptive scheme provides a significant improvement in system performance.

A. *Emergent Patterns in Cellular Networks*

The concept of emergence is an integral part of self-organizing systems in nature. Emergence can be understood as resultant behavior at a macrolevel based on interactions of a system's constituent parts at a microlevel [5].

In the specific context of self-organization in wireless cellular networks, various definitions, design principles, and methodologies have been outlined in [6]. One interesting finding is how self-organized systems in nature follow simple rules that result in an emergent pattern. Dynamical systems with an emergent pattern have a global behavior due to interactions among local neighbors. These global patterns can neither be traced back taking the individual components in isolation nor can the process be easily modeled analytically due to their increased statistical complexity. Important characteristics of self-organized systems include system adaptability, autonomy, scalability, and stability. In designing such self-organized systems, any emergent patterns that result from localized interactions among the system components should also be adaptive to variations of its operating environment.

In this paper, we apply CA theory, which is an efficient method in modeling biological complex systems, to combine adaptive emergent patterns as a first step in achieving a self-organized system by modeling an interference coordination scheme among neighboring cells. The key concept here is that the power allocation for cell-edge and cell-center users is dependent not only on the user distribution in a sector but on the cell-edge area, power allocation, and user distribution of neighboring sectors as well. We have interestingly discovered from our results that using simple localized rules among a defined neighborhood results in an emergent pattern that meets the desired system objective.

B. *New CA-Based FFR Scheme*

For a cloverleaf cellular system model [7], each sector has two regions, namely, an inner region close to the serving eNodeB referred to as the cell center and the remaining outer region referred to as the cell edge. These regions can be varied, and we first show that the ratio of the cell-edge area to the cell-center area influences the system performance. This ratio is one of the major factors that determine the power amplification factor for cell-edge users in soft frequency reuse (SFR). We also vary the ratio of power transmitted to cell-edge and cell-center users in accordance with the variation in user distribution among neighboring sectors. We are able to provide an analysis of the relationship between the ratio of the cell-edge area to the cell-center area and power amplification factor.

Our major contribution is in proposing an adaptive and autonomous FFR scheme by applying CA theory whose motivation is from nature where self-organization can result as an emergent pattern. This is based on applying simple rules in a defined local neighborhood, which we also apply for ICIC via FFR.

C. *Paper Outline*

The rest of this paper is organized as follows: In Section II, we give an overview of OFDMA-based cellular networks and then provide the fundamentals of frequency reuse schemes deployed in such networks. We expand on interference analysis in FFR schemes and on resource sharing between cell-edge and cell-center users. In Section III, we introduce CA theory, providing fundamental definitions and properties. We also mention previous attempts in the literature aimed at applying CA in wireless cellular networks. Section IV describes our system model, and we formulate our problem based on determining an optimum resource allocation characteristic for each individual cell with the objective of applying a more distributed, adaptive, and autonomous FFR scheme. Section V describes our proposed solutions based on CoG and an enhancement of this using CA to show an emergent behavior. We discuss the simulation results obtained in Section VI and conclude in Section VII with a summary of findings and contributions. We also highlight limitations of the proposed scheme and suggest potential areas for future research.

II. Overview of Resource Allocation Schemes in an Orthogonal Frequency-Division Multiple Access-Based Cellular Network

An interesting fact that governs cellular system design is that the signal power falls off with distance. It allows frequency resource to be reused at a spatially separated location such that signal power diminishes to the extent that it does not cause any significant interference. The distance at which the frequency resource can be reused is known as the *reuse distance*. This concept of *frequency reuse*[8] helps in increasing the system capacity, while making the system interference limited. The interference due to frequency reuse is known as *intercell interference* (ICI). Here, we give an overview of an OFDMA-based cellular network, the preferred solutions to reduce ICI, and the various static and dynamic resource allocation schemes deployed therein. Our emphasis is on determining the resource partitions and transmit power for dynamic reuse schemes. We also illustrate the metrics used for performance evaluation and comparison of the different reuse schemes.

A. *OFDMA-Based Cellular Network*

The ability of orthogonal frequency-division multiplexing (OFDM) to combat frequency-selective fading for downlink data transmission justifies its use in current and future cellular networks. OFDM transforms the wideband frequency-selective channel into several narrowband channels, which are known as *subcarriers*. It transmits the digital symbols over a group of subcarriers for a user, with certain transmit power and modulation and coding scheme (MCS). Due to the narrowband subcarriers, each transmission undergoes flat fading. This makes the system robust to multipath fading and narrowband interference [8]. In a multiuser environment, each subcarrier may exhibit different fading characteristics to different users at different time instants. This is due to the time-variant wireless channel and the variation in the user's location. This feature can be advantageous by assigning subcarriers to those users who can use them in the best possible way at that particular time instant. Such an OFDM-based multiple-access scheme is known as OFDMA. In OFDMA, a contiguous or noncontiguous set of subcarriers[1] are allocated to a user for a predetermined time interval. This is known as a physical resource block (PRB) as per the Third Generation Partnership Project Long-Term Evolution (3GPP-LTE) specifications [9]. Thus, PRBs have both time and frequency dimension, and it is the minimum resource that can be allocated to a user. In addition to PRB allocation, the transmit power and MCS can be varied based on the channel condition at the level of the subcarrier group assigned to a user. Thus, OFDMA facilitates flexible resource planning due to the granularity of the resources available for allocation.

To maximize spectral efficiency, next-generation systems recommend frequency reuse of 1, i.e., each neighboring cell uses the same resources. In such a case, different users in the neighboring cells may use the same PRB, and if the signals are strong enough, users (particularly the cell-edge users) are likely to suffer from severe ICI. Various interference management (averaging, avoidance, and coordination) schemes have been proposed to combat ICI [3]. ICIC is often adopted due to its improved performance and spectral efficiency compared with other schemes [7]. To achieve ICIC, different variants of FFR schemes have been proposed in the literature, which essentially allocates different resources to the interfering areas of neighboring cells. Such schemes reduce the amount of ICI experienced by the cell-edge users. The different variants of FFR schemes are illustrated in the following section.

B. *Variants of FFR Schemes*

To illustrate and compare the different variants of FFR schemes, we have used the cloverleaf cellular system model in this paper, where each cell site comprises three hexagonal sectors with one eNB (base station is known as eNodeB (eNB) in the LTE standard) located at the common vertex of these three sectors. The hexagonal geometry of sectors is used as an approximation for irregular or sometimes circular shape of a cell coverage area. The motivation for the cloverleaf model is that it appropriately demarcates the radiation pattern of a cell site utilizing three sector antennas, as shown in Fig. 1. We give an overview of the widely used static and dynamic reuse schemes in the following sections.

1) Static Reuse Schemes: Due to the fact that cell-edge users are more prone to ICI compared with cell-center users, the cell-edge users are usually allocated a distinct frequency resource. The users are classified as cell center or cell edge based on either their geographical location in the cell or their experienced signal-to-interference-plus-noise ratio (SINR) from the eNodeB (which is indicative of the ICI they experience), and then, different reuse patterns can be applied. When the resources allocated for cell-center and cell-edge users are fixed, the scheme is said to be *Static*. Static ICIC schemes exhibit lower implementation complexity and less overheads. When the fixed resource partitions are integer in number, it is known as *integer frequency reuse scheme*. For example, *Frequency Reuse 1* (FR1) is typically deployed in an OFDMA-based cellular network, where all cells in the system are allowed to use the same resources without any restrictions, as shown in Fig. 2(a). All resources are available in all cells, and the resource utilization efficiency is high and gives good performance during low traffic conditions. When the traffic load (i.e., user density) increases, the interference effects cannot be neglected, and significant ICI is experienced by the cell-edge users.

[1]It is known as a subchannel in OFDMA. However, we will not differentiate between the terms subcarrier and subchannel in this paper.

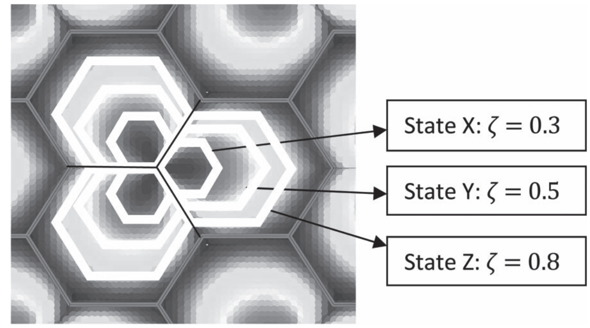

Fig. 1. Defining cell sector states.

To alleviate this problem of ICI at the cell edge, a frequency reuse scheme with a higher reuse factor (frequency reuse 3) can be deployed. In *Frequency Reuse 3* (FR3), adjacent sectors operate on three different subbands, which, in total, constitute the available number of subbands [see Fig. 2(b)]. Due to the use of distinct subbands in neighboring cells, the problem of ICI is mitigated to a large extent. However, with this subband partitioning, the available number of resources in each sector is reduced to one third. This penalty in terms of reduced resource utilization efficiency is paid to achieve improved edge user's performance.

With *FFR schemes*, it is possible to have a tradeoff between achieving high resource utilization efficiency as in FR1 and improved edge user's performance as in FR3. It is clear that resource partitioning is beneficial in improving edge user's performance. However, the cell-center users do not suffer from ICI, and therefore, resource partitioning is not a key factor in characterizing their performance. FFR schemes exploit these facts and use a combination of the two integer frequency reuse schemes previously mentioned to achieve this tradeoff. The key concept of all FFR schemes is that the cell is geographically divided into two regions: cell center and cell edge with FR1 deployed for cell-center users and FR3 for the cell-edge users.

There are different variants of FFR in the literature. One of the most predominant is *strict FFR (S-FFR)*, in which the cell-center region deploys FR1, and the edge region deploys FR3. Thus, cell-center users do not share the spectrum with the edge users, as shown in Fig. 2(c). This scheme improves the cell-edge performance substantially but compromises on the system throughput and resource utilization due to the availability of only a quarter of the total resources in the cell-center and cell-edge region.

Another approach to improving the resource utilization efficiency and system performance is to exploit the two dimensions

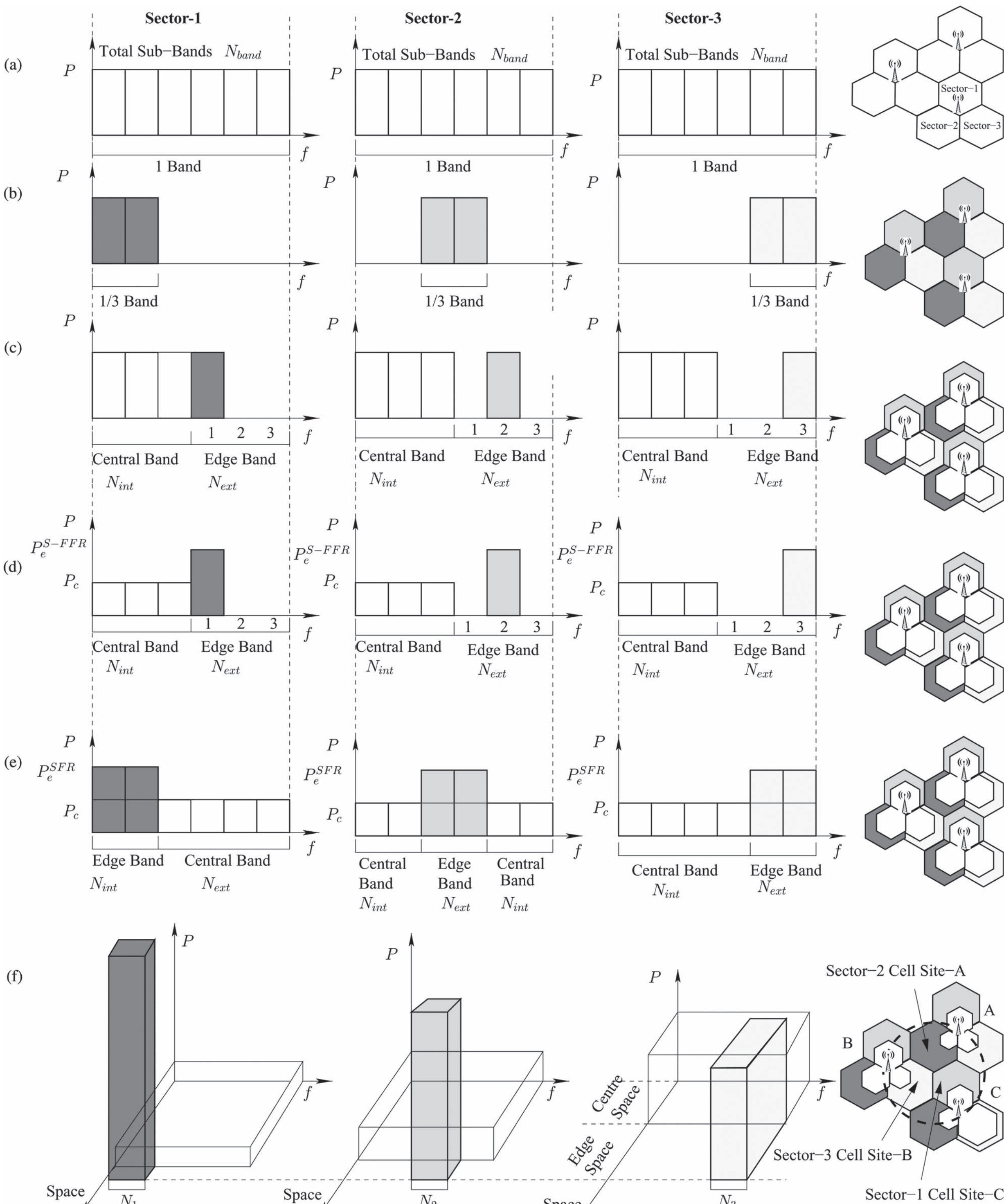

Fig. 2. Different reuse schemes for OFDMA-based cellular networks. (a) FR-1. (b) FR-3. (c) Strict FFR. (d) Partial reuse. (e) SFR. (f) Proposed FFR.

of resources available: spectrum and power. *Partial reuse* [10] and *SFR*[2] are two such schemes widely reported in the literature. They involve power control along with applying different reuse factors to the cell center and cell edge. Partial reuse employs the same resource partitioning strategy as S-FFR, with the only difference being the resources reserved for cell-center users are utilized with a lower power level, whereas a reuse factor of 3 with a higher power level is deployed for the cell-edge users [see Fig. 2(d)].

SFR [3], [11] is one of the FFR schemes that efficiently exploits the power and spectrum resources. It employs the same

[2]Throughout this paper, our reference to SFR is in accordance to the original scheme proposed in [3] and [11]

resource partitioning and power allocation strategy as the partial reuse scheme; however, in SFR, all resources are available for the cell-center users if they are unused by the users at the cell edge of the same sector. However, the resources used by cell-center users are at a lower power level and can also be used by cell-edge users in neighboring cells. This is achieved by employing power control for users that use the same band (low power for users in the center region and high power for users in the edge region of the neighboring cell). This is also shown in Fig. 2(e).

2) Dynamic Reuse Schemes: All the static reuse schemes implement fixed resource partitioning and, therefore, hard limits the achievable user throughput. In dynamic reuse schemes, a flexible resource partitioning is performed between the cell-center and cell-edge users, which can be based on factors such as the amount of interference power experienced by users and the traffic density. Such schemes have the potential of achieving efficient resource utilization and improved system throughput.

A dynamic reuse scheme has been proposed in [12], which the authors refer to as "softer" frequency reuse (SerFR). Here, the reuse factor for both cell-center and cell-edge users is 1, and a modified proportional fair scheduler is used, which gives preference to edge users over cell-center users and ensures fairness among them as well. It is thus essential for resource management algorithms to adapt to system dynamics while keeping the flexibility of using the entire spectrum resource in every region. The idea is to keep the resource planning adaptive with no inherent constraints from a design perspective.

In general, dynamic resource plans for interference mitigation are proposed in [13] and [14] and tend to perform better than their static counterparts due to the fact that they provide the flexibility of using all the available resources. The generation of soft-FFR patterns in a self-organized manner is featured in [15] and [16], where resource allocation (i.e., determining the number of subcarriers and power assignment) is performed by dynamically adapting to the traffic dynamics for a constant bit rate and best-effort traffic. They have compared the performance for two cases, i.e., with and without eNBs coordination, and showed that performance is better with coordination.

Mehta *et al.* in [17] have proposed one variant of dynamic FFR specifically tailored for a relay-assisted cellular network, which performs an intelligent allocation of resources such that no two neighboring edge regions are allocated the same channels. Such a scheme based on the interfering neighbor set gives improved edge user's throughput and area spectral efficiency (ASE) compared with all other variants of reuse schemes. However, in the case of nonuniform traffic density, the resource allocation policy does not perform very well. Thus, we observe that no particular reuse policy works for all possible scenarios. If a policy is optimal for a given scenario and improves one performance metric, then it compromises on other metrics. Moreover, the variation in user traffic density affects the performance of the reuse policy, which needs to be taken into account.

An illustration of determining the transmit power and interference calculation for the different reuse schemes is given in the following section.

C. Resource Partitions and Transmit Power Levels for Dynamic Reuse Schemes

The maximum transmit power available in the cell is influenced by the reuse scheme because different fractions of resources are available for cell-center and cell-edge regions of the cell for different reuse schemes. We illustrate the concept further as follows.

Let P_T be the maximum transmit power budget in the cell.
Let P_{PRB} be the transmit power per PRB.
Let N_{band} be the total number of PRBs available in the system.
Let N_{int} be the number of PRBs used by center users in a sector.
Let N_{ext} be the number of PRBs used by edge users in a sector.

Assuming equal power allocation, the transmit power per PRB for FR1 in each sector will be

$$P_{\text{PRB}} = \frac{P_T}{N_{\text{band}}}. \tag{1}$$

For S-FFR, the number of PRBs available in the cell-center and cell-edge region will depend on the ratio of cell-center area to cell-edge area [18]. Let s_{int} represent the radius of the cell-center region and s_{ext} the radius of the entire sector. For cell-center users

$$N_{\text{int}} = N_{\text{band}} \times (s_{\text{int}}/s_{\text{ext}})^2 \tag{2}$$

and resources for cell-edge users will thus be

$$N_{\text{ext}} = (N_{\text{band}} - N_{\text{int}})/3. \tag{3}$$

The factor 3 is due to the minimum number of nonoverlapping sector edges. This is synonymous to the chromatic index in graph coloring [19].

The power transmitted to cell-center users and cell-edge users will be

$$P_c = P_{\text{PRB}} \times N_{\text{int}} \tag{4}$$

$$P_e^{(\text{S-FFR})} = P_{\text{PRB}} \times N_{\text{ext}}. \tag{5}$$

In SFR, the calculation of N_{ext} changes as the users in the cell-edge area have their received power boosted by the power amplification factor β_s. The amount of PRBs used in the cell edge is not dependent on that used in the cell center as was in the case of S-FFR. Cell-center users can use a maximum number of PRBs available irrespective of the allocation to cell-edge users. Thus N_{int} can be obtained using (2), whereas the number of PRBs available to cell-edge users is

$$N_{\text{ext}} = \max[N_{\text{band}}/3, N_{\text{band}} - N_{\text{int}}]. \tag{6}$$

The power transmitted to cell-center users will be the same as in the case of S-FFR given in (4), and the power transmitted to cell-edge users will be

$$P_e^{(\text{SFR})} = \beta_s \times P_{\text{PRB}} \times N_{\text{ext}}. \tag{7}$$

D. System Performance Metrics

1) SINR and Sum Rate: The SINR performance of users gives a good indication of their received signal strength and the amount of interference. Other metrics to characterize system performance are also usually a function of SINR. One such metric is the sum rate, which represents the available rate achieved by all users. In the results presented later in Section VI, we show the sum rate of cell-edge users for different frequency reuse schemes and the total system sum rate. However, a tradeoff is expected between achieving a high sum rate and maximum resource utilization.

2) Outage Probability: We also consider outage probability as one of the performance metrics in our analysis. We consider a user to be in outage if it experiences SINR below a predefined threshold, i.e.,

$$\text{Prob}(\text{outage}) = \text{Prob}(SINR > SINR_{\text{threshold}}). \quad (8)$$

As the cell-edge users are more prone to ICI, they are likely to experience low SINR and, hence, remain in outage. The outage probability comparison for cell-edge users is therefore significant when comparing different reuse schemes.

Outage probability is expected to be higher in systems using frequency reuse of 1 compared with systems employing FFR schemes. In SFR, as the power allocated to edge users is increased, the lower the probability of users having their SINR below the required threshold.

3) ASE: The spectral efficiency is measured as the maximum achievable throughput (bits per second) per unit of bandwidth. Its unit is bits/sec/Hz and is evaluated as

$$\eta_{\text{SE}} = \frac{1}{\mathcal{B}} \sum_{k\in\mathcal{K}} \mathcal{B}_k \log_2(1 + SINR_k) \quad (9)$$

where $\mathcal{K}$ is the set of users in the system, $\mathcal{B}$ is the total system bandwidth, $\mathcal{B}_k$ is the bandwidth of the PRBs used by each user, and $SINR_k$ is the $SINR$ of user k.

As compared with spectral efficiency, ASE is the measured throughput per hertz per unit area for a given cell resource [20]. This gives a practical representation of the improvement in capacity achieved relative to cell size (and reuse distance) with available resources. This is one of the significant performance metrics used to compare different frequency planning schemes, which greatly impacts cellular system design. This determines achievable system throughput per unit frequency per unit area (bits/sec/Hz/km^2). It is computed as

$$\eta_{\text{ASE}} = \sum_{r\in\mathcal{R}} \frac{\frac{1}{\mathcal{B}} \sum_{k\in\mathcal{K}} \mathcal{B}_k \log_2(1 + SINR_k)}{A_r}. \quad (10)$$

$\mathcal{R}$ is the set of all nonoverlapping regions, and A_r is the area of any region r.

III. Cellular Automata

CA is a *new kind of science* that can be used to model complex dynamic systems [21]. They are large decentralized systems made up of simple identical components with defined localized neighbor relations. The state of individual simple components (usually referred to as cells) synchronously changes and is triggered by state updates in neighboring cells. These updates are based on local rules and previous states of neighbors. CA is suitable for modeling autonomous systems, as the fundamental concepts use inspiration from complex biological systems. These natural systems are autonomous and made up of large numbers of small cells. The basic idea is that a system that needs to be automated is modeled as an aggregation of a large number of small cells. Each cell follows simple rules and updates its individual states based on its current state and that of the neighboring cells [21]. Detailed studies on modeling dynamic systems using CA can be found in [22]. Emergence and self-organized systems in nature have similar operational principles to CA. It is thus inferred from the literature that CA is one of the most extant natural approaches toward designing self-organized networks [23].

In applying CA algorithms, a neighborhood function must be clearly defined. This determines the cell states that affect the future states of the reference cell. Various types of neighborhoods can be defined, but the most common are the Von Neumann, Moore, and Hexagonal [22]. We adopt a hexagonal neighborhood as it is analogous to our system model for wireless cellular communication networks where we consider the coverage of each eNodeB's sector to be hexagonal in shape.

A 2-D CA can be represented as a five tuple $(\mathcal{W}, N, \psi, \zeta, t)$, where the following statements hold.

- $\mathcal{W}$ is the lattice 2-D cell represented by hexagons at position (x, y), $\mathcal{W} = \{\mathcal{W}_n, n = 1, 2, \ldots, \mathcal{N}\}$.
- N is the neighborhood set, a finite subset of $\mathcal{W}$, $N \subset \mathcal{W}$, $N = \{\boldsymbol{n_1}, \boldsymbol{n_2}, \ldots, \mathbf{n}_{\mathcal{N}}\}$.
- ζ is a finite set of configuration states of each cell, $\zeta_i^{t+1} = f(\zeta_{i-\mathcal{N}}^t, \ldots, \zeta_{i-1}^t, \zeta_i^t, \zeta_{i+1}^t, \ldots, \zeta_{i+\mathcal{N}}^t)$, where ζ_i^t is the state of cell i in time t.
- ψ is the localized rule that triggers the state transition. The local rule is a function $f : \zeta^{\mathcal{N}} \to \zeta$, where $\mathcal{N}$ is the size of the neighborhood.
- t is the transition time of a cell moving from its current state to its final state.

The neighborhood vector N determines the neighborhood relationship or better described as the neighbor cell list. We give more insights into the neighborhood relation we use in our proposed solution in Section V. The transition time is important to prevent frequent change of states, which may lead to instability and increased system convergence time.

CA have many diverse properties, but we highlight relevant properties for our work as follows.

- CA systems are complex systems but consist of a large number of simple objects.
- Evolution of each component is based on interactions with their localized neighborhood.
- They follow simple rules and result in an emergent pattern.
- All components synchronously operate in parallel.

In wireless cellular communication systems, it has been established that adaptive and autonomous systems depend on local interactions with their neighbors, which results in an emergent pattern. In simulating such large dynamic complex systems, CA is a viable approach.

Some attempts have been made to apply CA in wireless cellular systems in general. In [24], we provide an introduction to CA as a viable tool for self-organizing solutions in wireless cellular systems, proposing potential use cases in addressing ICIC and energy efficiency challenges. In [25], a self-organized channel assignment scheme using CA theory with distributed control has been presented. Therein, Beigy and Meybodi used learning automata to adjust the state transition probabilities. The most significant application of CA is the work by Ho *et al.* in [26], where a CA-based approach toward coverage optimization has been developed. They describe how each base station updates its neighbor cell list (NCL) when a new node is deployed. This is determined by calculating the distance from other nodes and setting its cell size by adjusting its power levels. However, to the best of our knowledge, no one has applied CA to address ICI via FFR for ICIC in OFDMA-based cellular networks. We address this problem by first proposing a novel distributed and adaptive FFR scheme that determines the CoG of user distribution in each sector and then applying the CA algorithm for its autonomous reconfiguration.

IV. System Model

Fig. 2(a)–(e) shows the current frequency reuse and FFR models, whereas Fig. 2(f) shows our proposed model. Consider a sector in Fig. 2(f), the white block indicates the band being used by central users. It is observed that they have the flexibility of using any part of the complete band but at low power (shown by the height of the white block). The colored blocks highlighted by the circle in Fig. 2(f) indicate the bands used by edge users in the neighboring cell sites. Note that the central users of a sector do not use those PRBs that are already used by the edge users of the same sector. In the neighboring cell site, central users can however reuse these PRBs at an acceptable power level (determined based on the user density in the cell-edge and cell-center region of that sector).

The power varies for each sector as the area of the edge region (along the space axis) varies. We observe that for a fixed amount of bandwidth in each sector, the amount of transmit power for cell center P_c and cell edge P_e users varies according to the area of concentration of majority of the users. The area of these two regions and their power level varies for every sector in each cell site. We thus seek to first estimate a parameter that uniquely characterizes the user distribution in each sector and then determine the optimum power allocation to cell-edge and cell-center users for both the reference cell site and its neighboring sites.

Consider a real network where user distribution is nonuniform, the ratio of the radius of cell-center area to the radius of cell-edge area ζ would vary for each sector depending on the user distribution. In determining the classification of users as either cell edge or cell center, a given SINR threshold is usually used, and users whose SINR is below this value are regarded as cell-edge users. However, for easy analysis, we can approximate the region where such users would be located with a hexagon, as shown in Fig. 1. This approximation is

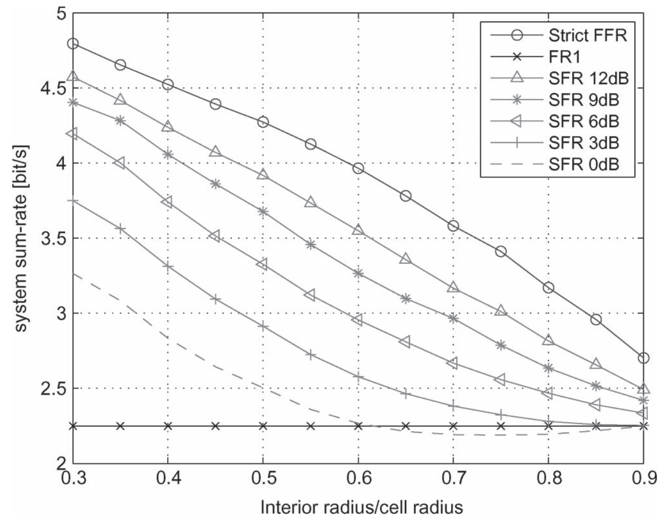

Fig. 3. Effect of $s_{\text{int}}/s_{\text{ext}}$ on various FFR schemes.

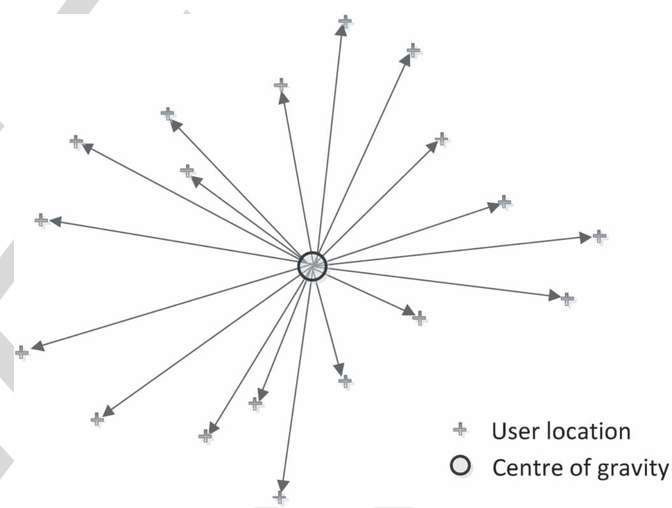

Fig. 4. Estimating central point (CoG) in each sector.

based on an SINR surface plot for a trisector antenna. This cell-edge region is variable, depending on the eNodeBs transmit power and downtilt, which invariably affects the user's SINR. The presence of hotspots at various locations further requires reconfiguration in such sectors to meet the desired system performance. Fig. 3 shows the performance of various frequency reuse schemes and SFR with different amplification factors β_s. We can infer that having a fixed ratio ζ for all sectors in all cell sites is not optimum. We demonstrate that the cell-edge and cell-center region would vary for each site and should be dependent on the user distribution, transmit power, and configuration of neighboring sites. We proceed by first determining a central point in each sector that has the shortest distance from the majority of user positions (see Fig. 4). We formulate a quadratic subproblem and, using the interior-point method, locate a unique point referred to as CoG within each sector. Second, we calculate the distance between the CoG and their serving eNodeB. We define three possible states for each sector as State X: $\zeta = 0.3$, State Y: $\zeta = 0.5$, and State Z: $\zeta = 0.8$. Each sector would assume any of these predetermined states, depending on the distance of the CoG to the eNodeB location.

Let $\mathcal{K}$ be the set of all users and $\mathcal{N}$ be the set of all sectors in the system for a cloverleaf model with three hexagonal sectors per cell site. Consider a user $k \in \mathcal{K}$ located at the cell edge, with sector $n \in \mathcal{N}$ as its serving sector. Given that the total transmit power budget is P_T, the power transmitted to users in the cell-edge area is P_e, and to users in the cell-center area as P_c, we have a constraint on power usage in each sector as

$$P_T = P_e + P_c. \tag{11}$$

Given that $P_e = \beta_s P_c$, the maximum transmit power can now be expressed as

$$P_T = \beta_s P_c + P_c \tag{12}$$

$$P_T = P_c(\beta_s + 1) \tag{13}$$

where β_s is the amplification factor of each sector. To ensure that P_T is preserved, we have

$$P_c \leq \frac{P_T}{\beta_s + 1} \tag{14}$$

and similarly

$$P_e \leq \frac{\beta_s}{\beta_s + 1} P_T. \tag{15}$$

Current solutions in the literature use values of β_s within the range of 1–20 and are usually selected using heuristics [18]. In current systems also, β_s is constant for all sectors. In our formulation however, we let β_s be dependent on the distribution of users in each sector, the ratio of users in cell edge to cell center (μ), and the value of ζ in the reference sector and its neighboring sectors. We thus aim to provide a utility function that determines β_s. This is used to determine the amount of power transmitted to users in the edge and center regions.

Let us characterize the unique distribution of users in each sector by its CoG $(CoG(x, y))$. This is a point $\boldsymbol{x} = [x, y]^T$ within the sector such that the sum of distance between this point and all user positions is minimum.

The distance is given by

$$d_k(\boldsymbol{x}) = \|\boldsymbol{x}_k - \boldsymbol{x}\|_2 = \sqrt{(x_k - x)^2 + (y_k - y)^2} \tag{16}$$

for $k = 1, 2, \ldots, K$ users in each sector. The objective is to find a unique point $\boldsymbol{x}$ that minimizes the objective function

$$CoG(x, y) = \hat{\boldsymbol{x}_n} = \arg\min_{(\boldsymbol{x})} \sum_{k=1}^{K} d_k(\boldsymbol{x}) \tag{17}$$

with inequality constraints described in Section V that specify the upper and lower bounds of possible values of $\boldsymbol{x}$. The constraints are expressed as any point within the geometrical coordinates of the hexagonal sector.

V. Proposed Solution

Our proposed solution involves two stages: The first stage is to determine the CoG of each sector and its corresponding "state." The next stage is to apply CA theory to obtain a global emergent state for all sectors.

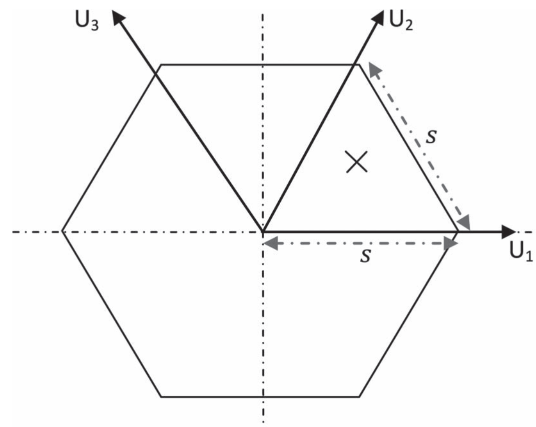

Fig. 5. Reference vectors.

A. CoG

To define a unique characteristic state for each sector based on its user distribution, we solve (17) via an iterative process. Consider three reference vectors ($\boldsymbol{u}_1$, $\boldsymbol{u}_2$, and $\boldsymbol{u}_3$) with the three orientations of the hexagon 0°, 60°, and 120° as shown in Fig. 5. The position vector $\boldsymbol{x_i}$ of any point chosen satisfies the constraints

$$\boldsymbol{x_i}.\boldsymbol{u_1} \leq s;\ \boldsymbol{x_i}.\boldsymbol{u_2} \leq s;\ \boldsymbol{x_i}.\boldsymbol{u_3} \leq s;\ \text{where } \boldsymbol{u}_1 = u_1\angle\, 0,$$
$$\boldsymbol{u}_2 = u_1\angle + \frac{\pi}{3},\ \text{and } \boldsymbol{u}_3 = u_1\angle + \frac{2\pi}{3}.$$

If $u_1 = 1$, scalar s represents the length of the side of the hexagon and $\boldsymbol{x}_i$ the position vector of any point within the hexagon. Any random point $\boldsymbol{x}_i$ can be chosen as our initial starting point for the iterative solution. The position vector can also be expressed as

$$\begin{bmatrix} 1 & 0 \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} - s \leq 0. \tag{18}$$

We denote the objective function in (17) as $f(\boldsymbol{x})$ and the inequality constraint in (18) as $g_k(\boldsymbol{x}) \leq 0$ and that they are both continuously differentiable in the whole region of $\mathbb{R}^n$. Equation (17) is a nonlinear 2-D optimization problem and can thus be solved using an iterative process.

In each iteration k, we linearize the inequality constraints and approximate the Lagrangian function, i.e.,

$$\mathcal{L}(\boldsymbol{x}, \lambda) = f(\boldsymbol{x}) - \lambda^T g_k(\boldsymbol{x}) \tag{19}$$

where $\boldsymbol{x}$ is our primal variable, and λ is the Lagrangian multiplier.

We thus form a quadratic subproblem assuming that in each iteration, $\boldsymbol{x}_k \in \mathbb{R}^n$ is an approximation to the solution, $v_k \in \mathbb{R}^n$ is an approximation of the multiplier, and $\boldsymbol{H}_k \in \mathbb{R}^{nxn}$ is an approximate Hessian of the Lagrangian function.

TABLE I
LIST OF NOTATIONS

Symbol	Description
N_{band}	Total number of PRBs in the system
N_{int}	Number of PRBs used by center users in a sector
N_{ext}	Number of PRBs used by edge users in a sector
P_T	Maximum transmit power budget in the cell
P_{PRB}	Transmit power per PRB
P_c	Transmit Power for cell-center users
P_e^{S-FFR}	Transmit Power for cell-edge users (Strict FFR)
P_e^{SFR}	Transmit Power for cell-edge users (SFR)
η_{SE}	Spectral Efficiency
η_{ASE}	Area Spectral Efficiency
$\mathcal{K}$	Set of all users in the system
$SINR_k$	SINR of user k
A_r	Area of any region r
A_c	Area of cell-centre region
A_e	Area of cell-edge region
A_{sector}	Area of a sector
R	Set of all regions
β_s	Power amplification factor (SFR)
$\mathcal{N}$	Set of all sectors in the system
N	Neighbourhood function of $\mathcal{N}$ sectors
(x_o, y_o)	Coordinates of BS
(x, y)	Coordinates of any point in a sector
$d_k(\boldsymbol{x})$	distance between k^{th} user coordinates and point $\boldsymbol{x}$
$CoG(x, y)$	Locus of points from serving BS
d_m	Distance of $CoG(x, y)$ from BS
s	Length of side of a hexagon
r_{int}	Cell radius of inner cell
R_{ext}	Cell radius of outer cell
ζ	Ratio of cell-edge area to cell-centre area
ψ	Localized Rule

The quadratic subproblem is thus

$$\min_{\boldsymbol{\omega}} \quad \frac{1}{2}\boldsymbol{\omega}^T \boldsymbol{H_k}\boldsymbol{\omega} + \triangledown f(\boldsymbol{x})^T\boldsymbol{\omega}$$
$$\text{subject to} \quad \triangledown g_k(\boldsymbol{x})^T\boldsymbol{\omega} + g_k(\boldsymbol{x}_k) \le 0 \tag{20}$$

where $\boldsymbol{\omega} \in \mathbb{R}^n$, and $\boldsymbol{H}$ is the Hessian.

Using sequential quadratic programming, we solve (20) by updating the Hessian matrix H in each iteration to obtain a quadratic programming problem that we solve by using the interior-point method [27].

This solution gives us the location of the CoG of the central point of all user positions in each sector. Based on the arguments previously presented, point $CoG(x, y)$ can define a locus of points from the serving eNodeB. We can thus estimate the distance of $CoG(x, y)$ from the eNodeB as

$$d_m = \|CoG(x, y) - \text{BS}(x_o, y_o)\|_2 \, . \tag{21}$$

For the sake of simplicity, we partition each sector into three portions representing three states X,Y, and Z. Table I shows this classification, and depending on the distance of $CG(x, y)$ from the eNodeB d_m, the sector state ζ is chosen.

B. Neighborhood Function and Localized Rule

In the following, we define the neighborhood function and localized rule used herein.

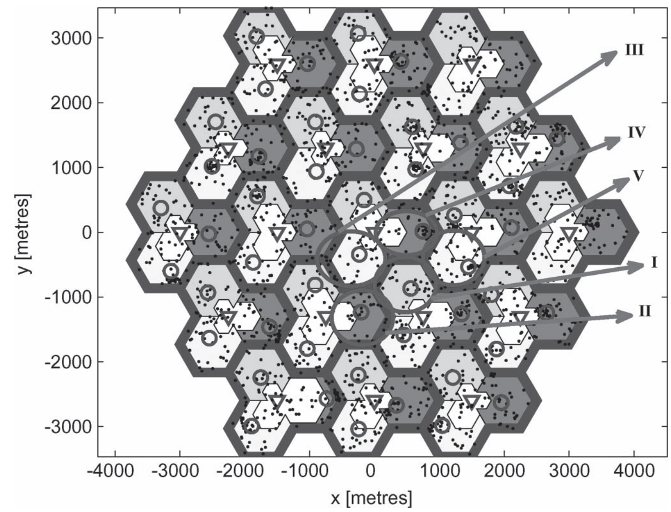

Fig. 6. System layout showing CoG of each sector.

Neighborhood Function (N)*:* Any two sectors n_1 and n_2 are said to be neighbors *iff*

$$n_1 \in N(n_2) \Longleftrightarrow n_2 \in N(n_1) \qquad \forall n_1, n_2 \in \mathcal{W}.$$

This hexagonal neighborhood relation N is a set of adjacent sectors of other cell sites with the exception that hexagonal sectors of the same cell site are not regarded as neighbors. This is due to the fact that in an OFDMA-based system, we are concerned with mitigating ICI only. The sector IDs of neighboring sectors are stored in the NCL. In the event that a sector hibernates, experiences a fault, or has been decommissioned, the NCL is updated via local communication over the X2 interface. Consider Fig. 6, where sector I has sectors II, III, IV, and V in its NCL, and the configuration settings of these sectors determine the next state of sector I.

Localized Rule (ψ)*:* Given four neighboring sectors with a set of three finite states ζ_i, the next state of sector n is the least used configuration state among its neighbors. If all states are evenly used, cell $n's$ state remains unchanged.

In implementing this rule, we first evaluate the modal state among the neighboring sectors and eliminate it from the set of possible new states. For example, in Fig. 6, if sector II has state Y, sector III has state X, sector IV has state Y, and sector V has state Y, the next state of sector I would be state X, which is the least used state among its neighboring sectors. The localized rule is chosen based on the fact that when a new node joins a network, having too low power would make it prone to interference from other sectors, whereas a power level that is too high would cause interference to other sectors. When two or more neighboring sectors need to change their state at the same time, priority is given to sectors based on their hierarchy in the NCL. It is reasoned that if a majority are on a “low,” it is tolerable to change state to a “high” provided at least one neighbor is already operating at that level, which shows that it is tolerable among its neighbors. It is important that the new state change is limited to a level already experienced by other neighbors. Thus, the rule is limited to the least used state among its neighbors.

TABLE II
MAPPING $CoG\ (x, y)$ TO ζ

$CoG(x, y)$	ζ
$d_m < s$	0.3
$s \leq d_m \leq 1.5s$	0.5
$d_m > 1.5$s	0.8

C. Cell-Edge Power Amplification β_s

In SFR, the power amplification factor β_s has to be carefully chosen as it determines the performance of cell-edge users and the amount of interference to other neighboring cells. We propose a utility function that determines the amplification factor β_s, based on the "state" of each sector, the ratio of users located in cell edge to cell center, and the current state of neighboring sectors. The state of each sector is dependent on the user distribution, which we characterize by its CoG (see Table II). We relate this system state ζ to the power amplification factor β_s, which varies for each sector.

Considering each sector represented as a hexagonal shape, the area of the sector is given as

$$A_{\text{sector}} = \frac{3\sqrt{3}}{2} \times s^2 \tag{22}$$

where $s =$ length of a side of hexagon (or half the diameter of the sector). The area of the center region can be expressed as

$$A_c = \frac{3\sqrt{3}}{2} \times (\zeta s)^2 \tag{23}$$

where the factor ζ scales the original hexagonal sector size to the center region. The area of the edge area is thus given by

$$A_e = \frac{3\sqrt{3}}{2} \times s^2(1 - \zeta^2). \tag{24}$$

We can thus obtain the ratio of edge area to center area as

$$\frac{A_e}{A_c} = \frac{1 - \zeta^2}{\zeta^2}. \tag{25}$$

The number of center and edge users is directly proportional to the area of center and edge regions assuming a uniform user distribution. If the user density (the number of users per unit area) is ρ and transmit power per user is P_k, we have

$$\mu = \rho \times P_k. \tag{26}$$

Equation (26) simplifies to give μ as the power per unit area. Thus, the transmit power to users in the edge region can be expressed as

$$P_e = \mu_e A_e. \tag{27}$$

Similarly, the power transmitted to the center region is

$$P_c = \mu_c A_c \tag{28}$$

with subscripts c referring to center and e referring to edge. In SFR, $P_e = \beta_s P_c$. Substituting this in (27) and dividing by (28), we obtain

$$\beta_s = \mu_r \frac{A_e}{A_c} \tag{29}$$

which can also be expressed as

$$\beta_s = \mu_r \frac{1 - \zeta^2}{\zeta^2}. \tag{30}$$

Having obtained this, we can now express the signal-to-noise-plus-interference ratio for any cell-edge users k as

$$\gamma_{\text{edge}} = \frac{\beta_s P_c \times G_k}{N + \sum_{n \in \mathcal{F}} \beta_s P_c \times G_k + \sum_{n = \mathcal{C}} P_c \times G_k}. \tag{31}$$

P_c is the transmitted power in sector n, G_k is the channel gain, N is noise power, $\mathcal{F}$ is the set of all sectors transmitting on the same frequency subband for cell-edge users, and $\mathcal{C}$ is a set of sectors using the same subband to serve cell-center users.

However, to ensure that our proposed scheme can autonomously adapt to spatiotemporal dynamics of the system, we need to consider the effect of these settings on neighboring cells in a defined neighborhood. We thus propose a method that would select an optimum value of ζ based on the $CoG(x, y)$ of its serving sector, the ratio of cell-edge to cell-center users μ, and the value of ζ in neighboring sectors. As the user distribution in a neighboring site changes, its power allocation for cell-edge user also varies. Thus, the sector has to adopt a new optimum power setting. This adaptive and autonomous scheme does not cause instability as the changes are restricted to a defined local neighborhood, and changes are triggered from user distribution patterns over a medium time scale that is usually hours to days [6]. We summarize steps in our proposed solution based on CA.

- Step 1) Based on user distribution and presence of hotspots at cell center or cell edge, calculate the CoG for each sector.
- Step 2) Classify each sector into states X, Y, or Z based on the distance of CoG from the serving eNodeB using Table II.
- Step 3) Apply the CA algorithm to obtain a new converged state for each sector and update NCL with new sector states.
- Step 4) Classify users as cell-edge and cell-center users based on new sector states and determine the power amplification factor β_s for each sector using (30).
- Step 5) Evaluate system performance, and if the average $SINR$ of each sector is less than the $SINR$ threshold, a new state change is triggered, thus going back to step 3.

VI. RESULTS

A system-level simulator has been used to validate our proposed scheme. All results presented are for the downlink, and the results presented in Figs. 3, 7, and 8 are obtained from Monte Carlo simulations. This is repeated for various user positions, which are randomly generated, and the average value of the performance metric is used. We also validated this scheme for different network sizes, employing a cloverleaf model that consists of three hexagonal sectors amalgamated together as one cell site. Three sector antennas were used, and simulation was performed for various random user distributions

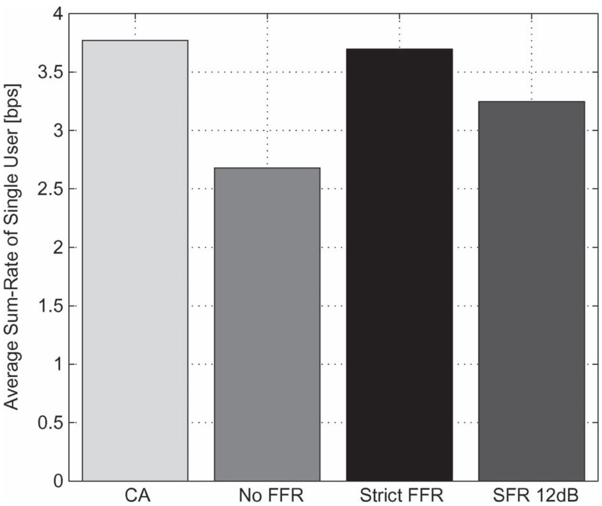

Fig. 7. Comparison of average sum rate of a user using various FFR schemes.

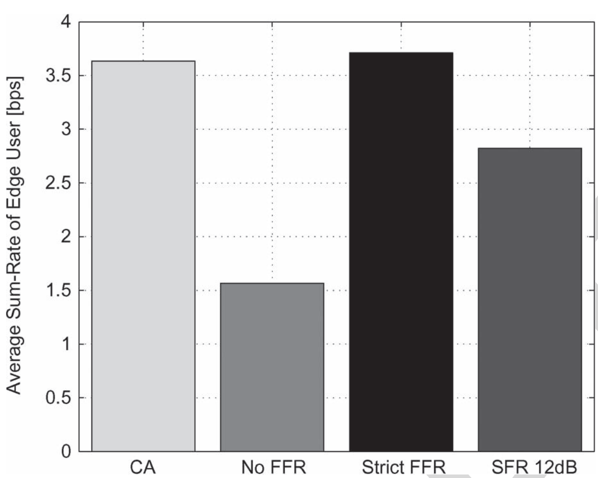

Fig. 8. Average sum rate of cell-edge users.

TABLE III
MAIN SIMULATION PARAMETERS USED

Parameter	Value
Total Bandwidth	5MHz
Inter Site Distance	1500m
eNodeB height	50m
UE height	1.5m
Transmit power	40dBm
Antenna Model	berger
Path loss Model	L = 128.1 + 37.6log D

and random hotspot locations. Other simulation parameters used are listed in Table III. Results were consistent for 21 and 57 sectors. We present results for discussion for 57 sectors. We use $N_{\text{band}} = 48$ in each sector.

Fig. 6 shows the system layout and user distribution of 150 users randomly placed in each sector. The CoG of user distribution is marked by blue circles, and as can be observed, their locations vary in each sector. Based on the classifications in Table II and illustration in Fig. 2, users located in the center white region are cell-center users and use any portion of the system bandwidth with a low power restriction. Fig. 7 shows the average user sum rate of the total system when FR1 (frequency reuse of 1 in all regions), S-FFR, SFR with optimum power amplification of 12 dB, and our proposed scheme based on CA. This is obtained by calculating the sum rate of all users in the system (both cell-edge and cell-center users) and dividing by the total number of users. S-FFR is expected to show better performance and avoidance of ICI due to its limitation of frequency allocations to cell regions. This is the classic ICI avoidance scheme and is not spectrally efficient.

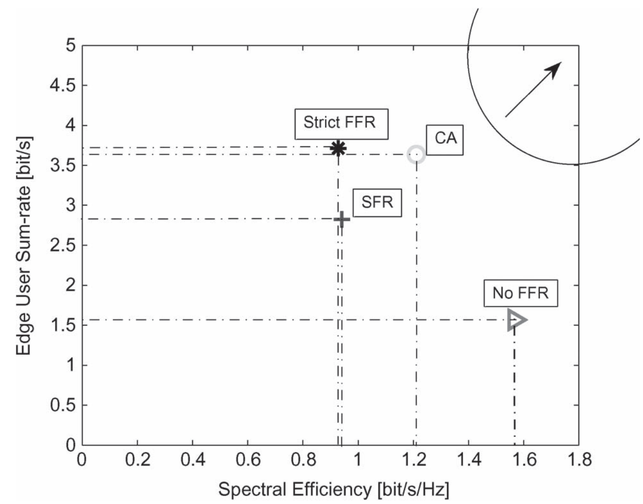

Fig. 9. Cell-edge sum rate and spectral efficiency tradeoff.

S-FFR, as expected, shows the best cell-edge user sum rate but has a fundamental tradeoff between achieving this improvement and the spectral efficiency. Thus, S-FFR achieves the highest edge user sum rate but at the expense of having lower resource utilization [28], [29]. However, our proposed scheme achieves a close performance with S-FFR and better performance than SFR in terms of the edge user's sum rate. This is also achieved at a better utilization of resources than S-FFR.

Focusing on the performance of the CA-based scheme for cell-edge users, Fig. 8 reveals an interesting result. As expected, the sum rate for cell-edge users employing frequency reuse of 1 experiences larger ICI; thus, its low sum rate for edge users. SFR also shows this effect, but due to transmission of higher power to cell-edge users, the interference is minimized. In the CA-based scheme, cell-edge users maintain a high performance better than SFR and comparable to S-FFR but with better spectrum utilization. We can thus see that CA helps serve as a tradeoff between S-FFR performance and high spectrum utilization of SFR.

Fig. 9 shows the tradeoff between the cell edge sum rate and the spectral efficiency of the schemes discussed. The objective is to design a scheme whose operating point lies in the upper-right half of the solution space (indicated by the arc and arrow). From this plot, we can see that the proposed scheme achieves higher spectral efficiency for a slightly lower performance in terms of sum rate than S-FFR.

In terms of cell-edge sum rate, S-FFR has a 4.8% better performance than the CA scheme. For its spectral efficiency, however, CA has an 18.1% better performance than S-FFR with "no FFR" as the reference. Maintaining good resource utilization is important as reduction in resource utilization can

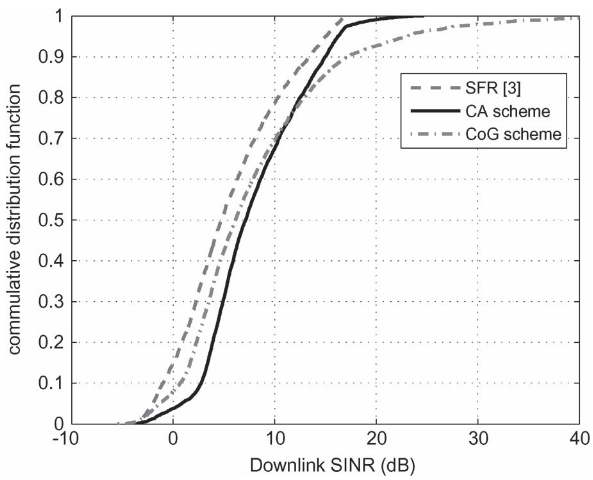

Fig. 10. System performance with CA and without (CoG).

lead to a dip in the peak data rate of the cell. This occurs when users with high rate requirements have restrictions from being allocated with sufficient number of PRBs they may require [18].

Finally, we consider the comparative performance of the proposed CA-based scheme with the simple adaptive scheme based on CoG. Fig. 10 shows the system performance using the downlink SINR as the performance metric. Two deductions can be made from this result. First is the improved performance of both proposed schemes (CoG and CA) over the SFR scheme proposed in [3] due to the distributed nature of our solution. Second is that with the CA-based solution, 75% of the users experience higher SINR than the CoG scheme. In the simple adaptive scheme (CoG), only 25% of the users experience higher SINR than the proposed solution. We can thus conclude that in employing CA, an optimal point is reached between improvements in cell-edge user performance at an acceptable decrease in performance of cell-center users.

The underlying reason behind the better performance of the CA-based approach is its distributed nature where different user locations would have different cell-edge and cell-center regions. Thus, an optimum power allocation is used in each sector. This reduces the power allocation of sectors based on their effect on neighboring sectors. The CA scheme dynamically changes its power allocation for different regions, thus showing even better performance compared with S-FFR but with better subband utilization than S-FFR.

VII. Conclusion and Future Work

In this paper, we have addressed a fundamental problem of OFDMA-based cellular networks, i.e., ICI. We have proposed a variant to the conventional FFR scheme that exploits the knowledge of user positions to determine the power ratio between cell-edge and cell-center users in individual sectors of a cell site. This scheme is based on the CoG of users in each sector. Our distributed and adaptive solution based on FFR was further enhanced by employing CA theory to achieve an emergent and adaptive solution. This is done to ensure that the distributed FFR scheme becomes autonomous via continuous reconfiguration in accordance with the configuration settings of neighboring sectors.

This proposed FFR scheme not only provides better sum rate for cell-edge users, which is comparable to the performance of the S-FFR scheme, but achieves this with higher resource utilization as well. We have also shown that our scheme outperforms the well-established SFR scheme in terms of its cell-edge user sum rate. Based on the information provided and results presented, we have thus initiated an important contribution on the relevance of emergence in adaptive and autonomous solutions for wireless cellular networks.

Despite the huge potential of applying CA in wireless cellular networks, more research still needs to be done to provide analysis of the stability and convergence of this technique. In addition to this, we would investigate applying these principles in heterogenous networks with defined localized rules for indoor base stations and well-defined neighborhood for effective interference coordination among macrocells and femtocells.

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