Game Theoretic based Distributed Dynamic Power Allocation in Irregular Geometry Multicellular Network

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Abstract
The extensive growth in data rate demand by the smart gadgets and mobile broadband application services in wireless cellular networks. To achieve higher data rate demand which leads to aggressive frequency reuse to improve network capacity at the price of Inter Cell Interference (ICI). Fractional Frequency Reuse (FFR) has been recognized as an effective scheme to get a higher data rate and mitigate ICI for perfect geometry network scenarios. In, an irregular geometric multicellular network, ICI mitigation is a challenging issue. The purpose of this paper is to develop distributed dynamic power allocation scheme for FFR based on game theory to mitigate ICI. In the proposed scheme, each cell region in an irregular multicellular scenario adopts a self-less behavior instead of selfish behavior to improve the overall utility function. This proposed scheme improves the overall data rate and mitigates ICI.
Keywords:
ICI, Game theory, FFR, Irregular Geometry, DRA

1. Introduction

The extensive growth in the cellular system and huge increase in mobile broadband applications services due to smart gadgets have increased the demand for higher data traffic. The impact of this higher demand consequently, a challenge for the cellular operator to increase their network capacity along with coverage. Therefore, efficient management of radio resources is getting more attention and it could open more opportunities for coverage and capacity enhancement [1]. In literature, the frequency reuse (FR) scheme is used to enhance network capacity due to limitations of the frequency spectrum. However, the aggressive reuse of frequency can boost the system capacity on the cost of intercell interference (ICI) and co-channel interference (CCI). There is a tradeoff between frequency reuse and interference [2].

To overcome the interference problem, the FFR scheme is proposed in the literature and used to overcome the issues of interference mitigation [3]. The basic idea behind FFR is to partition cell coverage areas into multiple regions. The frequency spectrum and power are allocated to each region in such a pattern to avoid the ICI [4].

Wireless cellular networks, signal power, and interference received by the Base Station (BS) or users are dependent on distance. The Signal to Interference plus Noise Ratio (SINR) is user distance and location dependent. Hence, the network performance is dependent on the BS configuration and network topology [5]. Finally, distributed resource allocation mechanism is a novel approach for users and BS to decide on their resources independently by utilizing existing resource allocation schemes with some enhancements [6].

The paper is organized as the related work is present in section 2, section 3 given system model design and assumptions along with the problem formulation; section 4 presents the development of the proposed game-theoretic discrete dynamic power allocation scheme. Performance analysis is done in section 5, whereas section 6 concludes the paper.

2. Related Work

The main purpose of FFR is to enhance the SINR by reducing ICI which tends to improve the system data rate by allocating orthogonal sub-band to regions [7]. Previously, the utilization of FFR is in hexagonal cellular geometry models. However, in practical cellular network scenario, where the cellular configuration is irregular, and it is different for each cell of multicellular network and each cell face different kind of ICI [8]. It is very difficult to give fixed power to cell regions to avoid ICI or replace the whole interfering sub-bands of regions of one part of the cell to another part to avoid ICI. Therefore, in case of irregular cell setup, the performance of FFR is not satisfactory [9]. ICI mitigation in irregular geometry is a challenging issue.

Thus, the resource allocation along with network topology is a key consideration to analyze the performance of the interference mitigation scheme. In the recent research, network topology and resource distribution are being considered on FFR with irregular geometry , However, these previous schemes are on SFR for irregular geometry only considered basic SFR schemes with only two cell regions and only [10] and only fixed power for regions is considered [11], Furthermore, distributed dynamic power allocation has never been taken in FFFR for irregular cellular geometry. Therefore, there is a need to develop distributed dynamic power allocation scheme for irregular geometry multicellular networks, which consider multi-cell regions while utilizing full frequency.

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3. System Model

In the system model, OFDMA based multicellular network is considered in irregular geometry for downlink transmission. Due to irregularity in cell shapes, the BSs locations are not fixed to any point. The Point Hardcore Point Process (PHCP) is used to place the BS and coverage of each cell is characterized by Voronoi tessellations with random coverage area [12][13]. The cell center region and cell edge region users do not have the same geographic interpretation. Therefore, SINR (γ) is the right tool to measure the distance between BS and users [9]. The cell center area $(\gamma \gg \gamma_{TH})$ is with higher SINR value and cell edge area $(\gamma \ll \gamma_{TH})$ is with lower SINR value. The total number of areas X becomes.

$$X = \{X_C, X_E\} \tag{1}$$

Where, X_C is a cell center region and X_E is a cell edge region. Furthermore, the cell edge area is further divided into multiple sub-areas which are called sectors S, where S = {1, 2, 3} then X_E becomes

$$X_E = \{X_1, X_2, X_3\} \tag{2}$$

The bandwidth allocation to each cell region is considered fixed as shown in Figure 1. The discrete power allocation for the regions as shown in the figure above is needed to intelligently allocate to regions due to irregularity in the cell regions.

The $N = \{1,2, \ldots .N\}$ is the total number of channels in the available system, where $n \in N$. The total bandwidth is defined as B^T. A set of K number of total users defined by $K = \{1,2, \ldots ., K\}$ in a cell, where $k \in K$. Furthermore, the power allocation vector for user k on channel n is defined by $p_k = \{p_k^{(1)}, p_k^{(2)}, p_k^{(3)}, \ldots .. p_k^{(N)}\}$, where $p_k^{(n)} \geq 0, \forall n \in N$ and $\sum_{n \in N} p_k^{(n)} \leq p_k^{max}$.

Data rate $R_{k,n}$ for user k on channel n, can be found by using Shannon's theorem as follows

$$R_{k,n} = \Delta f . \log_2(1 + \gamma_k^{(n)}) \tag{3}$$

Where, Δf is channel spacing, N_k is the number of channels allocated to user while B_k is allocated bandwidth to user k, then equation can be written as

$$R_k = \sum_{n=1}^{N_k} R_{k,n} = \Delta f \sum_{n=1}^{N_k} \log_2(1 + \gamma_k^{(n)}) \tag{4}$$

The overall data rate of a serving BS i can be written as

$$R_k^i = \sum_{k=1}^{K} R_k \tag{5}$$

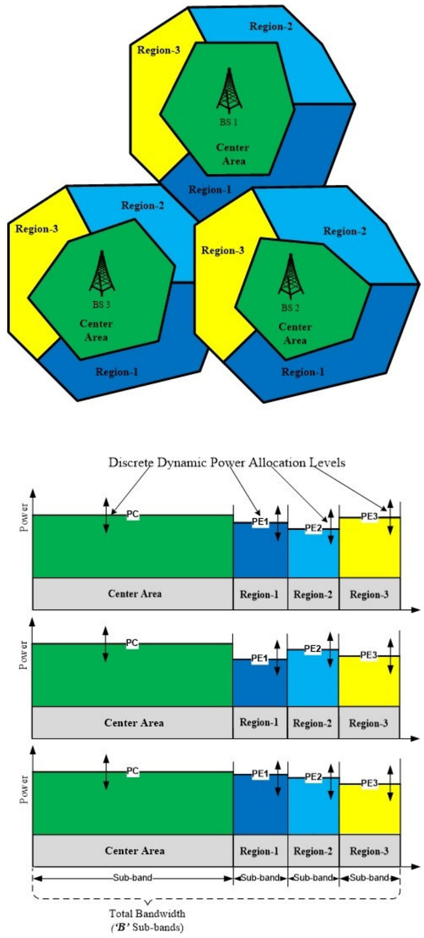

Fig. 1. Cell Region Formation & Dynamic Power Allocation

In this paper, power allocation management is adopted to avoid the Inter-Cell Interference (ICI). The ICI mitigation is achieved through power allocation to maintain orthogonality among allocated sub-bands or regions. In the proposed scheme discrete dynamic power allocation is based on requirements. Therefore, the problem of discrete and dynamic power allocation in the proposed scheme can be formulated for overall data rate maximization.

$$\max_{(p)} (\sum_{k=1}^{K} \sum_{n=1}^{N} R_k^{(n)}) \tag{6}$$

$$s.t. \{p \leq P^{max}\} \tag{7}$$

Each cell region has a different number of users with different resource demand, therefore,

$$K = K_C + K_E \tag{8}$$

Where, K_C are the users of the cell center region and K_E are the users of cell edge regions. Furthermore, the edge region is consisting of multiple sub-regions are expressed as $K_E = \sum_{s=1}^{S} K_s$. Furthermore, $B^T = \{B_C, B_E\}$, where B_C

is a cell center allocated bandwidth and B_E is a cell edge region allocated bandwidth The cell edge is further divided into multiple regions and bandwidth B_E can be written as $B_E = \sum_{s=1}^{S} B_s$.The bandwidth allocation to each cell region is considered fixed as shown in Figure 1.

Therefore, the problem of discrete and dynamic power allocation in the proposed scheme can be formulated as the total data rate maximization problem. Mathematically can be expressed as,

$$\max_{P\in(p_x)} \left\{\sum_{k_x=1}^{K_x} \sum_{n_x=1}^{N_x} R_{k_x}^{(n_x)} (p_x)\right\} \quad (9)$$

$$s.t. \begin{cases} R_{k_x}^{(n_x)} \geq R_{k_x,min}^{(n_x)} \\ p_x \leq P_{x,max} \end{cases} \quad (10)$$

The resource allocation problem is to maximize the overall data rate of the system as mentioned in Equation (9) allocating distributed power allocation optimally to regions and utilization of full bandwidth. The minimum data rate and maximum power allocation are the constraints which are mentioned in Equation (10).

4. Game Theoretic Discrete Power Allocation

The discrete power allocation to the region is based on the game theoretic framework. The game theory components are described as 3- tuple game which is mentioned in following Equation (11).

$$G = (X, \{p_x\}_{x\in X}, \{U_x\}_{x\in X} \quad (11)$$

In this game setup, where the regions are considered as 'players' which are resource contenders. The set of players X (regions and players are used interchangeably), regions of neighboring irregular cells act as players. Regions can take decisions based on their demands, but they are unable to implement an action selection process. Therefore, the regions are virtual game players. The actual game is established and played by BS who act as referees or region coordinators. The power allocation to regions as per the desired equilibrium by the BS. The power p_x is the selection by the region x is the strategy of the player x. Each region updates BS about its power requirements in the type of data rate demand d_x. The data rate is a function of power. Hence, the 'utility function' U_x of the region, x is mentioned in Equation (12) as.

$$U_x(p_x, p_{-x}) = \min\left(\frac{R_x(p_x,p_{-x})}{d_x}, 1\right) \quad (12)$$

Where, d_x is a vector of data rate demand. All the players are intelligent and independent, each of these regions is interested to maximize its utility, U_x. The action taken by each independent region $x \in X$ is self-interested given by Equation (13)

$$p_x = argmax\ U_x(p_x, p_{-x}), \forall x \in X \quad (13)$$

Where, $p_{-x} = \{p_1, p_2, \dots p_{x-1}, p_{x+1}, \dots p_x\}$ is the power allocation strategy of all regions except region x. Each region is a non-cooperative player, where each player is interested to maximize its own utility by allocating power to its own sub-bands. This strategy of players comes as non-cooperative game, in which non-cooperative behavior of regions are independent to allocate their power to sub-band regardless of how the actions taken by other regions of other cells. The proposed maximization problem as follows,

$$\max_{P\in(p_x)} \left\{\sum_{k_x=1}^{K_x} \sum_{n_x=1}^{N_x} R_{k_x}^{(n_x)} (p_x, p_{-x})\right\} \quad (14)$$

$$s.t. \begin{cases} R_{k_x}^{(n_x)} \geq R_{k_x,min}^{(n_x)} \\ p_x \leq P_{x,max} \end{cases} \quad (15)$$

4.1. Power Allocation Action and Regulation

Each action taken by regions is self-enforcing without any cooperation or coordination among regions [14]. It is necessary to take care of co-tier interference to the neighboring cells besides the allocation of power to the regions. Each region is a naturally selfish (self-interested) player and interested to maximize its utility without thinking about the impact of selfishness on its neighboring cell region. However, this conduct of region can be regulated by putting limits of its own which can make them self-sacrificing or selfless. The utility function is further distributed into two parts, such as

1. Self-Interested (SI) Utility
2. Self-Sacrificed (SS) Utility

The self-interested utility is based on data rate demand of by the regions, which given in Equation 16

$$U_x^{SI}(p_x, p_{-x}) = min(\frac{R_x(p_x,p_{-x})}{d_x}, 1) \quad (16)$$

The above-mentioned Equation 16 is a linearly increasing function that is dependent on the data rate Rx, when $0 \leq R_x \leq d_x$ and above Equation 16 goes constant at $U_x^{SI} = 1$, when $R_x \geq d_x$,

The regions with self-interested behavior, each region independently likes to achieve data rate either as per data rate demand or higher, which tends the players in a competition. The self-interested attitude of players disrespects the utilization of resources which leads to interference caused by the strategies adopted. To overcome the self-interested (SI) attitude, a self-sacrificed (SS) utility is introduced by the BS. The main purpose of this new self-sacrificed utility is to enhance the overall utility by regulating the self-interested utility by regions. With the self-sacrificed, the competing regions will be penalized for using excess power. Initially, the cost function is used as a penalty [15] for using excessive use of resources to avoid co-tier interference.

A proposed self-sacrificed utility function can control its action to avoid contributing to co-tier interference for competing regions. SS works in a distributed manner to avoid co-tier interference without taking much coordination from the network which helps to improve network performance by enhancing data rate while utilizing fewer resources. The SS utility function mentioned in Equation (17) is for power regulation.

$$U_x^{(SS)}(p_x, p_{-x}) = \frac{P_{x,max} - \delta(\sum_{n_x-1}^{N_x} p_x^{(n_x)})}{P_{x,max} + \delta(\sum_{n_x-1}^{N_x} p_x^{(n_x)})} \qquad (17)$$

The equation above is a monotonically decreasing function with an increase in sum used in power p_x. The region's utility will decrease with an increase in power. Where δ is a controlling factor to control the excessive use of power. The value of δ is adjustable based on region type whether it is a cell center region or cell edge region, where $1 \leq \delta \leq 2$. For the cell center region, which is a low impact on interference the value of δ is considered 1. For the cell edge region, the value of δ is dependent on the cell edge sectoring. Low edge sectoring means a higher impact of interference and higher the value of δ and vice versa.

Therefore, the impact of both the above-mentioned utilities (SI and SS) is to increase the overall resultant utility of each player/region based on the regulated utilization of discrete power levels. Hence, this tends to motivate the region not to increase the limits of utilized power level on specified sub-channels. This act will improve overall network performance by controlling discrete power levels on interfering channels and increase utility. Finally, the utility function for the region's power allocation action with both SI and SS regulation utility is given in the following Equation (18) which is a combination of Equation (16) and (17). Therefore,

$$U_x(p_x, p_{-x}) = U_x^{SI}(p_x, p_{-x}) + U_x^{(SS)}(p_x, p_{-x}) \quad (18)$$

In Figure 2, the impact of region's possible action on utility is shown. In the utility graph of Figure 2, the region's utility declines as the data rate exceeds the limit of data rate demand $R_x \geq d_x$. The edge region data rate R_x is more dependent on the SS utility function. The edge region can cannot increase its utility independently above the demand level d_x, this phenomenon tends to reduce and control the overall interference of the network. Improvement in network interference help to maximize overall data rate of the system.

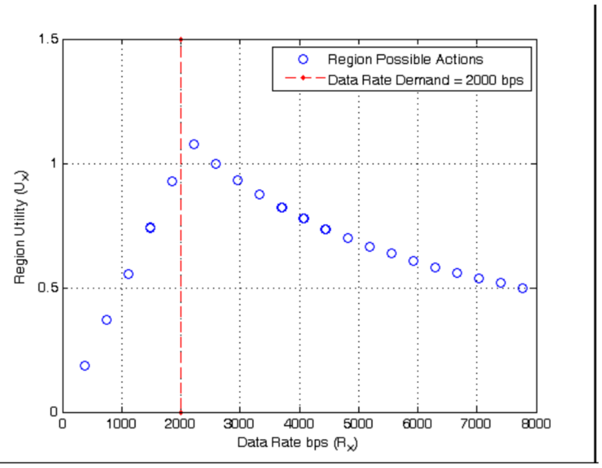

Fig. 2. Region's Possible Actions

The complete flow chart of discrete dynamic power allocation is shown in Figure 3,

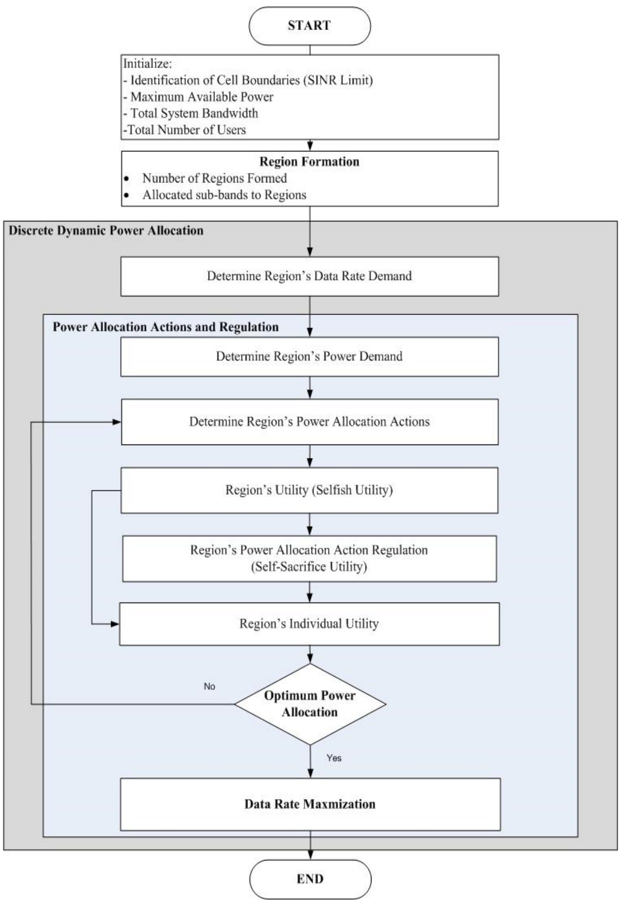

Fig. 3. Proposed Scheme Flow Chart

5. Performance Analysis

This section gives the performance analysis of the proposed discrete dynamic power allocation scheme for the irregular multicellular network. Initially, the analysis is done for 3 sectors scenario, which is compared with the GFFR scheme and FFR-3 schemes. Furthermore, 3 sector scenario is compared with the 4 sectors and 6 sectors scenarios.

5.1. Power Allocation

Initially, all regions (players) randomly adopted their actions from the action space. The power selected by the regions can cause interference due to overlapping regions. However, with time every region can adjust its power dynamically and independently to avoid ICI. The utility function equation helps to avoid self-interested behavior by regulating their move through self-sacrificed utility. Finally, correlated equilibrium is achieved.

5.2. Overall Data Rate

The data rate is calculated based on the Shannon Theorem and the expression for the total cell data R_x is mentioned in the above section.

Figure 6 shows the Cumulative Distribution Function (CDF) of the user's achieved data rate. The result shows that the proposed scheme of resource allocation outperforms all the previous schemes. The interference is avoided by allocating optimum power dynamically on cell edge region sub-bands. Hence, significant improvement in the user's data rate. A 58.64% improvement in the user's data rate has been achieved in comparison with Generalized- FFR (GFFR) and a 37.93% improvement have been noted compared to FFR-3 Scheme.

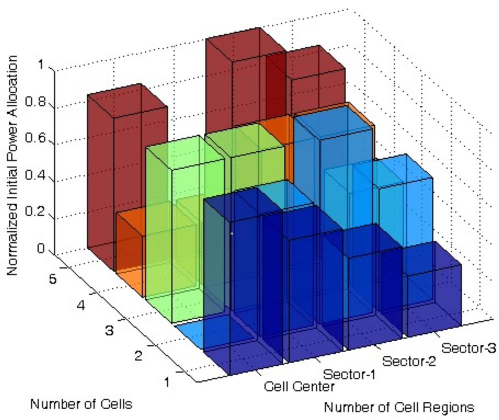

Fig. 4. Power Allocation (Initial)

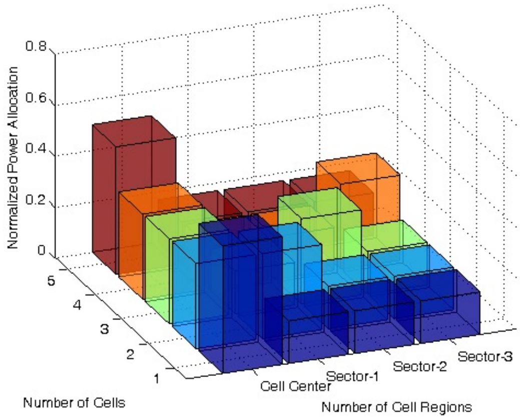

Fig. 5. Power Allocation (Convergence)

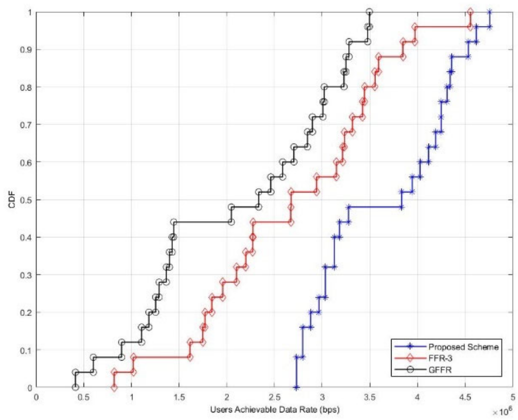

Fig. 6. CDF of Cell Users Data Rate

5.3. Performance with Different Cell Edge Sectoring

Increase in higher number of cell edge sectors in the irregular geometry based proposed scheme. The increase in the edge region sectoring, further reduce the ICI. The Figure shows the achievable data rate of proposed resource allocation scheme with different sectoring combination. From sectoring 3 to 6 in cell edge region, the improvement in cell data rate by 56.32%. The improvement has found when sectoring increase from 3 to 4 in the cell data rate by 30.2%. Hence, higher order sectoring in the irregular geometric cellular network improves the system performance by efficiently allocation of power on allocated sub-bands.

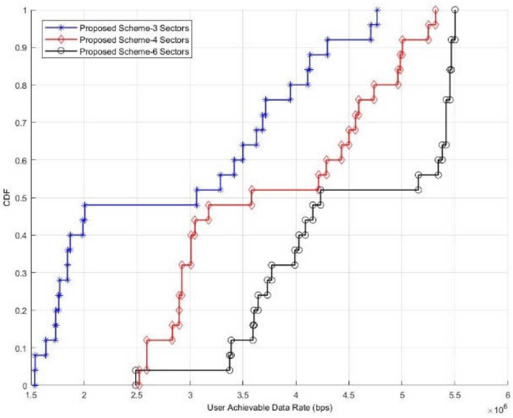

Fig. 7. CDF of all user data with multiple cell edge sectoring

6. Conclusion

In this paper, distributed dynamic power allocation scheme is developed to mitigate ICI for irregular geometry in multicellular network. The PHCP is considered for BS placement and users are randomly distributed in the BS coverage region. The cell is divided into multiple regions, initially cell center region and cell edge region while, cell edge is sectored into further multiple regions. Full frequency allocation and utilization is considered, which is distributed among regions. Due to irregularities in region area and randomness in users is considered, therefore each cell region has different power requirements for their sub-bands. Fixed power allocation tends to reduce the efficiency of the system by underutilization of resources. The proposed scheme is based on game theory for power allocation on different cell regions based on their requirements. Moreover, ICI is avoided by achieving the utility function along with dynamic optimal power allocation on regions. The performance of proposed scheme is evaluated in 2 stages. In the first stage proposed is compared with the previous basic schemes. In the second stage, the proposed scheme is analyzed by changing the number of cell edge sectoring from 3 to 4 and 3 to 6. The proposed scheme enhanced overall cell data rate by 58.64% and 37.93% in comparison with GFFR and FFR-3 respectively. Furthermore, the proposed scheme with 6 sectors enhanced overall cell data rate by 56.32% and proposed scheme with 4 sectors enhanced overall cell data rate by 30.2% compared to 3 sector configurations. These result show that by controlling self-interested behavior of regions help to mitigate ICI and improves system performance.

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