Dynamic fractional frequency reuse (D-FFR) for multicell OFDMA networks using a graph framework

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ABSTRACT

A graph-based framework is proposed in this paper to implement dynamic fractional frequency reuse (D-FFR) in a multicell Orthogonal Frequency Division Multiple Access (OFDMA) network. FFR is a promising resource-allocation technique that can effectively mitigate intercell interference (ICI) in OFDMA networks. The proposed D-FFR scheme enhances the conventional FFR by enabling adaptive spectral sharing as per cell-load conditions. Such adaptation has significant benefits in practical systems where traffic loads in different cells are usually unequal and time-varying. The dynamic adaptation is accomplished via a graph framework in which the resource-allocation problem is solved in two phases: (1) constructing an interference graph that matches the specific realization of FFR and the network topology and (2) coloring the graph by use of a heuristic algorithm. Various realizations of FFR can easily be incorporated in the framework by manipulating the first phase. The performance improvement enabled by the proposed D-FFR scheme is demonstrated by computer simulation for a 19-cell network with equal and unequal cell loads. In the unequal-load scenario, the proposed D-FFR scheme offers significant performance improvement in terms of cell throughput and service rate as compared to conventional FFR and previous interference management schemes. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
fractional frequency reuse (FFR); graph theory; intercell interference (ICI) management; Orthogonal Frequency Division Multiple Access (OFDMA); IEEE 802.16m; Long-Term Evolution Advanced (LTE-A)

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1. INTRODUCTION

Thanks to its effectiveness and flexibility in radio resource-allocation, as well as its capability of combating frequency-selective fading, Orthogonal Frequency Division Multiple Access (OFDMA) has been widely adopted in many next-generation cellular systems such as Long-Term Evolution Advanced (LTE-A) [2] and IEEE 802.16m advanced WiMAX [3]. Since radio spectrum has long been deemed the most scarce resource, advanced radio resource management (RRM) scheme that can increase the OFDMA network capacity and reduce the deployment cost has been in dire demand. The need for such an RRM algorithm becomes even more acute today, as the number of subscribers experiences unprecedented growth globally and the volume of traffic increases exponentially.

To improve the spectral efficiency, the same frequency band† is often reused in multiple geographical areas or cells. However, intercell interference (ICI) will inevitably be incurred when users or mobile stations (MSs) in adjacent cells share the same spectrum. Since ICI is the major performance-limiting issue in wireless cellular networks [4], a simple interference management (IM) scheme that can effectively mitigate ICI is a central part of RRM.

One simple form of IM suggests the allocation of disjoint bands to adjacent cells and shared bands to geographically distant cells. This way, the communication links in the network will not cause any pronounced interference to each other. Such deployment, however, tends to lose more band-
width efficiency than what can be gained in signal quality improvement by ICI reduction. Therefore, recent research activities have outlined several improved IM schemes for next-generation OFDMA systems. FFR is one such technique supported in WiMAX [5]. FFR is designed with the objective of striking a better tradeoff between spectral efficiency (i.e., advantage of admitting more users) and interference mitigation (i.e., advantage of improving signal-to-interference-plus-noise ratio, or SINR) by leveraging the very different experience of ICI in the cell center and the cell edge. In particular, since cell-edge MSs are more prone to ICI than cell-center MSs, the cell edge is granted a bigger reuse factor (e.g., 3) while the cell center is granted with a smaller reuse factor (e.g., 1).

FFR has drawn significant research attention due to its efficiency and simplicity. Examples and applications of FFR were discussed in [6–8], and variations of FFR were proposed and compared in [9,10]. All these schemes are of fixed configuration; that is, their spectrum allocation is predetermined and unadaptable to cell-load variations. This rigidity hinders the realization of FFR’s full potential and may result in inefficient spectral usage. For example, in an unequal cell-load environment, heavy-load areas may experience a shortage of spectral resource while light-load areas experience a surplus of resource due to this rigidity.

A dynamic FFR scheme was proposed in [11], where resources are dynamically partitioned into a super group and a regular group. This scheme demonstrates higher system throughput but lower cell-edge throughput performance compared with a static FFR scheme. An adaptive FFR scheme was proposed in [12]. This scheme suggests that only cells that are dominant interferers of the cell-edge users in service are required to employ FFR, while the remaining cells may still employ a reuse factor of 1. However, a practical algorithm that can systematically achieve the resource-allocation principle suggested by all these FFR schemes is missing.

Based on the above observations, we are motivated to develop a novel multicell OFDMA channel-assignment framework that can systematically implement dynamic FFR which yields superior cell-edge throughput performance compared with fixed FFR. Our scheme, specifically termed dynamic fractional frequency reuse (D-FFR), can adapt to varying and unequal traffic loads in adjacent cells by judiciously redistributing the radio resource among cells. This adaptation is realized by a novel graph approach in which the FFR-enabled network is first presented by an interference graph and then the resource-allocation is accomplished by coloring the graph intelligently. Various versions of FFR can easily be incorporated into our D-FFR framework.

The rest of the paper is organized as follows. The multicell system model and mathematical description are presented in Section 2. In order to establish performance benchmarks and provide background for our proposed method, previous IM schemes and the graph approach to resource-allocation are introduced in Section 3. The proposed D-FFR framework is described in Section 4 with its performance demonstrated in Section 5. Finally, concluding remarks are given in Section 6.

2. SYSTEM DESCRIPTION

2.1. Multicell OFDMA networks

A hexagonal multicell OFDMA network is considered in this paper. One example network with seven cells is shown in Figure 1. Each cell is served by a base station (BS) at the center of the cell, and there are a set of MSs within each cell. Based on its physical proximity to the BS, each MS is classified as either in the cell-center or the cell-edge area. The boundary that separates the cell center and the cell edge can be a design parameter. In OFDMA systems, the radio resource that will be allocated to users is the subchannel. A subchannel is a group of subcarriers that may or may not be contiguous, depending on the specific permutation scheme used. A permutation scheme determines the mapping from physical subcarriers to logical subchannels. For example, IEEE 802.16e standard [13] has specified partial usage of subchannels (PUSC) and adaptive modulation and coding (AMC) as two permutation schemes for noncontiguous and contiguous subcarrier mapping, respectively.

2.2. The diversity set

In regular multicell operation, each MS is registered and communicates with a single BS, which is called the anchor or serving BS. However, in some scenarios such as soft handover and base station cooperation (BSC) [14], an MS may communicate with multiple BSs simultaneously. To keep
track of both the anchor BS and neighbor BSs\(^\dagger\) that are within the communication range of each MS, a diversity set is defined in the IEEE 802.16e standard [13]. The diversity set of MS \(m\) is denoted as \(\mathbb{D}_m = A_m \cup B_m\), where \(A_m\) is the anchor BS set that has only one element (i.e., anchor BS \(A_m\)) and \(B_m\) is the neighbor BS set that may contain 0, 1, or multiple elements (i.e., nearby BSs). Note that the number of elements in set \(B_m\) depends on the geographic location of MS \(m\) in relation to its neighboring BSs and on some path-loss threshold. Specifically, to form the diversity set, MS \(m\) monitors the signal from different BSs, and determines whether or not to add each BS to its diversity set \(\mathbb{D}_m\) depending on whether the corresponding measured signal strength is above a predetermined path-loss threshold. The diversity set information is maintained at both the MS and the BS, and can readily be used by the radio network controller (RNC) to perform centralized ICI-aware resource-allocation. Note that when defining the SINR at the MS, we consider all BSs in the network (rather than only those in the diversity set of the MS) as the potential interfering source. This consideration will be presented in Section 2.3 and used in the simulation in Section 5.

2.3. System model and performance metrics

We consider a downlink hexagonal cellular network as described in Section 2.1. In our network, there are \(L\) BSs, each with \(N_T\) antennas. Meanwhile, in the area of cell \(l\), there are \(M_l\) MSs, each with \(N_A\) antennas, that have pending traffic. Idle MSs are neglected as they will not affect OFDMA resource-allocation. The total number of MSs in the entire network is therefore \(M = \sum_{l=1}^L M_l\). Among the \(M_l\) MSs, a subset of them, denoted by \(S_l\) and \(|S_l| \leq M_l\), is served by BS \(l\) at a given time, where \(|\cdot|\) is the cardinality of a set. Each MS, depending on its proximity to the BS, is labeled as either a cell-center or a cell-edge user. Let \(S_l^c\) be the set of cell-center MSs served in cell \(l\), and \(M_l^c\) be the number of total cell-center MSs (served or unserved) in cell \(l\). Likewise, \(S_l^e\) is the set of cell-edge MSs served in cell \(l\), and \(M_l^e\) is the number of total cell-edge MSs (served or unserved) in cell \(l\). Thus, \(S_l = S_l^c \cup S_l^e\) and \(M_l = M_l^c + M_l^e\).

Assume a set of \(N\) subchannels is available for resource-allocation in the network. Depending on the specific resource-allocation method used, an entire or partial set of the subchannels may be available to each cell. Let \(\mathcal{O}_l^c\), \(\mathcal{O}_l^e\), and \(\mathcal{O}_l^f\) be the set of subchannels allocated to cell \(l\), the cell center of cell \(l\), and the cell edge of cell \(l\), respectively. Due to the intrachannel allocation constraint in OFDMA networks, which restricts the use of a subchannel by at most one MS within the same cell, \(\mathcal{O}_l^c \cap \mathcal{O}_l^e = \emptyset\) and \(\mathcal{O}_l^c \cup \mathcal{O}_l^e = \mathcal{O}_l^f\). For the same reason, the number of served MSs must be less than or equal to the number of subchannels available,\(^\ddagger\) that is, \(|\mathcal{O}_l^c| \leq |\mathcal{O}_l^e|\), \(|\mathcal{O}_l^c| \leq |\mathcal{O}_l^f|\), and \(|\mathcal{O}_l^e| \leq |\mathcal{O}_l^f|\) for all \(l\).

Signal transmission in the multicell OFDMA system is modeled as follows. We consider an arbitrary symbol in an OFDMA frame for the interference study in the ensuing discussion. An arbitrary MS \(m, m \in \{1, 2, \ldots, M\}\), that has pending traffic and will be served in the network is considered. Let the \(N_R \times N_T\) matrix \(H_{mn}^H\) represent the channel from BS \(l\) to MS \(m\) in the subchannel \(n\), which has complex Gaussian elements. Let the \(L_m \times 1\) vector \(s_m\) be the data intended for MS \(m\) transmitted using subchannel \(n\), which has zero mean and normalized power, that is, \(E[s_m^H s_m^H] = I_{L_m}\). The vector \(s_m\) is precoded by an \(N_T \times L_m\) precoding matrix,\(^\|$\) \(T_m\), which also has normalized power, that is, \(|T_m|_F^2 = 1\), where \(|\cdot|_F^2\) is the Frobenius norm of a matrix.

Suppose that downlink power control is employed to reduce the ICI caused to neighbor cells. That is, the downlink signal for MS \(m\) is sent with power \(P_m\), depending on its proximity to the BS. In particular, we have

\[
P_m = \begin{cases} 
P_0, & \text{if MS is in the cell center} \\ 
P_1, & \text{if MS is in the cell edge} 
\end{cases}
\]

where \(P_0 < P_1\).

In the typical operation, each MS communicates with one BS.\(^\S\) Thus, the received baseband discrete-time signal at MS \(m\) that uses subchannel \(n\) after matched filtering and sampling, \(r_m\), comprises useful signal from the serving BS \(A_m\), and the interference from neighbor BSs \(B_m\). serving MS \(n\) plus noise, that is,

\[
r_m = \sqrt{P_m} H_{mn}^H T_m s_m + \sum_{v \in I_m} \sqrt{P_v} H_{mn}^H T_v s_v + n_m
\]

\((2)\)

\(I_m\) is the set of MSs whose serving BS will cause interference to MS \(m\)’s reception from its serving BS \(A_m\). \(n_m\) is the additive white Gaussian noise with noise power \(E[n_m^H n_m] = N_0 W\), where \(N_0\) is the thermal noise density and \(W\) is the subchannel bandwidth. Based on (2), the SINR (in the linear scale) of the received signal at MS \(m\) that uses

\(\dagger\) It is worthwhile to make a distinction between neighbor and adjacent when designating cells or BSs. Adjacency refers strictly to the physical proximity of cells, and in a typical hexagonal deployment each cell has six adjacent cells. Neighbors refer generally to nearby cells which may be nonadjacent but have the potential to interfere with the center cell.

\(\ddagger\) Here, we assume no space-division multiple-access (SDMA) [15] is used in the network.

\|$\) The precoding matrix design is beyond the scope of this paper. We refer interested readers to [16] and references therein.

\(\S\) The IEEE 802.16 standard allows the use of Macro Diversity HandOver (MDHO) and BSC in which an MS may communicate with more than one BS simultaneously. The interference management for such scenarios is studied in [17].
subchannel $n$ is given by

$$\text{SINR}_{mn} = \frac{P_m |H_{mn}|^2}{\sum_{l \in \mathcal{L}_m} P_l |H_{ml}|^2} + N_0 W$$

(3)

Note that the SINR corresponds to the measured signal strength used to create the diversity set of each MS. Thus, the SINR information is implicitly used in the proposed framework presented in Section 4, which leverages the diversity set information.

Several key performance metrics are considered for network performance evaluation. Specifically, we consider cell throughput and service rate. Cell throughput is used to quantify the aggregate network performance of IM schemes with different reuse factors. To model it mathematically, consider a served MS $m$ in cell $l$, $m \in \mathcal{O}_l$, using a set of subchannel(s) $\mathcal{N}_m \in \mathcal{O}_l$. Then, the theoretical cell throughput for cell $l$ (bps) is given by the Shannon capacity:

$$T_l = \sum_{m \in \mathcal{O}_l} \sum_{n \in \mathcal{N}_m} W \log_2 (1 + \text{SINR}_{mn})$$

(4)

Likewise, the cell-center and cell-edge throughput for cell $l$ are $T_l^c = \sum_{m \in \mathcal{O}_l^c} \sum_{n \in \mathcal{N}_m} W \log_2 (1 + \text{SINR}_{mn})$ and $T_l^e = \sum_{m \in \mathcal{O}_l^e} \sum_{n \in \mathcal{N}_m} W \log_2 (1 + \text{SINR}_{mn})$, where $\mathcal{N}_m \in \mathcal{O}_l^c$ ($\mathcal{N}_m \in \mathcal{O}_l^e$) represents the set of subchannel(s) used by a served MS $m$ in the cell center (edge) of cell $l$. To facilitate the study of theoretical throughput performance, it is assumed that all served MSs have infinite backlogged data to receive.

Service rate is used to study the service capacity of reuse-$n$ and FFR systems where typically only a fraction of total MSs are granted service at a given time. The service rate in cell $l$ (%) is defined by the ratio between the number of served MSs and the total number of MSs that have pending traffic in cell $l$, that is,

$$G_l = \frac{|\mathcal{O}_l|}{M_l} \times 100$$

(5)

3. RELATED WORK

In this Section, we present several IM schemes that are related to our work and introduce the graph approach to resource-allocation, which will lay the foundation for the discussion of our proposed schemes in Section 4.

3.1. Previous IM schemes

3.1.1. Reuse-3.

The simplest IM scheme is a reuse-$n$ ($n > 1$) system [18]. A reuse-$n$ system partitions a geographical area into $n$ regions, each of which is exclusively allocated a band in such a way that cells adjacent to each other are assigned with different bands and cells sufficiently distant from each other may use the same band. The rate at which the same band is reused is dictated by the reuse factor $n$. A reuse-3 ($n = 3$) scheme is depicted in Figure 2a, wherein each of the three adjacent cells uses one-third of the total bandwidth. The three-cell scheme shown here constitutes the basic building block for an arbitrary-sized geographical area, so the principle can generalize to more cells. In a typical reuse-3 network, each cell is surrounded by six adjacent cells that occupy a band different from that of the center cell. Due to aggravated loss of spectral efficiency, reuse-$n$ schemes with $n > 3$ (e.g., 4, 7, and 9) are not considered in this work.

3.1.2. Reuse-1.

A reuse-1 system, also known as the universal reuse, allocates the total bandwidth to every cell in the network. A reuse-1 scheme is used in many modern cellular OFDMA systems due to its effectiveness in relieving loss of spectral efficiency in reuse-$n$ ($n > 1$) systems [18]. Nevertheless, users of the reuse-1 system, especially those in the cell edge, admittedly suffer more severe ICI compared with users of the reuse-$n$ ($n > 1$) system. Thus, an IM scheme is often embedded into the reuse-1 system to address this problem [17,19,20]. In [19], beamforming antennas in combination with interference coordination between cells were used to achieve ICI reduction. ICI coordination (ICIC) enhanced reuse-1 schemes were proposed in [17], where the overall ICI is reduced by judiciously coordinating the channel allocation for strong ICI-prone MSs in adjacent cells. In [20], a two-level algorithm that performs dynamic interference avoidance was used to achieve higher network throughput in the reuse-1 system.

3.1.3. FFR.

FFR is developed as a flexible frequency reuse scheme to strike a better tradeoff between spectral efficiency and interference mitigation than the generic frequency reuse. FFR can be realized in many different fashions [8,10,11,20,21], which are variations of the two representative realizations as described in the following.

- **FFR-A**: One realization, termed FFR-A in this paper, follows the principle that all adjacent cells’ cell center share the same band while their cell edge use orthogonal bands. In addition, the cell-center band of one cell and the cell-edge band of an adjacent cell are nonoverlapping. An FFR-A scheme with an exemplary bandwidth partitioning is shown in Figure 2b. A fixed FFR-A scheme is such that the bandwidth partitioning is determined initially and remains fixed regardless of changes in the cell load.

- **FFR-B**: Another realization, termed FFR-B, follows the principle that all adjacent cells’ cell edge use orthogonal bands. Different from FFR-A, FFR-B allows partial overlapping between the cell-center band of one cell and the cell-edge band of an adjacent cell. An example is shown in Figure 2c. A fixed FFR-B
scheme, similar to fixed FFR-A, is one in which the bandwidth partitioning is performed only initially and oblivious of any subsequent change in the cell load.

3.2. The Graph Approach to Resource-Allocation

Graph multi-coloring method has been used extensively to address the channel assignment problem in cellular and mesh networks (e.g., [22-24]). In the traditional formulation, each node in a graph corresponds to a BS or an access point (AP) in the network to which channels are assigned. The edge that connects two nodes represents the potential co-channel interference between the two BSs/APs, and, typically, the severity of this co-channel interference is related to the geographical proximity between the two BSs/APs represented by the two nodes. Once the graph is constructed, the channel-assignment problem is formulated as a node-coloring problem. The objective is to find the minimal number of colors necessary for coloring the entire graph (i.e., the chromatic number of the graph) provided that no two interfering nodes have colors in common, or equivalently, are assigned with the same channel.

Recently, this graph approach finds its application in reuse-1 OFDMA networks [17]. In this new application, a node in the graph represents an MS rather than a BS, and the edge is assigned an integer rather than a binary weight to represent different interference levels. A new coloring approach is also devised in [17], incorporating an ICI-mitigation mechanism that selectively assigns the same color to two interfering nodes. This method, however, cannot be directly applied to nonreuse-1 systems, including FFR-enabled OFDMA networks. The reason is that FFR presents a new resource-allocation problem as summarized below:

- Unlike the systems investigated in [22-24], where graph coloring aims at minimizing the use of colors (subchannels), an OFDMA network has a fixed and predetermined number of colors (subchannels) available to use.
- Different from the coloring approach in [17], where nodes are always colored, the coloring algorithm in the nonreuse-1 setting should accommodate the fact that some MSs may be suspended from service and therefore the corresponding nodes are uncolored.

Motivated by the above observations, we have developed a new graph framework to achieve efficient resource-assignment in FFR-enabled OFDMA networks, which is presented next.

4. PROPOSED DYNAMIC FFR (D-FFR) FRAMEWORK

4.1. Graph Construction

The first phase of our proposed graph approach to FFR resource-allocation is to construct an interference graph according to the OFDMA network topology. Consider an illustrative example with three BSs and five MSs as shown in Figure 3. Our objective is to construct an undirected interference graph, denoted by $G = (V, E)$, based on the topology and the bandwidth-assignment requirement of FFR-A or FFR-B. In this graph, set $V$ contains nodes that

![Figure 2](image-url)
Table I. The diversity set of MSs in Figure 3.

<table>
<thead>
<tr>
<th>MS</th>
<th>Anchor BS set</th>
<th>Neighbor BS set</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS 1</td>
<td>$A_1 = {3}$</td>
<td>$B_1 = {2}$</td>
</tr>
<tr>
<td>MS 2</td>
<td>$A_2 = {2}$</td>
<td>$B_2 = \emptyset$</td>
</tr>
<tr>
<td>MS 3</td>
<td>$A_3 = {1}$</td>
<td>$B_3 = \emptyset$</td>
</tr>
<tr>
<td>MS 4</td>
<td>$A_4 = {2}$</td>
<td>$B_4 = {3}$</td>
</tr>
<tr>
<td>MS 5</td>
<td>$A_5 = {1}$</td>
<td>$B_5 = {2, 3}$</td>
</tr>
</tbody>
</table>

are labeled to represent MSs in the multicell network, that is, $V = \{1, 2, \ldots, M\}$. Set $E$ contains two-element subsets of $V$, and induces a symmetric binary relation on $V$ that is called the adjacency relation of $G$. Specifically, node $a$ and node $b$ are said to be adjacent to each other if they are connected by an edge, or equivalently, if $(a, b) \in E$.

To determine the edge set, $E$, a practical method based on the diversity set is used. The basic idea is to infer the MS’s geographic location, and consequently the adjacency relation, from both the diversity set and the site deployment information available at RNC. To provide an example, the diversity set for the scenario in Figure 3 is shown in Table I, where each row indicates the diversity set maintained for the corresponding MS. Each MS has an anchor BS and possibly several neighbor BSs if it is located at the cell edge. For instance, MS 5 belongs to BS 1, but since MS 5 also detects signals from BS 2 and BS 3 it includes them in the neighbor BS set. As a result, we have $A_5 = \{1\}$ and $B_5 = \{2, 3\}$ for MS 5. Given the diversity set in Table I, the following information can be obtained:

- MS $a$ is a cell-center (or cell-edge) user if its neighbor BS set, $B_a$, is an empty (or nonempty) set. For example, MS 2 is a cell-center user and MS 4 is a cell-edge user.
- MS $a$ and MS $b$ are users of the same cell if they have the same anchor BS (i.e., $A_a = A_b$). For example, MS 2 and MS 4 are users of the same cell.
- MS $a$ and MS $b$ are users of two adjacent cells if their anchor BSs, according to the site deployment information maintained at RNC, serve two adjacent cells. For example, MS 2 and MS 3 are users of two adjacent cells.

The analysis is performed for every pair of MSs to determine the pairwise relation between them. Then, this information is used in the edge construction for dynamic FFR-A (D-FFR-A) and dynamic FFR-B (D-FFR-B) schemes, as described as follows.

4.1.1. D-FFR-A.

The edge-construction algorithm for D-FFR-A is described in Table II. Two nodes are connected by an edge if they satisfy specific pairwise relations. Specifically, a pair of nodes will be connected by an edge if the corresponding MSs have intracell relation (A1) or some intercell relations (A2 and A3), which, according to the FFR-A principle, pose channel-assignment constraints. Since two cell-center MSs of adjacent cells are permitted to use overlapping bands in FFR-A, corresponding nodes are not connected by an edge.

After running the edge-construction algorithm for all pairs of nodes, the interference graph can be constructed for D-FFR-A. The resulting interference graph that corresponds to the scenario in Figure 3 is drawn in Figure 4. It is seen that all pairs of nodes, except for nodes 2 and 3, satisfy some relation in A1–A3 and therefore are connected by an edge.

4.1.2. D-FFR-B.

The edge-construction algorithm for D-FFR-B is described in Table III. Again, a pair of nodes will have an edge if the corresponding MSs have intracell relation (B1) or particular intercell relation (B2). Different from FFR-A, however, the intercell constraints posed by the FFR-B principle include only the use of nonoverlapping bands for two cell-edge MSs of adjacent cells.

The interference graph constructed for D-FFR-B that corresponds to the scenario in Figure 3 is drawn in Figure 5. Note that the graph for D-FFR-B has fewer edges compared with the graph for D-FFR-A. This is due to fewer intercell
constraints presented by the FFR-B principle, as discussed previously.

4.2. Graph coloring

The second phase of the graph approach to OFDMA resource-allocation is to color the nodes in the interference graph. A color represents a subchannel, and coloring the nodes corresponds to the physical meaning of allocating subchannels to the MSs. A coloring of a graph is called proper if the coloring constraint is met; that is, no two adjacent nodes in the graph have colors in common.

Many heuristic coloring algorithms have been proposed to color a graph efficiently. Most of the algorithms (e.g., the methods compared in [25]) were proposed to color a graph given that the graph is colorable, that is, the number of available colors is no less than the best-known chromatic number of the graph. These algorithms aim at improving the execution time and/or the percentage of arriving at the best-known result upon termination of the algorithm.

In the graph for OFDMA networks, the number of colors (i.e., subchannels) is constant while the size of the graph is variable to different network load. As a result, when the network is heavily loaded, colors become under-provided and coloring the entire graph becomes infeasible. Therefore, a mechanism to color only selective nodes must be incorporated, which will serve as an admission control mechanism in the network. On the other hand, when the network is lightly loaded, or equivalently, when colors are over-provided, diversifying colors is desired to avoid unnecessary color collisions. These considerations are incorporated in the new graph coloring problem that extends the original formulation [22] as follows.

P. Given an interference graph $G = (V, E)$ with $|V| = M$ nodes, an augmented set of colors $C_{\text{aug}}$ containing a regular color set $C = \{1, 2, \ldots, N\}$ and a blank color set $\{0\}$, and a function $f$ that assigns to each $v \in V$ a subset $f(v)$ of $C_{\text{aug}}$, find a coloring of the graph such that

1. $C_1$: $\forall v$, $|f(v)| = 1$, that is, each node is assigned a single color.
2. $C_2$: $\forall (u, v) \in E$, $f(u) \cap f(v) = \emptyset$ or $\{0\}$, that is, no two adjacent nodes have regular colors in common.
3. $C_3$: With $C_1$ and $C_2$ met, $|\{v \in V\mid f(v) = \emptyset\}|$ is minimized and the use of colors is balanced.

Constraints $C_1$–$C_2$ are the coloring constraints that guarantee a proper coloring. Note that constraint $C_2$ has accommodated the possibility that a node may be uncolded,

Table III. Edge construction algorithm for D-FFR-B.

<table>
<thead>
<tr>
<th>Algorithm 2:</th>
<th>$\text{GRAPHEDGEFFFRRB}(a, b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>comment:</strong> Any pair of nodes $a, b \in V, a \neq b$</td>
<td></td>
</tr>
<tr>
<td>if (B1) $a$ and $b$ are users of the same cell</td>
<td></td>
</tr>
<tr>
<td>or (B2) $a$ and $b$ are cell-edge users of two adjacent cells</td>
<td></td>
</tr>
<tr>
<td>then ${a, b} \in E, z \leftarrow 1$</td>
<td></td>
</tr>
<tr>
<td>else ${a, b} \notin E, z \leftarrow 0$</td>
<td></td>
</tr>
<tr>
<td>return $(z)$</td>
<td></td>
</tr>
</tbody>
</table>
Table IV. Modified Dsatur algorithm for solving graph coloring for D-FFR schemes.

<table>
<thead>
<tr>
<th>Algorithm 3: MODIFIEDDSATUR(G)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initialization:</strong> Let $U$ be the set of unexamined nodes, where $U = V$. Let $a(x)$ be the available color set for node $x \in V$, where $a(x) = C, \forall x \in V$. The set $a(x)$ contains colors that may be used to color node $x$ such that the coloring constraints $C1-C2$ are respected.</td>
</tr>
<tr>
<td><strong>Step 1.</strong> Select from $U$ a node whose available color set is of minimal size. In case of ties, select the node whose degree is maximal, but otherwise arbitrarily. Denote the selected node by node $y$.</td>
</tr>
<tr>
<td><strong>Step 2.</strong> Color node $y$ with a randomly selected color from $a(y)$. If $a(y) = \phi$, leave node $y$ uncolored.</td>
</tr>
<tr>
<td><strong>Step 3.</strong> $U = U \setminus {y}$. Update $a(x)$ for all $x \in U$. If $U \neq \phi$, go to Step 1; otherwise stop.</td>
</tr>
</tbody>
</table>

*The degree of a node is the number of edges incident to the node.*

that is, assigned the blank color. Without violating constraints $C1-C2$, however, an uninteresting solution where all nodes are uncolored may be yielded. Constraint $C3$ is therefore added, which states that the number of uncolored nodes should be minimized and the use of colors should be balanced (‘balancing’ here follows the same concept as in [25]). Note that $C3$ is a soft constraint in the sense that violating it will not invalidate a coloring but fulfilling it will improve the performance of a coloring. This is achieved by maximizing the service potential of the network and reducing channel collision, as suggested by constraint $C3$.

A heuristic algorithm is proposed to solve Problem $P$. Since many considerations in Problem $P$ are new and not addressed in any existing coloring algorithm, we propose to modify an efficient coloring algorithm, that is, the Dsatur algorithm [25], to meet these needs in OFDMA networks. The modified Dsatur algorithm is presented in Table IV, with the interference graph $G$ as its input. Note that two modifications are made to the original Dsatur algorithm in Step 2. First, the selected node is given a randomly selected (instead of the least possible or lowest numbered) color from the available color set of this node. Second, when a node’s available color set is empty, the node is allowed to remain uncolored. The first modification helps achieve color balancing when colors are over-provided, and the second modification accommodates the case of under-provided colors. The algorithm terminates when all nodes are examined, that is, either colored or, by decision, uncolored.

### 4.3. Further discussion on the proposed framework

Some discussions on the complexity issues, mechanics, and applications of the proposed framework are presented here.

#### 4.3.1. Complexity.

We evaluate the computational complexity of the proposed method in terms of the total number of MSs in the network, $M$, to understand the scalability of the proposed method to the size of the network. The proposed framework consists of two phases: graph construction and graph coloring. The complexity of graph construction comes from examining the pairwise relations between nodes, as in edge-construction algorithms in Tables II and III, and therefore depends on the number of all possible two-element subsets of $V$. Since $|V| = M$, the complexity of graph construction is on the order of $O(M^2)$. The complexity of graph coloring can be understood by studying the three steps in the coloring algorithm in Table IV. The algorithm iterates $M$ times, each time with a node examined and then excluded from the set $U$. As a result, each iteration of the algorithm requires diminishing computational efforts as more nodes are excluded from $U$. To get an idea of the approximate complexity, however, we approximate the complexity involved in subsequent iterations by the first one. To realize Step 1, a sorting procedure where nodes in $U$ are sorted in ascending order of the size of their available color set is needed. Sorting algorithms that require operations on the order of $M \log M$ exist [26], and thus after $M$ iterations the complexity requirement for Step 1 is approximately $O(M^2 \log M)$. The operation in Step 2 is independent of $M$ and does not grow with the size of the network. The complexity of Step 3 arises from updating the available color set for all nodes in $U$. Since in each iteration nodes in $U$ need only to look at the selected node to update their available color set, the complexity of Step 3 is $O(M)$. The overall complexity requirement for Step 3 is therefore $O(M^2)$. In sum, the complexity of graph construction is $O(M^2)$ and the complexity of graph coloring is dominated by $O(M^2 \log M)$. Thus, the proposed method is of polynomial-time complexity in terms of the size of the network, making it practical even for expansive networks.
4.3.2. Sectorized FFR systems.
While the discussion in this paper has focused on the nonsectorized cell structure, the concept of FFR can also be applied to sectorized systems [11]. With simple modification, the proposed D-FFR framework can be adapted to sectorized scenarios. Specifically, an edge-construction algorithm similar to the ones in Tables II and III can still be used, however with new pairwise relations, that is, intra-sector and inter-sector relations. The same coloring algorithm in Table IV is then used to complete the resource-allocation.

4.3.3. The mechanics of adaptation.
The proposed dynamic allocation method can be applied in practical OFDMA networks on either a periodic or on-demand basis. A periodic approach is explained by Figure 6, which shows the grouping of IEEE 802.16e OFDMA frames into periods. In the first frame of each period, the dynamic FFR allocation is triggered and the allocation result, conveyed to MSs using downlink signaling (e.g., DL-MAP message), remains unchanged until the next period. The period $T$ can be chosen by considering the network-load variability as well as the mobility of users. In an on-demand approach, instead of periodically reassigning channel resources, the RNC will perform channel allocation when the system performance (e.g., network throughput) drops below a predetermined performance threshold. This fashion gives the on-demand approach a potential edge in yielding the best performance.

4.3.4. Quality of service.
The proposed D-FFR framework is performed in a ‘best-effort’ fashion and cannot guarantee the quality of service demanded by each individual MS. That is, when a user requests a priority service or extra resource (or equivalently, a node in the graph requests preemptive coloring or multiple colors), the algorithm in Table IV will not guarantee the requested resource. The algorithm can however be augmented by an initialization process where the demands from the priority MSs are first fulfilled (provided that this is within the network capacity), followed by same steps in Table IV to allocate the residual resource to other nonpriority/best-effort MSs in the network. Extension of this primitive scheme to take into account fairness and prioritization across MSs is a worthwhile future work.

5. SIMULATION RESULTS
Here, we study the performance of the proposed schemes by computer simulation. The performance of the proposed D-FFR schemes is compared with some previous IM schemes described in Section 3. The proposed schemes and the benchmarks are summarized in Figure 7. By considering these benchmarks with various frequency reuse factors and comparing their performance side-by-side, a thorough understanding of cellular network planning, frequency reuse, and particularly the proposed D-FFR schemes can be gained. Note that in this Section, we will use the parent scheme in the taxonomy tree (Figure 7a) to represent all its children schemes and their shared properties. For example, ‘FFR’ is used to refer to FFR-A and FFR-B combined, and ‘FFR-A’ is used to refer to both F-FFR-A and D-FFR-A, etc.

5.1. Simulation setup
The simulation setup closely follows the IEEE 802.16m evaluation methodology [27] and is summarized in Table V. Note that although a single-input single-output (SISO) system is considered in the throughput evaluation, the comparison result is readily extensible to a simple multiple-input multiple-output (MIMO) system (i.e., no BSC or SDMA is used) with increased throughput capacity. To fairly evaluate the performance of different schemes, the total bandwidth is properly apportioned among cells. For

<table>
<thead>
<tr>
<th>Table V. Simulation setup.</th>
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<tr>
<td><strong>Cell parameters</strong></td>
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<tr>
<td>Number of cells, $L$</td>
</tr>
<tr>
<td>Cell (cell-center) radius</td>
</tr>
<tr>
<td>Antennas $N_T$, $N_R$</td>
</tr>
<tr>
<td>Frequency reuse factor</td>
</tr>
<tr>
<td><strong>OFDMA parameters</strong></td>
</tr>
<tr>
<td>Total bandwidth</td>
</tr>
<tr>
<td>Number of subchannels, $N$</td>
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<tr>
<td>DL Permutation type</td>
</tr>
<tr>
<td><strong>Channel model</strong></td>
</tr>
<tr>
<td>Path loss (dB)</td>
</tr>
<tr>
<td>Fast fading</td>
</tr>
<tr>
<td><strong>Power control parameters</strong></td>
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<tr>
<td>Cell-center trans. power, $P_0$</td>
</tr>
<tr>
<td>Cell-edge trans. power, $P_1$</td>
</tr>
<tr>
<td>Thermal noise density, $N_0$</td>
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</tbody>
</table>
Reusing-3, without prior knowledge of the traffic load in different cells, it is reasonable to allocate one-third of the total bandwidth for each cell; that is, $|O_{cl}| = 10$ for all cell $l$s. Similarly, for F-FFR-B it is reasonable to have a cell edge that occupies one-third of the total bandwidth; that is, $|O_{el}| = 10$ and $|O_{cl}| = 20$ for all cell $l$s. To fairly evaluate F-FFR-A, we need to carefully partition the total bandwidth such that the band allocated to the cell center and the cell edge is roughly proportional to their traffic/user loads. Under the uniform traffic model, it can be shown that with the size of the cell-center area defined in Table V, the traffic ratio between the cell center and the cell edge is roughly 1:1. Thus, we adopt $|O_{cl}| = 15$, which leads to $|O_{el}| = 5$, for all cell $l$s. Furthermore, to conduct fair comparison between F-FFR-A and D-FFR-A, we consider a common size of the cell-center band to equalize the ‘white spectrum’ in F-FFR-A and D-FFR-A; that is, $|O_{cl}| = 15$ for both schemes. Note that the above bandwidth allocation corresponds roughly to the illustration in Figure 2a–c.

5.2. Results and discussion

5.2.1. Equal cell-load scenarios.

First, we simulate the equal cell-load scenario, where each cell has the same number of uniformly distributed MSs. Figure 8a shows the cell throughput performance, obtained by (4) and averaged over all cells, for different IM schemes in comparison. It is seen that in low-load conditions (i.e., no more than 10 MSs per cell), Reusing-3 outperforms all others. This is because in low-load conditions Reusing-3 achieves complete nullification of ICI from all interferers in the adjacent cells and has 100% service rate, as shown in Figure 8b. As the traffic load increases, Reusing-3 becomes increasingly inefficient as more users are rejected from service, as revealed by the diminishing service rate in Figure 8b and the stagnant cell throughput in Figure 8a. This inefficiency is remedied by FFR. As shown in Figure 8b, in medium-load conditions, FFR-A and FFR-B have much improved service rates, which contribute to the higher cell throughput in Figure 8a. This inefficiency is remedied by FFR. As shown in Figure 8b, in medium-load conditions, FFR-A and FFR-B have much improved service rates, which contribute to the higher cell throughput in Figure 8a. This inefficiency is remedied by FFR. As shown in Figure 8b, in medium-load conditions, FFR-A and FFR-B have much improved service rates, which contribute to the higher cell throughput in Figure 8a. This inefficiency is remedied by FFR. As shown in Figure 8b, in medium-load conditions, FFR-A and FFR-B have much improved service rates, which contribute to the higher cell throughput in Figure 8a. This inefficiency is remedied by FFR. As shown in Figure 8b, in medium-load conditions, FFR-A and FFR-B have much improved service rates, which contribute to the higher cell throughput in Figure 8a. This inefficiency is remedied by FFR. As shown in Figure 8b, in medium-load conditions, FFR-A and FFR-B have much improved service rates, which contribute to the higher cell throughput in Figure 8a. This inefficiency is remedied by FFR. 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Reuse-1-ICIC achieves very good performance, yet largely comparable with FFR-A.

In heavy-load conditions, the throughput of Reuse-1-ICIC decays because of the aggravated ICI and the fact that it always serves all MSs. The throughput of FFR schemes, however, increases consistently at the cost of more MSs being rejected from service. The Reuse-1-BL scheme performs poorly regardless of the load, because no IM scheme is employed.

Comparing FFR-A and FFR-B, it is seen that FFR-A outperforms FFR-B in throughput despite the lower service rate (Figure 8b). The reason is that while fewer MSs
are served, a served MS experiences better SINR (i.e., per-user throughput) for FFR-A. Furthermore, while FFR-A yields higher aggregate cell throughput, it achieves lower cell-edge throughput compared to FFR-B, as illustrated in Figure 9. The higher aggregate cell throughput of FFR-A is largely contributed by its higher cell-center throughput. The above observation introduces tradeoffs in choosing FFR-A or FFR-B as an IM scheme.

5.2.2. Unequal cell-load scenarios.

Second, we simulate the unequal cell-load scenario. We define the traffic load ratio as the load proportion of heavy-to light-load cells. For every three adjacent cells, we consider two light-load cells (with two MSs each) and one heavy-load cell (with a varying load controlled by the traffic load ratio). We plot the same performance measures against different traffic load ratios in Figure 10. It is seen, in sharp contrast to the equal cell-load scenario, that D-FFR-A (D-FFR-B) achieves substantially better performance in terms of cell throughput (Figure 10a) and service rate (Figure 10b) than F-FFR-A (F-FFR-B). Specifically, when the traffic load ratio is equal to 15, D-FFR-A outperforms F-FFR-A by 12% in cell throughput and 33% in service rate, and outperforms Reuse-3 by 70% in cell throughput and 107% in service rate. This is due to the flexibility in borrowing light-load cells’ resource for the use of heavy-load cells in the dynamic scheme.

In Figure 10, we also observe that the performance gap between D-FFR-A and F-FFR-A is bigger than that between D-FFR-B and F-FFR-B. This is because the dynamic mechanism in D-FFR-B benefits the cell edge significantly but not the cell center; in fact, D-FFR-B performs worse than F-FFR-B in the cell center, as shown in Figure 11. This results
from the band-allocation structure of FFR-B, which, while yields higher throughput in the cell edge, causes more interference to the cell center due to band overlapping between one cell’s cell center and adjacent cells’ cell edge. Comparing FFR-A and FFR-B, FFR-A yields lower cell-edge throughput but higher cell-center throughput than FFR-B, as shown in Figure 11. This is similar to the equal-load case.

Note that in this unequal-load scenario, Reuse-1-ICIC achieves the best throughput performance. This is because the scenario concerned has a fairly light overall load, as each of the light-load cells has only two MSs. As a result, Reuse-1-ICIC can leverage its full flexibility in utilizing all the available band as well as performing ICI mitigation through a pure algorithmic approach without any constraint on the band allocation as exhibited in FFR-A and FFR-B.

More specifically, in the heavy-load condition in Figure 8, Reuse-1-ICIC trades its throughput for its service rate; here in Figure 10, due to the lighter load, the perfect service rate is achieved without much compromise in throughput. It is expected, however, that a similar degradation in throughput will be observed for Reuse-1-ICIC when the light-load cells start to increase their load in this unequal-load scenario.

Figure 12 shows the snapshot of channel-assignment results yielded by FFR-A for a specific topology and an unequal cell-load scenario with two cells of two MSs and one cell of 20 MSs. Each square node in the figure represents an MS, and the color and the number shown on each square indicate the band and the subchannel assigned to the MS. The colors shown here match those in Figure 2 (e.g., a ‘dark-red 16’ node represents an MS in the cell edge of
cell 1 that is assigned subchannel 16). MSs not served are uncolored and marked by ‘N.’ It is seen in Figure 12 that D-FFR-A can serve much more MSs in the cell edge as compared with F-FFR-A (in fact, no more than five cell-edge MSs can be served by F-FFR-A because \(|O_f| = 5\). The reason is that D-FFR-A can borrow bandwidth from adjacent light-load cells so that the cell-edge band of the heavy-load cell essentially expands. FFR-B presents similar results when it comes to the comparison shown in Figure 12. The snapshot confirms the superior performance of the dynamic scheme shown in Figure 10.

6. CONCLUSION

A D-FFR framework for multicell OFDMA networks was proposed in this work. The dynamic feature is characterized by the capability of redistributing the spectral resource according to the varying cell load. The adaptation is accomplished via a graph approach in which the resource-allocation problem is translated to a graph coloring problem. Different versions of FFR can be easily realized in this framework by customizing the graph to match the specific FFR principle. The proposed dynamic scheme is shown to yield better cell throughput and service rate performance, especially in unequal cell-load scenarios. The proposed method is simple yet effective, and can be used in next-generation cellular systems such as LTE-A and IEEE 802.16m.

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