Dynamic Fractional Frequency Reuse based on an Improved Water-Filling for Network MIMO

Noor Shahida M. K[1, 2], Rosdiadee Nordin[1], Mahamod Ismail[1]
[1] Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[E-mail: {adee,mahamod}@ukm.edu.my]
[2] Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[E-mail: noorshahida@utem.edu.my]
*Corresponding author: Noor Shahida M.K

Received November 12, 2015; revised February 21, 2016; accepted February 27, 2016; published May 31, 2016

Abstract

In Long Term Evolution-Advanced (LTE-A) systems, Inter-cell Interference (ICI) is a prominent limiting factor that affects the performance of the systems, especially at the cell edges. Based on the literature, Fractional Frequency Reuse (FFR) methods are known as efficient interference management techniques. In this report, the proposed Dynamic Fractional Frequency Reuse (DFFR) technique improved the capacity and cell edge coverage performance by 70% compared to the Fractional Frequency Reuse (FFR) technique. In this study, an improved power allocation method was adopted into the DFFR technique to reach the goal of not only reducing the ICI mitigation at the cell edges, but also improving the overall capacity of the LTE-A systems. Hence, an improved water-filling algorithm was proposed, and its performance was compared with that of other methods that were considered. Through the simulation results and comparisons with other frequency reuse techniques, it was shown that the proposed method significantly improved the performance of the cell edge throughput by 42%, the capacity by 75%, and the coverage by 80%. Based on the analysis and numerical expressions, it was concluded that the proposed DFFR method provides significant performance improvements, especially for cell edge users.

Keywords: Dynamic Fractional Frequency Reuse (DFFR), FFR, power allocation, water-filling algorithm

The authors acknowledge the financial contribution from Ministry of Science, Technology and Innovation (MOSTI) Malaysia, under grant ref. no. 01-01-02-SF1297 for the publication of this work. This study was supported by the Universiti Teknikal Malaysia Melaka (UTeM), and the Ministry of Higher Education of Malaysia.

http://dx.doi.org/10.3837/tiis.2016.05.010 **ISSN : 1976-7277**

1. Introduction

There are several radio access technologies that can be used for delivering broadband mobile services. Long Term Evolution-Advanced (LTE-A) is one such technology created by the 3rd Generation Partnership Project (3GPP). The LTE-A system has the potential to be in high demand in the future; additionally, it has several advantages in terms of high data rates, capacity and flexibility using multi-input multi-output (MIMO) and orthogonal frequency division multiple access (OFDMA) techniques. The OFDMA is a multiple access technique that has been used in downlink LTE-A, and it is possible to obtain robustness against the multipath with a combination of the MIMO downlink transmissions.

Furthermore, the OFDMA technique allows high spectrum efficiency and flexibility of frequency allocation to users, which occurs because the spectra are orthogonal to each other and distributed to a large number of narrow-band sub-carriers. However, in LTE-A networks, the performance of the system is restrained by the Inter-cell Interference (ICI) due to frequency reuse [1]. Therefore, the 3rd Generation Partnership Project (3GPP) has carried out many studies on techniques to mitigate the ICI in LTE-A. Co-channel interference has become a serious issue that corrupts the performance of wireless communication systems, and it can be classified into (i) intra-cell interference, where orthogonal frequency resources are allocated and fixed, and (ii) inter-cell interference, which uses the concept of Frequency Reuse (FR) techniques by mitigating the interference and improving the spectrum efficiency. Because the FR uses the same frequency as the neighbouring cells, it can remain and reduce the performance of the cell edge throughput and the spectral efficiency in LTE-A systems, as discussed in [2]. Hence, Fractional Frequency Reuse (FFR) [3][4] techniques are the most common approaches that use a higher reuse factor for cell edge users (CEUs) to confront the drawbacks of FR due to improvements in the cell edge throughput and the spectral efficiency of the system.

The available frequency resources have been divided by FFR into cell centre users (CCUs) and CEUs. However, the main shortcoming of the FFR scheme is at the cell edge because the CEUs cannot use the whole spectrum. Therefore, the frequency resource is wasted, thus causing the spectral efficiency to decrease. Unlike the FFR, the DFFR is a flexible version that allows the CEUs to use the whole spectrum while offering a high throughput compared to the work stated in [3] and [4]. Besides, it was mentioned by [5] that with an increase in the cell edge traffic, the allocated sub-bands of the cell edge will be shared by the neighbouring cells. On the other hand, the sum rate capacity will be similar to that of the strict FFR, the reason being that there will be no sub-bands to be shared as the cell-edge traffic is evenly distributed. Besides, a frequency sharing capability is able to handle the occasional bursts of traffic in one cell. This is one of the factors that limits the strict FFR.

Power allocation is an important issue in a system since a superior performance can be realized by proper allocation of power. Several studies have been carried out to investigate the combination of FFR schemes and power allocation. One such FFR scheme is the Soft Frequency Reuse (SFR) scheme. For instance, [6] addressed a resource allocation and power allocation algorithm by jointly adjusting the subcarrier and power allocation. In the proposed algorithm, a joint subcarrier and power allocation optimization were considered for the SFR scheme. Although the joint optimization of the SFR scheme improved the performance of the system’s throughput, as proposed in [6], the proposed method did not give an accurate representation of the cell centre and the cell edge data rate. Meanwhile, the performance of the systems's throughput cannot be significantly improved by controlling the power or limiting the resource. Hence, these problems can be solved by introducing an algorithm that combines both resource and power allocations.

Both industry and academia have recently focused their studies on the Network MIMO technique [7][8]. The primary goal of Network MIMO is to mitigate ICI. The capability of Network MIMO can be further explored by using frequency partitioning and cell sectoring because the cells and mobiles are geographically distributed. Furthermore, Network MIMO can mitigate ICI between BSs by requiring a consistent and high-speed backbone connection to obtain the channel state information (CSI) and mobile messages between the cooperating cells.

In this study, a power allocation was introduced for zero-forcing based on the Network MIMO environment with the aim of increasing the coverage and achievable rate of users in a cellular network. Additionally, by combining Network MIMO and the DFFR scheme, the throughput of the CEUs can be improved due to the increase in the received signal-to interference-plus noise ratio (SINR), and it also can be quite powerful in terms of capacity enhancement. The main novelty of this study was the extension of the water-filling (WF) algorithm, which allowed the water-filling level, λ to be found efficiently and the capacity to be maximized so as to overcome the limitations of the WF algorithm for multi-user communications. The contributions of this study can be given as follows:

i.) An enhanced version of the DFFR method is introduced that can adaptively allocate transmission power to each sub-channel using an improved Water-Filling (IWF) algorithm to achieve additional capacity.

ii.) The focus is on cell-edge user performance, where cell edge users are more inclined to ICI compared to cell centre users. Hence, a trade-off can be achieved between the resource utilization and the ICI mitigation, where a higher reuse factor is only used for cell edge users.

An IWF algorithm was proposed in this work to increase the overall capacity of the system compared to the conventional WF algorithm and the Equal Power (EP) algorithm, where at a certain SNR, the performance of both the WF and the EP do not offer significant improvements. The remainder of this paper has been organized as follows. In Section 2, the different frequency reuse methods in the LTE-A systems are discussed. In Section 3, the related work is reviewed, and the contributions of the report are summarized. In Section 4, a system model is presented. In Section 5, the proposed method and the analytical framework for the theoretical calculations are described. The power allocation approach is discussed in detail in Section 6. Then, the simulation parameters are presented in Section 7. The simulation results and analysis are compared with the different frequency reuse techniques and are presented in Section 8. Finally, Section 9 concludes the study.

2. Fractional Frequency Reuse

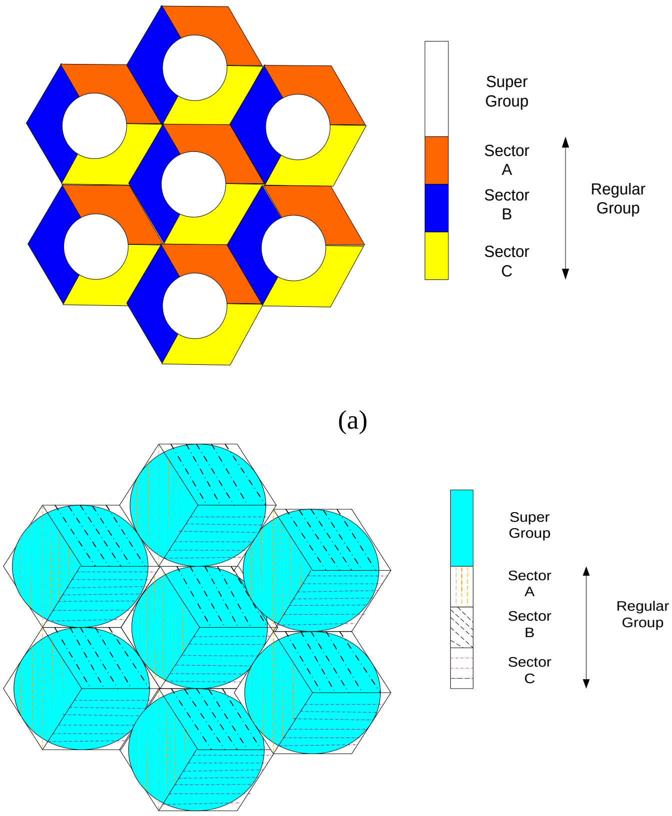
Frequency Reuse One (FR1) is the simplest FFR method, where the total bandwidth available in each cell is reused. FFR methods have been introduced to gain the full frequency reuse of the coverage and capacity. The FFR is able to divide users into two regions within a cell area: (i) CCUs, where users are adjacent to the BS at the centre of the cell, and (ii) CEUs, where the users are close to the cell edges. The mitigation of ICI at the cell edges uses a larger frequency reuse compared to that at the CCUs. In the FFR methods, the bandwidths of the cells can be distributed. Therefore, interference with the CEUs of adjacent cells does not occur and will be reduced when the interference is received by the CCUs. Furthermore, the FFR method uses a greater spectrum compared to the classical frequency reuse technique [3].

Cellular networks use the FFR method as an effective and feasible solution for ICI in order to improve the rate, coverage and throughput of the sum network, and the spectral efficiency of the CEUs. There are two FFR models:

i.) Strict FFR: This is an enhancement of the traditional frequency reuse method, where the exterior sub-bands are not shared with the inner frequency bands, as illustrated in **Fig. 1**(a).

ii.) Dynamic FFR (DFFR): This model, developed from the conventional strict FFR, is illustrated in **Fig. 1**(b).

The users and the subcarriers of the DFFR can be divded into two groups: (i) a super group, and (ii) a regular group, where the regular group is split into three sectors. The users can be covered by the entire cell surface. Meanwhile, the subcarriers are allocated to any user of the super group and the sectors within the regular group in the cell.



(a)

(b)

Fig. 1. Architecture of (a) Strict and (b) Dynamic Fractional Frequency Reuse

3. Related Works and Contribution

The FFR method has become an important subject among researchers because it offers a higher spectral efficiency and improves the coverage for CEUs. Variations in the FFR were proposed and compared in [9], [10]. However, the authors applied the fixed configuration method in all these approaches, where the spectrum allocation is fixed and inflexible with regard to variations in the cell-load. The inflexibility of the spectrum allocation hampers the conception of the FFR potential and can cause useless spectral usage.

Recently, a large number of approaches on the DFFR method have been proposed and studied. Based on the simulation results obtained from a previous study in [5], ICI can be reduced when the spectrum is divided into different sectors. Additionally, the DFFR method indicates a better performance in terms of coverage and cell throughput because it can cope instantaneously with network conditions, such as the load changes, without using a theoretical resource partitioning.

The resource allocation with a FFR-based multi-cell OFDMA system was adapted into a colour graph by [5]. The proposed DFFR method allows adaptive spectral sharing per cell load conditions by enhancing the conventional FFR. In a practical environment, the adaptation has benefits that can be asymmetric and time-varying to the traffic load in different cells. The proposed dynamic method indicates that the results in unequal cell load scenarios have better cell throughput and service rate performance. However, this technique imposes a hard limit based on the assignment of the number of users to each sub-band and the total power used. The authors in [11] introduced the idea of designing a Cooperative Frequency Reuse (CFR) scheme, which divides the cell-edge area of each cell into two types of zones and defines a frequency reuse rule to support the CoMP transmission for users in these zones. The existing inter-cell interference coordination (ICIC) strategies, however, are not suitable for Network MIMO systems because their frequency reuse rules are designed in the absence of multi-cell coordination scenarios.

In [7], the authors introduced a combination of clustered Network MIMO and FFR. In this power allocation approach, a WF algorithm is used to obtain the optimal power loading. However, it is hard for the scheme to achieve a local optimum, and it can also become unbalanced due to a delay in the control signals between the BSs. A cluster of three cells in a cooperative MIMO base station with an FFR scheme was proposed by [8]. From the simulation, a better spectrum efficiency performance can be achieved via a rearrangement of the antenna in two ways; the first way is the application of the MIMO using cooperative base stations, and the second involves reducing the inter-group interference (IGI) from different clusters. However, the proposed method introduced a problem, where the computational complexity of the pre-coding matrix increased when an instantaneous channel feedback was required.

A power allocation algorithm was presented in [12] and [13] with a fixed subcarrier allocation that maximized the network capacity. A dynamic frequency reuse scheme, complemented by an intuitive explanation on how each cell can selfishly try to minimize its power usage based on the number of subcarriers and power requirements, was presented in [12]. Meanwhile, two different algorithms were developed in the work by [13], namely (i) a Multi-sector Gradient (MGR) algorithm, which requires some information to be exchanged between neighbouring sectors, and (ii) a Sector Autonomous (SA) algorithm, which is completely distributed and requires no exchange of information. However, both proposed methods had a problem, where the methods operated at the granularity of the sub-bands and not at the resource blocks (RBs). The power allocation at the sub-band granularity level may lead to the overallocation of power to some of the RBs if they are located in a sub-band that serves edge users.

There are no works in the open literature that considered the power allocation in a combination of the DFFR and Network MIMO. Thus, in [14], a WF power allocation algorithm and a dynamic scheme in Network MIMO were introduced to resolve the problem in LTE-A networks. In certain circumstances, the WF algorithm is simple and easy to implement because it uses a single water level and a power constraint. However, the WF algorithm is not always efficient and has limited performance due to its power constraint; when the subcarriers are deactivated and are ineffective throughout the algorithm, the overall capacity of the system decreases. Hence, in this report, an IWF algorithm was proposed to improve the throughput and allocate the power to increase the channel capacity. In this study, an IWF algorithm was adopted in the DFFR method to maximize the capacity and overcome the limitation of the WF algorithm.

4. System Model

Consider Network MIMO with two antennas at the base stations, a single antenna at each mobile user and different transmit powers, P_s for 7 cells, where the centre cell has two-tier neighboring cells. **Fig. 2** shows that each cell is divided into four regions, a circular area with a radius, r in the centre of the cell that is served by an omnidirectional antenna, and three 120° sectors at the cell edges that are served by sectorial antennas. The four antennas are co-located and allocated a total power, P_{sc} per sub-carrier. The total bandwidth is split into two bands, B_A and B_B, which are allocated to the cell centre and the cell edge areas, respectively. Furthermore, the cell edge bandwidth, B_B is divided into three equal sub-bands, namely, B_{B1}, B_{B2} and B_{B3}, that can be allocated to different sectors in two ways depending on the transmission scheme employed. In the regular distribution, all the sectors with the same main-beam direction are allocated a different frequency band. The systems consist of three sectors, and each sector is equipped with one sector antenna. Thus, assuming a subcarrier bandwidth equal to Δf, and given a total bandwidth, B, the system has $N_{SC} = B/\Delta f$ sub-carriers, out of which $N_{cSC} = B_C/\Delta f$ are allocated to the centre region and $N_{eSC} = B_{Bi}/\Delta f$ to each of the edge sectors. The number of users with receiving antennas $N_R = 1$, are uniformly distributed in each sector. The received signal at user u is written as

$$y_u = h_{u,s} x_s + \sum_{i \neq j, i = I} h_{u,i} x_i + n_u \tag{1}$$

where $h_{u,s}$ is the channel response from the BS s and a user u. n_u represents the additive noise at the u-th user, and I is the set of interfering BSs for user u. Equation (2) represents the channel response

$$h_{u,s} = \alpha_{u,s} \sqrt{\beta_{u,s} A(\theta_{u,s}) d_{u,s}^{\ -\mu}} \tag{2}$$

where $\alpha_{u,s}$ and $\beta_{u,s}$ are the fast Rayleigh fading and shadowing, respectively; $A(\theta_{u,s})$ is the antenna gain for user u with respect to the BS, s whose value is a function of $\theta_{k,s}$ based on (2); $d_{u,s}$ is the distance between the BS, s and user u; and μ is the path loss exponent [8]. The gain pattern used for each sector antenna was defined by [8] as

$$A(\theta)_{dB} = \begin{cases} 1 & \text{omnidirectional} \\ -\min\left[12\left(\dfrac{\theta}{\theta_{3dB}}\right)^2, A_m\right] & \text{sectorial} \end{cases} \tag{3}$$

where $\theta_{3dB} = 70^{o}$ is the angle at which the antenna gain is 3 dB lower than the antenna gain at the main-beam direction, and the parameter, A_m = 20 dB, is the maximum attenuation measured at the sidelobe [8].

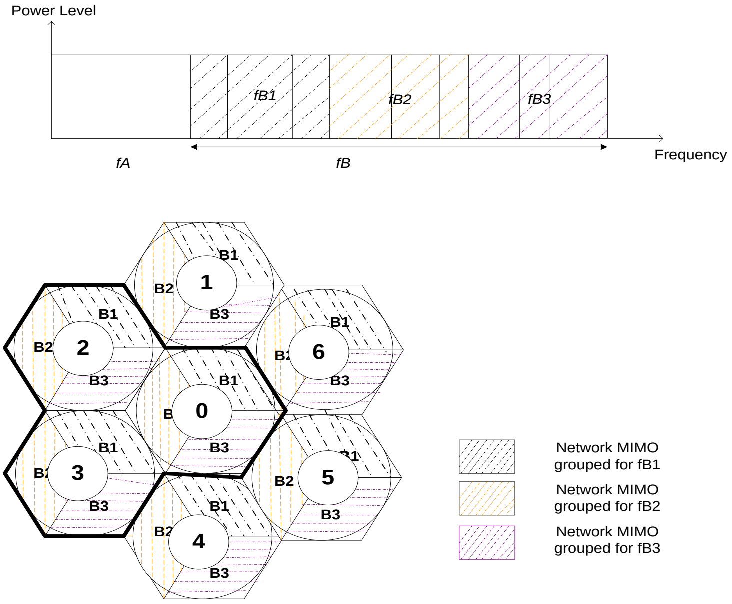


Fig. 2. Dynamic Frequency Allocation

5. Model Description and Proposed DFFR Method

In this section, the design of the ICIC strategy on top of the Network MIMO involves the DFFR and power allocation.

5.1 Network MIMO

In this work, Network MIMO with M base stations (BSs) and U users was considered. Each BS was equipped with two antennas N_T, while each user N_R was equipped with a single antenna and different transmit powers, P_u. The signal vector transmitted by the BSs can be expressed as

$$x = Ws \begin{bmatrix} w_{1,1} & \cdots & w_{1,M} \\ \vdots & & \vdots \\ w_{M,1} & \cdots & w_{M,M} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_M \end{bmatrix} \quad u = 1,\ldots,M \tag{4}$$

where w_u is the precoding weighting vector, and s_u is the data symbol of the u-th user that is cooperatively served by the sector BSs. Note that depending on the design of W, the cooperating BSs will need to share their CSI. From the above equation, the received signal of the user, u can be represented as

$$y_{i,u} = H_{i,u} x_i + \sum_{j \neq i}^{M} H_{j \rightarrow i,u} x_j + n_{i,u} \tag{5}$$

where $H_{i,u}$ is the channel between the *i*-th BS and the *u*-th user, while, $H_{j\rightarrow i,u}$ is the channel matrix between the *j*-th BS and the *u*-th user in the *i*-th BS, and $n_{i,u}$ is the noise vector of the *u*-th user in the *i*-th BS. In the downlink channel, assuming that the transmitted power in the *u*-th antenna is P_u, and the power for each antenna is limited by the maximum downlink transmitted power: $P_u \leq P_{max,BS,}$ $U = 1,2,3,\ldots, M$.

5.2 Dynamic Fractional Frequency Reuse (DFFR) on Network MIMO

A simplified hexagonal cell was represented in the system model, where a user, *u* was served by a base station, *s*. The SINR distribution at a random location could be calculated while considering a random channel characteristic such as fading and shadowing [3]. The users were uniformly distributed within the coverage area of a cell randomly, and each user was served by its nearest base station. The SINR of the *u*-th user is given as follows:

$$SINR = \frac{P_{s,u} h r^{-\alpha}}{\sigma^2 + I_r} \tag{6}$$

where the power transmitted by the base station, *s* for the user, *u* is given by $P_{s,u}$; *r* is the distance between the user and the base station and is assumed to be a random variable with a Rayleigh distribution; *h* is a random variable that represents the exponential distribution with the cumulative effect of small scale fading and shadowing; the path loss exponent is α; and σ^2 represents the noise power.

The sum of the received power from all the other base stations, also known as the interference power, is given by I_r, where *g* is the statistical distribution that consists of shadowing, the value of fading and anything of random effect that is required; *R* is the distance from the users to other stations, and *u* represents each user, which interferes with the user whose SINR is being calculated.

$$I_r = \sum_{u \in \phi / b_o} \left(g_u R_u^{-\alpha} \right) \tag{7}$$

5.3 Cell Partition and Sectoring

The first step towards effective ICI mitigation is to divide the cell into sectors. The sectoring layouts of 120° cell sectorization are presented in **Fig. 2**, where the boresight of each sector is defined as the direction in which the antenna gives the maximum gain. The average SINR received between the cells will be used to determine whether the users can be CEUs or CCUs, and this is also shown in **Fig. 3**. The effect of the ICI can be evaluated using the SINR in the LTE-A downlink. If the SINR is higher than the β-th SINR threshold, the user is deemed to belong to the cell centre, while the rest of the users are considered to belong to the cell edges.

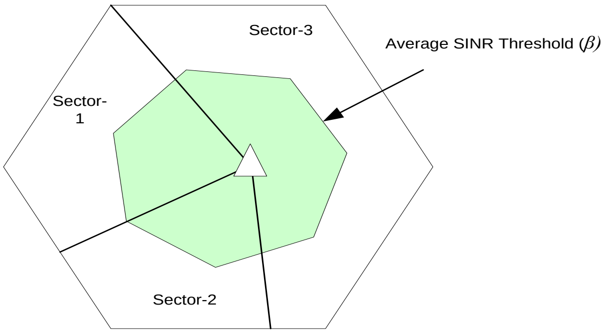


Fig. 3. Cell Partition based on average SINR received

5.4 Dynamic Frequency Allocation

The users are uniformly distributed within the cell, such that each sector has a different number of users. The required bandwidth can be higher if a higher number of users is allocated in the larger sector. For each allocated sector, the spectrum is dynamically based on the required bandwidth. The fixed and dynamic frequency allocation techniques are illustrated in **Figs. 4** (a) and (b), respectively. The proposed dynamic frequency allocation method can be formulated as follows:

$$BW_{total} = BW_{center} + BW_{edge} \tag{8}$$

where BW_{total} is the total available bandwidth, which is the sum of the BW_{center} bandwidth assigned to the cell centre zone and the BW_{edge} bandwidth assigned to the cell edge zone.
The total area of the cell, A_{cell} is expressed below, where A_{center} is the area of the cell centre zone, and A_{edge} is the area of the cell edge zone.

$$A_{cell} = A_{center} + A_{edge} \tag{9}$$

A_{edge} can be described as the sum of the areas of all the sectors, as presented in Equation (10). Equation (11) represents the spectrum assigned to the centre zone, and Equation (12) represents the spectrum assigned to each sector in the edge zone.

$$A_{edge} = \sum_{i=1}^{3} A_{sector-i} \tag{10}$$

$$BW_{center} = BW_{total} * \left(\frac{A_{center}}{A_{cell}} \right) \tag{11}$$

$$BW_{sector-i} = (BW_{total} - BW_{center}) * \left(\frac{A_{sector-i}}{A_{edge}} \right) \tag{12}$$

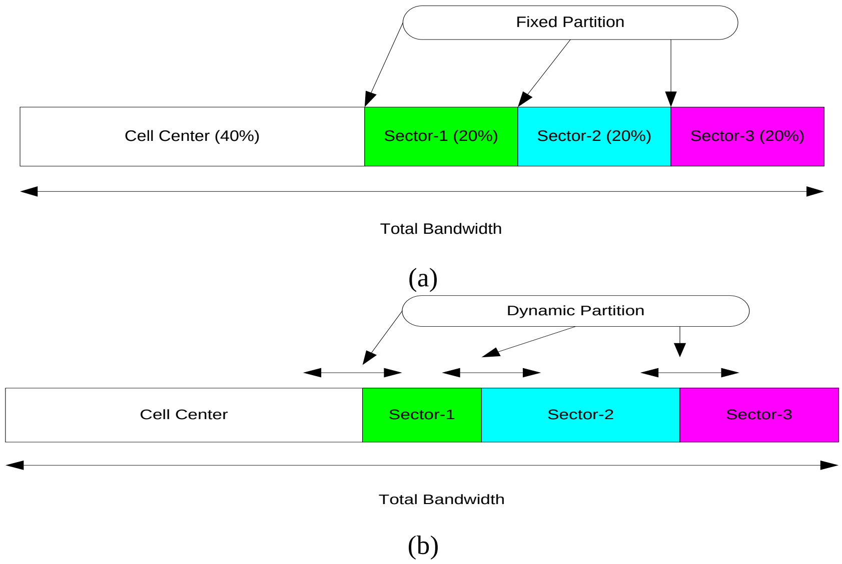


Fig. 4. Bandwidth allocated based on the proposed method for (a) Fixed Frequency Reuse; and (b) Dynamic Frequency Reuse

5.5 Coverage Probability

This section presents the general coverage probability expressions for the DFFR scheme. Coverage is regarded as an important metric that has a large effect of QoS especially on CEUs, and it can also describe the overall network capacity when combined with resource efficiency, such as power allocation. Equation (13) shows how coverage probability in a downlink cellular network is derived by using equation (6), where it depends on random parameters, such as the location of users and the channel fading coefficients. This can also be defined as (i) the probability of achieving the target SINR by a random user, (ii) the average fraction of users that can achieve SINR at any time, or (iii) the average fraction of the network that is within the coverage at any time. Since the CDF is provided as $P[SINR > \beta]$, the equation represents the CCDF of the SINR that covers the network completely. If the SINR of the user is larger than β, the user is within the coverage, and when the SINR is below β, the coverage will be decreased. The value of β is a target threshold SINR value.

$$p_c(\beta) \cong P\left[SINR > \beta\right] \quad (13)$$

6. Power Allocation Approach

For Network MIMO systems, each BS of a cooperative cell set (CCS) has to simultaneously serve its CCUs and CEUs under a transmit power constraint. The goal of power allocation in a cell is thus to help raise the signal quality of both the CCUs and CEUs, while at the same time not degrading the performance of its CCUs. It will be shown that the DFFR can achieve this goal by means of the proposed method of managing power.

6.1 Zero-forcing based on Network MIMO

ZF precoding is known to completely eliminate interference from other users. ZF is applied to invert the channel to obtain $hW = I_N$, where I_N is an N x N identity matrix, and the weight matrix (W) is the pseudo-inverse of the channel matrix [10]. Hence, the received signal model is found to be

$$Y = Hx + n = HWs + n = s + n \tag{14}$$

The ZF-based precoding matrix, W can be chosen as the pseudo-inverse of H

$$W = H^H \left[HH^H \right]^{-1} \tag{15}$$

where $H = \left[h_1 ...., h_M \right]^T$. Let P_u be the transmit power allocated to the u-th user. The capacity of the ZF-based Network MIMO can be written as

$$C_{ZF} = \sum_{u=1}^{U} log_2 \left(1 + SINR_u \right) \tag{16}$$

Here,

$$SINR_u = \frac{g_u P_u}{\sigma^2 + \sum_{s=1, s \neq u} g_u P_s} \tag{17}$$

with

$$g_u = \frac{1}{\left\| w(u) \right\|^2} = \frac{1}{\left[\left(HH^H \right)^{-1} \right]_{u,u}} \tag{18}$$

which can be interpreted as the effective channel power gain to the u-th user while, $\sum_{s=1, s \neq u} g_u P_s$ represents the signal power of interference from the others BSs. It should fulfill the power constraint condition, $P_{max,BS}$

$$\sum_{u=1}^{U} P_u \left| w_u \right|^2 \leq P_{\max,BS} \tag{19}$$

Two typical power allocation schemes are WF [15][16] and EP. The basic WF algorithm is always used in power allocation because it is simple to analyse and, in practice, its calculation is straightforward, while EP is also a simple power allocation scheme, where EP is optimal when the CSI is not recognized at the transmitter.

6.1.1 WF Algorithm

In this section, the WF algorithm is introduced because it is one of the well-known solutions used for power allocation. Hence, the approximate optimal power allocation is developed to maximize the capacity. Based on Equation (16), the design of the power allocation scheme for the multi-objective optimization problem is summarized as

$$max \quad \sum_{u=1}^{U} log_2 \left(1 + g_u P_u \right) \tag{20}$$

$$subject \quad to \qquad C1 \; : \; P_u \;\geq\; P_{max,BS} \tag{21}$$

$$C2 \; : \; \sum_{u=1}^{U} log_2\left(1 \; + \; g_u P_u\right) \;\geq\; R_{min} \tag{22}$$

The transmission power allocated has been formulated in constraint (21), where each subchannel power has a range within $0\text{-}P_{max,BS}$, and (22) represents the normalized rate requirement, where R_{min} is the minimum rate threshold required by user, u. Therefore, the Lagrange Multiplier technique is introduced to solve the problem from Equation (16) with constraint (21)

$$\forall(P,\, \lambda,\, \mu) \;=\; \sum_{u=1}^{U} log_2\left(1 \;+\; g_u P_u\right) + \sum_{u=1}^{U} \lambda\left(P_u \;-\; P_{max,BS}\right) + \; \mu\left(\sum_{u=1}^{U} P_u \;-\; P_{max,BS}\right) \tag{23}$$

where the vectors of the Lagrange Multiplier represent μ and λ, respectively. Then, the point $[P^{+},\lambda,\mu]$ can be concluded as

$$\begin{cases} 1 \;+\; g_u P_u \;=\; \dfrac{g_u}{ln(2)L_u} \\ L_u \;=\; -\left(\lambda \displaystyle\sum_{u=1}^{U} \left|w_u\right|^2 \;+\; \ldots \;+\; \mu \displaystyle\sum_{u=1}^{U} \left|w_u\right|^2\right) \\ \displaystyle\sum_{u=1}^{U} P_u \left|w_u\right|^2 \;=\; P_{max,BS} \end{cases} \tag{24}$$

Therefore, the optimal power allocation WF algorithm is written as

$$P_u \;=\; \left[\frac{1}{g_u} \;-\; \frac{1}{\mu}\right]_0^{P_{max,BS}} \tag{25}$$

where the function $[-]_0^{P_{max,BS}}$ confines the range of p_u as per (21), and μ is a water level; Using (6), the SINR of the ZF-based Network MIMO can be written as

$$SINR_u \;=\; \frac{P_u}{\sigma^2 \;+\; \displaystyle\sum_{u=1}^{U} P_u \left|h_{u,s} w_{u,s}\right|^2} \tag{26}$$

The capacity of a Network MIMO is the algebraic sum of the capacities of all the channels, and it can be expressed as follows:

$$capacity = \sum_{u=1}^{U} \log_2(1 + SINR_u) \tag{27}$$

6.1.2 IWF Algorithm

An IWF algorithm was proposed to enhance the capacity and remove the limitations of the equally distributed power. From Equation (27), the following optimization problem was formulated in order to maximize the overall capacity with constraint (21). The maximum of the total squared weights among all the BSs was defined as

$$K_u = \max_{s=1,\dots,M}\left(\left|w_u^s\right|^2\right) \tag{28}$$

Therefore,

$$\begin{aligned}&\max\left\{\sum_{u=1}^{U}\upsilon_u * \left(\log_2\left(1+g_u P_u\right)\right)\right\}\\&s.t\\&\sum_{u=1}^{U} P_u K_u \le P_{\max,BS}\end{aligned} \tag{29}$$

An IWF power allocation algorithm was proposed by introducing the Lagrange Multiplier technique, as defined below:

$$\sum_{u=1}^{U}\upsilon_u * log_2\left(1 + g_u P_u\right) + \mu\left(\sum_{u=1}^{U} P_u K_u - P_{max,BS}\right) \tag{30}$$

where the vectors of the Lagrange Multiplier represent μ, and $\upsilon_u \in [0,1]$ represents each user priority. In certain cases of equal priority, $\upsilon_u = 1/U$ for all u. This corresponds to an IWF distribution with variable water levels that can be changed only by the user priorities.
The set of equations can be recast as:

$$\frac{\upsilon_u}{2\ln(2)}\frac{g_u}{1+g_u P_u} + \mu \mathrm{K}_u = 0 \tag{31}$$

Hence

$$P_u + \frac{1}{g_u} = -\frac{\upsilon_u}{2\ln(2)\mu \mathrm{K}_u} \tag{32}$$

Referring to Equation (32), the new power allocation expression can be written as follows:

$$P_u = \left[W \frac{\upsilon_u}{K_u} - \frac{1}{g_u}\right]_0^{P_{max,BS}} \tag{33}$$

where $[-]_0^{P_{max,BS}}$ represents the maximum between zero and the $P_{max,BS}$, g_u is the channel realization, while W is a constant value for all the power, P_u within the range of 0 to 1. Using Equation (6), the SINR of the user was obtained as

$$SINR_u = \frac{g_u P_u}{\sigma^2} \tag{34}$$

The channel capacity was defined as follows:

$$Capacity = \sum_{u=1}^{U}\upsilon_u * log_2(1 + SINR_u) \tag{35}$$

Algorithm: Improved Water-Filling

Input: Set of $\{g_u\}$, υ, W and $P_{max,BS}$ $u = 1,\ldots,U$

Output: $\{P_u\}$and *Capacity*

1. Initialization: Set $P_{total} = P_{max,BS}$

2. Calculate allocated power:

1: Sort g_u in decreasing order

2: $(g_u \geq g_u + 1)$

3: for given g_u, obtain the solution of P_u according to (33)

4: if $\mu = 0$ and $\lambda \geq P_{total}$

5: $P_u = 0$

6: else if $\mu > 0$ and $\lambda \leq P_{total}$

7: then, $P_u = W\frac{v_u}{K_u} - \frac{1}{g_u}$

3. Calculate Capacity:

1: $Capacity = \sum_{u=1}^{U} v_u \log_2 (1 + SINR_u)$

Fig. 5. Pseudo-code for the improved water-filling algorithm

7. Simulation Settings and Environments

The LTE-A Release 13 [17] was used for the physical (PHY) simulation parameters. Seven cells with hexagonal grid structures were considered in the simulation, and the SINR threshold was used for allocating the centre users and the edge users. The base station was located at the centre of each cell, and a frequency reuse factor, $r = 3$, was considered. Twenty users were uniformly randomly distributed in each cell. All available PRBs in each cell were used, and a full traffic load was assumed for the capabilities of the network.

The primary parameters are summarized in **Table 1**, and **Fig. 6** presents the hexagonal cells with random UE distributions. The channel gains of the users were considered as a reciprocally independent random process, which could be specified by the sum of two terms: (i) path loss and (ii) shadowing. A path-loss exponent of $\alpha = 4$, and a slow log-normal shadowing model similar to [9] were assumed.

Table 1. System Parameters for Urban Evaluation Environments [17]

Parameters	Values
Channel Bandwidth	10 MHz
Carrier frequency	2 GHz
Number of Subcarriers	1200
Cell Radius	1 km
Grid Layout	3-sectored hexagonal 7 Cells
Distribution of Users	Uniformly distributed 15 to 20 [4]
Frequency Spacing	15 kHz
Path loss exponent	4 (urban area)
BS Transmit Power	43 dBm
Noise Density	-174 dBm
SINR Threshold (β)	1 dB [3]
R_{min}	2 Mbps [14]
$P_{max,BS}$	1.5 mW

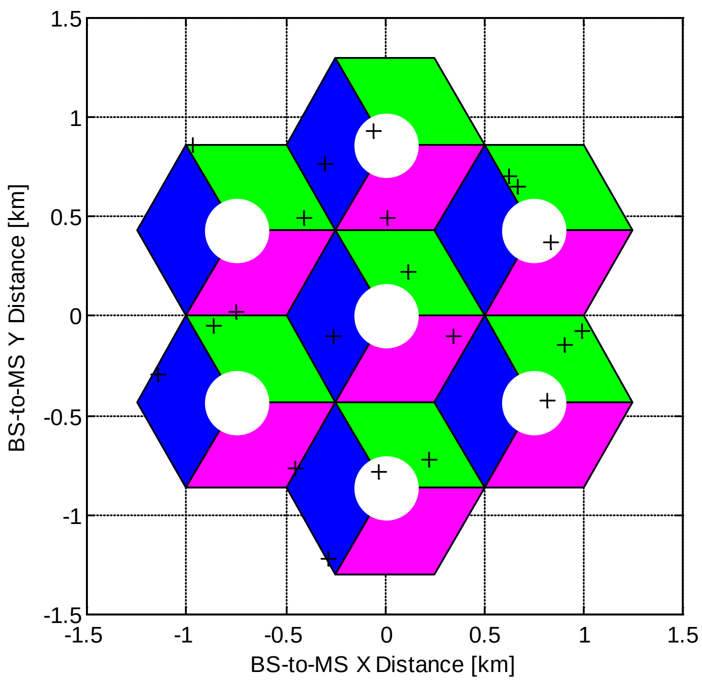


Fig. 6. Hexagonal cells with random UE distributions

8. Simulation Results and Analysis

This section presents the performance evaluation of different methods: CFR [11], FFR [7] using tri-sector cells, DFFR with equal power (DFFR EP) [5], DFFR with a water-filling algorithm (DFFR WF) [14] and DFFR with an improved water-filling algorithm (DFFR IWF). Previous works were selected for comparison since they considered the fractional frequency reuse strategy in addition to theoretical works on power allocation, which were similar to the proposed DFFR IWF. The value of β was 1 dB, which provided the best SINR performance for the FFR-based cellular network being considered [3]. A lower value of β may push too many users from the cell edge to the cell centre resources, while a higher β value may increase the number of cell edge users. Typically, the LTE design parameters used an interference-free SNR of 10 dB [18].

Fig. 7 presents the probability of coverage for the cell edge users with respect to the SINR threshold. From the graph, the five methods being considered were plotted with $\beta = 1$ dB, and were then compared with the CFR, FFR, DFFR EP, DFFR WF and DFFR with an improved water-filling algorithm (DFFR IWF). Based on the results, it could be observed that the DFFR IWF offered a better signal quality of approximately 80% on the cell edge area compared to the other considered methods. Thus, by introducing an improved power allocation method, the DFFR IWF helped to raise the signal quality of the CEUs.

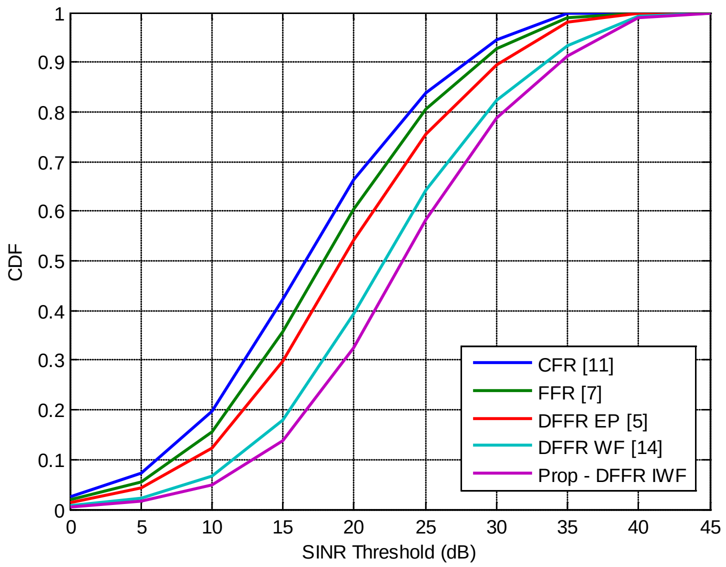


Fig. 7. Probability of coverage for edge users for different frequency reuse methods

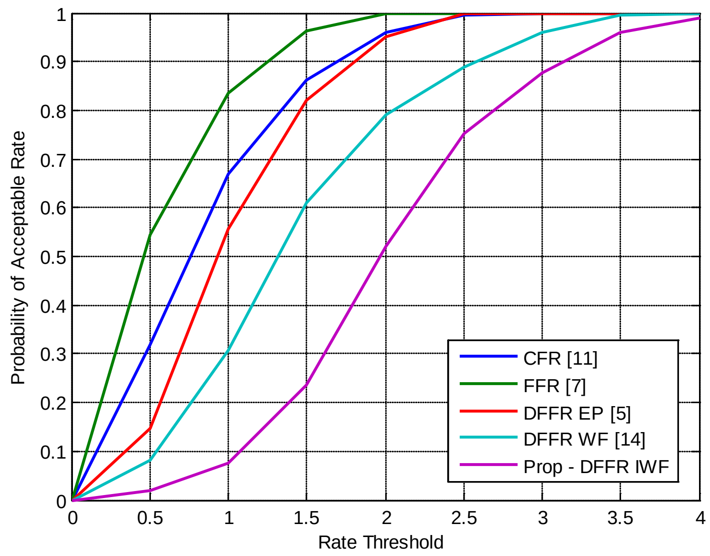


Fig. 8. Achievable rate edge users for different frequency reuse methods

The achievable rate in **Fig. 8** indicates that the DFFR IWF method achieved approximately 6% at 4 bps when compared to the DFFR WF method. The CFR method performed better than the FFR method because the CFR method used all the frequency resources and the total bandwidth, while the FFR method used only one-third of the total bandwidth.

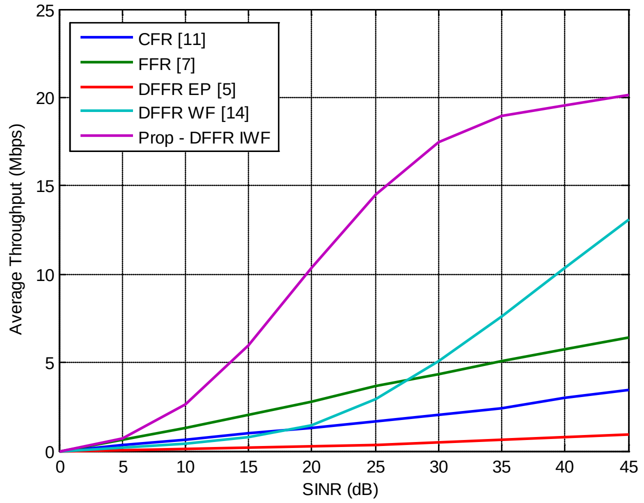


Fig. 9. User throughput versus average SINR (dB)

For the user throughput, a simulation was conducted by varying the average SINR (dB), as presented in **Fig. 9**. From the graph, the DFFR EP was poor in all the SINR regions where, in the low SINR regions, the user throughput dropped sharply. It was observed that the water-filling algorithm performed better compared to the equal power allocation technique. Based on the power allocation method for any channel, the power allocated to the resources was proportionate to the channel gain. If more power was allocated to the users, and the observation effects and channel noise were considered, then the overall system throughput could be maximized; however, this was not applicable for the case of equal power. Furthermore, the results in **Fig. 8** indicated that the CFR, FFR, DFFR WF and DFFR IWF methods were all inclined to improve the CEU throughput. Additionally, a comparison with existing studies was performed to validate the performance of the proposed technique. The proposed method showed a considerable improvement over [5] of 42% at an SINR of 25 dB.

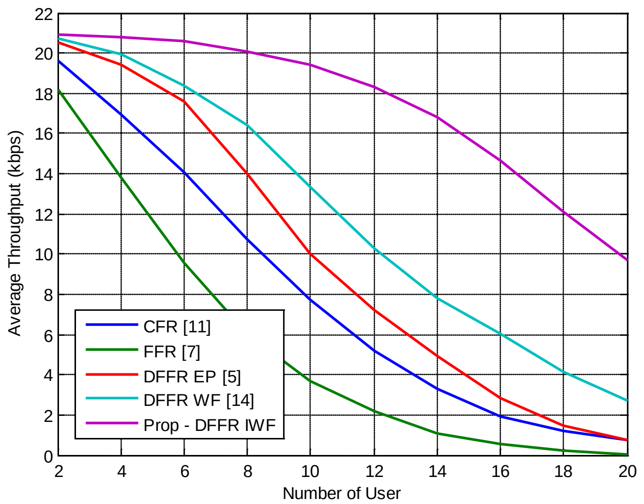


Fig. 10. Average throughput versus number of users

Fig. 10 shows the average cell throughput with respect to the number of users for the different methods. With few users in each cell, the FFR indicated a lower CEU throughput than the other methods. As the number of users increased, the DFFR IWF method achieved a considerable cell edge performance compared to the other methods. For the highest degree of ICI, the FFR experienced low levels of interference because the neighboring cells used different sub-bands. However, the CEU throughput of the DFFR EP, DFFR WF and DFFR IWF methods decreased as the number of users increased. There was a limitation for them to improve the performance of the cell boundary users through the resource reservation for the CEU. The FFR indicated the lowest cell throughput because it used only one-third of the total bandwidth. Conversely, the CFR used the entire frequency allocation and achieved a high throughput performance. It is also possible to allocate the total bandwidth using the DFFR, but a few frequencies have to be reserved for the CEU in case the channel experiences bad conditions. Consequently, the cell throughput of the DFFR EP was lower than the CFR. In a wireless system, the number of users and the throughput are related to the wireless transmission limit of the SNR and the bandwidth of the received signal. Once the number of users is increased, the throughput decreases; consequently, the system performance improves and the data transmission will be faster because the number of bits influence the maximum value with less number of users.

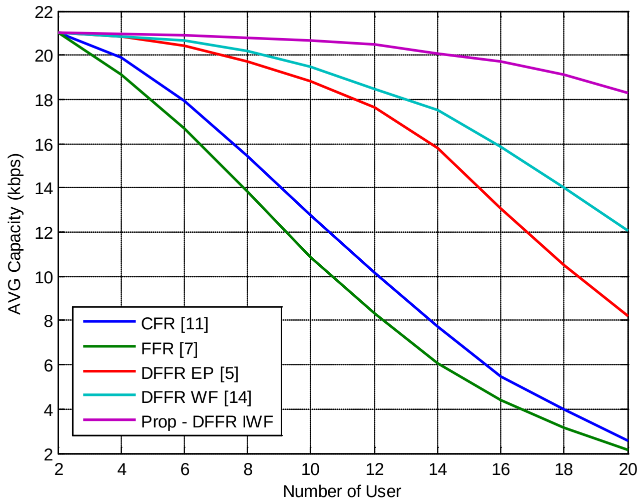


Fig. 11. Average capacity versus number of users

Fig. 11 represents the average capacity for the different number of users. The result indicates that the DFFR IWF method was able to produce a higher average cell capacity. With an increase in the number of users, the graph illustrates that the DFFR method performed significantly better than the CFR and FFR methods. The CFR method had a lower average capacity compared to the proposed DFFR method, even though it offered a greater bandwidth. In fact, lower power had been transmitted to the CEUs for the DFFR WF method compared to those using the DFFR IWF method, and the adjacent CCUs in the directly neighbouring cells had interference simultaneously. The users decreased with less power when the channel capacity decreased (**Fig. 11**).

9. Conclusion

To improve the performance of the DFFR in LTE-A downlink networks, an IWF solution was proposed, developed and validated in an LTE-A environment. Each eNodeB in a network performed the proposed power allocation locally by significantly addressing the mutual interference produced by both the CEUs and CCUs. The simulation results indicated that compared to other methods, an IWF algorithm achieved a considerable increase in the cell capacity and the CEUs, while maintaining the required capacity for the CCUs. Additionally, based on the power allocation algorithm, the performance of the DFFR method was consistently accomplished in the networks and was able to effectively improve the coverage, data rate and throughput for the cell edge users. This finding proved that an enhanced DFFR method is capable of being more effectively utilized for all users, including both CEUs and CCUs.

References

[1] Miyim, A.M., Mahamod Ismail, and Rosdiadee Nordin, "Fast Networks as a Candidate for LTE-Advanced Networks," *Smart Computing Review*, vol. 3, no. 2, pp. 74-85, April 2013. Article (CrossRef Link)

[2] Young-June Choi, Cheol Seung Kim, and Saewoong Bahk, "Flexible Design of Frequency Reuse Factor in OFDMA Cellular Network," in *Proc. of IEEE International Conference on Communications*, Istanbul, Turkey, 2006. Article (CrossRef Link)

[3] T. Novlan, R. Ganti, A. Ghosh, and J. Andrews, "Analytical Evaluation Of Fractional Frequency Reuse For OFDMA Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 12 (pp. 4294-4305), 2011. Article (CrossRef Link)

[4] Syed Hussain Ali and Victor C. M. Leung, "Dynamic Frequency Allocation in Fractional Frequency Reused OFDMA Networks," *IEEE Transactions On Wireless Communications*, vol. 8, No. 8, 2009. Article (CrossRef Link)

[5] Ronald Y. Chang, Zhifeng Tao, Jinyun Zhang and C.-C. Jay Kuo, "Dynamic Fractional Frequency Reuse (D-FFR) For Multicell OFDMA Networks Using a Graph Framework," *Research Article, Wireless Communication and Mobile Computer*, (pp. 12–27), 2013. Article (CrossRef Link)

[6] M.Qian, W.Hardjawana, Y.Li, B.Vucetic, J.Shi, X.Yang, "Inter-cell Interference Coordination Through Adaptive Soft Frequency Reuse in LTE networks", *IEEE wireless Communications and Networking Conference*, 2012. Article (CrossRef Link)

[7] A. Thampi, S. Armour, Z. Fan, and D. Kaleshi, "Clustered Network MIMO and Fractional Frequency Reuse for the Downlink in LTE-A Systems," *European Wireless*. pp. 802–807, 2014. Article (CrossRef Link)

[8] Li Chun Wang and Chu Jung Yeh, "3-Cell Network MIMO Architecture with Sectorization and Fractional Frequency Reuse," *IEEE Journal on Selected Areas In Communications*, vol.29, No. 6, 2011. Article (CrossRef Link)

[9] IEEE C802.16m-08/034, "Adaptive frequency reuse for interference management in IEEE 802.16m system," 2008. Article (CrossRef Link)

[10] XiangY, Luo J,Hartmann C, "Inter-cell interference mitigation through flexible resource reuse in OFDMA based communication networks," in *Proc. of 13th European Wireless Conference*, 2007. Article (CrossRef Link)

[11] J. Li, H. Zhang, X. Xu, X. Tao, T. Svensson, C. Botella and B. Liu, "A novel frequency reuse scheme for coordinated multi-point transmission," in *IEEE Conference Vehicular Technology*, pp. 16–19, 2010. Article (CrossRef Link)

[12] A. L. Stolyar and H. Viswanathan, "Self-Organizing Dynamic Fractional Frequency Reuse in OFDMA Systems," in *Proc. of IEEE INFOCOM*, pp. 691-699, 2008. Article (CrossRef Link)

[13] A. L. Stolyar and H. Viswanathan, "Self-Organizing Dynamic Fractional Frequency Reuse for Best-Effort Traffic through Distributed Inter-Cell Coordination," in *Proc. of IEEE INFOCOM*, pp. 1287-1295, 2009. Article (CrossRef Link)
[14] Noor Shahida M.K, Rosdiadee Nordin and Mahamod Ismail, "Power Allocation for Dynamic Fractional Frequency Reuse (DFFR) in Downlink LTE-A System," in *Proc. of Asia-Pacific Conference on Communications(APCC), Kyoto, Japan*, Oct 2015. Article (CrossRef Link)
[15] Mangayarkarasi, P., M. Ramya, and S. Jayashri, "Analysis of various power allocation algorithms for wireless networks," in *Proc. of International Conference on Communication and Signal Processing*, 2012. Article (CrossRef Link)
[16] Qilin Qi, Andrew Minturn, and Yaoqing (Lamar) Yang, "An Efficient Water-Filling Algorithm for Power Allocation in OFDM-Based Cognitive Radio Systems," in Proc. of *International Conference on Systems and Informatics (ICSAI)*, 2012. Article (CrossRef Link)
[17] 3GPP TR 36.897 V13.0.0, "Study on elevation beamforming / Full-Dimension (FD) Multiple Input Multiple Output (MIMO) for LTE," (Release 13), 2015. Article (CrossRef Link)
[18] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic, "Interference coordination and cancellation for 4G networks," *IEEE Communications Magazine*, vol. 47, no. 4, (pp. 74–81), 2009. Article (CrossRef Link)

Noor Shahida M.K is a PhD candidate in the Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia. She received her B. Eng. from Universiti Teknologi Mara in 2006 and M.Sc. Communication Engineering from Universiti Teknologi Mara in 2008. Her research interests are in the area of wireless communication and Multiple-Input Multiple-Output (MIMO).

Rosdiadee Nordin received his B. Eng. from Universiti Kebangsaan Malaysia in 2001 and Ph.D. from University of Bristol, United Kingdom in 2011. He is currently a senior lecturer in Department of Electrical, Electronic, and Systems Engineering in Universiti Kebangsaan Malaysia. His research interests include peer-to-peer (P2P) routing protocol, resource allocation, Multiple-Input Multiple-Output (MIMO), Orthogonal Frequency-Division Multiple Access (OFDMA), green radio and indoor wireless localization.

Mahamod Ismail is currently a professor in Communications Engineering at, and the Head of Department of the Electrical, Electronic, and Systems department at the Universiti Kebangsaan Malaysia (UKM). He received the B.Sc. in Electrical and Electronics from University of Strathclyde, U.K. in 1985, the M.Sc. in Communication Engineering and Digital Electronics from UMIST, Manchester U.K. in 1987, and the Ph.D. from University of Bradford, U.K. in 1996. Professor Mahamod is an executive member of Communications/Vehicular Technology Society, IEEE Malaysia chapter. His current research interests include Mobile Communications and Wireless Networking.