

A Simulation Framework for the Evaluation of Frequency Reuse in LTE-A Systems

Dimitrios Bilios, Computer Technology Institute & Press “Diophantus”, Computer Engineering and Informatics Department, University of Patras, Patras, Greece

Christos Bouras, Computer Technology Institute & Press “Diophantus”, Computer Engineering and Informatics Department, University of Patras, Patras, Greece

Georgios Diles, Computer Technology Institute & Press “Diophantus”, Computer Engineering and Informatics Department, University of Patras, Patras, Greece

Vasileios Kokkinos, Computer Technology Institute & Press “Diophantus”, Patras, Greece

Andreas Papazois, Computer Technology Institute & Press “Diophantus”, Computer Engineering and Informatics Department, University of Patras, Patras, Greece

Georgia Tselioui, Computer Engineering and Informatics Department, University of Patras, Patras, Greece

ABSTRACT

Long Term Evolution Advanced (LTE-A) technology is considered as the most possible candidate for next generation mobile communications. LTE-A networks offer high capacity and are specified and designed to accommodate small, high performance, power-efficient end-user devices. Similarly to its predecessor LTE, LTE-A incorporates inter-cell interference mitigation methods in order to mitigate interference and to enhance efficiency in bandwidth usage. These methods include power and frequency allocation schemes that allow neighbouring cells and femtocells in heterogeneous networks to co-ordinately share and reuse available spectral resources, in order to avoid performance degradation for interference suffering cell-edge users. In this paper, the authors study the LTE-A multi-cell systems' performance using a simulation framework, which integrates several frequency reuse techniques and provides a user-friendly graphical presentation of the evaluation results. The optimal Fractional Frequency Reuse (FFR) configuration for the user-defined network instance is also determined, based on overall performance and fairness index metrics. Finally, the authors examine FFR techniques in two-tier femtocell/macrocell environments and evaluate them based on the optimization of different metrics, depending on the network operator's needs.

Keywords: Channel Interference, Fractional/Soft Frequency Reuse, Jain's Fairness Index, Two-Tier Environments, Weighted Throughput

DOI: 10.4018/ijwnbt.2014040104

INTRODUCTION

The newly emerged data-minded cellular standard Long Term Evolution Advanced (LTE-A), which is the most promising candidate for next generation mobile communication networks, has been derived by the demand for higher capacity and data rates on mobile networks. Orthogonal Frequency Division Multiple Access (OFDMA) technology has been proposed in order to achieve the aforementioned goals. It is based on dividing the available spectrum into a number of parallel orthogonal narrowband subcarriers through Orthogonal Frequency Division Multiplexing (OFDM), allowing dynamic assignment of the subcarriers to different users at different time instances, thus providing higher data rates and increased spectral efficiency.

The goal of spectral efficiency though, can be easily converted to performance liability, due to the interference phenomenon that affects mostly neighbouring areas using the same frequency, namely Co-Channel Interference (CCI). The situation is worse for users located near the edges of the cells, since both the reception of a weakened signal power from the Base Station (BS) and the simultaneous use of the same subcarriers by different users in adjacent cells, can lead to major performance degradation.

Several frequency reuse schemes have been discussed for OFDMA-based networks, each one exhibiting different efficiency and complexity, in order to achieve the conflicted goals of utilizing the limited radio spectrum efficiently,

and mitigating interference effects on network performance. Resource partitioning schemes are common means to overcome the CCI problems, i.e., from transmitters located in neighbouring cells with the same frequency bands as the reference cell of interest. The most common techniques are Soft Frequency Reuse (SFR) and Fractional Frequency Reuse (FFR). In all these schemes the whole frequency band is divided into several sub-bands. The network is then divided in areas that may utilize all or part of the sub-bands depending on the scheme implemented.

The two-tier femtocell/macrocen-vironment environments comprise of a conventional cellular network overlaid with shorter-range self-configurable BS, called femtocells (Chandrasekhar & Andrews, 2008). Femtocells or home BSs use antennas with low transmission power, which are typically connected to high-speed backhubs. They are one of the emerging cost-effective solutions for both operators and users aiming to expand mobile coverage and to support higher data rates by bridging mobile handsets with broadband wired networks. Femtocells constitute an economical solution conceived for improving the indoor coverage and achieving high network capacity. The main reason lies in the fact that they are deployed in an unplanned manner with minimal radio frequency RF planning, thereby resulting in cost savings for the operator. In order to deploy femtocells in a pre-existing macrocellular network, intelligent frequency band allocation considering the effect of CCI for femtocells and con-

ventional macrocells is required in order for them to operate harmoniously in the same network (Lopez-Perez, Valcarce, Roche & Zhang, 2009).

The limiting factor in two-tier femtocell/macrocell networks is the interference between macrocells and femtocells that can suffocate the capacity due to the near-far problem. A macrocell BS may receive interference from femtocell BS, whereas a femtocell BS may receive interference from both macrocells and femtocells. It can impair the spatial frequency reuse gain. Since femtocell BSs are user deployed and thus are installed in an unplanned, random manner, the technical difficulties of interference management is increased (Son, Lee, Yi & Chong, 2011). This means that femtocells should use a different frequency channel from the one of the potentially nearby high-power macrocell users (MUs).

In this paper, we investigate the LTE-A multi-cell systems' performance using a simulation framework, which integrates several frequency reuse techniques and provides a user-friendly graphical presentation of the evaluation results. The framework uses an FFR technique that takes into account real parameters from the network operator's side and achieves optimization of the network configuration. It simulates LTE-A multi-cell topologies and evaluates the performance of the resulting networks focusing on the impact of inter-cell interference coordination on the latter. The framework receives user input to configure the size of the network and the number of residing mobile users, the

bandwidth that is available, the modulation and the frequency reuse scheme. It simulates user activity inside the network and calculates the cells' throughput and the fairness of resource allocation. Furthermore an optimization mechanism is triggered, in order to configure the optimal parameters of frequency subbands allocation and area division. The optimization strategy can be based on three different approaches: the 1st approach finds the optimal inner region radius and frequency allocation based on the maximization of the network's Total Throughput, the 2nd one is based on the Jain's Fairness Index and the 3rd one is based on a new metric, which is called Weighted Throughput. This metric aims to make a trade-off between the total cell throughput values and the per-user throughput values that occur from the two previous approaches, so that higher cell throughput is achieved simultaneously with similar per-user throughput values. Finally, we discuss the results obtained by the framework and compare the outcomes of different configurations and deployments that incorporate femtocells. The framework is implemented in the Matlab programming language and provides interactive environment for numerical computation and simulations. The framework is available through IBPsim (2012) for reference, test purposes or any unrestricted modification for further research.

The rest of this paper is structured as follows: all the information on the related work is described in Section 0. Frequency reuse schemes in macrocell and femtocell/macrocell environments

are presented in Section 0. The system model and the adopted metrics are described in Section 0. In Section 0 we provide an overview of our simulation framework's architecture and we briefly explain its functions as well as its usage. All the carried out experimental procedure along with its results can be found in Section 0. The final conclusions and proposals for future work are drawn up in Sections 0 and 0, respectively.

RELATED WORK

There are several published related works on frequency reuse techniques for interference mitigation in LTE-A deployments. An evaluation of various frequency reuse schemes including Integer Frequency Reuse (IFR), FFR and Two Level Power Control (TLPC) is presented in the work of Godlewski, Maqbool, Coupechoux and Kelif (2008). A brief comparison of these schemes is also provided and concludes that FFR and TLPC with appropriate settings of inner region radius and power ratio provide the best performance when a scheduler fair in throughput is assumed. Jia, Zhang, Yu, Cheng and Li (2007), based on the system level simulation of the average Signal to Interference-plus-Noise Ratio (SINR) in the 802.16 system, estimate the performance metrics of system throughput and outage probability and obtain the optimal frequency planning strategies, in terms of the frequency reuse pattern and the subcarrier permutation mode.

SFR was introduced and discussed by 3GPP (3rd Generation Partnership Project Tech. Rep. R1-050507, 2005;

3rd Generation Partnership Project Tech. Rep. R1-050841, 2005). First, in 3rd Generation Partnership Project Tech. Rep. R1-050507 (2005) some benefits of the scheme for the application in the Evolved Universal Terrestrial Radio Access (E-UTRA) along with multi-carrier based transmission technologies are discussed. Next, in 3rd Generation Partnership Project Tech. Rep. R1-050841 (2005) the authors suggest that SFR should be thought as one candidate solution for inter-cell interference mitigation since it can improve cell edge data rate and adapt the variation of location based traffic distribution, by rightly adjusting the power ratio.

A comparison between the latter scheme and the strict FFR in the work of Novlan, Andrews, Sohn, Ganti & Ghosh (2010), attributes better overall throughput and cell-edge SINR for FFR but better balance in terms of spectral efficiency and interference reduction for SFR. Two variations of FFR are presented in the work of He et al. (2007) that compensate for the reduced capacity experienced by cell-edge users in standard FFR while a novel FFR scheme for multicellular systems that improves overall throughput is described by Lei, Zhang, Zhang and Yang (2007).

Lopez-Perez, Valcarce, Roche and Zhang (2009) propose a scheme that adjusts its radio frequency parameters taking into account all the network conditions and show that co-channel assignment of the spectrum can lead to higher cell throughputs thanks to the greater availability of sub-channels. However, this will be in exchange for a

higher computational load in the network nodes (both femtocells and macrocells). Furthermore, Guvenc, Jeong, Watanabe and Inamura (2008) introduce a hybrid frequency assignment framework for femtocells and different scenarios of femtocell CCI are analysed. Lee, Lee, Jeong and Shin (2010) propose a frequency planning mechanism, in which femtocells choose the frequency sub-bands that will not be used in the sub-region of a macrocell using FFR in an integrated macrocell/femtocell network.

Han, Park, Lee, Ahn and Jang (2008) propose a novel frequency partitioning method, in which both sub-channels for inner cell region and sub-channels for outer region are allowed to be used in the inner region of cells while sub-channels for outer region are defined differently from cell to cell to reduce CCI. Another FFR scheme is introduced by Giuliano, Monti and Loreti (2008), that note that the inner and the outer regions can be served in a different way, not only in terms of frequency sub-bands but also in terms of time slots. This scheme is extended further by Hamoudal, Yeh, Kim, Wooram and Kwon (2009) that employ the concept of making cell sectors.

An optimization mechanism for FFR configuration is presented by Bilios, Bouras, Kokkinos, Papazois and Tseliou (2012) to achieve better system performance based on dynamic cluster sizing and frequency allocation. Some simulation tools for reproducing LTE-A systems with inter-cell interference mitigation schemes include the thorough Vienna LTE Simulator (Ikuno, Wrulich

& Rupp, 2010) and LTE-sim of Piro, Grieco, Boggia, Capozzi and Camarda (2011). Unfortunately, the former incorporates exclusively FFR techniques, (though with high level of flexibility in its implementation), and the latter encompasses IFR schemes of factor 1, 3 and 4. The omission of schemes such as SFR in the above tools makes the comparison between the available techniques difficult. Moreover, to our knowledge, there is no other available free tool that offers simulating capabilities focusing on all LTE-A main frequency allocation schemes that are included in this work, and the possibility of applying them on the same configurations for cross comparison. In addition, although these works are very useful and significant in their own right, they do not offer methods that take into consideration real parameters from the network operator's side neither they optimize the network conditions according to them. In this paper, we focus on the downlink process of a multicellular LTE-A environment by evaluating several metrics related to the fairness of the network resources and proposing a simulation framework available at IBPsim (2012).

FREQUENCY ALLOCATION

In this section we discuss the main frequency reuse schemes in single-tier macrocellular networks as well as in two-tier femtocell/macrocell environments that are also integrated in the implemented simulation framework.

Frequency Reuse Schemes

Figure 1 shows the main frequency allocation schemes that, along with their variations, have attracted the attention of both research community and industry: IFR1, IFR3, FFR and SFR. Each one is characterized by different degree of complexity, spectral efficiency and interference mitigation. IFR1 provides the simplest form where all sub-bands are used by all cells without distinction.

Its main advantage is the reuse factor of 1, at cost though, of severe co-channel interference effects, especially at the borders of the cell. Though it results to the best spectrum utilization, CCI severely limits the network capacity. IFR of factor 3 allocates different sub-bands for adjacent cells as shown in Figure 1(b). Interference is significantly reduced and performance gets improved, at expense of low spectrum utilization.

Figure 1. Frequency reuse in macrocellular environments: (a) IFR1, (b) IFR3, (c) FFR, (d) SFR



A more complex approach is considered in FFR (Figure 1(c)). The total available bandwidth of the system is split into four uneven spectrums (or resource sets), denoted by yellow (A), blue (B), red (C), and green (D) colours. In this scheme the cell area is divided in two regions: the inner one, which is denoted by yellow color and is close to the BS, and outer one, which is located at the borders of the cell. All the sub-bands are distributed non-uniformly to outer region and to inner region of the cells. The part of the frequency band dedicated to the cell center users is common for every cell of the network, achieving a reuse factor of 1. The rest is divided in three sub-bands that are allocated to the outer regions of the cells similarly to the IFR3 distribution, achieving a reuse factor of 3. Since there is no conflict between adjacent areas in FFR, intra-cell interference is eliminated, and inter-cell interference is substantially reduced (Necker, 2007).

SFR utilizes frequency similarly to FFR but allowing the inner areas of the cell to share sub-bands of edge users of adjacent cells. It is best suited for situations where spectrum utilization is of major significance, and small increase in interference compared to FFR can be tolerated. Different power transmission levels are usually attributed between the cell-centre and cell-edge areas for better performance, since users close to the BS experience less path loss, requiring less transmit power on behalf of the BS. Thus, a positive power control is adapted to define the ratio of different

areas' power levels (Novlan, Andrews, Sohn, Ganti & Ghosh, 2010).

FFR in Two-Tier Femtocell/Macrocell Environments

In FFR the whole frequency band is divided into several sub-bands, and each one is differently assigned to inner and outer region of the cell respectively. In order to ensure that the mutual interference between users and BSs remains below a harmful level, adjacent cells use different frequencies. The interference scenarios that appear in such two-tier femtocell/macrocell environments during the downlink session are described in Figure 2. Furthermore, except for these scenarios, interference can occur due to the adjacent cells that use the same frequency bands.

In order to mitigate these kinds of interference, we apply a specific frequency allocation scheme for the MUs and FUs. As shown in Figure 3 and previously mentioned in Subsection 0 for the case of macrocell environment, the total available bandwidth of the system is split into four uneven spectrums (or resource sets), denoted by yellow (A), blue (B), red (C) and green (D) colours. All the MUs that are located in the inner region of each cell, are assigned sub-band A. The MUs located in the outer region will be assigned one of the rest sub-bands (B, C or D). If a FU is located in the outer region of a cell, then the sub-band used for the inner region plus the sub-bands that are used in the outer region of the neighbouring

Figure 2. Interference scenarios in a two-tier femtocell/macrocell environment for downlink

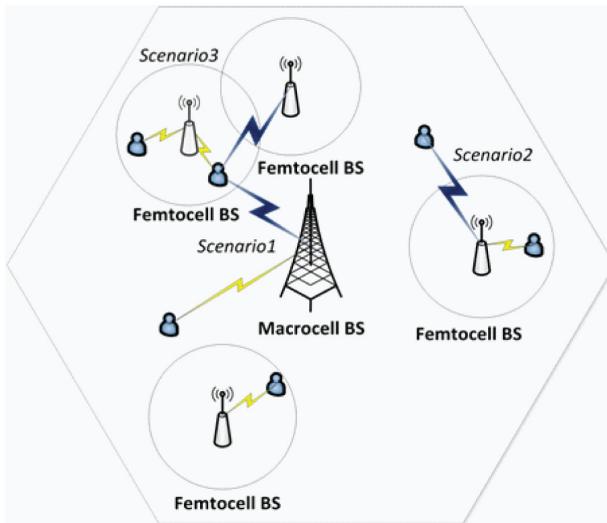
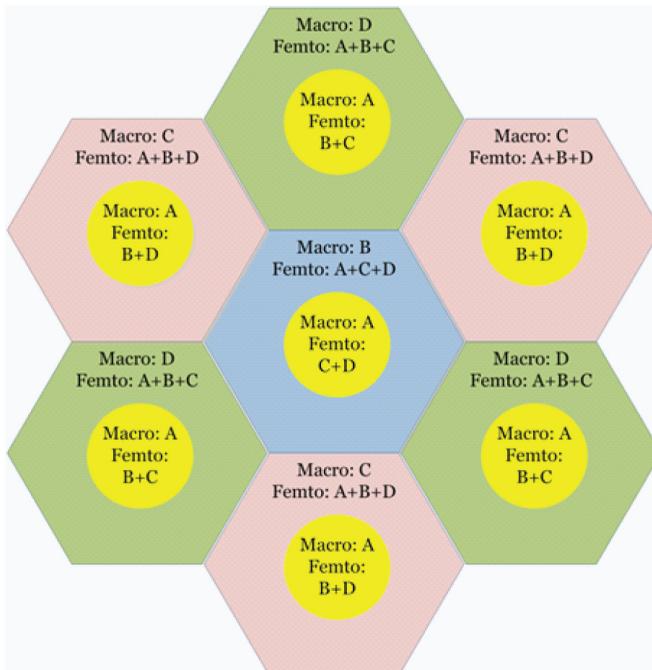


Figure 3. Proposed frequency allocation for a two-tier femtocell/macrocell environment



cells can be reused. According to this allocation, each femtocell BS adopts an effective frequency assignment, assuring that MUs/FUs use different frequencies and the CCI is reduced. As it can be observed, in the case that FUs do not exist in the topology Figure 3 coincides with Figure 1 (c).

SYSTEM MODEL

In this section, we present the theoretical background as well as the adopted metrics. We assume that the overall network is composed of N adjacent cells. Each cell contains a number of users, either MUs or FUs, seeking to share a group of subcarriers. The macrocell BSs are located at the centre of each cell. Femtocell BSs are uniformly distributed in the topology. Moreover, we consider that the MUs are outdoor users whereas the FUs are located indoors. We use the path loss suburban model described in 3rd Generation Partnership Project Tech. Rep. TR 36.814 (2010), for the calculation of the path loss between an outdoor MU and a macro BS with frequency of 2GHz:

$$PL_{MU}[dB] = 15.3 + 37.6 \log_{10}(d[m]) + S^{out} \quad (1)$$

where d is the distance between the transmitter and the receiver and S^{out} factor represents the outdoor shadowing which is characterized by the Gaussian distribution with zero mean. In the same way, we calculate the path loss between an indoor FU and a femtocell BS:

$$PL_{FU}[dB] = 38.46 + 20 \log_{10}(d[m]) + 0.7d_{2D,indoor} + 18.3n^{((n+2)/(n+1)-0.46)} \quad (2)$$

where n is the number of penetrated floors and in case of a single-floor house, the last term equals to zero. The term $0.7d_{2D,indoor}$ takes into account the penetration loss by the walls inside a house with $d_{2D,indoor}$ representing the distance in the house. So now we can define the channel gain as the 3rd Generation Partnership Project Tech. Rep. R1-050507 (2005):

$$G = 10^{-\frac{PL}{10}} \quad (3)$$

The downlink SINR that a user receives depends on the interference of the cells that include the user within their range. For the case of MU m on subcarrier n , we consider both the impact of the adjacent macrocells and overlaid femtocells. So the SINR for this case is defined as shown in Box 1 (Lei, Zhang, Zhang & Yang, 2007) where $P_{x,n}$ is the transmit power of the serving BS X on subcarrier n (X can be either the macrocell M or the neighbouring macrocell $neigM$ or the femtocell F). The term $G_{x,x,n}$ refers to the channel gain between user x and the serving cell X (where x can be a MU or a FU and X the corresponding BS). For its calculation, the PL is calculated from (1) for the MU and from (2) for the FU. Finally, the term σ_n^2 is the power of the Additive White Gaussian Noise (AWGN). Consequently, the expression for the SINR of a FU is expressed as follows, taking into account the interference caused by neighbouring femtocells ($neigF$) and the macrocells that use the same frequency bands (See Box 2).

Box 1.

$$SINR_{m,n} = \frac{G_{M,m,n} \cdot P_{M,n}}{\sigma_n^2 + \sum_{neigM} G_{m,neigM,n} \cdot P_{neigM,n} + \sum_F G_{m,F,n} \cdot P_{F,n}} \quad (4)$$

Box 2.

$$SINR_{f,n} = \frac{G_{F,f,n} \cdot P_{F,n}}{\sigma_n^2 + \sum_{neigF} G_{f,neigF,n} \cdot P_{neigF,n} + \sum_M G_{f,M,n} \cdot P_{M,n}} \quad (5)$$

After the SINR estimation, we proceed to the throughput calculation. The capacity of user x on subcarrier n can be calculated by the following (Lei, Zhang, Zhang & Yang, 2007):

$$C_{x,n} = \Delta f \cdot \log_2(1 + aSINR_{x,n}) \quad (6)$$

where, Δf refers to the subcarrier spacing. The constant term α denotes the target bit error rate (BER) and it is defined by $\alpha = -1.5 / \ln(5BER)$.

The overall throughput of a serving macrocell can be expressed as follows (Lee, Lee, Jeong & Shin, 2010):

$$T_M = \sum_m \sum_n \beta_{m,n} \cdot C_{m,n} \quad (7)$$

where, $\beta_{m,n}$ represents the subcarrier assigned to MU m . When $\beta_{m,n} = 1$, the subcarrier n is assigned to MU m . Otherwise, $\beta_{m,n} = 0$. A similar expression can be derived for FUs, and by aggregating

the Total Throughput achieved for all the users of an examined topology, we calculate the first examined metric, namely the Total Throughput.

The second metric is the Jain's Fairness Index, introduced by Jain, Chiu & Hawe (1984), which addresses the issue of fairness of the examined technique. It is calculated as the square sum of the users' throughput divided by the product of the sum of squared users' throughput and the number of users. It physically presents the deviation of users' throughput in the area, thus expressing the fairness of provided services across different areas of the cells. Specifically, assuming the allocated throughput for user i is x_i , Jain's Fairness Index JI is defined as:

$$JI = \frac{(\sum_{i=1}^{\#users} x_i)^2}{\#users \cdot \sum_{i=1}^{\#users} x_i^2} \quad (8)$$

The Jain's Fairness Index metric is appropriate for the evaluation of the proposed method due to its properties. It is scale-independent, applicable for different number of users and it is bounded between $[0, 1]$, where 0 means "total unfairness" and 1 means "total fairness" in terms of throughput division among the users. In the following section, we prove that the optimization of the throughput favours the users that are located next to the BS whereas the optimization of Jain's Fairness Index assigns similar per-user throughput values but the total cell throughput remains quite low.

The third metric is named Weighted Throughput and is introduced in order to address the trade-off between the two former metrics. It is obvious that the Total Throughput reflects the level of system's capacity exploitation but without dealing with how fairly the system's capacity is distributed. On the other hand, Jain's Fairness Index addresses the variance in users' throughput but without reflecting the throughput level for each user. Therefore, we define Weighted Throughput WT with the following equation:

$$WT_x = JI_x \cdot T_x \quad (9)$$

where x is the examined user, either FU or MU. By introducing the Weighted Throughput, we aim not only at the low variance of the per-user throughput values but also at higher values of the overall cell throughput.

SIMULATION FRAMEWORK

In this section we provide an overview of our simulation framework's architecture and we also describe the usage and the interface of the developed simulation framework.

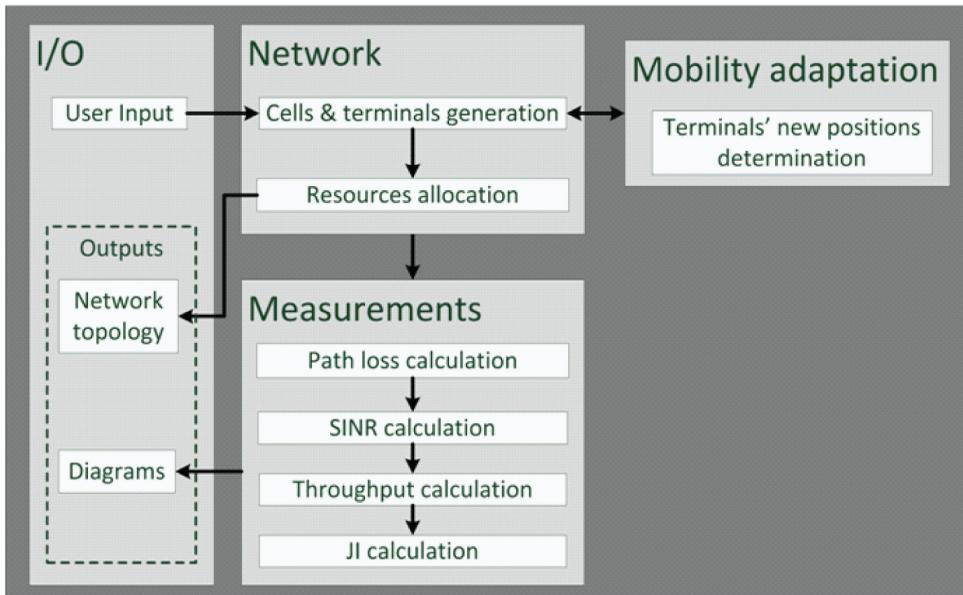
Software Architecture

The simulation software that was developed for the purposes of this paper is available at IBPsim (2012). In Figure 4 we provide an overview of the simulation framework's software structure. A modular software design has been followed in order to assure that the system can be easily reused and extended by any interested member of the scientific community.

The simulation framework includes an I/O component that provides the user with the ability to insert his input in terms of network topology and spectral characteristics. A user-friendly graphical user interface is provided for this purpose and is described in the next subsection. The input is transferred to the core of the system where the network topology, including the BSs' and mobile terminal's positions, is generated. Subsequently, the allocation of the spectrum resources is executed based on the frequency reuse scheme selected by the user and as a first step the graphical user interface is able to illustrate the generated topology.

The next step of the simulation procedure is the execution of the measurements. For this purpose the analytical

Figure 4. Block diagram providing an overview of the simulation framework architecture



models presented in Section 0 are used for the SINR and throughput estimation, as well as for the calculation of the adopted metrics. After the estimation of all the three metrics the results are extracted in the form of diagrams.

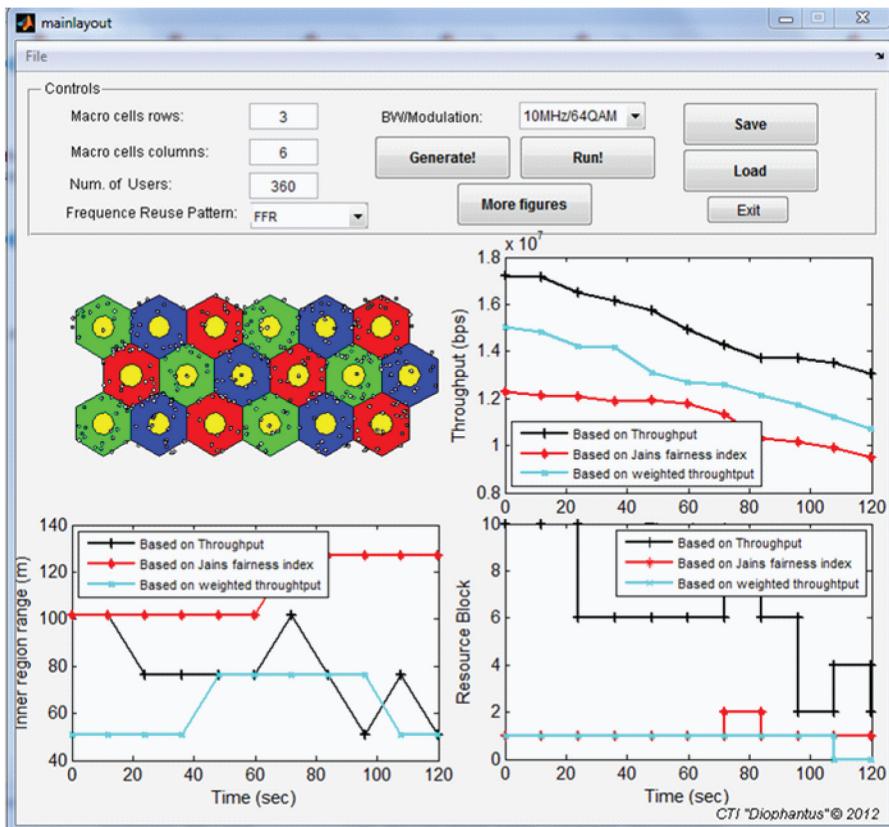
In case that user mobility is also simulated, there is an additional component that has been implemented in order to adapt the previously generated network topology to the terminals' mobility patterns. This component is employed each time an updated network topology is generated, and is able to estimate the new positions of the mobile terminals and feed them to the module that is responsible for the generation of the network topology.

User Interface

A typical instance of the simulation framework graphical interface is illustrated in Figure 5. User is required to enter the desired network dimensions and the number of residing users. The type of frequency reuse is selected among the available IFR1, IFR3, FFR, SFR schemes, as well as the system bandwidth (20, 15, 10, 5, 3, or 1.4MHz) and modulation scheme (64QAM, 16QAM, or QPSK).

After the inputs have been defined, the generation of the topology takes place. Firstly, the network is constructed and is presented graphically to the user. Secondly, the user instances are generat-

Figure 5. Typical instance of the framework's graphical user interface



ed and they are scattered uniformly over the network cells. A random percentage of the total user population is chosen to correspond to mobile users and random mobility is simulated for this portion of the population. Based on the positions of the users in relation to the macrocell BS, and taking into account the path loss and signal propagation loss, SINR and throughput of each user are calculated. Afterwards, Total Throughput, Jain's Fairness Index and Weighted Throughput are estimated. In case of FFR and SFR, an extensive search is taking place for the optimal radius of the inner area of the cell, as well as for the frequency

sub-bands allocation based on Total Throughput or Jain's Fairness Index or Weighted Throughput metrics. Finally, an overview of results is graphically presented to the user.

Default Frequency Reuse Scheme

By default, the simulation framework operates using the FFR method that was presented in Figure 3. It receives as input either the macrocell or the two-tier femtocell/macrocell environment with all its parameters, i.e., the number of femtocells, macrocells, FUs, MUs, and

their positions in the deployment. In order to find the optimal FFR scheme, the method divides each cell into two regions, the inner and the outer one, and examines all possible inner region radii and frequency allocations.

The frequency allocation is examined in terms of Resource Blocks (RBs), the minimum allocation unit in LTE both for protocol side and system resource allocation (3rd Generation Partnership Project Tech. Rep. TR 36.814, 2010). For each RB, the method calculates the per-user throughput, the cell's Total Throughput, Jain's Fairness Index and Weighted Throughput. This procedure is repeated for successive inner region radii from 0 to R , where R is the cell radius. After the above calculations, the

method chooses the optimal FFR scheme that maximizes the cell's Total Throughput, the Jain's Fairness Index and the Weighted Throughput. The pseudo-code shown in Box 3 describes the main idea of the proposed FFR method.

PERFORMANCE EVALUATION

This section evaluates the performance of the proposed mechanism both for a macrocell and a two-tier femtocell/macrocell environment. The main simulation parameters considered for the experiments are presented in Section 0. Afterwards, several experimental results obtained by the simulation are presented and discussed, showcasing its capabilities.

Box 3.

```
% Proposed FFR Method
1:generate_network();
2:generate_MUs();
3:generate_FUs();
4:for r=0:R           %scan all the radii
5:  for all b         %scan all the RBs
6:    allocate_RB(); %allocate RBs to regions
7:    for x=1:X       %for all users
8:      calculate_sinr(x);
9:      calculate_capacity(x);
10:     calculate_througput(x);
11:    end
12:    calculate_total_througput(r,b);
13:    calculate_JI(r,b);
14:    calculate_WT(r,b);
15:  end
16:end
17:select_optimal_radius&rb_totthrpupApproach();%1st approach
18:select_optimal_radius&rb_JIApproach();      %2nd approach
19:select_optimal_radius&rb_WTApproach();      %3rd approach
```

Simulation Parameters

The simulation parameters that are necessary for the conduction of the experimental procedure are presented in Table 1. They follow ITU-R guidelines (International Telecommunications Union Radio (ITU-R) Report ITU-R M.2135-1, 2009) and 3GPP specifications (3rd Generation Partnership Project Tech. Rep. TR 36.814, 2010).

The topology consists of multiple adjacent macro sites of radius 250m and macro BS transmitting power of 20W, wherein arbitrary number of users are distributed. System bandwidth and RBs follow LTE-A specifications. Each RB is divided into 12 sub-carriers each having 15KHz of bandwidth. The scenario deployed is typical urban, which exists in urban areas served by macrocells. Path losses are calculated according to

Cost-Hata Model and the correlation distance of the shadowing is set to 40m. Channel bandwidth was set at 10MHz and the modulation used was 64QAM.

Macrocell Environments

In this subsection we present several experiments on a macrocell environment. Paragraphs 0 and 0 present the results of our simulation framework operation while paragraph 0 assesses the performance of the proposed mechanism for a scenario with moving users by comparing the performance of the selected FFR scheme with other frequency reuse schemes. For the needs of results' presentation, a topology of 18 adjacent macro sites with 360 randomly generated MUs was considered such as the one depicted in Figure 5.

Table 1. Simulation parameters

Parameter	Units	Value
System bandwidth	MHz	10
Carrier frequency	MHz	2000
Modulation Mode		64QAM
Macrocell Radius	m	250
Femtocell Radius	m	40
Correlation distance	m	40
Channel model		3GPP Typical Urban
Path loss	dB	Cost-Hata Model
Macrocell BS transmit power	W	20
Femtocell BS transmit power	mW	20
Power Noise Density	dbm/Hz	-174
Inter-site Distance	m	500

FFR Optimization

Firstly we show the optimization process in the case of a macrocell environment. Figure 6 presents the selection of inner region radius and Figure 7 displays the resource allocation values that were found to accomplish the maximum Total Throughput, Jain's Fairness Index and Weighted Throughput.

In both figures, we mark the optimal combination of inner region radius and RBs for each approach. In the 1st approach, the maximum value of the Total Throughput of the examined topology is 268.3Mbps (76.23m inner region radius and 8 RBs assigned to inner region). In the 2nd approach the Jain's Fairness Index is maximized (0.7986) for 127m and 3RBs assigned to inner region. Finally,

the 3rd approach maximizes the Weighted Throughput of the topology (171Mbps) for 76.23m radius and 2RBs.

Per-User Throughput

In this paragraph, we examine the per-user throughput achieved by each one of the three approaches. Our experiment focuses on one cell of the topology residing at the second row and third column of the topology presented in Figure 5. Figure 8 depicts the per-user throughput of 17 MUs residing in the examined cell.

According to the results, the 1st approach, which chooses the optimal inner region radius and RB based on the cell's Total Throughput, leads to a quite unfair distribution of the available frequency resources. There are users that achieve

Figure 6. Selection of optimal inner region radius in a macrocell environment

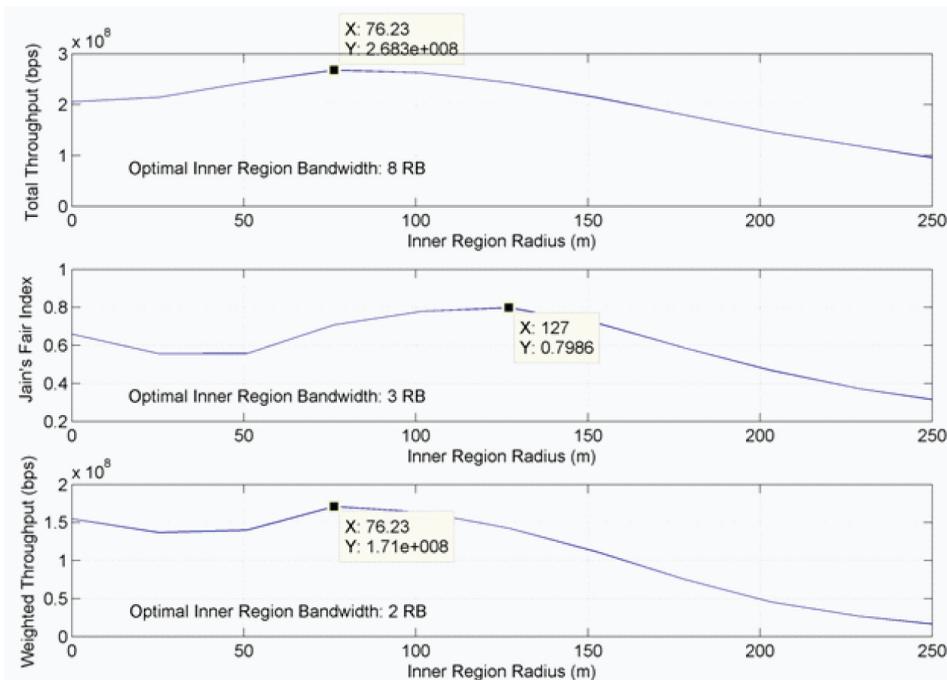


Figure 7. Selection of inner region RBs in a macrocell environment

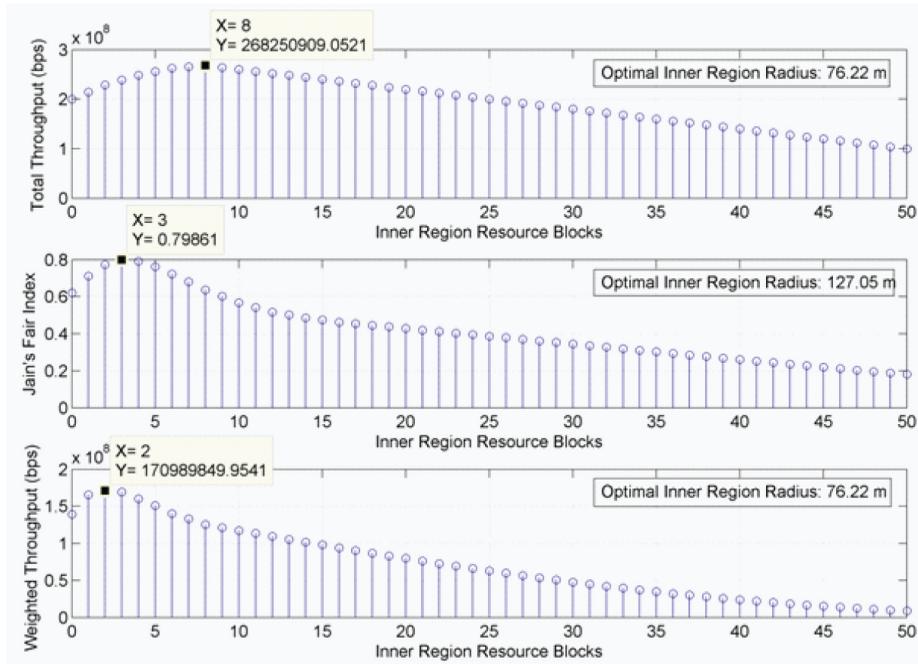
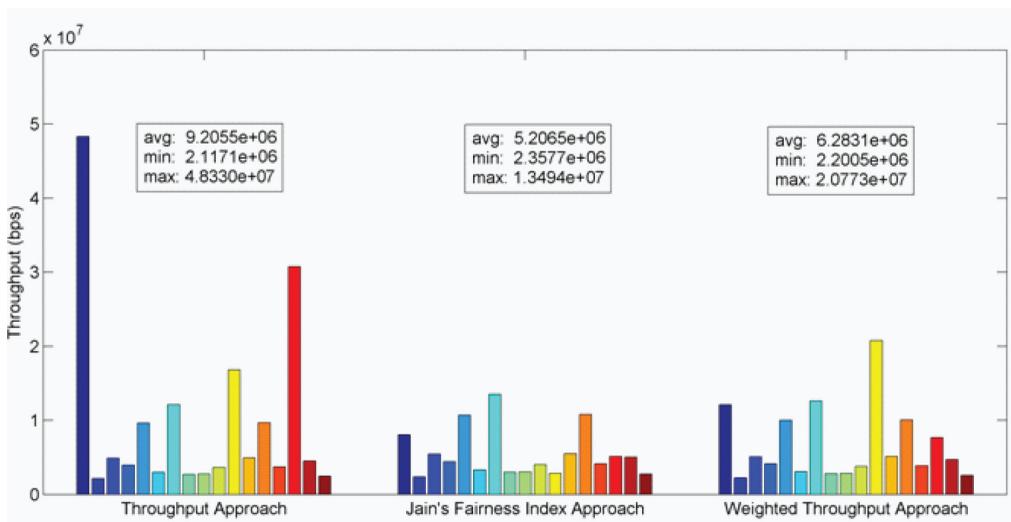


Figure 8. Per-user throughput for the three approaches in a macrocell environment



very high throughput values, i.e., user #1 with the highest throughput value (48.33Mbps), whereas there are others that obtain low throughput values, i.e., user #2 with the lowest throughput value (2.1171Mbps). In this case the average per-user throughput equals to 9.2055Mbps.

The 2nd approach, which selects the optimal inner region radius and RB based on the Jain's Fairness Index metric, achieves a fairer distribution of the bandwidth resources among the users. However, the total cell throughput is quite low in comparison to the other two approaches. This approach results in an average user throughput equal to 5.2065Mbps, while the minimum value is 2.3577Mbps and the maximum value is 13.494Mbps.

The previous results justify the introduction of the 3rd approach, which is based on Weighted Throughput metric. When the 3rd approach is used, the throughput values range between the ones occurred by the two former approaches, fluctuation is lower than that of the 1st's approach, and the average per-user throughput is 6.2831Mbps. This proves clearly that this approach compensates for the trade-off between the previous two ones due to the fact that it ensures both high cell's Total Throughput and similar per-user throughput values among the MUs.

User Mobility Scenario

This paragraph shows the operation of the simulation framework with the selected FFR method, for mobile users that move at random speeds and

direction for a time frame that covered 120sec. It also compares the results of the selected FFR method with the other frequency allocation methods presented in Subsection 0.

The comparison between the different frequency allocation schemes is given via accumulated results to show-case the trade-off between the system performance and resource utilization, which affects the choice of the examined frequency reuse scheme for interference mitigation. As seen in Figure 9 and also expected, SFR exhibits the worst performance regarding overall average throughput, while IFR3 the best one as a result of exclusive frequency allocation for better interference mitigation. On the other hand, SFR and IFR1 provide a settlement between the two.

Since the optimization process for SFR and FFR has been based on the Weighted Throughput approach. SFR schemes seem that it performs poorly, but it should be noted that beside the added interference in SFR case, part of the difference with FFR is attributed to the reduced transmit power for the inner region users, which is not actually perceived as performance degradation by users. This can be observed clearer in Figure 10 that shows the throughput achieved throughout the network for inner region and outer region users, distinctively, mostly highlighting the impact of interference on cell-edge users, where the power levels are similar and the performance is critical.

It is crucial to note that the main motivation for adopting the proposed FFR scheme depends on the custom

Figure 9. Average throughput comparison between frequency allocation schemes for entire network

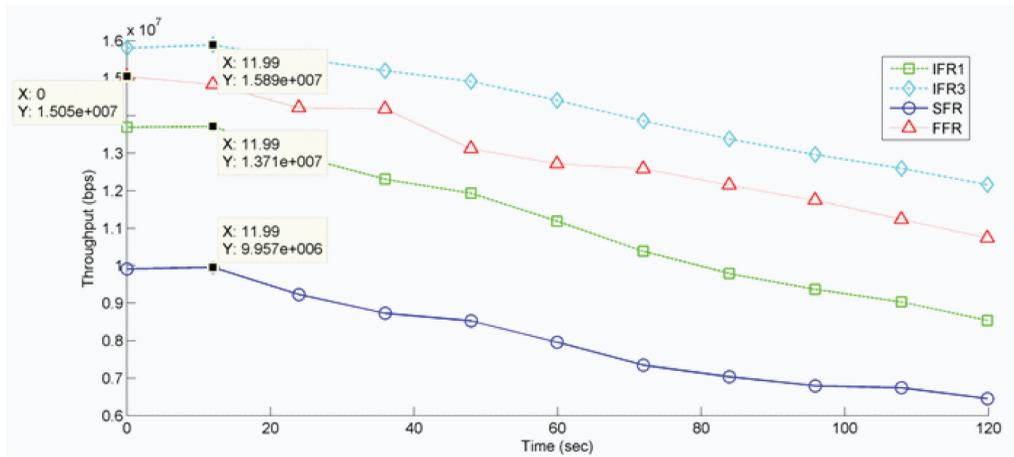
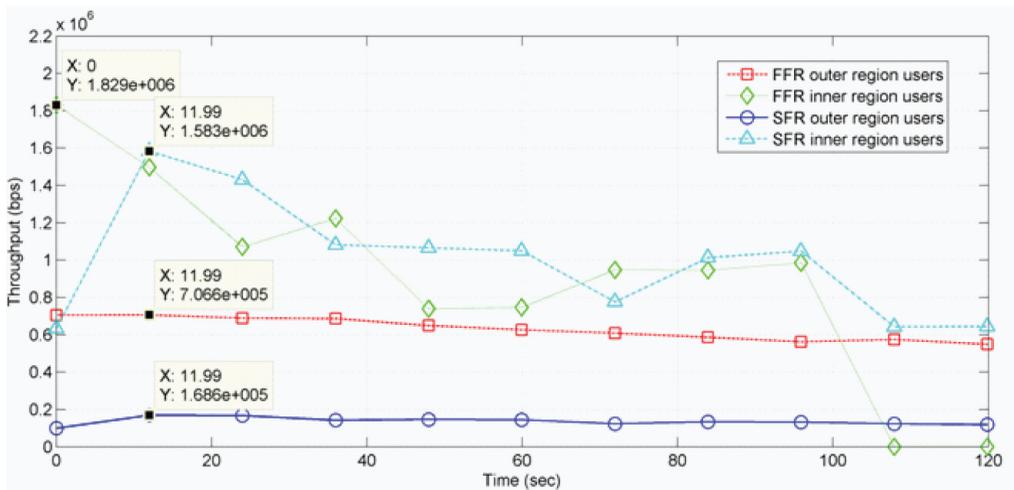


Figure 10. Average throughput comparison between FFR and SFR schemes by distinguishing outer region from inner region users. Selection has been made based on the 3rd approach.



defined parameters, such as tolerable interference levels, overall and outer region performance goal, transmission power levels and the achieved spectral efficiency. Thus, the results offered a behavioural overview of each case, as

well as attempted to showcase the simulator’s capability to extract the trade-offs that are involved in seeking the optimal selection, between the different aspects of network performance and resource utilization.

Finally, according to Figure 11, when the simulation framework uses the proposed FFR method and optimizes the inner region radius and RB based on Weighted Throughput, the inner region radius and RBs show very small fluctuation. This leads us to the conclusion that despite the user mobility this approach allows the network to provide adequate coverage without need for large modification of its main configuration.

Two-Tier Environments

This subsection presents the operation of the simulation framework with the proposed FFR method in two-tier femtocell/macrocell environments. We consider a similar topology to the previous experiment with 360 uniformly distributed users and 90 uniformly distributed femtocells (See Figure 12). Our experiments focus on one cell of

Figure 11. Inner region radius and RBs for each mobility step

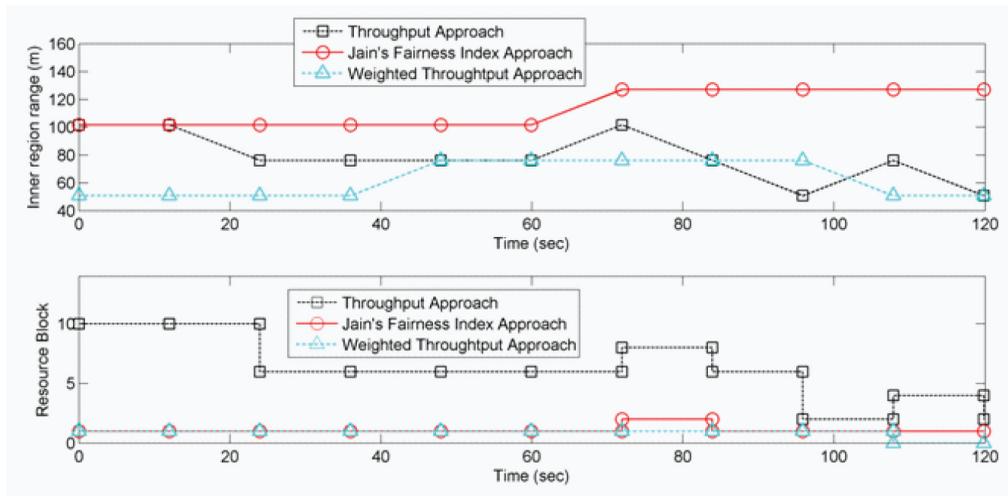
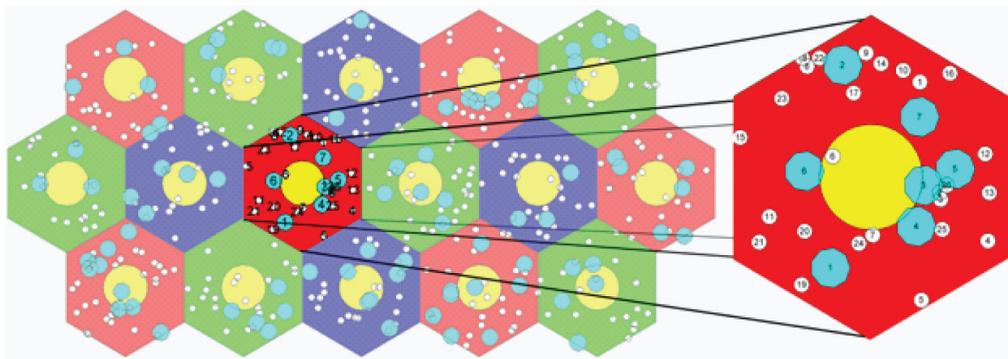


Figure 12. Two-tier femtocell/macrocell environment



the topology residing at the second row and third column. This cell contains 7 femtocells, 5 FUs and 22 MUs.

FFR Optimization

The first experiment shows how the proposed FFR method chooses the optimal inner region radius and frequency allocation for the three approaches. Figure 13 depicts the selection of the optimal inner region radius whereas Figure 14 shows how each metric changes while the number of RBs allocated to the inner region varies from 0 to 50.

In both figures, we mark the optimal combination of inner region radius and RB for each approach. In the 1st approach,

the maximum value of the cell's Total Throughput is 66.58Mbps (150.1m inner region radius and 50 inner region RBs). This means that the method assigns all the RBs to the inner region due to the fact that almost all the users are located in the inner region. In the 2nd approach, the Jain's Fairness Index is maximized (0.9104) for 169.7m radius and 35 RBs. Finally, the 3rd approach maximizes the Weighted Throughput (64.67Mbps) for 150.1m radius and 27 RBs.

Per-User Throughput

After demonstrating the operation of the proposed FFR method for the three approaches, we examine the per-user

Figure 13. Selection of optimal inner region radius

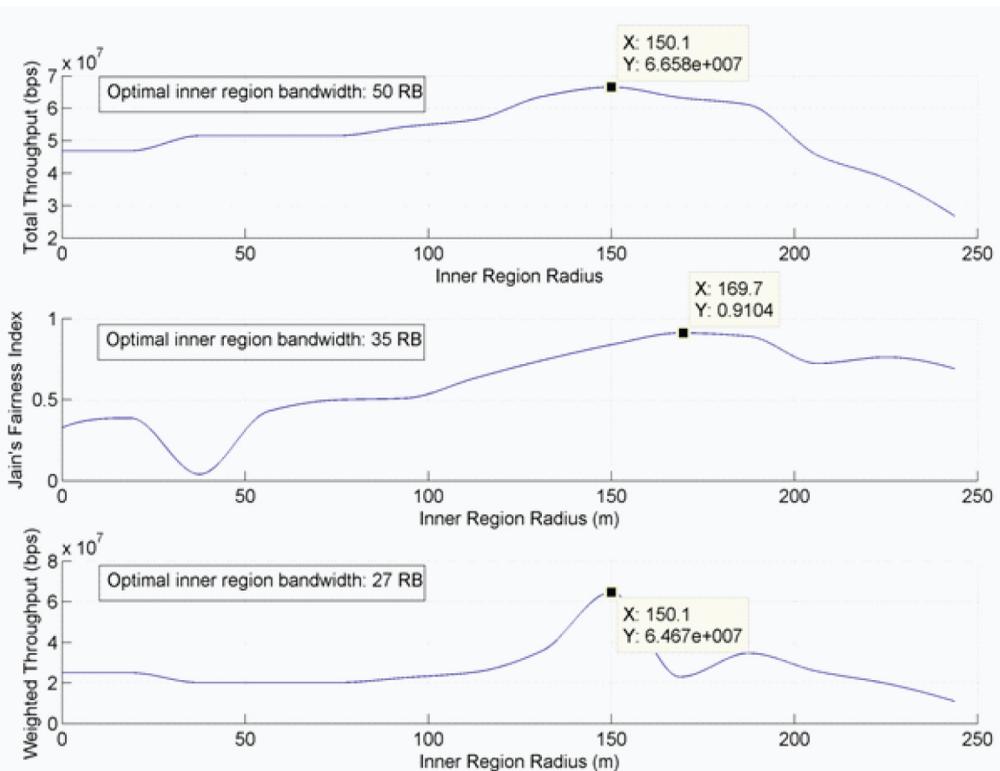
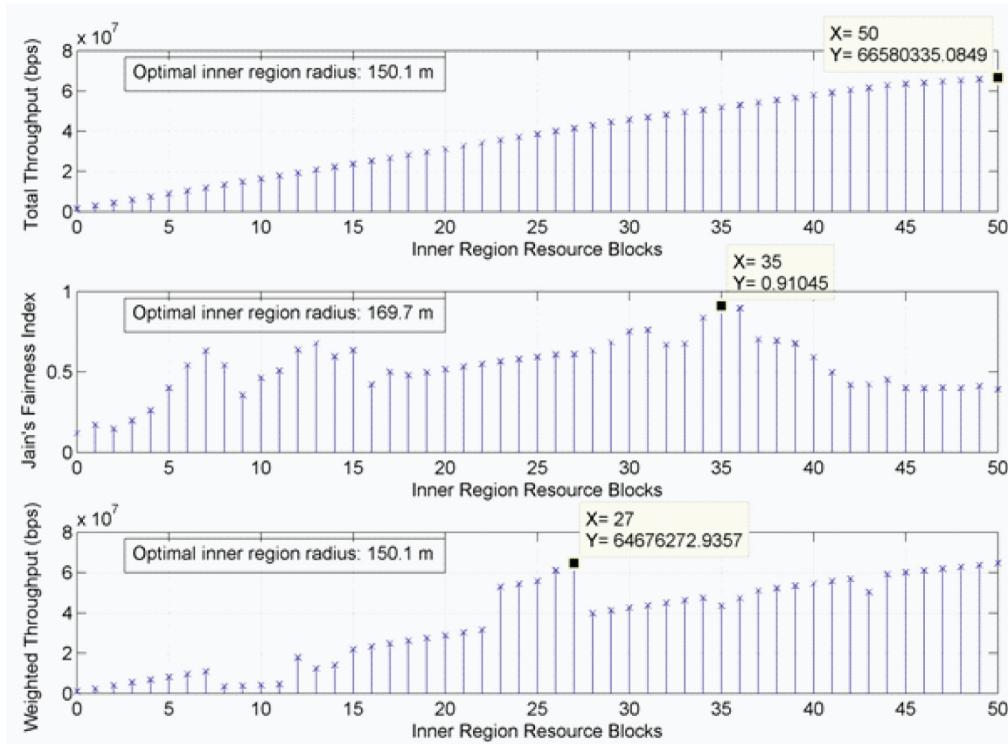


Figure 14. Selection of optimal inner region RB



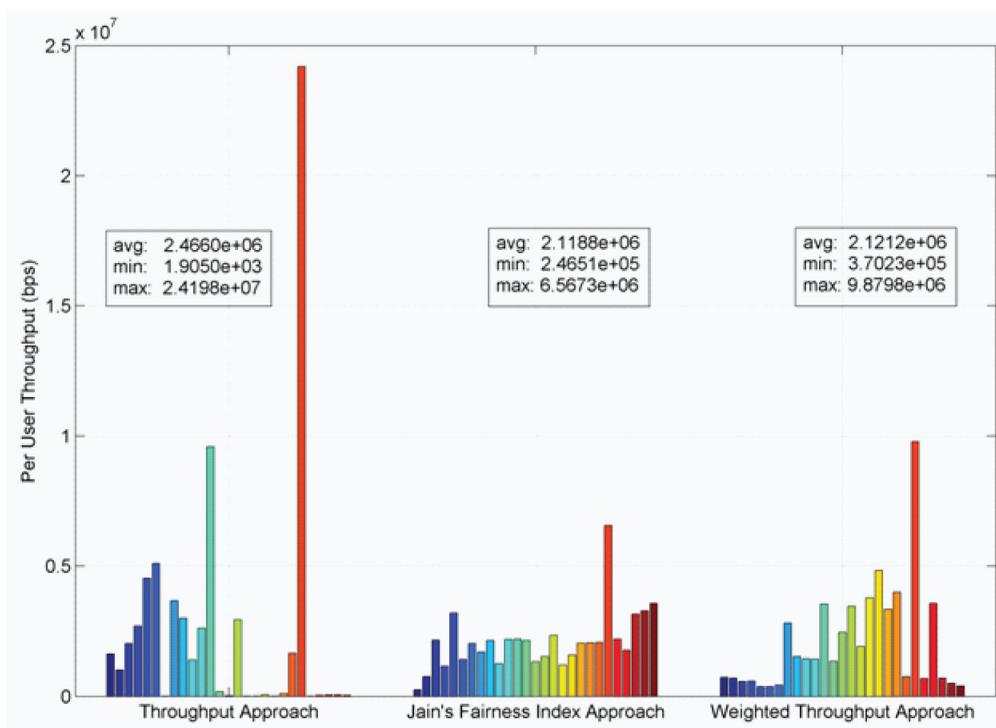
throughput achieved by each one of the approaches.

Figure 15 depicts the per-user throughput of an environment consisting of 5 FUs (users #5, #6, #12, #15 and #22) and 22 MUs for the three approaches. The 1st approach that chooses the optimal inner region radius and RB based on the Total Throughput, leads to an unfair distribution of the available frequency resources. It is remarkable, that in this case the users are treated in two different ways; there are users that achieve very high throughput values whereas there are others with quite low values. This is rational, because the 1st approach assigns all the available bandwidth to the inner region and the

users of the outer region are not served. Consequently the femtocells BS of the outer region are allocated with the biggest bandwidth part whereas the ones located in the inner region achieve quite low values (See Figure 3). That is the reason why FU 22, covered by femtocell 2 (See Figure 12) achieves the highest throughput value (24.198 Mbps). For this approach the average user throughput equals to 2.466Mbps and the minimum throughput value is 1.905Kbps.

In the 2nd approach, the FFR method finds the optimal inner region radius and frequency allocation based on the Jain's Fairness Index. We can observe that this approach allocates the frequency resources in a way that allows all us-

Figure 15. Per-user throughput for each approach



ers to have similar throughput values. The average throughput value equals to 2.1188Mbps, when the maximum is 6.5673Mbps and the minimum is 0.24651Mbps. So, this approach not only assures the serving of inner region users but also the ones located in the outer region. However, the total cell throughput is lower compared to the 1st approach.

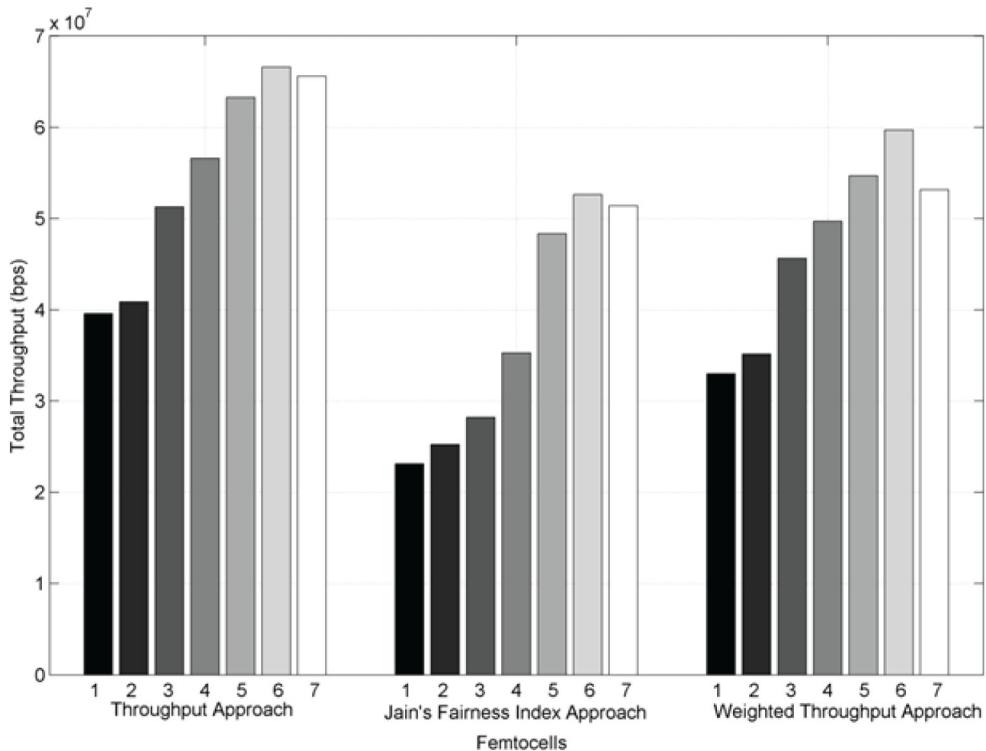
This is the reason why we introduce Weighted Throughput approach where the throughput values are ranged between the ones occurred by the previous approaches. In this case the average per-user throughput is 2.1212Mbps, whereas the maximum equals to 9.8798Mbps and the minimum to 0.37023Mbps. To

sum up, this approach makes a trade-off between the previous two, because it ensures both high cell's Total Throughput and similar per-user throughput values among FUs and MUs.

Variable Number of Femtocells

For this part of the experimental evaluation, we assume a two-tier femtocell/macrocell environment consisting of a variable number of femtocells. Figure 16 shows how the cell's Total Throughput changes as the number of femtocells per macrocell increases from 1 to 7, for each one of the three approaches. Moreover, Figure 17 presents the combination of in-

Figure 16. Total throughput for each femtocell added to the topology



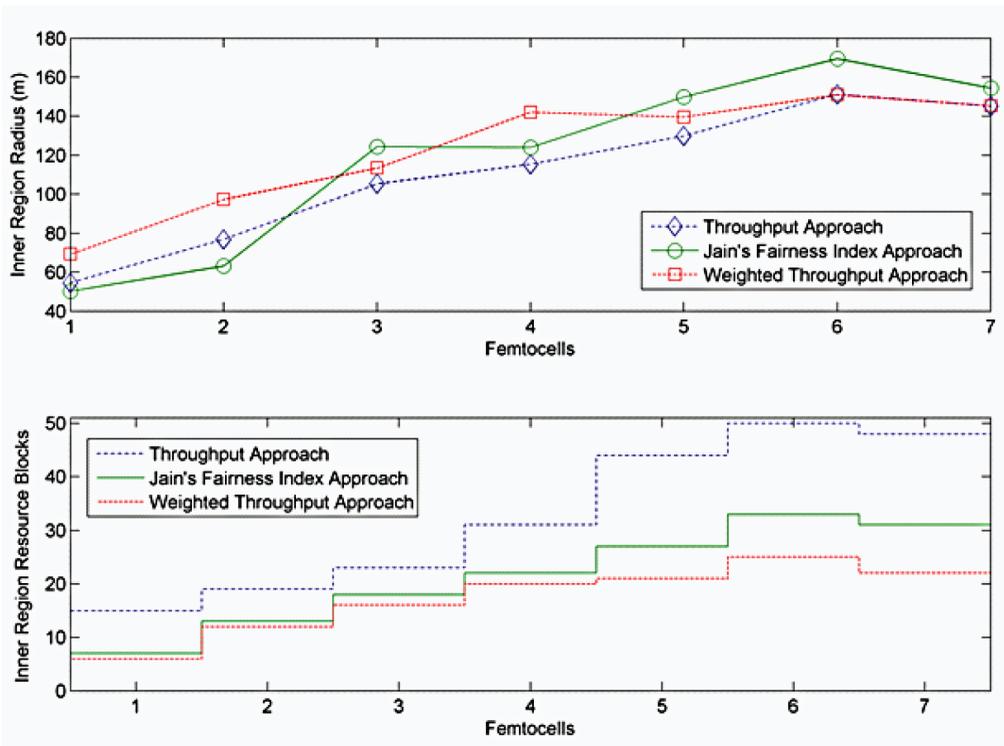
ner region radius and RBs for each added femtocell. According to these figures, for the 1st approach the maximum value (66.581Mbps) is achieved when the 6th femtocell is added to the environment (for 151.2m radius and 50RBs). The throughput value when the 7th femtocell is added to the environment is quite close to the maximum one.

For the 2nd approach, the highest achieved throughput value equals to 52.622Mbps for 169.5m inner region radius and 33 RBs (6th femtocell). Finally, for the 3rd approach, the maximum Total Throughput (59.675Mbps) is succeeded when the 6th femtocell is added to the

topology, for 150.9m inner region radius and 25 inner region RBs.

The proposed FFR method can efficiently adapt to the addition of new femtocells into the two-tier femtocell/macrocell environment. As Figure 17 shows, when optimal inner region radius and RBs are selected based on Weighted Throughput, the inner region radius and RBs remain in similar values after the addition of the 4th femtocell. It is worth noting, that in this case, the method can succeed in satisfying total cell throughput values without the need of altering the inner region radius and frequency allocation of the examined

Figure 17. Inner region radius and RBs for each femtocell



environment which is a demanding task by the network operator's side. So, we conclude that this approach seems to be the most economical in terms of network operational activities.

CONCLUSION

In this paper we present the results of our study on the frequency reuse over LTE-A systems including two-tier macrocell/femtocell networks. For the purposes of our experimental evaluation, we introduced a simulation framework and we estimated the optimal frequency allocation and inner region radius for various frequency allocation schemes.

The optimization process was based on three different metrics: the cell's Total Throughput, Jain's Fairness Index and a newly introduced metric named Weighted Throughput. The Weighted Throughput metric addresses the trade-off between the two former approaches, due to the fact that apart from lowering the variance among per-user throughput values it also tends to increase the per-user throughput within the cell. The application of the optimization process based on Weighted Throughput in combination with the proposed FFR frequency allocation scheme largely reduce the interference within two-tier macrocell/femtocell LTE-A networks.

The simulation framework estimates the performance experienced by users in custom size and occupancy networks. The performance is measured and presented in terms of throughput and service distribution fairness, with the latter representing the balance of quality in offered services within an area. The simulator integrates all the main frequency allocation schemes, IFR, FFR and SFR. In the cases of FFR, SFR, an algorithm is employed seeking the optimal size and frequency configuration of the scheme, based on the metrics mentioned above. User mobility is simulated, and periodical recalculation for every network state is applied to ensure the optimal adaptation in each current state.

FUTURE WORK

There are several future directions that this work could follow. One potential direction could be the optimization of the mechanism in order to minimize the scanning process and to reduce its complexity. Especially when assuming pedestrian users, it is expected that the new users' positions will be close to the initial ones. Therefore, it is expected to have small changes in the optimal frequency allocation and the optimal radius of the inner region. In brief, the optimized mechanism could reduce the scanning procedure after taking into account the "expected" frequency allocation and "expected" inner region radius. Another potential future step for this work is to integrate several realis-

tic network parameters in the proposed method and evaluate it in real conditions.

Finally, the simulation platform could be extended in several directions. Dynamic frequency reuse schemes instead of the proposed static ones used for the frequency assignment, and the capability of dynamic inter-cell interference coordination based on coordination between BSs could be interesting enhancements. Further available customization of the tool, including different frequency or cell divisions such as adaptive SFR would also be a useful extension of this work.

REFERENCES

- 3rd Generation Partnership Project Tech. Rep. R1-050507. (2005). *Soft frequency reuse scheme for UTRAN LTE*.
- 3rd Generation Partnership Project Tech. Rep. R1-050841. (2005). *Further analysis of soft frequency reuse scheme*.
- 3rd Generation Partnership Project Tech. Rep. TR 36.814. (2010). 3rd generation partnership project; Technical specification group radio access network; Evolved universal terrestrial radio access (E-UTRA); Further advancements for E-UTRA physical layer aspects.
- Bilios, D., Bouras, C., Kokkinos, V., Papazois, A., & Tseliou, G. (2012, April). *Optimization of fractional frequency reuse in long term evolution networks*. Paper presented at the 2012 IEEE Wireless Communications and Networking Conference (WCNC 2012), Shanghai, Republic of China (pp. 1853-1857). doi:10.1109/WCNC.2012.6214087

- Chandrasekhar, V., Andrews, J. G., & Gatherer, A. (2008). Femtocell networks: A survey. *IEEE Communications Magazine*, 46(9), 59–67. doi:10.1109/MCOM.2008.4623708
- Giuliano, R., Monti, C., & Loreti, P. (2008). WiMAX fractional frequency reuse for rural environments. *IEEE Wireless Communications*, 15(3), 60–65. doi:10.1109/MWC.2008.4547524
- Godlewski, P., Maqbool, M., Coupechoux, M., & Kelif, J.-M. (2008, October). *Analytical evaluation of various frequency reuse schemes in cellular OFDMA networks*. Paper presented at the 3rd International Conference on Performance Evaluation Methodologies and Tools (ValueTools '08. ICST), Brussels, Belgium (pp. 32:1-32:10). doi:10.4108/ICST.VALUETOOLS2008.4372
- Guvenc, I., Jeong, M.-R., Watanabe, F., & Inamura, H. (2008). A hybrid frequency assignment for femtocells and coverage area analysis for co-channel operation. *IEEE Communications Letters*, 12(12), 880–882. doi:10.1109/LCOMM.2008.081273
- Hamoudal, S., Yeh, C., Kim, J., Wooram, S., & Kwon, D. S. (2009). *Dynamic hard fractional frequency reuse for mobile WiMAX*. Paper presented at the IEEE international conference on pervasive computing and communications (PerCom 2009), Galveston, TX (pp. 1-6).
- Han, S. S., Park, J., Lee, T.-J., Ahn, H. G., & Jang, K. (2008). A new frequency partitioning and allocation of subcarriers for fractional frequency reuse in mobile communication systems. *IEICE Transactions on Communications*, E91-B(8), 2748–2751. doi:10.1093/ietcom/e91-b.8.2748
- He, C., Liu, F., Yang, H., Chen, C., Sun, H., May, W., & Zhang, J. (2007). *Co-channel interference mitigation in MIMO-OFDM system*. Paper presented at the 2007 International Conference on Wireless Communications, Networking and Mobile Computing (WiCom 2007), Shanghai, Republic of China (pp. 204-208). doi:10.1109/WICOM.2007.58
- IBPsim. (2012). *ICIC behaviour and performance simulator*. Retrieved from <http://ru6.cti.gr/ru6/IBPsim.zip>
- Ikuno, J., Wrulich, M., & Rupp, M. (2010). *System level simulation of LTE networks*. Paper presented at the 2010 IEEE 71st Vehicular Technology Conference (VTC 2010-Spring), Taipei, Taiwan (pp. 1-5). doi:10.1109/VETECS.2010.5494007
- International Telecommunications Union Radio (ITU-R) Report ITU-R M. 2135-1. (2009). *Guidelines for evaluation of radio interference technologies for IMT-advanced*.
- Jain, R., Chiu, D. M., & Hawe, W. R. (1984). *A quantitative measure of fairness and discrimination for resource allocation in shared computer systems*. Digital Equipment Corporation technical report TR-301.
- Jia, H., Zhang, Z., Yu, G., Cheng, P., & Li, S. (2007, June). *On the performance of IEEE 802.16 OFDMA system under different frequency reuse and subcarrier permutation patterns*. Paper presented at the 2007 IEEE International Conference on Communications (ICC '07), Glasgow, UK (pp. 5720-5725). doi:10.1109/ICC.2007.948

- Lee, P., Lee, T., Jeong, J., & Shin, J. (2010, February). *Interference management in LTE femtocell systems using fractional frequency reuse*. Paper presented at the International Conference on Advanced Communication Technology (ICACT 2010), Phoenix Park, Korea (pp. 1047-1051).
- Lei, H., Zhang, L., Zhang, X., & Yang, D. (2007). *A novel multi-cell OFDMA system structure using fractional frequency reuse*. Paper presented at the 18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, (PIMRC 2007), Athens, Greece (pp. 1-5). doi:10.1109/PIMRC.2007.4394228
- Lopez-Perez, D., Valcarce, A., Roche, G., & Zhang, J. (2009). OFDMA femtocells: A roadmap on interference avoidance. *IEEE Communications Magazine*, 47(9), 41–48. doi:10.1109/MCOM.2009.5277454
- Necker, M. (2007, October). *Local interference coordination in cellular OFDMA networks*. Paper presented at the 2007 IEEE 66th Vehicular Technology Conference (VTC 2007-Fall), Baltimore, MD (pp. 1741-1746). doi:10.1109/VETECF.2007.368
- Novlan, T., Andrews, J., Sohn, I., Ganti, R., & Ghosh, A. (2010, December). *Comparison of fractional frequency reuse approaches in the OFDMA cellular downlink*. Paper presented at the 2010 IEEE Global Telecommunications Conference (GLOBECOM 2010), Miami, FL (pp. 1-5). doi:10.1109/GLOCOM.2010.5683973
- Piro, G., Grieco, L., Boggia, G., Capozzi, F., & Camarda, P. (2011). Simulating LTE cellular systems: An open-source framework. *IEEE Transactions on Vehicular Technology*, 60(2), 498–513. doi:10.1109/TVT.2010.2091660
- Son, K., Lee, S., Yi, Y., & Chong, S. (2011). REFIM: A practical interference management in heterogeneous wireless access networks. *IEEE Journal on Selected Areas in Communications*, 29(6), 1260–1272. doi:10.1109/JSAC.2011.110613