Dynamic Frequency Planning Versus Frequency Reuse Schemes in OFDMA Networks

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***Abstract*—In order to avoid inter-cell interference, OFDMA networks are flexible in terms of radio resource management techniques, supporting different frequency reuse schemes (FRSs), which in turn, may decrease inter-cell interference and increase network performance. However, because most of them are based on fix patterns, these FRSs cannot cope with the uneven distribution and dynamic behavior of the traffic throughout the day.**

This work introduces a novel approach to the frequency assignment problem called Dynamic Frequency Planning (DFP) tailored to OFDMA networks. The proposed approach dynamically adapts the radio frequency parameters to the environment taking the user and channel conditions into account. Moreover, a variant of DFP, called vertical DFP, based on the fractional frequency reuse schemes (FFRSs) concept is proposed. In comparison to the traditional FRSs, these techniques notably mitigate inter-cell interference and enhance network performance.

I. INTRODUCTION

Interference has been proven to be the major problem of wireless communication systems across the years, because:

- the radio spectrum is a very limited resource.
- the number of customers continuously increases.

When different customers are using the same portion of the spectrum at the same area and time, the system suffers from interference, and the quality of the communications is degraded. Depending on the nature and the source of the interference, it can be classified as:

- By nature: *Co-channel* or *Adjacent-channel interference*. When the two different interfering signals are using the same frequency, co-channel interference happens. Otherwise, if they are using different but insufficiently separated frequencies, adjacent-channel interference occurs.
- By source: *Intra-cell* or *Inter-cell interference*. When the two different interfering signals are carried by the same sector, intra-cell interference happens. Otherwise, if they are carried by different neighboring sectors, inter-cell interference occurs.

In the early years of wireless systems, when the number of users was small compared to the available frequencies, interference was not a problem. However, over the last decades, the number of user has dramatically increased, and a severe reuse of the spectrum is needed.

In the 90's, GSM [1] networks were used to fulfill the demands of the users, mostly based on voice services. In this kind of systems, the spectrum is broken down into channels, and multi-user access is achieved by assigning different channels to different users. Therefore, a careful radio frequency planning (RFP) [2] must be used in order to reuse the spectrum and increase the network capacity. Such RFP must be robust against interference, dealing with intra-cell and inter-cell co-channel interference, and in second place, with adjacent-channel interference, which might be neglected due to the features of the Gaussian minimum shift keying (GMSK) (modulation bandwidth $\simeq$ channel bandwidth) [3].

Currently, technologies such as WCDMA [4] and HSPA [5] are used to satisfy the requirements of the users, now based on voice and data services. In this kind of systems, all the communications share the same carrier, and multi-user access is achieved by assigning different pseudo-random codes with special properties against interference to different users [6]. Therefore, the RFP is completely unnecessary in this case, and the operator must deal with intra-cell and inter-cell co-channel interference in order to successfully deploy the network.

However, in the near future, the demands of the users will continue growing, and new services and applications will be needed, requiring larger levels of quality of service (QoS) and bit rates. To satisfy these requirements, the research community is working on the standardization of two new technologies: WiMAX [7] and LTE [8].

Both technologies (downlink case) are based on an OFDMA physical layer [9], which supports several key characteristics necessary for delivering broadband services at high mobility, e.g. scalable channel bandwidths, high spectral efficiency and multi-path tolerance.

In WiMAX or LTE networks, intra-cell interference may be neglected due to the sub-carrier orthogonality in OFDMA. Therefore, operators must cope with inter-cell interference in order to enhance the network capacity and performance. To overcome inter-cell interference, OFDMA networks are flexible in terms of radio resource management techniques, supporting different FRSs, which in turn, may decrease inter-cell interference and increase network performance [10]. However, most of these FRSs cannot cope with the uneven distribution and dynamic behavior of the traffic throughout the day, because they are based on fix patterns [11] [12], e.g. a congested sector is not allowed to borrow sub-channels from the neighboring sectors even if they have idle resources.

This work goes beyond the study of fixed FRSs, and establishes the fundamentals of a novel approach that exploit the flexibility of the OFDMA physical layer by dynamically adapting the frequency assignment of the cells, according to the changing conditions of the traffic and radio channel [13].

The rest of the paper presents the following:

- Section II, the main features of OFDMA and FRSs.
- Section III, the DFP algorithm, and its 2 implementation: horizontal-DFP and vertical-DFP.
- Section IV, the capacity enhancement when using DFP compared to the classical FRSs.
- Section V, the conclusion extracted from this work.

II. OFDMA AND FREQUENCY REUSE SCHEMES

OFDMA is a multi-carrier technology where the available bandwidth is formed by many orthogonal sub-carriers that may be combined into several groups called sub-channels. When using OFDMA and time division duplex (TDD), the time domain is divided into OFDM symbols (Figure 1). The number of available sub-channels and symbols depends on the network configuration, and they could vary to support different traffic profiles.

The slot is the minimum frequency-time resource-unit that can be allocated by the base station (BS). The slot is composed of one sub-channel and one, two or three OFDM symbols, which depends on the network configuration. Different but contiguous slots may be allocated to different users in the form of burst as a multiple-access mechanism. The bandwidth allocated to each user is a function of the bandwidth demand, QoS requirements and channels conditions.

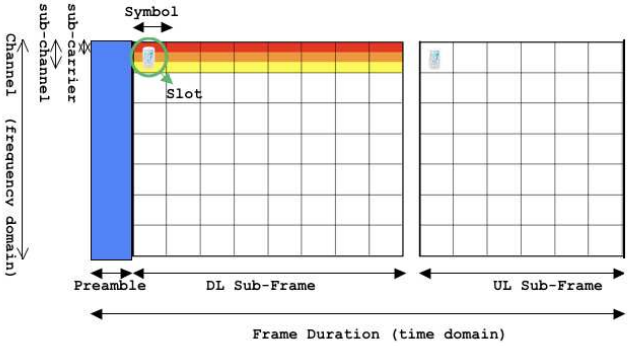


Fig. 1. OFDMA Frame.

In order to avoid inter-cell interference, OFDMA exploits its physical (PHY) and medium access control (MAC) layer flexibility and allows the use of a large variety of FRSs [11]. These FRSs are described by the notation $N_c \times N_s \times N_f$, where N_c denotes the number of channels, N_s indicates the number of sectors per BS, and N_f shows the number of fragments in which each channel is divided.

In the following, the most representative FRSs and their variants are introduced, since they will be used in the following sections for performance comparison:

A. Frequency Reuse Scheme $1 \times 3 \times 1$

When using $1 \times 3 \times 1$ (Figure 2) [12], there is only 1 radio channel available F, and each BS of the network has 3 sectors. Then, every sector of the network is allowed to use every sub-channel of the channel.

By using this FRS, no frequency planning is needed, simplifying the task of the operator, but the chance of inter-cell interference coordination is neglected.

B. Frequency Reuse Scheme $1 \times 3 \times 3$

When using $1 \times 3 \times 3$ (Figure 2) [12], the channel F is divided in 3 segments: F_1, F_2, F_3, and each segment is assigned to each sector. This scheme simplifies the RFP design, since the operator only needs to assign segments to sectors. Additionally, this FRS mitigates inter-cell interference by reducing the probability of slots collision by a factor of 3. However, the sector capacity is also reduced by a factor of 3.

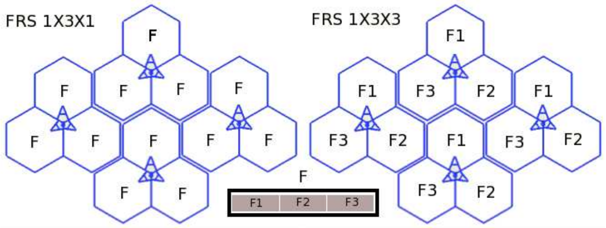


Fig. 2. Frequency Reuse Scheme.

C. Fractional Frequency Reuse Scheme

The OFDMA/TDD frame may include multiple vertical zones to allow the system to dynamically adapt the radio parameters to the different types and conditions of the users. In this way, a sector can deploy different permutation schemes, frequency reuse schemes or allocation techniques concurrently. Therefore, 2 different FRS can co-exist in the same frame, building a FFRS [12].

An example of this kind of scheme is illustrated in Figure 3. In this case, the OFDMA/TDD frame is divided into 2 zones. Zone 1 uses a FRS $1 \times 3 \times 1$, while zone 2 uses a FRS $1 \times 3 \times 3$.

When using this FFRS, users with different signal qualities are located in different zones:

- Users close to the BS are allocated in zone 1, having the whole radio channel available for them, since they are subject to small interference.
- Users in the cell edge are allocated in zone 2, having the chance of interference coordination, since they are subject to large interference.

As a result, the capacity of the sector is not so greatly reduced as with FRS $1 \times 3 \times 1$, and inter-cell interference is mitigated as with FRS $1 \times 3 \times 3$.

III. DYNAMIC FREQUENCY PLANNING

In order to improve the performance of the classical FRSs, a novel approach to the frequency assignment problem called

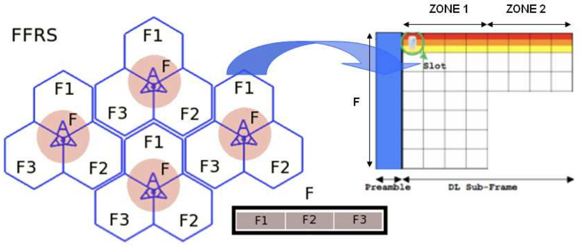


Fig. 3. Fractional Frequency Reuse Scheme.

DFP tailored to OFDMA networks is presented in [13]. DFP dynamically adapts the radio frequency parameters to the environment taking the user and channel conditions into account, running from a few times a day down to on a second by second basis depending on the needs of the operator.

A. DFP Approach

First of all, let us model an OFDMA network as a set of N sectors $\{S_0, S_i, S_j ... S_{N-1}\}$ and K available sub-channels $\{0, k...K-1\}$, where at a given time, each sector S_i requires a certain number of sub-channels D_i. Then, the DFP problem consists on assigning a certain number of sub-channels D_i to each sector S_i, while minimizing the global system interference, taking the interference restrictions and sub-channel reuse between sectors into account.

The *1st key step of DFP* is to estimate the number of sub-channels D_i required to satisfy the bandwidth demand of the users connected to the sector S_i, taking the users requirements in terms of bandwidth and throughput into account.

The *2nd key step of DFP* is to characterize the inter-cell interference of the network.The system inter-cell interference is characterized by a *Restriction Matrix* $W[N,N]$ [14] [15], in which $w_{i,j}$ represents the inter-cell interference between sectors S_i, S_j, in terms of percentage of interference time. Let us introduce the concept of Interference Event (IE). Two sectors, S_i (server) and S_j (neighbour), interfere with each other ($IE_{i,j}++$) every time the power level of the carrier signal C_i (from S_i to a served user) is smaller than the power level of a neighbouring interfering signal I_j (from S_j to the same user) plus a given threshold ($Thres = 12\ dB$), as condition (1) indicates. The threshold is a protection margin against interference and it is set by the operator, depending on planning targets.

$$C_i < I_j + Thres \tag{1}$$

Note that the power level of the server and neigbouring cells is reported using Measurement Reports (MRs) ($MR_{i,j}$). Then, the system inter-cell interference is modelled by W, as (2):

$$w_{i,j} = IE_{i,j} / MR_{i,j} \tag{2}$$

The procedures used to compute the sub-channel demands and the restriction matrix are presented in [13].

Once the inputs are known, the DFP assignment can be defined as a Mixed Integer Programing problem as follows, where the target is to find the optimal solution that minimizes the given cost function representing the overall network interference.

$$min \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \sum_{k=0}^{K-1} \frac{w_{i,j}}{D_i \cdot D_j} \cdot y_{i,j,k} \tag{3a}$$

subject to:

$$\sum_{k=0}^{K} x_{i,k} = D_i \qquad \forall i,k \tag{3b}$$

$$x_{i,k} + x_{j,k} - 1 \leq y_{i,j,k} \qquad \forall i,j,k \tag{3c}$$

$$y_{i,j,k} \geq 0 \qquad \forall i,j,k \tag{3d}$$

$$x_{i,k} \in \{0,1\} \qquad \forall i,k \tag{3e}$$

where $x_{i,k}$ indicates that sector S_i uses frequency k. Constraint (3b) imposes that sector S_i must use D_i sub-channels. Inequalities (3c) and (3d) together force that in an optimal solution $y_{i,j,k} = 1$ if and only if both sectors S_i and S_j use frequency k and $y_{i,j,k} = 0$ otherwise. Finally, the cost function is the sum of the interference between all pair of sectors S_i, S_j taking into account all the frequencies k. Since the capacity of the sectors is not considered when the restriction matrix $W[N,N]$ is built, the interference restrictions $w_{i,j}$ must be divided by the number of used sub-channels D_i, D_j for both sectors S_i, S_j. In this way, the percentage of time in which both sectors S_i and S_j are transmitting with the same frequency k is estimated.

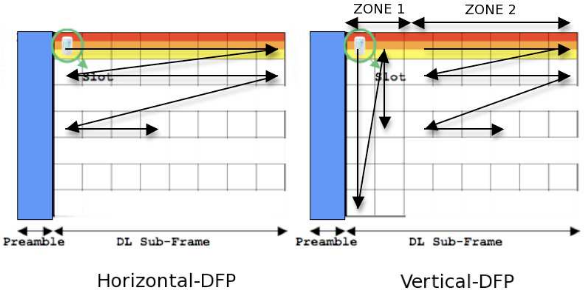
Different approaches can be proposed to find the optimal or at least a good solution for the DFP assignment problem. In [13], the performance of approaches based on simulated annealing, tabu search and greedy algorithms are compared. Because in the future DFP will run on the BS itself, the trade-off between the quality and running time of the solution should be taken into account. As a conclusion in [13], it can be said that meta-heuristics will find higher quality solutions than greedy algorithms at the expense of longer running times. However, it may be worth using faster approaches (greedy algorithms), since they produce only slightly worse solutions. The faster the optimization method, the more responsive the system will be to the changes of the traffic and the channel. In this work, such greedy algorithms have been used.

B. Horizontal-DFP

In this subsection, a method to apply DFP to the network called Horizontal-DFP is introduced.

- Firstly, the sub-channel demand D_i and the restriction matrix $W[N,N]$ are estimated. When using HDFP, all the users connected to the sector are considered when estimating the demanded number of sub-channels per sector D_i.
- Secondly, the DFP assignment problem (3) is solved, and a frequency planning is obtained. When using HDFP, the frequency planning indicates which sub-channels from the available set can be used in each sector and which are forbidden.
- Finally, the sector will allocate slots to the users from the group of allowed sub-channels (Figure 4).

Note that if the load of the network is large, the demanded number of sub-channels per sector will also be large, and it may be close to the maximum K. If this happens, the frequency planning will lose freedom in the assignment procedure, and the interference avoidance will be minimum.



Horizontal-DFP

Vertical-DFP

Fig. 4. Horizontal and Vertical DFP.

C. Vertical-DFP

Vertical-DFP is an enhanced method to apply DFP to the network based on the concept of FFRs that overcomes the loss of freedom of HDFP when the network load increases.

In VDFP, the set of users is divided into 2 groups according to their signal to interference-plus-noise ratio (SINR). The first group consist of users with large SINR values, while the second group consist of users with low SINR values. To divide the set of users into 2 groups a SINR threshold is used, which is calculated dynamically and independently by each sector. The SINR threshold is selected as the maximum value of a given range that warranties a sub-channel occupation ratio (D_i/K) in the second group smaller than R_{target}. A value of $R_{target} = 0.66$ value ensures a good level of freedom when performing the frequency planning. The SINR threshold ranges from 40dB to 23.3dB, which is the SINR threshold of the highest user profile (modulation & coding).

Once the 2 groups are built, the 2 zones of the OFDMA/TDD frame are defined. Users of the first group will be allocated in zone 1, which uses FRS $1 \times 3 \times 1$, while users of the second group will be allocated in zone 2, which uses HDFP. As a result, the number of users in the HDFP zone is reduced (increasing freedom), and the overall inter-cell interference is mitigated.

To increase the freedom of the frequency planning in zone 2, the 2 zones are built using an top to botton slot allocation fashion in zone 1, and a left to right slot allocation fashion in zone 2. This is shown in (Figure 4).

It should be noted that if the network load is low, the selected SINR threshold will be large. Then, group 1 will be empty and group 2 will be full. As a result, VDFP will perform as HDFP.

IV. EXPERIMENTAL EVALUATION

This section presents an experimental evaluation and performance comparison of the presented FRSs and the proposed DFP algorithms by means of system-level simulations (SLSs). The Centre for Wireless Network Design's (CWiND) SLS [16] was used for this experimental evaluation.

The scenario used was a non-regular deployed WiMAX network composed of 27 sectors. Two different types of traffic pattern have been used to simulate the uneven distribution of the users across the scenario: one background traffic map and four different hot spots with a density of 40 $user/km^2$ and 80 $user/km^2$, respectively. These values follow the recommendation of Forsk Atoll [17] for urban and dense urban areas. The scenario and simulation parameters can be seen in Figure 5 and Table I, respectively.

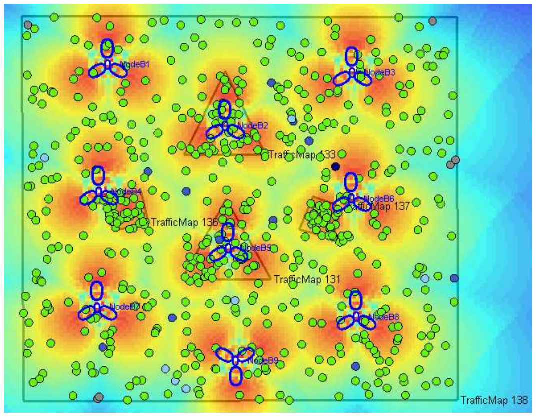


Fig. 5. Dynamic Frequency Planning with vertical zone.

Before analyzing the results of the simulation, it is necessary to understand the different possible user states derived from the SLS:

- No RAB (Radio Access Bearer or User Profile): When the SINR reported by the channel quality indicator is smaller than the SINR required to get the minimum user profile.
- No Resources: If the user has a user profile, but the network has not sufficient resources to satisfy their minimum requested service throughput.
- Tx Failure: When the user is transmitting, but the user has not achieved the minimum requested throughput.
- Tx Success: When the user is transmitting, and the user has achieved the minimum requested throughput.

TABLE I
SIMULATION PARAMETERS

Parameter	**Value**	**Parameter**	**Value**
Sites	9	CPE Ant. Gain	$0\,dBi$
Sector/site	3	CPE Ant. Pattern	Omni
Carrier Frequency	$3.5\,GHz$	CPE Ant. Height	$1.5\,m$
Channel Bandwidth	$10\,MHz$	CPE Noise Figure	$5\,dB$
DL:UL Ratio	1:1	CPE Cable Loss	$0\,dB$
Permutation Scheme	AMC	Type of Service	Video
Frame Duration	$5\,ms$	Min Service TP	$64\,kbps$
Sub-channels	16	Max Service TP	$128\,kbps$
DL symbols	19	σ(Shadow Fading)	$8\,dB$
BS Tx Power	$43\,dBm$	Intra BS correlation	0.7
BS Ant. Gain	$18\,dBi$	Inter BS correlation	0.5
BS Ant. Beam Width	65	Path Loss Model	Hata
BS Ant. Height	$30\,m$	Traffic Map Density	45 u/km^2
BS Ant. Tilt	3	Hot spot Density	90 u/km^2
BS Noise Figure	$4\,dB$	Scheduling	Best SINR
BS Cable Loss	$3\,dB$	Resource Allocation	CA[1]
CPE Tx Power	$23\,dBm$	Snapshots	100

[1] Contiguous Allocation

In the following, the results of the SLS summarized in Table II are analyzed. Note that the number of users was 800, and that the results are averaged over 100 snapshots.

When using FRS $1 \times 3 \times 1$, there are not any problems of lacks of resources in the sectors (No Resource = 0.00%), but this scheme produces a large number of user outages due to the large interference (No RAB = 16.56% + Tx Failure = 0.17%). Since there is a heavy traffic load and no interference coordination in the hot spots, the probability of slot collision between sectors is large. This results in a poor signal quality (reduced throughput) or in an outage for some users.

Analyzing FRS $1 \times 3 \times 3$, two results can be derived. On the one hand, some problems of lack of resources (7.62%) appear in the hot spots, due to the reduction of the sectors capacity by a factor of 3. On the other hand, the number of user outages decreases (2.81% + 0.33%), due to the reduction of the slot collision probability by a factor of 3. Here, there is a trade off between capacity and interference coordination. However, interference coordination has been proven to be more effective (TX Success = 81.95% vs. 88.08%).

By using the HDFP algorithm, the sectors in the hot spots are able to borrow sub-channels from the neighboring sectors provided they have idle resources. Then, the problems of lack of resources disappear (No Resource = 0.00%). In addition, HDFP also produces a larger interference avoidance than both FRSs (TX Success = 94.21%). As expected, HDFP performs better than FRSs (by around 12% and 6 %), since it is able to adapt the radio parameters to the environment. It can be seen that the Tx Failure factor has increased when using DFP compared with the FRSs. It is because DFP has reduced the outage and now there are more users transmitting.

Furthermore, if HDFP and VDFP are compared,it can seen how VDFP produce a better performance (TX Success = 94.21% vs. 95.70%). Remark that in VDFP, users with high SINR are allocated in zone 1, while users with a poor SINR are placed in zone 2. Therefore, the number of users and sub-channels that we have to plan when using VDFP (users in zone 2) is smaller than when using HDFP (all users). This is translated to a higher freedom when calculating the frequency plan, since the number of available sub-channels is the same, 16, but the number of sub-channels needed per sector is smaller, D_i. In this case, the quality of the frequency planning is larger, and therefore, the probability of interference avoidance is also larger.

TABLE II
SIMULATION RESULTS: CAPACITY

Technique	TX Succ.	No RAB	No Reso.	TX Fail.	Mbps
$1 \times 3 \times 1$	81.95%	16.56%	0.0%	0.17%	52.36
$1 \times 3 \times 3$	88.08%	2.81%	7.6%	0.33%	51.60
HDFP	94.21%	0.99%	0.0%	3.48%	60.72
VDFP	95.70%	1.16%	0.0%	1.16%	62.96

Finally, the average network throughput corroborates what has been exposed before. The algorithm with no interference coordination produced the worst cell average throughput, while VDFP, which is the most sophisticated of the presented techniques, provides the best cell average thoughput.

V. CONCLUSION

This paper has introduced a new approach to the frequency assignment problem called DFP tailored to OFDMA networks. This approach have been proven to perform well in dynamic scenarios where the traffic and the channel conditions rapidly changes with the time. An enhancement of the DFP algorithm called Vertical-DFP based on the concept of FFRSs has also been presented. It was able to enhance network capacity and throughput by around 15% compared to standard FRSs such as $1 \times 3 \times 1$ and $1 \times 3 \times 3$.

This paper has also given a detailed description of the FRS techniques and DFP algorithms used in this framework. In addition, experimental evaluations based on system level simulations using a realistic scenario has been shown. Finally, an extensive discussion of the obtained results have been given.

VI. ACKNOWLEDGEMENT

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