Abstract—Fractional frequency reuse for the downlink of multicellular WiMAX networks is examined in this work. Three different schemes are explored through simulations, namely distance-based and SINR-based approaches, as well as a new scheme which is based on load-balancing between different reuse regions. The proposed load-balancing scheme overcomes the main weakness of the SINR-based approach, namely its inability to manage efficiently the available resources of both Reuse-1 and Reuse-3 zones, as their size varies. The simulation results exhibit a clearly better performance of the proposed algorithm compared to distance-based and SINR-based approaches. It is shown that the employment of fractional frequency reuse with the proposed load-balancing approach improves the performance of WiMAX networks in terms of a variety of metrics, such as blocking probability and achievable bit rate.

I. INTRODUCTION

One of the most substantial features of WiMAX [1], which is also adopted by the 3GPP Long Term Evolution [2], is the Orthogonal Frequency Division Multiple Access (OFDMA). Besides the profound advantages of OFDMA on physical layer, such as immunity to multipath propagation and efficiency on bandwidth exploitation, OFDMA provides a flexible framework for the allocation of resources, providing new potential to the network radio resource management. Contrary to conventional schemes of Multiple Access, where the radio resource management problem is one-dimensional, OFDMA converts the radio resource management problem to two-dimensional, as the basic resource unit is expanded on both frequency and time.

In this context, the WiMAX frame is a two-dimensional set of resources. The time axis is divided into OFDM symbols while the frequency axis is divided into logical subchannels, which are groups of OFDM subcarriers. Based on the mode that the subcarriers are selected from the set of used subcarriers to form a subchannel, two main subchannelization types are described. The first type, namely diversity subcarrier permutations, aims at providing interference averaging, as subcarriers are pseudo-randomly selected to form the subchannel. Partial and Full Usage of Subchannels (PUSC and FUSC respectively) permutation modes belong to this category. On the contrary, the second type, namely contiguous subcarrier permutations, aims at exploiting multi-user diversity, based on users’ feedback. In this case, the subchannel consists of adjacent subcarriers. Adaptive Modulation and Coding (AMC) permutation mode belongs to contiguous subcarrier permutations.

The standard [1] foresees that the WiMAX frame can be divided into several permutation zones, each one expanded on several OFDM symbols (cf. [3], Fig. 10). Each permutation zone employs a permutation mode and a frequency reuse factor (FRF), defining this way the fraction of the available bandwidth that this zone occupies. The introduction of multiple permutation zones into the WiMAX frame with different FRFs enables the employment of fractional frequency reuse (FFR). In general, the solutions that have been proposed for the employment of FFR in WiMAX can be divided into two categories, namely solutions based on distance [4], [5] and solutions based on Signal to Interference plus Noise Ratio (SINR) [6], [7].

This work tackles the problem of frequency reuse factor selection for multicellular WiMAX networks. A new approach is proposed, based on a load-balancing concept. This approach is evaluated through simulations and its performance results are compared with two already proposed methods. The remainder of this work is organized as follows: section II provides a detailed description of the WiMAX network model that is used for the evaluation of the FFR schemes. In section III the operations of the network are described and the FRF selection problem is analysed along with the proposed solutions. Section IV provides further detail on the simulation process employed herein. The simulation results are included in section V with a comparative analysis on the performance of the different schemes. Finally, the conclusions of this work are drawn in section VI.

II. NETWORK ARCHITECTURE

The network encompasses $N_s = 19$ hexagonal cells, divided into $S = 3$ sectors, with BS-to-BS distance $R = 1000m$. The network occupies $BW = 10MHz$ of bandwidth, divided into $N_{FFT} = 1024$ OFDM subcarriers with subcarrier spacing $\Delta f = 10.9375kHz$. Time Division Duplexing (TDD) is employed with downlink to uplink ratio DL:UL=2:1. The frame duration is set to $T_f = 5ms$ and it contains 47 OFDM symbols. The DL subframe contains 31 OFDM symbols. As stated in [3], the frame overhead to account for Preamble, MAP overhead and UL Control Channel is 7 OFDM symbols. The DL subframe contains 31 OFDM symbols. As stated in [3], the frame overhead to account for Preamble, MAP overhead and UL Control Channel is 7 OFDM symbols for the DL. As a result, DL subframe contains 24 OFDM symbols available for data transmission. In order to include the concept of multiple permutation zones in the WiMAX frame, the later is divided into 2 different permutation zones,
each applying a different frequency reuse factor under PUSC permutation mode, as depicted in Fig. 1.

As far as the FRF is concerned, the notation used herein is that $FRF = 1$ means that the available bandwidth is reused at every sector of the network while $FRF = 3$ means that the available bandwidth is reused at every cell of the network. When $FRF = 1$, every sector can use and allocate to its users all the subchannels. On the contrary, when $FRF = 3$, the standard defines a segmentation procedure for PUSC permutation mode. In brief, the available subchannels are divided into 6 groups, 3 major and 3 minor groups. Each one of the major groups is assigned to each sector. The assignment of the 3 minor groups is not predefined but it is dynamically conducted in order to cover the increased load of a sector.

In general, when FFR is employed, the FRF of each sector is defined by (1),

$$FRF = \frac{1 \times N_{PUSC-1} + 3 \times N_{PUSC-3}}{N_{PUSC-1} + N_{PUSC-3}}$$

where $N_{PUSC-1}$ stands for the number of OFDM symbols in PUSC permutation zone with $FRF = 1$ (PUSC-1) while $N_{PUSC-3}$ is the number of OFDM symbols in PUSC permutation zone with $FRF = 3$ (PUSC-3). The FRF definition depends only on the length (in number of OFDM symbols) of each permutation zone, depicting this way the proportion of resources that are allocated to each reuse region.

Each permutation zone consists of a set of slots. The slot is a rectangular allocation unit, expanding on both frequency and time domain. At frequency domain, the slot consists of one subchannel while at time domain it expands on 2 OFDM symbols. As stated earlier, for PUSC permutation mode, the subcarriers that form a subchannel are pseudo-randomly selected from the set of used subcarriers. As a result, the PUSC permutation zone can be considered as a set of equivalent slots.

Each PUSC slot contains 48 data subcarriers and 8 pilot subcarriers (24 data and 4 pilot subcarriers per OFDM symbol). Each OFDM subcarrier can carry one symbol, which corresponds to several bits, depending on the Modulation and Coding Scheme (MCS) employed. Each slot is transmitted once each $T_f = 5ms$ and it corresponds to a data symbol rate of $R_s = 9600$ symbols/sec. The concept adopted herein is that each slot is a basic allocation unit that can provide a data symbol rate of $R_s = 9600$ symbols/sec.

The standard provides a wide variety of MCSs, depending on the modulating constellation, coding rate and coding type. The SINR thresholds proposed in [8] have been employed in this work (Table I). These SINR values reassure that the BER is less than $10^{-6}$ if Convolutional Turbo Coding (CTC) is used in Additive White Gaussian Noise (AWGN) channel.

Furthermore, in order to eliminate edge effect, a wraparound technique is employed. In further detail, it is assumed that the network under consideration is located at multiple positions around the simulated network. Concluding this description for the network architecture, the parameters related to propagation model, base station (BS) and subscriber station (SS) equipment are given in Table II, derived mainly from [9].

### TABLE I

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Bits/Symbol</th>
<th>$SINR_{T H R E S H O L D}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>1.5</td>
<td>2.9</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>3</td>
<td>6.3</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/6</td>
<td>5</td>
<td>12.7</td>
</tr>
</tbody>
</table>

### III. NETWORK OPERATIONS

The simulation starts with the generation of a new user $\tilde{u}$ within the geographical area of the network with specific bit rate $R_u$ requirements under the predefined BER of $10^{-6}$. The location of the new user is defined as a 2D random variable that follows the uniform distribution while his DL bit rate is randomly selected from the set $S_{BR} = \{64kbps, 128kbps, 256kbps, 512kbps, 1024kbps\}$.

#### A. Sector Assignment

In the next step, the user tries to establish a connection with the network. In order to define the sector that will serve the user, the average channel gain (over all used subcarriers\(^{1}\)) is calculated for all the sectors of the network. The serving BS $\tilde{k}$ and sector $\tilde{s}$ for the new user are given by (2),

$$\left(\tilde{k}, \tilde{s}\right) = \arg\max_{(k,s)} \sum_{n=1}^{N_{used}} \sum_{t \in DL} G_{\tilde{u},n,t,k,s}$$

\(^{1}\)Specific subcarriers remain unused, considered as left and right guard bands as well as the DC subcarrier. For PUSC permutation zone and $N_FPF = 1024$, $N_{used} = 840$. 

where $G_{\bar{u},n,t,k,s}$ stands for the channel gain between user $\bar{u}$ and the sector $s$ of the BS $k$, on the OFDM subcarrier $n$, during the OFDM symbol $t$. In order for the selected sector to provide DL data to the user, a number of slots must be allocated from the DL subframe.

**B. Permutation Zone - Frequency Reuse Factor Selection**

At the beginning of the slot allocation procedure, the BS that serves the user must define the permutation zone from which the slots will be allocated. The serving BS asks the user to report back the effective SINR on each permutation zone. This procedure can be implemented through REP-REQ/REP-RSP messages. The mean instantaneous capacity (MIC) effective SINR [10] is calculated over all the pilot subcarriers of each permutation zone.

Following the notation of (2), the SINR on subcarrier $n$ during OFDM symbol $t$ is defined as:

$$SINR_{\bar{u},n,t,k,s} = \frac{\rho_{n,t,k,s} G_{\bar{u},n,t,k,s} P_{BS}}{N_{\text{used}}}$$

(3)

where $m$ denotes the index of the permutation zone load.

The SINR threshold, denoted as $SINR_{th}$ in Alg. 2, is selected so as to minimize the outage probability of the network, i.e. $SINR_{th} = \min_{MCS} \{SINR_{MCS}^{min}\} = 2.9dB$. The concept behind this choice is that the users that would be in outage if served by PUSC-1 permutation zone, will be served by PUSC-3 permutation zone.

**Algorithm 2: SINR-based Approach (SBA)**

1. if $SINR_{\bar{u},k,s} > SINR_{th}$ then
2. $r = 1 \rightarrow$ User $\bar{u}$ is served by PUSC-1 zone
3. else
4. $r = 3 \rightarrow$ User $\bar{u}$ is served by PUSC-3 zone

3) Load-Balancing Approach: Both previous approaches do not take under consideration the load conditions of each permutation zone. The approach that this work proposes, referred to as “Load-Balancing” approach (LBA), aims at achieving a balance between channel conditions and permutation zone load.

The mapping of SINR values to the corresponding spectral efficiencies of Table I is represented by the function $f$. The reported effective SINR for each permutation zone is given by (4)

$$SINR_{\bar{u},k,s}^{r,P} = \frac{\sum_{i \in PUSC-r} \sum_{n \in \mathcal{P}(t)} SINR_{\bar{u},n,t,k,s}^{PUSC-r}}{\sum_{i \in PUSC-r} |\mathcal{P}(t)|} - 1$$

where $SINR_{\bar{u},k,s}^{r,P}$ stands for the MIC effective SINR of PUSC-$r$ permutation zone, $r \in \{1,3\}$.

- **Distance-based Approach**: According to the distance-based approach (DBA) as presented in [5], the inner area ($FRF = 1$) is assumed to be a cyclic area with radius $\sqrt{\frac{3}{\pi}}$. The FRF in [5] is defined as $FRF = \eta \cdot 1 + (1-\eta) \cdot 3 = 3 - 2 \cdot \eta$ where $\eta$ stands for the area ratio of the inner area to the total cell area. Based on this definition, the $R_{th}$ is calculated as:

$$R_{th} = \sqrt{\frac{1}{4\pi} \left(3 - FRF\right) \cdot R}$$

The algorithm employed for permutation zone selection in this case is Alg. 1.

**Algorithm 1: Distance-based Approach (DBA)**

/* $d_{\bar{u},k}$ : distance between user $\bar{u}$ and his serving BS $k$ */

1. if $d_{\bar{u},k} < R_{th}$ then
2. $r = 1 \rightarrow$ User $\bar{u}$ is served by PUSC-1 zone
3. else
4. $r = 3 \rightarrow$ User $\bar{u}$ is served by PUSC-3 zone

TABLE II

<table>
<thead>
<tr>
<th>Propagation Model Parameters</th>
</tr>
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<tbody>
<tr>
<td>Carrier frequency $f_c = 2.56GHz$</td>
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<tr>
<td>Path loss model COST-HATA-231 Suburban</td>
</tr>
<tr>
<td>Channel model AWGN</td>
</tr>
<tr>
<td>Log normal shadowing stddev $\sigma_{SF} = 8.9dB$</td>
</tr>
<tr>
<td>Shadowing correlation $\xi_{SF} = 0.5$</td>
</tr>
<tr>
<td>Penetration and other losses $L_P = 10dB$</td>
</tr>
<tr>
<td>Thermal noise density $N_0 = -174dBm/Hz$</td>
</tr>
</tbody>
</table>

**Base Station Equipment Parameters**

| Base station transmit power per sector $P_{BS} = 43dBm$ |
| Base station height $H_{BS} = 32m$ |
| Gain (boresight) $G_{BS} = 16dB$ |
| Antenna radiation pattern $\theta_{BS} = 70^\circ$ |
| 3-dB beamwidth $G_{FB} = 25dB$ |
| Front-to-back power ratio $\theta_{FB} = 70^\circ$ |

**Subscriber Station Equipment Parameters**

| Subscriber station height $H_{SS} = 1.5m$ |
| Gain (boresight) $G_{SS} = 0dB$ |
| Antenna radiation pattern Omni |
| Noise figure $NF_{SS} = 7dB$ |

When $u,n,t,s$ permut zone is served by PUSC-3 permutation zone, and $s$ permut zone is served by PUSC-1 permutation zone, will be served by PUSC-3 permutation zone.

7) Load-Balancing Approach: Both previous approaches do not take under consideration the load conditions of each permutation zone. The approach that this work proposes, referred to as “Load-Balancing” approach (LBA), aims at achieving a balance between channel conditions and permutation zone load.

The mapping of SINR values to the corresponding spectral efficiencies of Table I is represented by the function $f$. The reported effective SINR for each permutation zone is given by (4)
is associated with a MCS and the corresponding spectral efficiency that the user channel can support, is given by \( b_{u,s,k}^P = f \left( SINR_{u,s,k}^P \right) \). At this point, the permutation zone selection process takes into account not only the user channel (through \( b_{u,s,k}^P \)) but also the resource availability of the permutation zone, through the number of available slots of each permutation zone, denoted as \( N_s^r \). The algorithm that presents this load-balancing approach is described in Alg. 3.

**Algorithm 3: Load-Balancing Approach (LBA)**

1. if \( b_{u,s,k}^1 > N_s^1 \) then
   2. \( r = 1 \rightarrow \) User \( u \) is served by PUSC-1 zone
3. else
4. \( r = 3 \rightarrow \) User \( u \) is served by PUSC-3 zone

The permutation zone that will provide the slots for the new user \( u \) is the one with the maximum product \( b_{u,s,k}^r \cdot N_s^r \). This product is proportional to the total available bit rate that the permutation zone can provide to the user and, in fact, it expresses the trade-off between Modulation and Coding Scheme robustness and efficiency. If user’s channel is poor, more resources are allocated to user and a more robust MCS is applied, though providing lower spectral efficiency. On the contrary, when user enjoys good channel conditions, less resources are allocated and a more effective MCS is applied, which is less robust but with higher spectral efficiency. This way, the slot allocation process is more balanced.

As PUSC-1 region encounters worse channel conditions, due to higher interference, resulting from tighter reuse, this leads to \( SINR_{u,s,k}^1 \leq SINR_{u,s,k}^3 \) and, consequently, \( b_{u,s,k}^1 \leq b_{u,s,k}^3 \). Taking under consideration the fact that \( f \) is an increasing function of \( SINR \), the number of available slots of each permutation zone \( N_s^r \) is the factor that defines the permutation zone selection, i.e., whether inequality \( b_{u,s,k}^1 > N_s^1 > b_{u,s,k}^3 \cdot N_s^3 \) holds or not. If \( N_s^r \) is large, this indicates low occupancy of slots. This means that PUSC-\( r \)-permutation zone is underused, leading to waste of resources. On the contrary, if \( N_s^r \) is small, the PUSC-\( r \) permutation zone is close to saturation and, consequently, the available resources should be used more cautiously. The success of LBA is due to the fact that this algorithm achieves to balance the load of different zones by appropriate allocation of users into the zones.

**C. Slot Allocation**

The number of slots required for satisfying user’s request on bit rate \( R_u \) is given by \( N_s^u = \left\lceil \frac{R_u}{b_{u,s,k}^P \cdot R_s} \right\rceil \). The selection of the preferred permutation zone is inelastic, in other words, if the user does not succeed to be served by this permutation zone, he will be rejected. As a result, the Call Admission Control (CAC) scheme adopted herein rejects the new user in two cases:

- The effective SINR of the selected permutation zone is too low to support any MCS (i.e. it is lower than 2.9dB).
- In this case, the user is in outage.
- The selected permutation zone has not enough available slots to serve the user with the requested bit rate under the reported effective SINR (i.e. \( N_s^r < N_s^u \)).

**IV. Simulation Process**

The deployment scenarios, that have been simulated, aim at defining the performance of a WiMAX network under different frequency reuse schemes. During the simulation process, users are generated, as previously described, and ask for admission to the network. The introduction of new users ends when a number of \( N_u = 570 \) users have tried to access the network, which corresponds to 10 users per sector in average.

When the aforementioned process of new user introduction to the network has ended, each user \( u \) that has obtained access calculates the MIC effective SINR of its own slots, based on SINR measurements on the data subcarriers of each slot \( s \),

\[
SINR_{u,k,s}^D = \frac{2 \sum_{(n,t) \in S_u} SINR_{u,n,s,k}^R}{|S_u|} - 1
\]  

where \( S_u \) stands for the set of pairs of OFDM symbols and corresponding data subcarriers that make up the slots allocated to user \( u \). The reported effective SINR is associated with a new MCS with probably different spectral efficiency, \( b_{u,s,k}^D = f \left( SINR_{u,s,k}^D \right) \). Based on the updated \( b_{u,s,k}^D \), the offered bit rate is calculated \( oR_u = b_{u,s,k}^D N_s^r R_s \).

It must be noticed that the difference between offered and requested Bit Rate is due to the difference between the channel estimation that the pilot subcarriers provide and the actual channel conditions that the data subcarriers encounter. Pilot symbols are always transmitted on pilot subcarriers and, as a result, the pilot subcarriers provide channel state information for a network that operates under full load. On the contrary, it is not rare the network to operate under partial loading. Consequently, the estimation that the pilot subcarriers provide, is pessimistic and the data subcarriers actually operate under better channel conditions.

**V. Simulation Results**

The results presented herein have been obtained through at least 100 Monte Carlo iterations. The figures that follow show the average value of the corresponding quantities.

Fig. 2a depicts the blocking probability that the users trying to enter the network encounter, i.e. the probability that any new user will be rejected, regardless of his location. First of all, it must be noted that SBA and LBA perform similarly for \( 1 \leq FRF \leq 1.833 \). From this point onwards, SBA curve increases and, at \( FRF = 3 \), it decreases abruptly. It is clear that in this range, SBA cannot efficiently manage the resources allocated to PUSC-3 permutation zone. Users are rejected due to lack of resources in PUSC-1 permutation zone, which is downsized as FRF increases, while PUSC-3 zone remains underused. It must also be noticed that the SBA shows worse performance than DBA for \( FRF \geq 2.667 \). Secondly, both SBA and LBA have a
minimum in the interval \((1, 3)\), specifically at \(FRF = 2.167\) for both. As a result, it is shown that the employment of FFR under these approaches improves the network performance in terms of blocking probability, in comparison with conventional reuse schemes of \(FRF = 1\) or \(FRF = 3\). It is clear that the LBA shows the best performance compared to the other two schemes, as it shows the lowest blocking probability.

The blocking probability is further analysed into outage probability (fig. 2b) and rejection probability due to resource shortage (2c). A user is said to be in outage when the effective SINR that he reports is too low to support any MCSs (i.e. it is lower than 2.9dB). Firstly, as it can be pointed out from Fig. 2a and 2b, when \(FRF = 1\), the blocking probability coincides with the outage probability, a fact that indicates an interference-limited network. On the contrary, for \(FRF = 3\), the outage probability is much lower than blocking probability. This shows that the network is not any more strictly interference-limited but it shows resource limitations as well. Secondly, the outage probability for DBA decreases linearly with FRF. As FRF increases from 1 to 3, the inner area decreases linearly and, as users are uniformly distributed on the network area, the number of users in the inner area also decreases linearly. This relation enforces the linearity between outage probability and FRF in DBA. Finally, it is clear that the curves of both SBA and LBA approximately coincide. In both methods, when a user is in outage for PUSC-1 region, he is served by PUSC-3 region. The selection of \(SINR_{th}\) was based on this criterion. As a result, for all FRFs except for \(FRF = 1\), the outage probability for both schemes coincides with the outage probability of PUSC-3 region.

Fig. 2c depicts the probability that a new user is rejected as a result of resource shortage while fig. 2d depicts the proportion of resources that are used for each FRF. First of all, it can be noticed that, for both SBA and LBA, for \(FRF > 1\), the majority of user rejections can be attributed to resource shortage despite the fact that the loading factor remains, in most cases, far from 100%. This phenomenon is caused by the limited capability of the algorithms to manage permutation zones of different sizes.

As FRF increases towards 3 and the resources of PUSC-3 zone increase, the performance of SBA deteriorates. This deterioration, as depicted in fig. 2c, is accredited to resource shortage but, as fig. 2d shows, there are available resources to be allocated. The SBA decides that a new user will be served by PUSC-3 zone if and only if he is in outage when served by PUSC-1, regardless of the load conditions for the two permutation zones. As a result, when FRF is close to 3 and PUSC-3 region is large, this strategy leads to under-occupation of PUSC-3 permutation zone and waste of resources. On the contrary, as PUSC-1 zone gets smaller, the available resources are quickly depleted, resulting in higher rejection probability due to resource shortage.

It is worth noticing that, for FRF close to 1, where the network appears mainly as interference limited, the performance of the two algorithms is comparable. But, as FRF increases to 3, from 1.833 onwards, their performance is differed. By Alg. 3, it is clear that if a user is in outage, he will be served by PUSC-3 zone but if a user is not in outage, contrary to SBA, he can be served by either zones. As a result, LBA achieves to manage the available capacity of PUSC-3 region, which gets larger as FRF increases to 3. This is the enhancement of the proposed LBA in comparison with the already proposed SBA for the employment of fractional frequency reuse techniques. Due to the capability of LBA to manage efficiently permutation zones of different size, the performance of a WiMAX network that employs fractional frequency reuse can be further improved.

Fig. 3. Requested Bit Rate \(\sum_u R_u\)

Fig. 3 depicts the total requested Bit Rate for the users that have achieved admission. It must be noticed that the requested Bit Rate metric for system performance is affected from both the FFR approach adopted and the CAC procedure employed.
It is clear that LBA outperforms both other approaches. In comparison with SBA, the difference in performance, as measured by this metric, increases as FRF increases towards 3. The SBA seems to have an inherent incapability to manage the shrinking size of PUSC-1 region and the growing size of PUSC-3 region. As a result, when a user requests bit rate at FRF close to 3, if PUSC-1 region is close to depletion, he will be served only if he is in outage in PUSC-1 region, regardless of the resource availability of PUSC-3 region.

It can be wrongly presumed that the inferior performance of SBA is due to the inappropriate value for the parameter $SINR_{th}$. This parameter defines the threshold, below which a user is served by PUSC-3 region. A different value for this parameter would lead to a shift of the curve to a different operational point, probably better, but the problem would remain. The better approach would be to define the value of this parameter as a function of the available resources of each zone. This is what LBA does while the employment of the algorithm does not charge the network with any further costs.

The offered bit rate is shown in Fig. 4. Offered Bit Rate can be treated as the total achievable bit rate of the network, if a resource re-allocation procedure is conducted in regular time intervals. Firstly, it can be seen from fig. 3 and 4 that the curve of the offered bit rate is higher than that of the requested bit rate. This means that the network has effectively achieved to serve the bit rate requirements of the accepted users. Furthermore, the fact that the offered bit rate is higher than the requested bit rate indicates that the estimation of effective SINR on pilot subcarriers is more pessimistic than the estimation on data subcarriers. This observation is of great importance since it seriously affects the call admission control procedure and it should be taken under consideration, when the network operates under low load. It can also be noticed that the maximum offered Bit Rate that LBA achieves, is greater than that achieved with either $FRF = 1$ or $FRF = 3$. It becomes clear that the employment of Fractional Frequency Reuse with LBA improves the performance of the WiMAX network in all cases. Finally, it is worth noticing that the maximum total offered bit rate of the network is $\sim 164.5$Mbps, which corresponds to 8.7Mbps per cell and 2.9Mbps per sector. This value is achieved when $FRF = 1.5 \Rightarrow N_{PUSC-1} : N_{PUSC-3} = 3 : 1$. This means that the 75% of the network resources are allocated to the "PUSC-1" permutation zone. This inevitably favours users that are located near the BS.

VI. CONCLUSIONS

Three approaches for the employment of fractional frequency reuse to the downlink of multicellular WiMAX networks are presented in this work. The first approach assigns users to different zones with different frequency reuse factors based on a distance criterion while the second one conducts assignment based on a Signal to Interference plus Noise Ratio criterion. The innovation of this work lies on the proposal of a third approach which assigns users to zones considering both user’s channel quality and the load of the zones.

A series of simulations has been conducted in order to evaluate the performance of a multicellular WiMAX network under different frequency reuse schemes. These simulation results confirm that the employment of fractional frequency reuse, in general, can improve the performance of the network. Simulation results show that the proposed load-balancing solution outperforms the already known distance-based and SINR-based approaches and improves all the performance indicators examined herein. The load-balancing scheme achieves to overcome the weakness of the SINR-based approach, that it cannot manage efficiently the available resources of both Reuse-1 and Reuse-3 zones, as their size varies.

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