

Advanced Interference Mitigation with Frequency Reuse Schemes in the IEEE 802.16m Uplink

Florian Wamser, David Mittelstädt, Dirk Staehle, Phuoc Tran-Gia
University of Würzburg, Institute of Computer Science, Chair of Communication Networks
Würzburg, Germany
{wamser,mittelstaedt,dstaehle,trangia}@informatik.uni-wuerzburg.de

ABSTRACT

Fractional frequency reuse is one of the key interference mitigation schemes of the IEEE 802.16m draft standard. This paper proposes a resource allocation strategy for the uplink fractional frequency reuse in the variant soft frequency reuse. Soft frequency reuse means that the resources of every sector are separated into a home partition and two side partitions. While resources of the home partition may be allocated to all users, resources of the side partitions are available for cell center users only. The main contribution of this paper is to use the most robust and power-efficient modulation and coding schemes on the side partitions as long as resources are available. A simulation study shows that with non-saturated users the system capacity can be increased when preferring power-efficient modulation and coding schemes on the side partitions.

Categories and Subject Descriptors

C.2.1 [COMPUTER-COMMUNICATION NETWORKS]: Network Architecture and Design—*Wireless communication*

General Terms

Algorithms, Performance

Keywords

IEEE 802.16m, WiMAX, OFDMA, Fractional Frequency Reuse, Uplink

1. INTRODUCTION

In future IMT advanced [12] compatible mobile communication systems like 3GPP LTE-Advanced [1] or IEEE 802.16m [11], a high utilization of the frequency spectrum is essential due to the ambitious requirements and performance objectives. Such a dense reuse of frequencies throughout the cells, results in high inter-cell

This work has been supported by the German Research Foundation (DFG) in context of the project *FunkOFDMA*.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

MSWiM'10, October 17–21, 2010, Bodrum, Turkey.

Copyright 2010 ACM 978-1-4503-0274-6/10/10 ...\$10.00.

interference (ICI). Consequently, benefiting from a dense reuse environment, requires the use of advanced interference mitigation schemes like cell/sector specific interleaving (CSSI), multi-base station MIMO, or (3) fractional frequency reuse (FFR) that either avoid ICI or ease its impact on concurrent transmissions. Some power control algorithms like fractional power control (FPC) [5,20] can also be counted as interference avoidance schemes [2,4].

Generally, FFR means that the available resources are partitioned in frequency or time domain and different reuse strategies are applied to the different partitions. Typically, every sector is assigned a home partition that should experience little ICI. Its resources may be allocated to all users in the sector. In particular, the low ICI allows to serve cell edge users in the home partition. Users in the cell center may additionally use either the side partitions, i.e. the home partition of the neighboring sectors, or a special partition shared by the cell center users of all sectors only. Assigning cell center users to side partitions is called soft frequency reuse (SFR) [9, 19, 21] and having an extra frequency reuse one (FR1) partition is called partial frequency reuse (PFR) [16, 18, 19]. Both variants and also their combination are supported and dynamically configurable in 802.16m. A more detailed overview of the different FFR schemes is given in Section 2.

In this paper, we focus on the evaluation of resource allocation strategies for an 802.16m network using SFR. In contrast to most previous work that considers the downlink with saturated users, we focus on the uplink with non-saturated users. Non-saturated users seem to be the more realistic choice for the uplink since the typical uplink traffic will consist of TCP ACKs, HTTP requests, voice, and video traffic, and some control packets. TCP connections with large data volume on the uplink are expected to occur only sporadically. The basic resource allocation strategy considered in this paper follows the approach presented in [17]. However, improved strategies how to allocate the resources on the side partitions are proposed. The key idea is to have a resource-efficient allocation on the home partition and in contrast, an interference- or power-efficient resource allocation on the side partitions. This is achieved by choosing high-data rate modulation and coding schemes (MCS) on the home partition and the most robust and power-efficient MCSs on the side partition. The effect of this interference-efficient resource allocation on the side partitions is evaluated with both homogeneous and clustered spatial user distributions.

The rest of the paper is structured as follows. In Section 2, different FFR schemes are described and an overview of the related work is given. Also, the parts of the 802.16m standard relevant for this paper are introduced. Section 3, describes the system model and the proposed resource allocation schemes. Section 4 gives details on how the different strategies are evaluated and in Section 5

the results are discussed. Finally, in Section 6, we summarize the main contribution of the paper and present our conclusions.

2. BACKGROUND & RELATED WORK

The background and related work on FFR is subdivided in three parts. First, the general idea of FFR and its different variants is introduced. Second, an overview of the related work on FFR schemes is given with a focus on results and evaluation methodology. Third, the specification of FFR in the IEEE 802.16m standard and related mechanisms are described.

2.1 Fractional Frequency Reuse

FFR in general means that ICI is mitigated by applying different frequency reuse factors over different parts of the transmission resource. The received signal quality is improved by serving mobiles in some frequency partitions with a frequency reuse factor close to one while in other partitions, interference to other cells is kept low with an interference efficient frequency reuse scheme.

In basic FFR, the resource blocks across the whole frame are system-wide grouped into resource partitions. This can be done in frequency as well as in time domain. Different frequency reuse schemes are applied to the resource partitions. Commonly, either three or four partitions are defined per frame [11]. Interference critical users, e.g. at the cell border, are allocated to a frequency partition with reuse factor greater than 1. Classically, FR3 is applied in case of three-sector sites. Thus, three partitions are applied per frame. Of these, one partition specifically belongs to one sector and is called home sector. The two other partitions are called side partitions and belong to the other sectors respectively. In a strict FR3, users are not allowed to use the side partitions at all. However, a typical case for FFR is that even the side partitions can be utilized up to a certain transmit power level. The power level is normally defined by a frequency power mask [3] which keeps the ICI below a maximum level. This means that per frequency partition, a power threshold is defined which the mobiles in the side partitions are not allowed to exceed. If additional to the home and side partitions one partition is reserved for users in the inner part of the cell, the FFR scheme is called PFR. Since users in the cell center generate less ICI, there a reuse factor of one is applied.

Other variants of FFR can omit an FR1 partition. In SFR, cell edge users are allocated to the home partition while cell center users may be allocated to both, the home and the side partitions. Choosing non-overlapping home partitions for neighboring sectors provides a low ICI which may be adjusted by the maximum side partition transmit power. In contrast to SFR, in coordinated reuse 1 (CR1), all users are allowed to use both, the side and home partitions without power limitation. However, the cell edge users are allocated to the home partition in order to achieve reuse factor three among them. Hence, in a scenario with non-saturated users, a large number of critical users are coordinated to use orthogonal resource partitions in such a way that they do not interfere with interference-critical users of other sectors. Coordinated reuse corresponds to an SFR scheme without power limitation in the side partitions.

In general, the number of resource partitions is not limited to three or four, they may be of different size, and the resources of a partition may be scattered over the whole frequency range. Furthermore, SFR can be combined with PFR by extending an SFR schemes with additional FR1 zone for the cell center users. The IEEE 802.16m standard provides a very flexible configuration of the FFR allowing both an PFR, an SFR, or a combined scheme.

2.2 Related Work

Xiang et al. [19] compare different fractional reuse schemes in OFDMA-based networks and their parametrization. They study SFR and PFR in comparison to simple FR1 and FR3 schemes in the downlink. They use a static power allocation on the available frequency band. Nevertheless, simulation is done with a sophisticated simulator which uses a packetized constant bit rate traffic model. The scheduling follows a channel-aware Round-Robin strategy. The cell edge/cell center users are differentiated by a geometry factor which is SINR based. Furthermore, they concentrate on Single-Input-Single-Output (SISO) antenna transmissions with fixed antenna patterns. Doppler et al. [7] also simulate SFR and PFR in the downlink. They use a SINR-based metric to determine an order to allocate the users. Critical users are allocated first. A scheduler is employed which is either a Round-Robin one or it schedules based on an equal throughput time domain fairness criteria. In contrast to other work, Doppler uses a Poisson arrival traffic model in a metropolitan Manhattan-like area as simulation scenario. Rahman et al. [14] does a comprehensive investigation of downlink FFR based on coordination with a utility function and a central controller. The central controller manages the allocation of mobiles to resources. Furthermore, they included TCP traffic in their simulation. Bohge et al. [3] investigate the impact of four different power mask configurations which result in FR1, FR3, SFR, and PFR. They compare the downlink performance of a network with a central controller against a network without a central controller. They reveal that there is a significant gap in performance between a locally optimal scheduler and the results of a global scheduler. Further on, in [21] Zhou and Zein simulate a mobile WiMAX system with OFDMA and PFR. They conclude that coverage and throughput increase compared to FR1 and FR3. The work is based on a simulated WiMAX system, but considers only the downlink, a full buffer, and PFR system. Simonsson [15] evaluates reuse schemes in the downlink and uplink of a 3GPP LTE network using a snapshot simulation with full buffer model. FR1, FR3, PFR, and soft reuse are considered. In the downlink a static transmit power is assumed. In the uplink, power control is employed and compensates for noise and path-loss. Multiple antenna configurations are tested. The best performing configurations for the reuse schemes are being compared. Link quality, spatial distribution, and service bandwidth impact are discussed. It is concluded that a simple FR1 performs best of the studied reuse schemes. It is further noted that dynamic co-ordination schemes are required to improve the performance for wideband packet data services. In general, FFR approaches are simple and easy to deploy. In fact, they do not rely on signaling. However, if signaling is additionally used, approaches like inter-cell interference coordination (ICIC) [8] or optimal interference mitigation solutions with a central controller [3, 14] can be applied. Finally, there are also graph theoretic approaches like [6, 13]. All the work uses homogeneous user distributions and to the best of our knowledge no work which focuses on the IEEE 802.16m standard exists.

2.3 IEEE 802.16m

In this section we introduce some key features of the IEEE 802.16m standard relevant for this paper. We also mention which configuration of the standard is chosen in the paper and where our model deviates from the standard.

In 802.16m the time is divided into 5ms frames that consist of 8 subframes. These subframes are separated into downlink and uplink subframes. In TDD mode, the ratio of downlink and uplink subframes is configurable but equal for all cells. A subframe consists of 5, 6, 7, or 9 OFDMA symbols, the typical value is six, other

subframe lengths are required to fill up a frame. In frequency domain a subframe is subdivided into physical resource units (PRUs) that span the whole subframe in time domain and consist of 18 subcarriers in frequency domain. In order to support FFR these PRUs are separated into up to four partitions in order to support different reuse schemes. For instance, partitioning pattern 1:0:0:0 leads to a FR1 scheme, 0:1:1:1 can be used for FR3 or for SFR, and 1:1:1:1 can be used for PFR or a combination of PFR and SFR. In the latter case, different ratios of the size of the first partition to the other three partitions are supported, e.g. 5:1:1:1 means that partition one is five times the size of the other partitions. The PRUs belonging to a partition are not contiguous in frequency domain but scattered individually or in groups of four over the whole frequency range. However, the partitioning scheme is a system-wide parameter and equal for all cells. The PRUs of a partition are mapped to logical resource units (LRU) which are numbered continuously. There are two types of LRUs, contiguous resource units (CRU) and distributed resource units (DRU). If a single CRU is mapped to a single individual PRU it is called a miniband, if a group of four neighbored CRUs is mapped to a group of four neighbored PRUs this is called a subband. The idea of CRUs is to enable a frequency selective scheduling. On the uplink, a PRU is further subdivided into three tiles of six subcarriers in frequency domain. All tiles of a partition that belong to PRUs corresponding to DRUs are permuted such that every DRU consists of three tiles scattered over the whole frequency band. The permutation is different in every cell and also for every subframe within a frame. Thus, a transmitted data burst consisting of several DRUs experiences a propagation loss averaged over the frequency band and also experiences an ICI averaged over the different interferences received from the mobiles in the neighboring cells. The DRUs enable a frequency diverse scheduling. The number of DRUs and CRUs is dynamically configurable per cell. In this paper, we consider partitioning pattern 0:1:1:1 with DRUs only, i.e. three partitions of equal size and a frequency diverse resource allocation.

The transmit power per partition is not directly limited by setting a maximum transmit power. Instead, a parameter called IoT is defined that defines the ratio of the measured downlink SIR to the SINR target, i.e.

$$\text{SINR target} = \text{IoT} \times \text{downlink SIR}.$$

The downlink SIR is measured at the mobile as the ratio of downlink received power to interference power. Uplink power control adjusts the transmit power of a mobile to match the SINR target. A lower IoT parameter also leads to a lower transmit power and consequently to a lower interference. Thus, lower IoT values are chosen for the side partitions and an IoT of one is selected for the home partition. Additionally, the SINR target also defines the maximum MCS available for the transmission.

Here, we deviate from the standard. First, per partition the transmit power per mobile is limited by a power factor which is common for all mobiles and cells. The power factor defines the percentage that a mobile is allowed to use of its maximum transmit power. With a power factor of 0.75, a mobile may not exceed 75% of its maximum transmit power. Second, we assume uplink power control according to the 802.16m open loop power control (OLPC) Mode 2, i.e. power control is adjusted to the SINR requirement of the MCS.² Third, we allow a dynamic selection from all MCSs with a satisfiable SINR requirement. A detailed description of our power control (PC) and adaptive modulation and coding (AMC) model is given in the next section. The 802.16m standard supports

²Please note that the OLPC Mode 2 was removed in the fourth version of the draft standard.

two possibilities to assign LRUs to a data burst. First, a data burst may consist of contiguous LRUs in a single subframe. Second, a data burst may consist of contiguous LRUs in all subframes. We deviate from that and assume that the LRUs are allocated to data bursts as in the IEEE802.16-2009 standard, i.e. all LRUs in a frame are first allocated in time domain and then in frequency domain in order to minimize the number of parallel LRUs in frequency domain.

3. SYSTEM MODEL

We consider a network with a set \mathcal{M} of M users connected to a set \mathcal{S} of S sectors. \mathcal{M}_x denotes the set of users connected to sector x and x_i is the sector user i is connected to. Using partitioning pattern 0:1:1:1 we have three partitions per sector and denote the home partition as A and the side partitions as B and C . The power factor $\hat{p}_{x,Z}$ defines the fraction of the maximum mobile transmit power P^{max} which is allowed for transmissions in partition $Z \in \{A, B, C\}$, i.e. the maximum transmit power is $P_{x,Z}^{max} = P^{max} \cdot \hat{p}_{x,Z}$. In the following, we assume that the power factor is equal for all sectors and the maximum power P_Z^{max} depends on the partition only.

3.1 Power Control and Adaptive Modulation and Coding

Let us now consider a user $i \in \mathcal{M}_x$ that has to transmit V bits of data. Further, let $I_{x,Z}$ be the average interference for partition Z at sector x and $L_{i,x}$ be the average propagation gain from i to x . If mobile i uses MCS k , it occupies $R_k(V)$ LRUs and requires an SINR γ_k^* . The power $P_{k,Z}^{sc}(V)$ that a mobile can spend per subcarrier depends first, on the power factor specified by the interference mitigation scheme and second, on the maximum number $C_k(V)$ of parallel subcarriers that the $R_k(V)$ LRUs occupy. Consequently, the power per subcarrier is $P_{k,Z}^{sc}(V) = P_Z^{max} / C_k(V)$. The OLPC adjusts the transmit power to the MCS specific SINR target γ_k^* such that the required power per subcarrier for MCS k is

$$P_k^*(I, L) = \gamma_k^* \cdot (N_0 + I) \cdot L \quad (1)$$

where N_0 is the noise power. Consequently, on partition Z a mobile i may use all MCSs that require less than the maximum power, i.e.

$$\mathcal{K}_{Z,i} = \{k | P_k^*(I_{x_i,Z}, L_{i,x_i}) \leq P_Z^{max}\} \quad (2)$$

is the set of available MCSs. If the standard AMC strategy is used that chooses the most resource-efficient MCS, then the MCS $k_{i,Z}$ selected for mobile i when allocated to partition Z is

$$k_{i,Z} = \arg \min_{k \in \mathcal{K}_{Z,i}} \{R_k(V)\}. \quad (3)$$

The required transmit power on partition Z is

$$P_{i,Z} = P_{k_{i,Z}}^*(I_{x_i,Z}, L_{i,x_i}) \quad (4)$$

and the number of required LRUs is $R_{i,Z} = R_{k_{i,Z}}(V)$.

3.2 Resource Allocation Strategy

This section describes an algorithm how to assign a given set of users to the three partitions of the network. The algorithm assumes, that the propagation gains to all sectors are known. In the following, we first describe the resource allocation algorithm defined in [17] and then we introduce the idea of a power-efficient resource allocation on the side partitions and different implementations.

The task of the resource allocation as defined in [17] is to allocate users to different partitions, the home partition A and the two side

partitions B and C depending on the interference per partition and the mobiles propagation loss to the different sectors.

The idea is to allocate interference critical users to the home partition. To do this the users within a sector are made comparable by defining a metric $O(i)$ that estimates the interference criticalness of a user i . Higher values of $O(i)$ indicate less critical users. In [17] different metrics like propagation gain, propagation gain ratio, and produced side partition ICI were compared. The maximum side partition ICI first metric showed the best performance so it is used in this paper. The side partition ICI is the ICI produced by a user when scheduled on the better side partition. It is defined as

$$I_i^{oc} = \min_{z \in \{B,C\}} R_{i,z} P_{i,z} \sum_{y \in S \setminus x} \frac{1}{L_{i,y}} \quad (5)$$

and its inverse is used as ordering metric. Let $U_{x,z}$ be the set with already allocated users for frequency band Z in sector x . Recall that $R_k(V)$ is defined as the number of LRUs needed with MCS k for a data volume V . Furthermore, R_Z^{max} is the maximum available number of LRUs in a band Z . The function

$$c(i, k, Z) = \begin{cases} 1 & \text{if } \sum_{j \in U_{x,z}} R_{k,j,z}(V_j) + R_k(V_i) \leq R_Z^{max} \\ 0 & \text{else} \end{cases} \quad (6)$$

checks if enough resources are available on band Z to allocate user i . The resource allocation starts with an empty set $U_{x,A}$ on the home partition and iteratively allocates mobiles i to partition A in ascending order of $O(i)$ as long as $c(i, k_{i,A}, A) = 1$. If the home partition is fully utilized, the remaining users are allocated to one of the two side partitions. This assignment takes place in order of a decreasing difference of required resources per side partition, i.e. those users who have a clear preference for one of the two side partitions are allocated first. If there are insufficient resources to allocate all users, one or more users experience outage. In order to maintain the spatial distribution within a cell, random users are iteratively removed from the set \mathcal{M}_x until sufficient resources may be allocated to all remaining users.

3.3 Interference-efficient Resource Allocation on the Side Partition

The standard AMC minimizes the number of resources required for transmitting a certain amount of data. This is achieved by using all available power in order to use the most resource-efficient MCS. A lower-order MCS is more robust, requires a lower SINR, and according to Eq. (1) a lower transmit power per symbol. On the other hand, the number of resources increases. Let us investigate the total power, i.e. not the power per symbol but the power to transmit the entire data volume, required by the different MCSs.

Assume that each user has to send the same amount of data. To transmit V bits with MCS k , $R_k(V)$ resource units are required. Further on, $P_k^*(I, L)$ denotes the required transmit power per sub-carrier and OFDMA symbol. With N_{RU} as the total number of symbols per resource unit, the cumulative transmit power of a mobile in a frame is

$$P_k^{cumul} = P_k^*(I, L) \cdot R_k(V) \cdot N_{RU}. \quad (7)$$

The power P_k^{cumul} is proportional to the interference the mobile produces in neighboring sectors as shown in Eq. (5).

Figure 1 shows P_k^{cumul} as a function of the used MCS. Interference from other mobiles is not assumed, i.e. $I_{x_i} = 0$, and the propagation loss L is set to -100 dB. Obviously, the cumulative transmit power is by far higher if higher-order MCSs are used. Also the difference between two consecutive MCSs is increasing. This

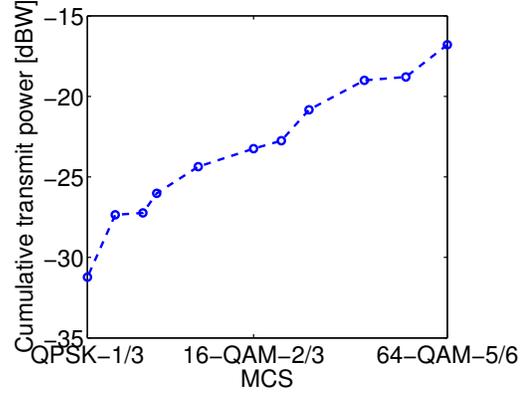


Figure 1: Relation of cumulative transmit power and MCS for a fixed data volume

becomes clear when considering that the Shannon capacity is increasing with the logarithm of the SINR. In contrast, the cumulative transmit power increases only linear with the number of resources. For the same data volume, the cumulative power required to send the data is considerably lower for a low-order MCS compared to a high-order MCS. This fact makes it favorable to select lower MCSs if possible. As a consequence, all LRUs should be utilized in order to enable lower-order MCSs instead of transmitting on a few LRUs with high-order MCS.

3.3.1 Application to FFR

A trade-off exists between using a lower-order MCS which is power-efficient and thus, also ICI reducing, and a high-order MCS which allows to support a large number of users.

With the MCS optimization we propose in this paper, the resource allocation is able to optimize the frame according to both objectives. As commonly done, the first objective is a resource-efficient allocation. Power control determines the power required for a transmission at MCS k and propagation loss L . MCS k is chosen by the AMC function. Thus, the primary goal of AMC/PC is the minimization of resources. This method works well for systems that are rather resource than interference-limited. This applies for an FR3 scheme in the home partition of an FFR, for instance. The allocation strategy for the home partition is to serve as many users as possible as the number of users is limited by the available resources only. Also, the ICI is not too critical since in the neighboring sector this partition is used as side partition and serves users with high propagation gain.

In an FR1 scheme, the situation is different. All resources can be used with the consequence that ICI occurs in the home partitions of neighboring sectors. The system becomes interference-limited. In such a case, reducing the MCS results in a more power-efficient transmission and hence decreases the total ICI. As mentioned above, the effect of a power-efficient resource allocation appears if there are available resources in some sectors while neighboring sectors are crowded. This happens with heterogeneous user distributions, due to under-utilized cells, or inefficiently scheduled frames. Especially in the uplink, where the typical traffic consists of acknowledgments and HTTP requests, the case that not all resources are utilized is rather frequent. If not all resources are used, it is better to choose a lower-order MCS to spread the users over all available resources. The power requirements of the users in such a cell becomes lower and consequently, the ICI is reduced and the

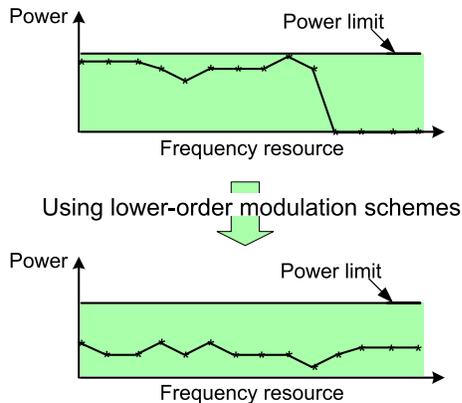


Figure 2: MCS optimization concept in the uplink

overall throughput of the network is increased. The fact is illustrated in Figure 2.

The side partitions of an SFR are extremely interference-critical since the users allocated to the side partitions produce interference to the home partition of the neighboring sectors. The power factor of the side partition is configured with the objective to maximize the system capacity when all cells are fully loaded. If some cells experience a lower load they will not entirely utilize the resources available on the side partition and there is room for selecting lower-order MCSs. This decreases the interference in the home partitions of the neighboring sectors such that more users can be allocated to these home partitions. Since the interference on the side partitions stays roughly the same, the same number of users can be allocated there. Thus, the total number of served users increases and the number of outage users decreases.

3.3.2 MCS Optimization

In this section we introduce an algorithm how to change a resource-efficient resource allocation to a power-efficient resource allocation. The general idea is to consider both side partitions separately and to start with a resource-efficient resource allocation according to the standard AMC as described in 3. Then, all users in the side partition are considered iteratively and the next MCS with lower-order is chosen if possible, i.e. if enough resources are available. Three metrics, highest MCS first, highest cumulative power first, and highest ICI first, are considered.

Concretely, the MCS optimization works as follows:

Let R_Z be the number of resources occupied in partition Z and R_Z^{max} be the number of available resources. Then, we define the next lower MCS k_i^{next} of user i as

$$k_i^{next} = \max \{k | R_k(V) > R_{k_i, Z}(V)\}. \quad (8)$$

The function

$$r(i) = \begin{cases} 0 & \text{if } R_Z - R_{k_i, Z}(V) + R_{k_i^{next}}(V) \leq R_Z^{max} \\ 1 & \text{else} \end{cases} \quad (9)$$

determines the possibility to allocate user i to the MCS with next lower order. Then, the algorithm is outlined in Algorithm 1. The following metrics are defined to choose the next user to consider:

Reduce Maximum MCS First

The idea is to choose the user with maximum MCS first. Ties are broken using the metric $O(i)$ used for assigning users to the home band. Reducing the highest MCS first yields the

highest gain per symbol. The next user is selected by

$$k = \max_{j \in Q} k_{j, Z} \quad (10)$$

$$i = \arg \min_{\{j \in Q | k_{j, Z} = k\}} O(i) \quad (11)$$

Reduce Maximum Power First

The idea is to choose the user with maximum cumulative power first.

$$i = \arg \max_{j \in Q} P_{k_{j, Z}}^*(I_{x_j, Z}, L_{j, x_j}) \cdot R_{k_{j, Z}}(V) \cdot N_{RU} \quad (12)$$

Reduce Maximum Interference First

The idea is reduce the MCS of the user that leads to the highest reduction in ICI per additional resource. The difference in ICI is defined as

$$T(j) = \frac{I_{j, k_{j, Z}, Z}^{oc} - I_{j, k_j^{next}, Z}^{oc}}{R_{k_{j, Z}}(V) - R_{k_j^{next}}(V)} \quad (13)$$

with

$$I_{j, k_{j, Z}, Z}^{oc} = P_{k_{j, Z}}^*(I_{x_j, Z}, L_{j, x_j}) \sum_{y \in S \setminus x} \frac{1}{L_{j, y}} \quad (14)$$

The next user is the one with maximum $T(j)$.

Algorithm 1 MCS optimization algorithm

```

Q = Ux, Z
while Q ≠ ∅ do
  Choose user i according to strategy
  if r(i) = 1 then
    RZ = RZ - Rki, Z(V) + Rkinext(V)
    ki, Z = kinext
  else
    Q ← Q \ i
  end if
end while

```

4. SIMULATION METHODOLOGY

The simulation of the resource allocation of the IEEE 802.16m uplink is carried out using a time-invariant Monte Carlo simulator. It is based on fundamentals of the IEEE 802.16m Evaluation Methodology Document [10].

The cell simulation considers a 5x5 deployment with hexagonal 3-sector sites. In order to avoid bounding effects and thus, an overestimation of the system performance, wrap around is applied which ensures that all cells experience the same interference characteristics. Table 1 provides central modeling parameters and assumptions. The simulator is able to process non-MIMO antenna configurations including different downtilts, diverse antenna patterns, and different user traffic volumes. In all simulations, error free feedback from the MS to the BS is assumed. For the simulations, frequencies in the 3.5 GHz band are chosen. We consider an OFDMA system with FFT size of 512 subcarriers. After eliminating the guard subcarriers, we effectively use 432 data subcarriers. One transmission frame is simulated with a fixed traffic demand of V bits per user. First, the users are randomly placed to the cell scenario. Next, the simulation allocates the resources of the frame to the users, assuming no ICI. The simulation is carried out and the received interference level at each sector is calculated. The steps are repeated as long as the interference does not converge from one

Table 1: Simulation parameters

Cellular layout	25 hexagonal, trisectorized cells
Site-to-site distance	0.5 km
BS/UE antenna height	30 m, 1.5 m
Carrier freq. f , Bandwidth	3.5 GHz, 5 MHz
FFT size, # subchannels	512, 24
Frame length	5 ms
Antenna configuration	Single-Input-Single-Output
Antenna horizontal pattern	$A(\theta) = -\min \left[12 \cdot \left(\frac{\theta}{\theta_{3dB}} \right)^2, A_M \right]$, $\theta_{3dB} = 70^\circ, A_m = 20dB$
Antenna vertical pattern	$A(\delta) = -\min \left[12 \cdot \left(\frac{\delta - \delta_{tilt}}{\delta_{3dB}} \right)^2, A_M \right]$, $\delta_{3dB} = 6.2^\circ, A_m = 18dB$
BS/UE antenna gain	14 dBi/0 dBi
Path loss model	$PL[dB] = 35.2 + 35 \log_{10}(d) + 26 \log_{10}(f/2)$
UE thermal noise density	-174 dBm/Hz
UE maximal power	200 mW
Channel State Information	Perfect CSI

iteration to the next iteration. During the simulation individual random users are blocked by the outage selection. This occurs if the system a) runs out of free resources, b) the power of the mobiles is not sufficient for transmission due to propagation loss or interference, or c) the user's transmission power is sufficient however it exceeds the maximum power limit defined by the power mask for the transmission resource.

The simulation supports different spatial user distributions. Users can be scattered according to a homogeneous spatial Poisson process or to a Matern cluster process. Spheres of fixed size t are generated. Each sphere is subsampled with a Poisson point distribution with a certain mean. The Matern processes can be easily modified by changing the Matern cluster radius. The simulation supports different power control algorithms and the partial FFR which are not investigated in this paper. The path loss is modeled with the urban macrocell path-loss model [10]. The user antenna is considered to be omni-directional with a gain of 0 dB.

4.1 Limitations of the System Model

To allow a large multi-cell simulation scenario and a feasible implementation of the model, assumptions are made which are enumerated below for completeness.

The model does not employ a time-variant scheduler. The focus lies on the resource allocation to examine the effects of FFR. In general, it is assumed that the scheduler can be decomposed into a QoS-based or fairness-based packet selection and the resource allocation. The resource allocation thereby is the final task to assign the data to the transmission resource. Thus, it is essential for all other functions in the network to optimize the resource allocation. Furthermore, the model does not consider the opportunities of MIMO and beamforming. Primarily focus is on the diverse effects of FFR as interference mitigation. Finally, HARQ and time-variant fading is not included in the model. Mainly, this is due to the complexity of the fading and HARQ, and the simulation type used for evaluation. A time-invariant Monte Carlo simulation is used to enable a comprehensive simulation which allows a large number of users and cells.

5. NUMERICAL RESULTS

The focus of this paper is to investigate the capability of FFR in the uplink of an IEEE 802.16m network in conjunction with the proposed MCS optimization on the side partitions. To provide a feasible evaluation, SFR is compared with other frequency reuse schemes. Furthermore, the behavior at high load and on different spatial user distributions is investigated.

5.1 Scenario

For the system evaluation, several parameters are used which are enumerated for completeness. The results are generated with 1 to 26 users per sector. The users transmit 1024 bits per frame. The vertical downtilt of the base station antenna is set to 11° . In this paper, we consider the average cell outage percentage as performance measure. It is calculated per cell sector and afterwards, the mean is derived of all 75 sectors to get the average outage. The outage percentage is equivalent to the throughput per sector due to a fixed transmission rate of the mobiles. Each curve shown in the results corresponds to the average of at least 20 samples. Additionally, the 95 % confidence intervals are included in all figures.

5.2 Simulation Results

To investigate the capability of SFR with MCS optimization, first the performance of SFR without MCS optimization is investigated in this section. It is compared to baseline FR3 and CR1. Then, the impact of the proposed MCS optimization is evaluated. Furthermore, since the SFR is highly dependent on the power factor, the outage is calculated versus the power factor with and without MCS optimization. Furthermore, we proposed different versions of the MCS optimization. In the following scenario, they are examined and compared. Finally, the performance of CR1 and SFR is evaluated with a clustered Matern process instead of a homogeneous spatial Poisson distribution.

In the following, the power factor of SFR $\hat{p}_{x,B}$ and $\hat{p}_{x,C}$ is set to -12 dB for the side partitions B, C of each sector x . Furthermore, the users are scattered according to a homogeneous spatial Poisson process with 1 to 26 users on average per cell.

We compare SFR without MCS optimization to FR3 and CR1. In Figure 3(a) the outage versus the mean number of users per sector is shown. FR3 generates outage at an average number of 16 users per cell. In contrast, with CR1 there is outage at an average number of 18 users. However, the curve of CR1 rises significantly faster since the interference becomes the limiting factor in the network. FR3 uses only one third of the transmission resources whereas CR1 uses the whole resources however accepting ICI. Further on, SFR has a similar shape as FR3 but experiences outage not before 21 users per sector. It employs the power mask threshold that keeps the interference to other sectors at a certain limit. SFR is able to utilize more resources than FR3 and generates less ICI than CR1. Thus, this scheme greatly tackles the trade-off between resource efficiency and ICI reduction. SFR performs at all loads better than either CR1 or FR3.

In the second scenario, the performance analysis of the additional MCS optimization is presented in Figure 3(b). We simulate CR1 and SFR. Both are evaluated with and without the MCS optimization. In case of SFR the MCS optimization is done in the side partitions. The "reduce maximum MCS" strategy is used. Both approaches perform significantly better with the MCS optimization enabled, independent of the average sector load. For CR1, the performance benefit is about 2 users per sector. In this case, for a load at 26 users there is still a gain with the MCS optimization. This gain decreases when further increasing the load. For SFR, one

additional user per sector can be accepted which results from the lower ICI due to the MCS reduction in the side partitions.

Next, we investigate the impact of the power factor of SFR. Figure 3(c) shows the power factor at the x-axis and the random outage at the y-axis. Again, the "reduce maximum MCS" strategy is used. Four curves are plotted. One curve reflects the parameter at a load of 26 users per sector on average. The other solid curve shows the same for 24 users. The dashed curves respectively show the behavior with MCS optimization enabled. The curves get smoother around the minimum with MCS optimization enabled. Thus, a less accurate adjustment of the factor can be tolerated. Furthermore, with increasing the average number of users, the minimum is shifting to higher power factors. Hence, the optimal setting for SFR, depends on the load in the sector. With MCS optimization enabled the minimum is at -12 dB for 26 users and at -10 dB for 24 users. However, considering the confidence intervals, with MCS optimization it is sufficient to choose a parameter at -10 dB since the error is only marginal.

In Figure 3(d), the different MCS optimization strategies "reduce maximum MCS", "reduce maximum transmit power", and "reduce maximum interference" are evaluated with the same configuration as in the figure before. There is no large impact on the performance of the MCS optimization if the power factor is chosen in a feasible way. The same behavior can be found for 24 users and 26 users. Furthermore, the plot shows the outage versus the power factor for 22 users. The minimum is at -6 dB. This additionally supports the outcome of Figure 3(c) that the power factor is dependent on the user load. The difference between the outage at -6 dB and -12 dB is again only marginal.

In all previous evaluations, the users were scattered according to a Poisson process in the network. In contrast, the performance evaluation is now investigated under more realistic conditions with a clustered Matern process. The number of clusters is set to 20. The first investigation is the impact of the cluster radius on CR1. Figure 3(e) shows the performance at either a cluster radius of 1 km or a radius of 0.5 km. The x-axis displays the overall average number of users per sector however this is now highly different in each sector since the users are clustered around 20 certain cluster centers. The y-axis shows the outage as in previous figures. As expected, with a decrease in the cluster radius, the outage probability increases since groups of users occur more frequently. A sector may experience outage while other sectors are idle. Here again, the MCS optimization plotted in dashed lines improves the system performance.

Finally, SFR is investigated with a clustered user distribution. In Figure 3(f) the same study is done as in Figure 3(c) except the user positions. The result is quite the same as in the homogeneous case. The MCS optimization allows a more robust choice of the optimal power fraction parameter used in the power mask of SFR.

6. CONCLUSION

In this paper, we considered an SFR scheme compliant to the FFR scheme proposed in the IEEE 802.16m draft standard. The focus is on the uplink with a non-saturated user model where a number of users have to send a certain amount of data in a single frame. This is realistic for the uplink where main traffic consists of TCP ACKs, requests, and voice packets while only sporadic TCP connections with large data volume on the uplink occur. This leads to the situation that neighboring cells can be unevenly loaded such that some cells require only a part of the resources available on the side partitions. We have proposed to use a power-efficient resource allocation instead of the standard resource-efficient allocation strategy on the side partitions while keeping the resource-efficient allo-

cation strategy on the home partition. The key idea of the power-efficient allocation strategy is to utilize all available resources in order to transmit with the most robust MCS that requires a considerably lower SINR and hence, a lower total transmit power.

The impact of this MCS optimization was investigated using a Monte-Carlo simulation with 25 cells. Two spatial user distributions were considered. In the first one, the users follow a homogeneous spatial Poisson process, in the second one, a clustered Matern process is used. The simulation studies lead to the following results: First, in the chosen scenario (uplink, non-saturated, frequency-diverse resource allocation) SFR clearly increases the system capacity compared to a coordinated reuse 1 or reuse 3 scheme. Second, choosing a power-efficient MCS allocation strategy (lowest possible MCS) instead of a resource-efficient MCS allocation strategy (highest possible MCS) on the side partition further increases the system capacity by up to two users. Third, a system with MCS optimization is more robust with respect to the power limitation. A large range of values lead to optimal performance independent of the number of users.

7. REFERENCES

- [1] 3rd Generation Partnership Project. 3GPP TS 36.913 V9.0.0.; Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) (LTE-Advanced), December 2009. V9.0.0.
- [2] M. Abaïi, G. Auer, F. Bokhari, M. Bublin, E. Hardouin, O. Hrdlicka, G. Mange, M. Rahman, and P. Svac. IST-4-027756 WINNER II; Interference avoidance concepts, June 2007.
- [3] M. Bohge, J. Gross, and A. Wolisz. Optimal power masking in soft frequency reuse based ofdma networks. In *Proc. of the European Wireless Conference 2009 (EW'09)*, pages 162–166, 2009.
- [4] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic. Interference Coordination and Cancellation for 4G Networks. *IEEE Communications Magazine*, 47(4):74–81, April 2009.
- [5] C. Castellanos, D. Villa, C. Rosa, K. Pedersen, F. Calabrese, P. Michaelsen, and J. Michel. Performance of uplink fractional power control in UTRAN LTE. In *Proc. IEEE Vehicular Technology Conference (VTC-Spring 2008)*, pages 2517–2521, 2008.
- [6] R. Chang, Z. Tao, J. Zhang, and C. Kuo. A Graph Approach to Dynamic Fractional Frequency Reuse (FFR) in Multi-Cell OFDMA Networks. In *Proc. of the IEEE ICC 2009*, June 2009.
- [7] K. Doppler, C. Wijting, and K. Valkealahti. Interference Aware Scheduling for Soft Frequency Reuse. In *Proc. of the IEEE Vehicular Technology Conference (VTC'09)*, 2009.
- [8] Ericsson and 3rd Generation Partnership Project. 3GPP R1-074444; On Inter-cell Interference Coordination Schemes without/with Traffic Load Indication, October 2007.
- [9] Huawei and 3rd Generation Partnership Project. 3GPP R1-050507; Soft Frequency Reuse Scheme for UTRAN LTE, May 2005.
- [10] IEEE. IEEE 802.16m Evaluation Methodology Document (EMD), January 2009.
- [11] IEEE P802.16m/D3. DRAFT Standard for Local and metropolitan area networks; Part 16: Air Interface for Broadband Wireless Access Systems, Advanced Air Interface, Dec. 2009.
- [12] ITU-R. REPORT ITU-R M.2134, Requirements related to

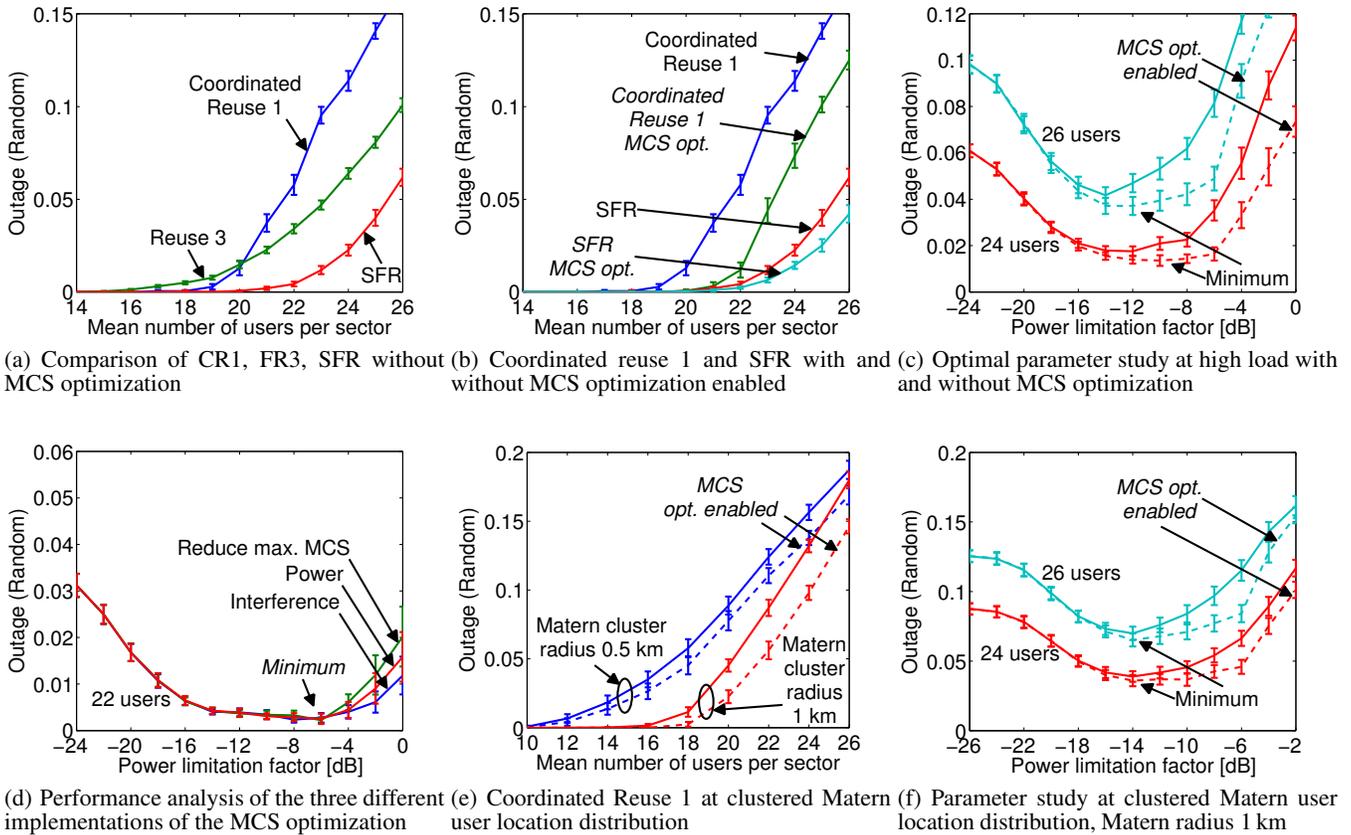


Figure 3: Performance analysis of the frequency reuse schemes at different loads and different kinds of user location distributions

technical performance for IMT-Advanced radio interface(s), Nov. 2008.

[13] M. Necker. A Graph-Based Scheme for Distributed Interference Coordination in Cellular OFDMA Networks. In *Proceedings of the 67th IEEE Vehicular Technology Conference (VTC2008 - Spring)*, May 2008.

[14] M. Rahman and H. Yanikomeroglu. Enhancing Cell-Edge Performance: A Downlink Dynamic Interference Avoidance Scheme with Inter-Cell Coordination. *IEEE Transactions on Wireless Communications*, page 1, 2010.

[15] A. Simonsson. Frequency reuse and intercell interference co-ordination in E-UTRA. *Proc. IEEE VTC 2007-Spring*, pages 3091–3095, 2007.

[16] M. Sternad, T. Ottoson, A. Ahlén, and A. Svensson. Attaining both Coverage and High Spectral Efficiency with Adaptive OFDM Downlinks. In *Proceedings of IEEE Vehicular Technology Conference, VTC2003-Fall*, Orlando, Florida, October 2003.

[17] F. Wamser, D. Mittelstädt, and D. Staehle. Soft Frequency Reuse in the Uplink of an OFDMA Network. In *IEEE VTC Spring 10*, Taipei, Taiwan, May 2010.

[18] WiMAX Forum. Mobile WiMAX Part I: A Technical Overview and Performance Evaluation, February 2006.

[19] Y. Xiang, J. Luo, and C. Hartmann. Inter-cell interference mitigation through flexible resource reuse in OFDMA based communication networks. In *13th European Wireless Conference EW2007*, 2007.

[20] W. Xiao, R. Ratasuk, A. Ghosh, R. Love, Y. Sun, and R. Nory. Uplink power control, interference coordination and resource allocation for 3GPP E-UTRA. in *Proc. IEEE VTC-2006*, pages 1–5, 2006.

[21] Y. Zhou and N. Zein. Simulation Study of Fractional Frequency Reuse for Mobile WiMAX. In *Proc. IEEE Vehicular Technology Conference VTC Spring 2008*, pages 2592–2595, 11–14 May 2008.