Fractional Frequency Reuse and Interference Suppression for OFDMA Networks

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Rizwan Ghaffar, Raymond Knopp
Eurecom, 2229 route des Crêtes B.P.193
06904 Sophia Antipolis Cedex FRANCE
Email: rizwan.ghaffar@eurecom.fr, raymond.knopp@eurecom.fr

***Abstract*—The downlink performance of cellular networks is known to be strongly limited by inter-cell interference. In order to mitigate this interference, a number of frequency reuse schemes have recently been proposed. This paper discusses a novel fractional frequency reuse (FFR) scheme combined with interference suppression for orthogonal frequency division multiple access (OFDMA) networks, which are currently being considered in LTE-A and WiMAX IEEE 802.16m standardization processes. We confine to the case of cell edge users and show that the novel FFR scheme improves the spectral efficiency by allowing one out-of-cell interference. Then the proposed subcarrier and rate allocation ensures interference exploitation by the mobile station (MS) which results in the reduction of power consumption at the base stations (BSs). Interestingly no inter-cell interference coordination but only *a priori* frequency planning is required in the proposed scheme.**

I. Introduction

The 4th Generation (4G) of wireless mobile systems is characterized by Long Term Evolution (LTE) [1] and WiMAX [2] technologies which continue to evolve with higher data rates and improved Quality of Service (QoS) even for the cell edge users as the main targets. In order to achieve these, MIMO antenna techniques have been incorporated in these standards. The capacity promised by MIMO systems may not be fully realizable by conventional cellular architectures without additional control of inter-cell interference which limits throughput, in particular for cell-edge users [3].

These standards use Orthogonal Frequency Division Multiple Access (OFDMA) as a combined transmission and multiple access technique in the downlink. With OFDMA, the system bandwidth is split into a number of sub-carriers, each featuring a bandwidth smaller than the systems coherence bandwidth, on which data of different users is transmitted in parallel. While the sub-carrier thinness and the resulting large OFDM symbol time reduces the effect of inter-symbol interference (ISI), the orthogonality among them mitigates inter-carrier interference (ICI). By using appropriate cyclic prefixes, ICI and ISI can almost completely be avoided. However a key issue with OFDMA is the co-channel interference (CCI) or inter-cell interference: especially terminals located at the cell border largely suffer from the power radiated by the base station (BS) of neighboring cells in their communication band. OFDMA provides the ability for each BS to selectively allocate frequency subbands, rates and power to the users depending on their location in the cell, according to some predefined frequency reuse pattern which may lead to significant capacity gains for the overall network. There are three major frequency reuse patterns for mitigating inter-cell interference: hard frequency reuse, fractional frequency reuse (FFR) and soft frequency reuse.

Hard frequency reuse splits the system bandwidth into a number of distinct sub-bands according to a chosen reuse factor and lets neighboring cells transmit on different subbands. FFR [4] splits the given bandwidth into an inner and an outer part. It allocates the inner part to the *near* users (located close to the BS in terms of path loss) with reduced power applying a frequency reuse factor of one i.e. the inner part is completely reused by all BSs. For users closer to the cell edge (*far* users), a fraction of the outer part of bandwidth is dedicated with the frequency reuse factor greater than one. With soft frequency reuse [5], the overall bandwidth is shared by all base stations (i.e. a reuse factor of one is applied), but for the transmission on each sub-carrier, the BSs are restricted to a certain power bound.

Hard frequency reuse though simple in implementation suffers from quite reduced spectral efficiency. On the other hand, soft frequency reuse [6] [7] [8] has full spectral efficiency and is a strong tool for inter-cell interference mitigation. But as it implies centralized, coordinated resource allocation, such a system can be impractical in realistic settings involving a large number of BSs, random traffic and realistic path-loss models. However, an encouraging result is that by using even limited (yet practical) levels of coordination, significant performance benefits can still be obtained over a conventional cellular architecture [9]. FFR is considered as a compromise between hard and soft frequency reuse and is therefore a proficient option for future wireless systems. In the context of OFDMA systems, it has mainly been discussed in cellular network standardization as 3GPP and 3GPP2 [4]. The notions of FFR and interference avoidance also appear in [10].

In this paper we particularly focus on the cell edge users and propose a novel FFR scheme coupled with interference suppression for these users. Unlike the traditional FFR, where outer frequency spectrum is orchestrated to eliminate the cell edge interference and resultantly has higher frequency reuse factor on cell boundaries, the proposed FFR ensures maximum of one interference to the targeted cell edge users and consequently has improved spectral efficiency. Subcarriers and corresponding rates are then allocated in a way not

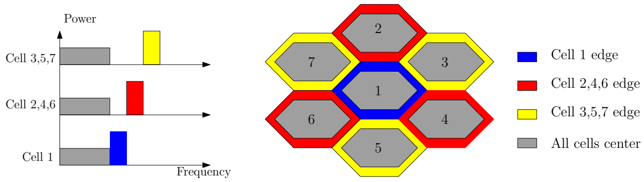

Fig. 1. FFR in LTE. Frequency reuse factor for cell edge users is 3.

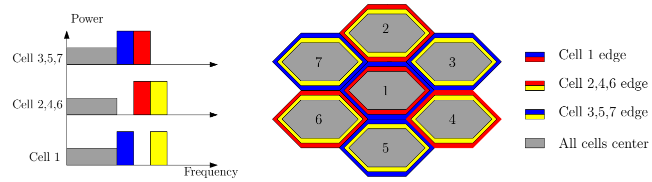

Fig. 2. Proposed FFR in LTE. Only one interference is ensured in the worst case scenario. Frequency reuse factor for cell edge users is 1.5.

only to satisfy the required data rates but also to enable the users to exploit the interference structure in the decoding of desired signals which implies minimization of the transmit power at the BSs. The key idea of our approach is based on the exploitation of lower rate interference stream in the the decoding of higher rate desired stream. We show that for a given user spatial distribution and data requirements, the proposed approach results in the minimization of the transmit power at the BSs. An important feature of our approach, which makes it feasible and attractive for application, is that little or no coordination is required between the BSs.

The paper is divided into five sections. In section II, we define the system model and propose the novel FFR while section III encompasses the key idea of the proposed approach. Section IV gives a detailed account of this approach in the context of interference suppression. In the end we elaborate some relevant conclusions and indicate directions for future work.

II. Proposed FFR and the System Model

We consider the downlink of an OFDMA cellular system in which users are assigned a set of subcarriers at specific time slots for transmission of packets. As already discussed, the OFDMA system supports FFR by division of subcarriers into subbands. Fig. 1 shows the traditional FFR for LTE whereas fig. 2 shows the proposed FFR. From now on, we only focus on the outer part of spectrum which is reserved for the cell edge users. Traditional FFR ensures orthogonal allocation of subbands in neighboring cells for cell edge users leading to zero interference for the cell edge users. However the frequency reuse factor for cell edge users increases to 3 which leads from the simple calculation $1/\left[\left(3\left(\frac{1}{3}\right)+3\left(\frac{1}{3}\right)+\frac{1}{3}\right)/7\right]$. On the other hand, proposed FFR ensures maximum of one interference for the cell edge users and the frequency reuse factor subsequently reduces to 1.5 leading from the calculation $1/\left[\left(3\left(\frac{2}{3}\right)+3\left(\frac{2}{3}\right)+\frac{2}{3}\right)/7\right]$. This leads to an improvement of spectral efficiency by 33%. Basing on the proposed FFR, we now discuss the system model.

Suppose we have K cells (sectors) $k \in \mathcal{K} = 1,...,K$, and J sub-bands for the cell edge users $j \in \mathcal{J} = 1,...,J$, in the system. Time is slotted, so that transmissions within the network is synchronized. The BSs employ bit interleaved coded modulation (BICM) [11] based OFDMA system using antenna cycling [12] i.e. the antenna used by a particular stream at a BS is randomly assigned per dimension so that each stream sees all the degrees of freedom of the channel. A transmission in a cell, assigned to a subcarrier, causes interference to only one user in the neighboring cells that is assigned to the same subcarrier. So the received signal by user i in cell k on subcarrier j is written as

$$\mathbf{y}_{k,i,j} = \mathbf{h}_{k,i,j} x_{k,i,j} + \mathbf{h}_{k',i,j} x_{k',i',j} + \mathbf{z}_{k,i,j} \quad (1)$$

We assume that the subcarriers are narrowband and model each subcarrier as a frequency flat fading channel so $\mathbf{h}_{k,i,j} \in \mathbb{C}^{n_r}$ is the vector characterizing flat fading channel response from k-th BS to n_r receive antennas of i-th user at j-th subcarrier. This vector has complex-valued multivariate Gaussian distribution with zero mean and unit variance. Each subcarrier corresponds to a symbol from a constellation map. $x_{k,i,j} \in \chi_{k,i,j}$ is the desired symbol where $\chi_{k,i,j}$ denotes QAM constellation. $\mathbf{y}_{k,i,j}, \mathbf{z}_{k,i,j} \in \mathbb{C}^{n_r}$ are the vectors of received symbols and circularly symmetric complex white Gaussian noise of double-sided power spectral density $N_0/2$ at n_r receive antennas. $\mathbf{h}_{k',i,j}$ is the channel from the interfering k'-th BS to i-th user whereas $x_{k',i',j} \in \chi_{k',i',j}$ is the interfering symbol. The complex symbols $x_{k,i,j}$ and $x_{k',i',j}$ are assumed to be independent. The max log MAP bit metric for p-th bit for bit value b of the desired symbol $x_{k,i,j}$ in its full form is given as [11]

$$\lambda^p(\mathbf{y}_{k,i,j}, b) \approx \min_{x_{k,i,j} \in \chi^{p,b}_{k,i,j}, x_{k',i',j} \in \chi_{k',i',j}} \left\| \mathbf{y}_{k,i,j} - \mathbf{h}_{k,i,j} x_{k,i,j} - \mathbf{h}_{k',i,j} x_{k',i',j} \right\|^2 \quad (2)$$

$\chi^{p,b}_{k,i,j}$ denotes the subset of the signal set $x_{k,i,j} \in \chi_{k,i,j}$ whose labels have the value $b \in \{0,1\}$ in the position p. A low complexity max log MAP detector was proposed in [13] where it was shown that we can reduce one complex dimension in (2) i.e. the cardinality of the search space reduces form $\left|\chi^{p,b}_{k,i,j}\right| \left|\chi_{k',i',j}\right|$ to $\left|\chi^{p,b}_{k,i,j}\right|$. So by using this low complexity detector, the complexity of detection remains unchanged even with the introduction of one interference.

III. Key Idea Behind the Proposed Approach

Till now we have shown that the proposed FFR improves the spectral efficiency by 33% and the resultant interference does not increase the complexity of detection. We now move to the key idea of our proposed approach which is based on coordinating the inter-cell interference while satisfying the requested data rates of the users in such a way that the structure of interference can be exploited in the detection of desired stream. This exploitation leads to the reduction of required SNR at the MS while ensuring a predefined QoS

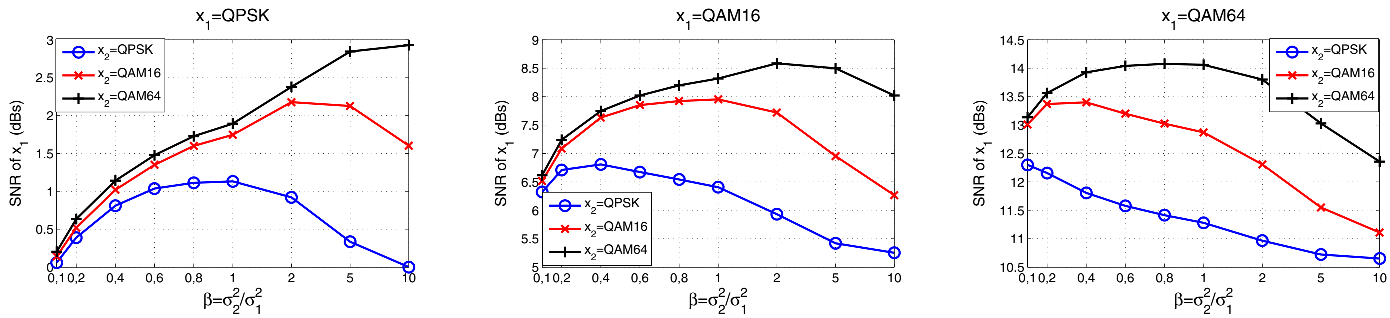

Fig. 3. For each value of β, SNR of x_1 is optimized to achieve target FER of 10^{-2}. 3GPP punctured rate 1/2 turbo code is used with 5 decoding iterations while the frame length of x_1 is fixed to 1056 information bits.

which subsequently leads to the minimization of transmitted power at the BSs.

Let $p_{k,i,j}$ be the power transmitted by k-th BS to i-th user at j-th subcarrier. So our objective in the network is to minimize the transmit power of BSs for the cell edge users while satisfying the required data rates for these users which can be written as

$$\min \sum_k \sum_i \sum_j p_{k,i,j}$$
$$\text{s.t.} \sum_{j \in k,i} \text{THR}_{k,i,j} \geq d_{k,i} \quad \text{For all values of } k \text{ and } i \tag{3}$$

where THR indicates throughput, d indicates the required data rate and $j \in k, i$ indicates the subcarriers allocated to i-th user in k-th cell.

Consider one of the cells, which needs to support N data flows to cell edge users. Then, for each such user $i \in \mathcal{I} = 1, ..., N$, the cell's BS can choose a group of subcarriers to assign it to. A good user-to-subcarrier assignment strategy, from the overall system performance point of view, would be one allowing the system to support the required/requested data rates with minimum transmitted power. As per the proposed FFR, assignment of a subcarrier to a user in a cell would cause interference to another user in one of the neighboring cells using the same subcarrier. Our objective is the allocation of rates/constellation to this subcarrier in both cells in a way that the generated interference can be exploited and therefore is beneficial in the decoding of the desired stream.

Consider fig. 3 which demonstrates the effect of rate and strength of interference stream in the decoding of desired stream using the low complexity version of (2). For these simulations, we have considered a MS equipped with two receive antennas receiving one interference stream x_2 along with the desired stream x_1 with the powers σ_2^2 and σ_1^2 respectively. $\beta = \sigma_2^2/\sigma_1^2$ defines the interference to signal ratio. The BSs use BICM OFDM system for downlink transmission using the punctured rate $1/2$ turbo code of 3GPP LTE [14][1]. Due to bit interleaving followed by OFDM, this can be termed as frequency interleaving. Therefore SIMO channel at each sub carrier from BS to MS has iid Gaussian matrix entries with zero mean and unit variance. Perfect CSI is assumed at the MS which can be realized in practice by ensuring orthogonal pilot signals of the neighboring BSs. The frame length of x_1 is fixed to 1056 information bits. For each value of β, SNR of x_1 is optimized to achieve target frame error rate (FER) of 10^{-2}. The simulations show that in case the interference x_2 has a lower rate as compared to the desired stream x_1, the required SNR decreases with the increase of interference strength which can be attributed to the partial decoding of interference by the max log MAP detector. In the case once interference and desired stream have same rate, decoding of x_1 starts getting benefit from x_2 once interference starts getting stronger than the desired stream, a case which is not relevant in cellular scenario due to handoff algorithms.

[1]The LTE turbo decoder design was performed using the coded modulation library www.iterativesolutions.com

IV. Proposed approach of Interference Suppression

Our proposed algorithm is based on the above discussed ability of interference exploitation. As the proposed FFR ensures maximum of one interference, so we consider only two neighboring cells U and V and focus on two cell edge users in each cell i.e. u_1 and u_2 in cell U while v_1 and v_2 in cell V. Without loss of generality, suppose that the required data rates imply transmission of QAM16 to u_1 and v_1 while QPSK to u_2 and v_2. Fig. 4 shows two possible ways of subcarrier assignment to fulfill the required data rates. In uniform rate streams (left figure), same subcarrier f_1 is used in both cells for transmission of QAM16 to u_1 and v_1 so both users see the interference from QAM 16 whereas same subcarrier is used for transmission of QPSK to u_2 and v_2 so these users see the interference from QPSK. In nonuniform rate streams (right figure), the subcarrier f_1 which is used for transmission of QAM16 to u_1 is used in the other cell for transmission of QPSK to v_2 and vice versa. In uniform rate streams, as both the interference and desired streams are from same constellation, so users can not efficiently exploit interference structure in the decoding of desired stream. However in the case of nonuniform rate streams, u_1 and v_1 see a lower rate interference stream and so subsequently can exploit it in decoding process. However u_2 and v_2 see higher rate interference and can not benefit from interference.

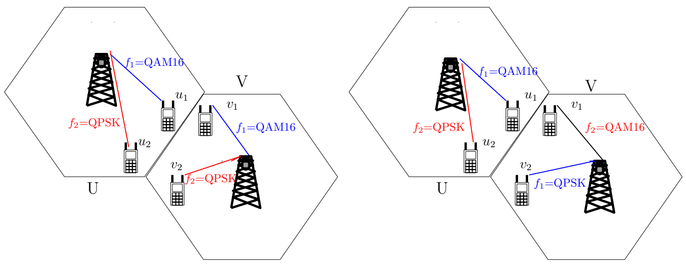

Fig. 4. Two ways of subcarrier assignment to the cell edge users. Left figure shows the case of uniform rate streams on a subcarrier in adjacent cells while right figure shows the case of nonuniform rate streams.

Now we consider the problem of power optimization in the case of nonuniform rate streams for a desired FER. We use the same model as was used in sec. III. We assume x_1 being the higher rate and x_2 being the lower rate stream. Firstly, we optimize SNR of x_1 to achieve the desired FER of 10^{-2} for different values of $\beta = \sigma_2^2/\sigma_1^2$. Then for these SNRs and the corresponding values of β, we find the corresponding SNRs of x_2 as $10 \log \left(\beta \times 10^{\text{SNR}_{x_1}/10}\right)$. Note that these SNRs of x_2 are not optimized to achieve the desired FERs. Subsequently for the considered values of σ_2^2/σ_1^2, we optimize the SNRs of x_2 to achieve the desired FER. Now this data gives an optimal value of β and the corresponding SNRs of x_1 and x_2 to achieve the desired FER on both streams.

To illustrate it further, consider the examples in fig. 5 where continuous lines indicate the required SNRs for decoding of x_1 and x_2 for different values of σ_2^2/σ_1^2 for the desired FER of 10^{-2}. For the required SNR for decoding of x_1, the corresponding SNR for x_2 is indicated by the dashed line. Note that the dashed line is not the required SNR of x_2 to achieve FER of 10^{-2}. The intersection of the dashed line and the continuous line (required SNR of x_2) gives us the operating point where both x_1 and x_2 will be decoded with the desired FER with the minimum power. This point has been indicated by dashed-dotted line.

Using this technique, the required SNRs with the corresponding β values for different combinations of constellations are shown in table (I).

Constellation combinations	Desired Parameters			
	$\beta = \frac{\sigma_2^2}{\sigma_1^2}$	SNR_{x_1}(dBs)	SNR_{x_2}(dBs)	$\frac{\sigma_1^2+\sigma_2^2}{N_0}$
x_1=QAM64, x_2=QPSK	0.117	12.22	2.90	18.62
x_1=QAM64, x_2=QAM16	0.329	13.38	8.55	28.94
x_1=QAM16, x_2=QPSK	0.347	6.75	2.15	6.37
x_1=QPSK, x_2=QPSK	1.0	1.13	1.13	2.59
x_1=QAM16, x_2=QAM16	1.0	7.95	7.95	12.47
x_1=QAM64, x_2=QAM64	1.0	14.06	14.06	50.94

TABLE I
OPTIMIZED VALUES OF β AND SNR OF x_1 AND x_2 TO ACHIEVE THE DESIRED FER OF 10^{-2} ON BOTH STREAMS.

The power savings by using the nonuniform rate streams with reference to uniform rate streams is shown in table (II). In this table two neighboring cells are considered where in each cell two cell edge users are considered with different data requirements. In uniform rate streams, same subcarrier in both cells has the same rate whereas in nonuniform rate streams, same frequency subcarrier in both cells has different rates thereby enabling some users to exploit the lower rate interference streams in the decoding process. The power indicated is the sum power of both the cells required to achieve FER of 10^{-2} for the users. Note that the power savings decline as the difference between the rates of two streams decreases which can be attributed to the reduction in the ability of exploiting interference structure.

Now the question is : Do the cells need to dynamically coordinate the allocation of subcarriers to ensure nonuniform rate streams in adjacent cells on same frequency resources? Such a coordination will certainly improve the performance but *a priori* frequency planning may also achieve limited objectives. One possible way is to divide the spectrum allocated for cell edge users into groups where subcarriers in each group have an upper rate limit. In the neighboring cells with overlapping frequency subcarriers, different rate limits for these groups can be incorporated in the frequency planning.

V. Conclusions

In this paper we have studied different frequency reuse schemes and have proposed a novel FFR scheme which has much improved spectral efficiency compared to the FFR strategy proposed for LTE which eliminates the inter cell interference. As the proposed FFR ensures maximum of one interferer to the cell edge users so we have further proposed an interference suppression strategy for these users, who will benefit from the interference exploitation. Our results show that a net power saving is achievable with our algorithm in the network satisfying the required QoS. This improvement comes at no cost of increased complexity or enhanced inter cell coordination.

VI. Future work

It is indeed worthwhile to compare the traditional and proposed FFR scheme though the two schemes have different spectral efficiencies. However by equating the spectral efficiency of two schemes, the power required to achieve the desired FER can be compared i.e. in traditional FFR, we can transmit a the data rate (e.g. QAM256) and can find the power required to achieve desired FER without interference. Then for the proposed FFR, we can use two subcarriers to transmit the same data rate (e.g. QPSK-QPSK) and then can find the power required to achieve the same FER but now each stream sees interference from the neighboring cell. Results on this comparison shall be included in the camera ready version.

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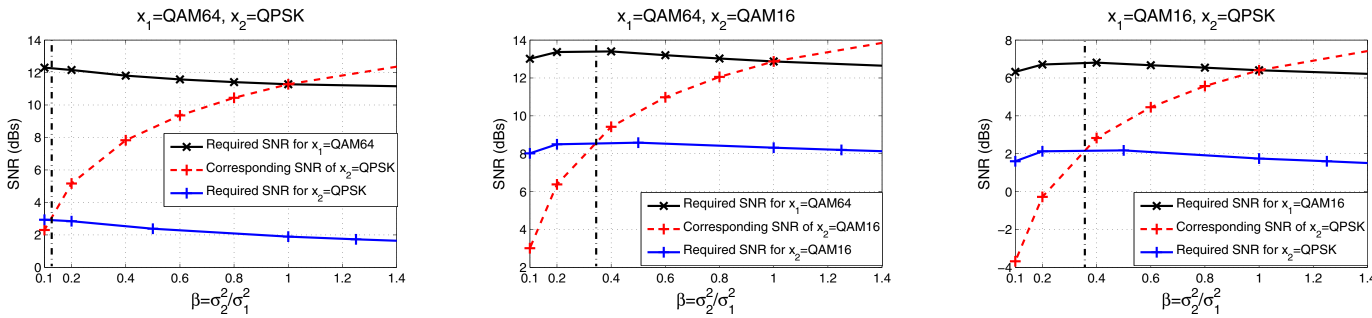

Fig. 5. Power optimization for two stream case. Higher rate stream is x_1 while lower rate stream is x_2. Desired FER is 10^{-2}. Continuous lines indicate the required SNRs to achieve this desired FER while dashed line indicate the corresponding SNR of x_2 for the required SNR of x_1. Dashed-dotted line indicates the optimal point where both streams achieve the desired FER with minimum SNRs.

Cell Edge Users		Uniform rate streams	Nonuniform rate streams	Power savings
Cell 1	Cell 2	$\frac{P_t}{N_0}$	$\frac{P_t}{N_0}$	%
1×QAM64, 1×QPSK	1×QAM64, 1×QPSK	50.94+2.59	18.62+18.62	30.43%
1×QAM16, 1×QPSK	1×QAM16, 1×QPSK	12.47+2.59	6.37+6.37	15.41%
1×QAM64, 1×QAM16	1×QAM64, 1×QAM16	50.94+12.47	28.94+28.94	8.72%

TABLE II
POWER SAVINGS OF NONUNIFORM RATE STREAMS OVER UNIFORM RATE STREAMS.

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