JOINT OPPORTUNISTIC BEAMFORMING AND SUBCARRIER ASSIGNMENT FOR MAXIMIZATION OF USER SATISFACTION IN OFDMA SYSTEMS

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***Abstract*—In this paper, we consider a system based on Orthogonal Frequency Division Multiple Access (OFDMA) and investigate the benefits of combining the Satisfaction Oriented Resource Allocation (SORA) algorithm [1], [2], which aims at maximizing the number of satisfied users in a system, and Orthogonal Random Beamforming (ORB) [3], [4], which provides spatial multiplexing gains and has low computacional complexity, low signaling demands, and high transparency to the User Equipment. Our investigations have shown that considerable gains in terms of throughput and user satisfaction can be achieved by combining SORA and ORB.**

I. INTRODUCTION

3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) represents an evolution step for 3rd Generation (3G) wireless communications systems. LTE aims at Uplink (UL) and Downlink (DL) data rates of up to 50 and 100 Mbps, respectively, and the technologies it employs at the Physical Layer (PHY) include Orthogonal Frequency Division Multiple Access (OFDMA), which allows to obtain Multiuser (MU) and frequency diversity gains using adaptive resource allocation [5], and Multiple Input Multiple Output (MIMO) antennas, which allows to obtain spatial multiplexing and diversity gains exploiting the spatial domain of radio channels [6]. In fact, standardization bodies have already started with the requirements definition and the investigation of technologies for the evolution of LTE, namely LTE-Advanced, which aims at meeting all requirements of the International Mobile Telecommunications (IMT)-Advanced initiative of the International Telecommunications Union (ITU) [7]. For this evolution, significant improvements in the Signal-to-Interference plus Noise Ratio (SINR) experienced by User Equipments (UEs) will be required and advanced MIMO techniques are being strongly considered.

In MU scenarios, Space Division Multiple Access (SDMA) can be used to simultaneously serve groups of UEs at the same frequency and so obtain spatial multiplexing and MU diversity gains [8]. Indeed, disposing of Channel State Information (CSI) at the transmitter and receivers permits that sophisticated spatial processing techniques be used, such as linear and non-linear precoding [9], and that system capacity be highly improved [6]. However, obtaining CSI requires that a considerable portion of bandwidth be dedicated for signaling, i.e., CSI estimation and/or feedback. For Time Division Duplexing (TDD) systems, channel reciprocity can usually be exploited and CSI estimated in UL can be used in DL, thus alleviating this issue. However, for Frequency Division Duplexing (FDD) systems, the CSI must be estimated in DL by the UEs and fed back to the Base Station (BS). In particular, for MU OFDMA-based systems using FDD, prohibitive signaling amounts would be needed if the complex channel coefficient for each transmit-receive antenna pair on each subcarrier had to be fed back to the BS. This issue inspired several schemes which do not rely on the CSI, i.e., on vectors or matrices of complex channel coefficients, but on scalar real-valued Channel Quality Indicators (CQIs) measuring the quality of the multi-antenna links. Examples are Fixed Switched Beams (FSB), also termed Grid of Beams (GoB) [10], Opportunistic Beamforming (OBF) [3], and Orthogonal Random Beamforming (ORB) [4]. Indeed, coherence grouping is usually considered for reducing signaling and a CQI is reported for a group of adjacent subcarriers, namely a Physical Resource Block (PRB) [11], instead of each subcarrier. CQI-based schemes have limited adaptivity but much lower signaling demands and complexity than CSI-based schemes. Moreover, they are efficient in exploiting MU/frequency diversity being asymptotically optimal for an increasing number of UEs [4].

In this paper, we extend the Satisfaction Oriented Resource Allocation (SORA) algorithm of [1], [2] – whose main goal is to guarantee that most of the users achieve their minimum Quality of Service (QoS) requirements – by combining it with ORB – which considers multiple antennas at the BS to randomly form narrow orthogonal beams used to multiplex several users in space and thus improve system capacity. Due to its reduced signaling demands, low complexity, and its ability to exploit MU and frequency diversity, ORB is a suitable technique to be combined with the SORA algorithm, as it will be seen in this paper. In section II, the considered system model is presented. In section III, the combination of the SORA algorithm with ORB is discussed and the extensions required to the SORA algorithm are introduced. Section IV presents the simulation results obtained for the conventional SORA and the SORA+ORB algorithms. Finally, section V draws some conclusions.

II. SYSTEM MODELING

We consider the DL of an OFDMA-based system with N subcarriers organized in a subcarrier set $\mathcal{N} = \{1, 2, \ldots, n, \ldots, N\}$, which are the system resources. A single

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BS equipped with an M-element Antenna Array (AA) is considered. It serves J single-antenna UEs organized in a UE set $\mathcal{J} = \{1, 2, \dots, j, \dots, J\}$. Dynamic subcarrier allocation works on a Transmission Time Interval (TTI) basis and the current TTI is indicated by k.

The channel coherence bandwidth is assumed much larger than the subcarrier bandwidth, so that we have flat fading on each subcarrier. The complex channel coefficients $h_{j,n,m}$ between the transmit antenna m and the UE j on subcarrier n are organized in the DL channel vector

$$\mathbf{h}_{j,n} = \begin{bmatrix} h_{j,n,1} & h_{j,n,2} & \dots & h_{j,n,M} \end{bmatrix} \in \mathbb{C}^{1 \times M}. \quad (1)$$

The BS can steer a narrow beam b towards a direction of interest by weighting the signals sent by each of its antennas. The complex weights $w_{n,m}$ used to steer beam b on subcarrier n are organized in the beamforming vector

$$\mathbf{w}_{n,b} = \begin{bmatrix} w_{n,1} & w_{n,2} & \dots & w_{n,M} \end{bmatrix}^{\mathrm{T}} \in \mathbb{C}^{M \times 1}, \quad (2)$$

which is assumed to have unitary norm. Indeed, the BS can steer B_n narrow beams on subcarrier n to spatially multiplex different data streams.

The total BS transmit power and the average noise power on each subcarrier are denoted by p and σ^2, respectively. The power p is divided among the subcarriers and the power of subcarrier n is denoted by p_n. The power p_n is further divided among the B_n beams of subcarrier n and the power of beam b on subcarrier n is denoted by $p_{n,b}$.

The Signal-to-Noise Ratio (SNR) $\gamma_{j,n,b}$ perceived by the UE j for beam b on subcarrier n is

$$\gamma_{j,n,b} = \frac{p_{n,b} \mathbf{w}_{n,b}^{\mathrm{H}} \mathbf{h}_{j,n}^{\mathrm{H}} \mathbf{h}_{j,n} \mathbf{w}_{n,b}}{\sigma^2}, \quad (3)$$

and the SINR $\tilde{\gamma}_{j,n,b}$ of UE j receiving data on beam b of subcarrier n is

$$\tilde{\gamma}_{j,n,b} = \frac{p_{n,b} \mathbf{w}_{n,b}^{\mathrm{H}} \mathbf{h}_{j,n}^{\mathrm{H}} \mathbf{h}_{j,n} \mathbf{w}_{n,b}}{\sigma^2 + \underbrace{\sum_{i=1, i \neq b}^{B_n} p_{n,i} \mathbf{w}_{n,i}^{\mathrm{H}} \mathbf{h}_{j,n}^{\mathrm{H}} \mathbf{h}_{j,n} \mathbf{w}_{n,i}}_{\text{intracell interference}}}, \quad (4)$$

so that the UE j is subject to interference from other beams.

Due to interference originating from the spatial reuse of subcarriers by UEs receiving data on different beams, a model to determine whether receptions are successfull is needed. Assuming interference as Gaussian-distributed and adding it directly to the noise, the Bit Error Rate (BER) for uncoded Quadrature Amplitude Modulation (QAM) can be approximated by

$$BER_{j,n,b} \approx 0.2 \exp\left[-(1.6 \tilde{\gamma}_{j,n,b})/(2^q - 1)\right], \quad (5)$$

where q is the number of bits/symbol [12]. Using (5) and considering that the data packet sent to user j on beam b of subcarrier n is decoded independently from other data, its Packet Error Probability (PER) can be written as

$$PER_{j,n,b} = 1 - (1 - BER_{j,n,b})^L, \quad (6)$$

where L is the number of bits contained in the packet [12].

III. Combination of SORA and ORB

In this section, the combination of the SORA algorithm with ORB is discussed. In section III-A, the SORA algorithm is presented. In section III-B, ORB is described and the related extensions to the SORA algorithm are discussed.

A. Satisfaction Oriented Resource Allocation

SORA is a low complexity algorithm conceived to exploit MU/frequency diversity as to satisfy as many UEs in the system as possible. For details, the reader is referred to [1], [2]. In the following, we shortly revisit the SORA algorithm.

As it is done in [5], the SORA algorithm divides the problem of maximizing the number of satisfied UEs into two steps:

- **Resource allocation step**: is responsible for determining how many subcarriers will be assigned to each UE. Its algorithm is shown in Table I, in which the cardinality of a set $\mathcal{S}$ is denoted by $|\mathcal{S}|$.
- **Resource assignment step**: decides which subcarriers are assigned to each UE. Its algorithm is shown in Table II.

In the allocation step, SORA builds per-service prioritized flow lists sorted by current QoS conditions. The highest priority flows of each service are scheduled for receiving data. In the assignment step, the scheduled flows get system resources assigned in an opportunistic way that aims at improving spectral efficiency.

In the allocation step, the algorithm first calculates the data rate Δr_j necessary for each UE j to achieve its average rate requirement $\overline{r}_j^{req}$ in the current TTI k. Δr_j can be negative for already satisfied UEs. In this step, $a_j[k]$ represents the time during which the UE j had data to receive from its associated buffer.

Let $F(\cdot)$ denote the link adaptation function that maps SNR values into data rates, $\lceil \cdot \rceil$ the lowest integer higher than or equal to the argument, and $\overline{\gamma}_j$ the average SNR of UE j over all subcarriers. Then, using $\overline{\gamma}_j$ the current subcarrier data rate of the UE j is estimated and used afterwards to calculate the number $m_j = \lceil \Delta r_j / F(\overline{\gamma}_j) \rceil$ of subcarriers needed to satisfy the UE on the TTI k and the number c_j of subcarriers necessary to empty its transmission buffer. Then, based on m_j, two sets are generated from $\mathcal{J}$:

- Set $\mathcal{S}$ of satisfied UEs: composed of UEs satisfied even if they do not receive data in the current TTI. UEs belonging to this set are have $m_j \leq 0$.
- Set $\mathcal{I}$ of unsatisfied UEs: composed of UEs that have the average data rate lower than their rate requirements. UEs belonging to this set have $m_j > 0$.

From $\mathcal{S}$ and $\mathcal{I}$, the allocation set $\mathcal{A}$ of UEs scheduled to receive data at the current TTI is composed by taking the UEs from $\mathcal{I}$ in ascending order of m_j values until the sum of allocated subcarriers $m_{alloc} = \sum_{j \in \mathcal{A}} m_j$ become higher than N. Moreover, if $\mathcal{I}$ is empty, the UE whose buffer can be empty more easily (smallest c_j) is scheduled.

In the assignment step, the UEs in $\mathcal{A}$, $\mathcal{I}$, and $\mathcal{S}$ are initially ordered by $\overline{\gamma}_j[k]$, cf. Table II. At this step, each UE in $\mathcal{A}$ has the opportunity to get one subcarrier assigned. When a

Table I
SORA RESOURCE ALLOCATION ALGORITHM.

for all $j \in \mathcal{J}$ **do**
  $\Delta r_j \leftarrow \overline{r}_j^{req} \cdot (a_j[k]+2) - \overline{r}_j[k-1] \cdot a_j[k]$
  if $F(\overline{\gamma}_j) = 0$ **then**
    if $\Delta r_j \geq 0$ **then**
      $m_j \leftarrow |\mathcal{N}|$
    else
      $m_j \leftarrow 0$
    end if
    $c_j \leftarrow m_j$
  else
    $m_j \leftarrow \lceil \Delta r_j / F(\overline{\gamma}_j) \rceil, \quad c_j \leftarrow \left\lceil r_j^{buf} / F(\overline{\gamma}_j) \right\rceil$
  end if
end for
$\mathcal{S} \leftarrow \{j | \Delta r_j \leq 0\}, \quad \mathcal{I} \leftarrow \{j | \Delta r_j > 0\}, \quad \mathcal{A} \leftarrow \emptyset$
if $\mathcal{I} = \emptyset$ **then**
  $j^\star \leftarrow \arg\min_j \{c_j | j \in \mathcal{S}\}$
  $\mathcal{A} \leftarrow j^\star, \quad \mathcal{S} \leftarrow \mathcal{S} \setminus \{j^\star\}$
else
  $m_{alloc} \leftarrow 0$
  $j^\star \leftarrow \arg\min_j \{m_j | j \in \mathcal{I}\}$
  while $m_{alloc} + m_{j^\star} \leq |\mathcal{N}|$ and $\mathcal{I} \neq \emptyset$ **do**
    $\mathcal{A} \leftarrow \mathcal{A} \cup \{j^\star\}, \quad \mathcal{I} \leftarrow \mathcal{I} \setminus \{j^\star\}, \quad m_{alloc} \leftarrow m_{alloc} + m_{j^\star}$
    $j^\star \leftarrow \arg\min_j \{m_j | j \in \mathcal{I}\}$
  end while
end if

Table II
SORA RESOURCE ASSIGNMENT ALGORITHM.

order $\mathcal{A}$, $\mathcal{I}$ and $\mathcal{S}$ by $\overline{\gamma}_j$
for all $j \in \mathcal{J}$ **do**
  $r_j \leftarrow 0$
end for
$j \leftarrow$ first element in $\mathcal{A}$
while $\mathcal{N} \neq \emptyset$ and $\mathcal{A} \neq \emptyset$ **do**
  $n^\star \leftarrow \arg\max_n \{\gamma_{j,n} | n \in \mathcal{N}\}$
  $\mathcal{N} \leftarrow \mathcal{N} \setminus \{n^\star\},\ r_j \leftarrow r_j + F(\gamma_{j,n^\star}),\ c_j \leftarrow \left\lceil (r_j^{buf} - r_j)/F(\overline{\gamma}_j) \right\rceil$
  if $r_j \geq r_j^{buf}$ **then**
    $\mathcal{A} \leftarrow \mathcal{A} \setminus \{j\}$
  else
    if $r_j \geq \Delta r_j$ **then**
      $\mathcal{S} \leftarrow \mathcal{S} \cup \{j\}, \quad \mathcal{A} \leftarrow \mathcal{A} \setminus \{j\}$
    end if
  end if
  if $\mathcal{A} = \emptyset$ **then**
    if $\mathcal{S} = \emptyset$ and $\mathcal{I} \neq \emptyset$ **then**
      $j^\star \leftarrow \arg\min_j \{m_j | j \in \mathcal{I}\}$
      $\mathcal{A} \leftarrow \mathcal{A} \cup \{j^\star\}, \quad \mathcal{I} \leftarrow \mathcal{I} \setminus \{j^\star\}$
    else
      $j^\star \leftarrow \arg\min_j \{c_j | j \in \mathcal{S}\}$
      $\mathcal{A} \leftarrow \mathcal{A} \cup \{j^\star\}, \quad \mathcal{S} \leftarrow \mathcal{S} \setminus \{j^\star\}$
    end if
  end if
  $j \leftarrow$ next element in $\mathcal{A}$
end while

UE j achieves its required data rate (Δr_j calculated with the instantaneous SNR $\gamma_{j,n}$) in the current TTI, it is moved to $\mathcal{S}$. If the buffer of a UE becomes empty, the UE is removed from $\mathcal{A}$. When all UEs in $\mathcal{A}$ become satisfied, the UE with the smallest c_j is scheduled. If, at any time, all allocated UEs become satisfied, all UEs in $\mathcal{I}$ are moved to $\mathcal{A}$. If $\mathcal{I}$ is also empty, then the UEs in $\mathcal{S}$ are moved to $\mathcal{A}$ to get more resources. By allowing satisfied UEs to get more resources, the probability of UEs being unsatisfied in the next TTIs is reduced.

B. Orthogonal Random Beamforming

The SORA algorithm has been designed for Single Input Single Output (SISO) OFDMA systems and, in order to cope with multiple antennas at the BS and exploit spatial multiplexing, needs to be extended. Such an extension considering ORB is discussed in the sequel.

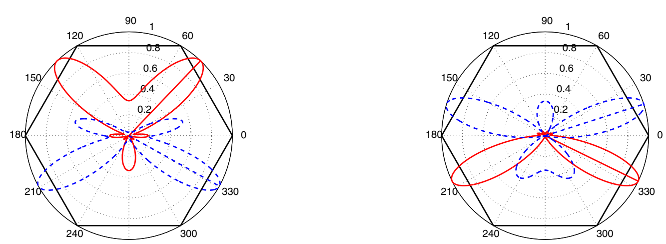
OBF is a technique in which weighting vectors of (2) are randomly set as to steer a beam towards a random direction [3]. Because the beam concentrates the radiated power towards its random direction, a UE will receive a signal with higher power whenever aligned with this direction. In this way, increased MU/frequency diversity is artificially induced by OBF [3].

In 3GPP LTE systems, random beams can be generated on each PRB by applying OBF and allow to obtain capacity and QoS gains with relative low impact on the system compared to other multi-antenna schemes, since OBF can be made almost transparent to the UEs [3].

ORB can be seen as an extension of OBF [4]. While OBF considers a single beam, ORB generates a number $B_n \leq M$ of orthogonal random beams on each subcarrier n [4]. For $B_n = 1$, OBF and ORB are indeed equivalent and share the same properties. For $B_n > 1$, ORB weighting vectors are forced to be orthogonal to each other, i.e., $\mathbf{w}_{n,b}^{\mathrm{H}} \mathbf{w}_{n,b'} = 0, \forall b \neq b'$. This orthogonalization can be acomplished with low complexity using Gram-Schmidt's process and, so, interference among the beams is reduced (or even completely suppressed) along the main direction of each beam. Moreover, new random beams must be periodically generated, thus allowing the whole cell to be covered and giving equal chance to all UEs to profit from the spatial filtering induced by ORB. Fig. 1 illustrates two orthogonal random beams generated on different TTIs.

Since on each subcarrier multiple beams are considered, UEs need to measure the received signal quality and generate a CQI (e.g., the perceived SNR) for each beam and subcarrier and fed back the CQIs to the BS, which uses these values to perform adaptive resource allocation. While multiple beams lead to increased signaling demands, they allow for spatial multiplexing in the form of SDMA, thus serving multiple UEs on the same subcarrier and, consequently, improving the system capacity. Nevertheless, signaling overheads may be reduced by reporting CQIs only of the best beams.

The extension of the SORA algorithm to cope with ORB is well suited to enhance the system capacity, since the latter artificially increases diversity. Moreover, ORB can be made almost transparent to SORA. Indeed, the SNR values of (3)



(a) Pattern on period 1. (b) Pattern on period 2.

Figure 1. Two orthogonal random beams on different update periods.

are the CQIs used by the SORA algorithm. ORB creates B_n *virtual* subcarriers for each *real* subcarrier, i.e., one per beam. However, if virtual subcarriers are grouped by beam, they become almost transparent to SORA. Because the order of the beams is not statistically relevant, they can be processed sequentially and the SORA algorithm can be applied to beam $b = 1$ of each subcarrier, then to beam $b = 2$, and so on.

The extension required to the SORA algorithm to cope with ORB can be described by two modifications intended to limit spatial inteference:

- **Beam blocking**: in SORA, whenever a subcarrier is allocated to a UE, it is removed from the set $\mathcal{N}$ of available subcarriers (cf. Tables I and II). In order to avoid that multiple UEs be allocated the same beam of a certain subcarrier, i.e., the same virtual subcarrier, whenever a UE j is allocated the beam b of subcarrier n, this beam is blocked to all other UEs $j' \neq j$. However, the other beams $b' \neq b$ of subcarrier n remain free to be assigned to other UEs.
- **Self-interference avoidance**: to avoid that a UE j be allocated multiple beams of the same subcarrier, whenever a beam b of subcarrier n is allocated to a UE j, all the other beams $b' \neq b$ on subcarrier n are blocked for UE j.

The above changes represent additional constraints which were implemented using a binary assignment map $\mathbf{A} \in \mathbb{B}^{J \times N \times B}$, that controls to which UEs the beams of which subcarrier can be assigned. The entries $a_{j,n,b}$ of $\mathbf{A}$ indicate whether beam b on subcarrier n can be assigned to UE j ($a_{j,n,b} = 1$). All the entries in $\mathbf{A}$ are initialized with 1. When beam b of subcarrier n is assigned to UE j, the entries of $\mathbf{A}$ are updated as

$$a_{j',n,b} = 0, \forall j' \neq j, \quad \text{and ,} \quad a_{j,n,b} = 0, \forall b. \tag{7}$$

If UEs allocated on a given subcarrier are perfectly aligned with random beams, they do not interfere with each other. However, this is a rather unlikely situation. The above constraints and the intrinsic properties of SORA reduce the probability of allocating strongly interfering UEs on the same subcarrier, but do not avoid completely this situation since CQIs do not capture interference among beams. Anyway, the proposed extension allows to combine SORA and ORB efficiently, as it will be seen in the sequel.

IV. Simulation results

In this section, the performance of SORA+ORB is compared to that of the original SORA algorithm by means of simulations. The 3GPP Spatial Channel Model (SCM) and the scenario “Urban micro” [13] are considered. The SORA+ORB algorithm has been compared with SORA for different number of random beams and a variable number of UEs. The most relevant simulation parameters considered in this work are listed in Table III.

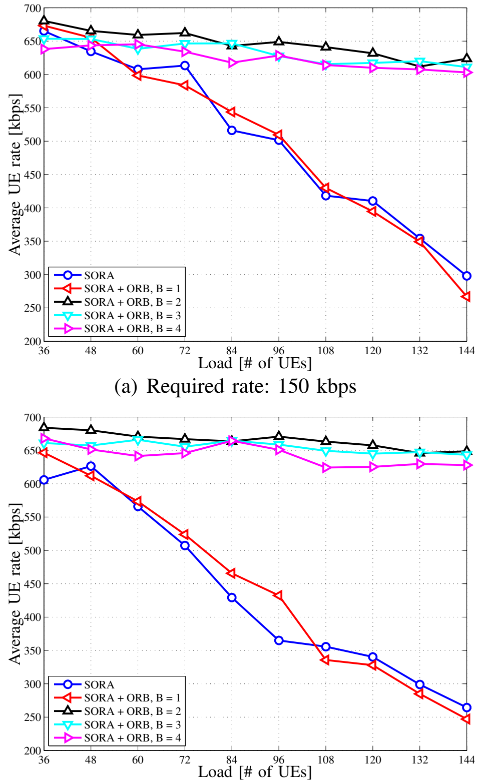
A total number of $M = 4$ antennas is considered at the BS. We assume Equal Power Allocation (EPA) among subcarriers. The power $p_n = p/N$ allocated to each subcarrier n is also equally divided among the B_n beams that the BS generates on this subcarrier, i.e., power $p_{n,b} = p_n/B_n$. A target BER of 10^{-3} and $L = m \cdot 7$ bits/packet are considered. Each TTI takes 0.5 ms and a random test is performed considering (6) to determine whether a given sent packet has been correctly received. If subcarrier n is not allocated, its power p_n is not used, i.e., there is no power reallocation among subcarriers. In a multi-cell scenario, this reduces intercell interference. On a subcarrier n, if not all the B_n beams are assigned to UEs, the power of the inactive beams is equally distributed among the allocated beams. Thus, there is power reallocation among beams of an allocated subcarrier. Anyway, other power allocation strategies could be considered.

Table III
SIMULATION PARAMETERS: SORA & ORB

Parameter	Value	Unit
Cell radius	500	m
BS transmission power	5	W
Simulation time	60	s
# of subcarriers	100	–
Subcarrier bandwidth	15	kHz
System operating frequency	2	GHz
UE-BS minimum distance	10	m
Shadowing standard deviation	8	dB
Noise power	-123.24	dBm
TTI time length	0.5	ms
# of transmit antennas	1, 4 (linear array, omnidirectional elements, half wavelength separtion)	–
Channel model	3GPP SCM Urban Micro [13]	–
Scheduling algorithms	SORA, SORA+ORB	–
Loads	36 to 144	UEs
# of samples/load	15	–
Rate requirement	150, 300	kbps
Service type	WWW	–
MCSs	[4,16,64]-QAM (uncoded)	–
Frequency of update of ORBs	20	TTI
Target BER	10^{-3}	TTI
Number of bits/packet (L)	$m \cdot 7$	–

Fig. 2 shows the average UE rate and Fig. 3 shows the average UE satisfaction, both against a varying load in number of UEs and for different number $B_n = B$ of beams. In Fig. 2, it can be seen the SORA+ORB and the SORA algorithm have almost the same average UE rate when $B = 1$, which is due to facts that OBF shall not provide array gains in Rayleigh fading scenarios [3] and that the SORA algorithm already exploits MU diversity [1], [2]. These results also shown that ORB is almost transparent to SORA. In Fig. 2, one also sees that the average UE rate decreases with the system load, as expected.

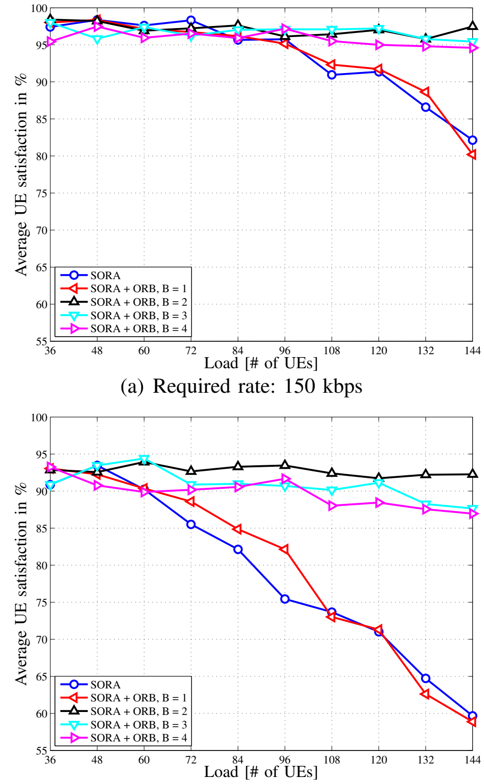
In Fig. 2, SORA+ORB surpasses the SORA algorithm when $B > 1$, achieving considerably higher average UE rates, which is due to spatial multiplexing. On the one hand, as B increases, higher spatial multiplexing gains might be obtained. On the other hand, higher interference among UEs on different beams of the same subcarrier may arise compromising throughput. For $B = 2$ active beams, slightly better results in terms of average rate are obtained, thus providing a good trade-off between spatial multiplexing and spatial interference. In Fig. 2, one also sees that the performance difference when $B = 2, 3,$ and 4 active beams is relatively small. This is due to the the power redistribution among the active beams, which helps increasing the throughput, and to the fact that having $B = 4$ does not necessarily means that the 4 beams will be active all the time, but that at most $B = 4$ beams might be active at each time. Thus, the potentially high interference situations



(a) Required rate: 150 kbps

(b) Required rate: 300 kbps

Figure 2. Average UE rate.



(a) Required rate: 150 kbps

(b) Required rate: 300 kbps

Figure 3. Average UE satisfaction.

are avoided. Compared to the SORA algorithm, it is shown in Fig. 2 that SORA+ORB provides higher gains in terms of average UE rate, specially for high system loads. This is expected, since ORB performs better for high loads in which MU diversity gains can be exploited intensively [4].

Fig. 3 shows that the average UE satisfaction also decreases when the system load increases, as expected. Similarly to the average UE rates, for $B = 1$ the percentage of satisfied UEs is almost the same using either SORA+ORB or simply the SORA algorithm. In Fig. 3(a) and Fig. 3(b), it is shown that SORA+ORB satisfies a higher fraction of UEs. While in Fig. 3(a) the performance of SORA+ORB with $B = 2, 3$ and 4 is almost the same, for the higher rate requirement considered in Fig. 3(b), a better satisfaction is obtained again for $B = 2$.

V. Conclusions

In this work, the SORA algorithm has been extended to work with ORB leading to the SORA+ORB algorithm, which has been shown to provide considerable gains in terms of average UE rate and average UE satisfaction without incurring in excessive complexity or control signaling to the system.

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