Utility-Based Resource Allocation with Spatial Multiplexing for Real Time Services in Multi-User OFDM Systems

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***Abstract*—In order to expand its market share and decrease churn, cellular network operators want to achieve the maximum possible number of satisfied clients. In this paper, we propose to solve the problem of user satisfaction maximization using an utility-based dynamic resource assignment algorithm that uses a sigmoidal utility function combined with either Orthogonal Random Beamforming (ORB) or Fixed Switching Beamforming (FSB). System-level evaluations of the downlink of an Orthogonal Frequency Division Multiple Access (OFDMA) system with real-time services demonstrate that there is an optimal number of spatial beams to be used by ORB and FSB, that FSB outperforms ORB with lower complexity, and also that the proposed joint resource assignment and beamforming outperforms other classical techniques found in the literature.**

I. Introduction

Efficient and innovative Radio Resource Allocation (RRA) techniques are essential to provide considerable gains in coverage, capacity and Quality of Service (QoS) for Orthogonal Frequency Division Multiple Access (OFDMA)-based broadband wireless networks. In a commercial wireless network, improved coverage, capacity and QoS represent better investment return rates and better radio services. For the customers, this should yield better services, higher fairness and enhanced QoS levels with widespread availability at possibly lower prices. Therefore, it is of utmost importance to investigate innovative means to optimize RRA techniques that deal with the resources and fully exploit all kinds of diversity offered by an OFDMA-based system, such as time, frequency, space and multi-user.

From the user's point of view, it is relevant to have a fair resource allocation, meet their QoS requirements and maximize their satisfaction independently of their channel situation. Furthermore, network operators want to have the maximum possible number of satisfied clients in order to keep and/or expand its market share and decrease churn.

In this paper, we consider the downlink of cellular networks based on OFDMA and multiple antenna technologies. We are interested at studying novel ways to improve satisfaction of users using Real Time (RT) services, such as Voice over IP (VoIP). Therefore, this work proposes a method to solve the satisfaction maximization problem using a Dynamic Resource Allocation (DRA) algorithm based on utility theory [1], [2] combined with either Orthogonal Random Beamforming (ORB) or Fixed Switching Beamforming (FSB) [3], [4].

In order to improve user satisfaction in a scenario with RT services, RRA techniques should take into account efficiency in the resource usage and QoS guarantees (delay bounds). We have classified some works that dealt with both factors in three main approaches: heuristics [5], cross-layer Packet Scheduling (PSC) [6]–[8], and utility theory [1], [9].

A heuristic scheduling algorithm, which was initially designed for the VoIP service and whose main objective is to maximize the number of satisfied RT users in the system, was proposed in [5]. To the best of our knowledge, this is the only work in the literature so far that deals with the specific problem of user satisfaction maximization in RT service scenarios.

The opportunistic PSC algorithms suitable for RT services found in the literature have priority functions that use QoS and efficiency indicators. A suitable QoS indicator should be based on delay, whereas efficiency indicators could be the ratio between the instantaneous transmission rate and throughput (proportional fairness policy) [7], [8] or the instantaneous transmission rate (rate maximization policy) [6], [7]. The idea is not only using the resources in the most efficient way but also giving priority to users with poorer QoS (higher delays).

The utility-based PSC algorithms consider a QoS indicator given by the marginal utility function based on delay. Since the utility functions can be freely designed to provide the desired result, the utility-based approach is more general than classic PSC priority functions. For example, [9] used z-shaped utility functions while [1] used particularly designed utility functions suitable to the services investigated therein.

As far as we are concerned, the present work is the first one to propose and evaluate a joint utility-based DRA and spatial beamforming with the specific objective of improving the percentage of satisfied RT users in an OFDMA system.

The rest of the paper is organized as follows. Section II presents the system modeling, while sections III and IV describes the proposed utility-based resource assignment and its combination with beamforming techniques, respectively. System-level simulation results are shown in section V and the conclusions of the work are drawn in section VI.

II. System Modeling

We consider an OFDMA system where all users form a set $\mathcal{J}$ with size J, and all Resource Blocks (RBs) to be assigned to the users form a set $\mathcal{K}$ with size K. We also assume a

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downlink Multiple Input Single Output (MISO) channel with M_T transmit antennas at the Base Station (BS) and a single receive antenna at the terminals, and $\mathbf{H}_{j,k}$ is an $1 \times M_T$ matrix whose elements $h_{j,k,m}$ consist in the channel transfer function between the receive antenna of terminal j and the transmit antenna m of the BS on RB k. We approximate the channel transfer function of the RB by the transfer function of the mid sub-carrier that composes the block. Furthermore, we assume that the channel coefficients remain constant during the period of a Transmission Time Interval (TTI). Also, perfect channel state information is assumed at both transmitter and receiver.

In a Multi-User (MU)-MISO scenario, the BS can steer a narrow beam b towards a direction of interest by weighting the signal sent by each of its antennas. The complex weights $w_{k,b}$ used to steer beam b on RB k are organized in a beamforming vector. From the whole set of beamforming vectors available for transmission on an RB k, the BS can choose to transmit using a subset $\mathcal{B}_k$ of active beams with size B_k, where $B_k \leq M_T$ in order to limit intercell interference. Using such B_k beams, the BS spatially multiplex different users on RB k.

The total BS transmit power P_{t} is constant and equally distributed among the RBs. Furthermore, the power p_k of each RB is equally divided between the B_k active beams.

We do not consider the intra-cell interference in the RRA decisions. After resource allocation, terminal j is subject to intra-cell interference from other terminals to which other beams have been assigned on the same resource. Users' data rates are determined using a link adaptation curve considering the Signal-to-Interference plus Noise Ratio (SINR) values after resource allocation [10].

III. Maximization of RT Users' Satisfaction Using Utility-Based Resource Allocation

Let us consider the utility-based optimization below:

$$\max_{\rho_{j,k}} \sum_{j \in \mathcal{J}} U\left(d_j^{\text{hol}}[n]\right) \tag{1a}$$

$$\text{subject to} \quad \rho_{j,k} \in \{0,1\},\ \forall j \in \mathcal{J} \text{ and } \forall k \in \mathcal{K}, \tag{1b}$$

$$\sum_{j \in \mathcal{J}} \rho_{j,k} = 1,\ \forall k \in \mathcal{K}, \tag{1c}$$

where $\rho_{j,k}$ is an assignment variable that assumes the value 1 if the RB k is assigned to the user j and 0 otherwise, and $U\left(d_j^{\text{hol}}[n]\right)$ is a decreasing utility function based on the current Head-Of-Line (HOL) packet delay $d_j^{\text{hol}}[n]$ of the user j in TTI n. The HOL delay is the time that the oldest packet in the user's buffer has to wait before gaining access to the channel. Constraints (1b) and (1c) state that the same resource cannot be shared by two or more users in the same TTI.

Since we are interested in formulating an RRA technique suitable for maximizing the satisfaction of RT services, we consider an utility function based on the users' HOL packet delays, which is a QoS parameter suitable for RT services.

It is demonstrated in [2] that a utility-based optimization problem like the one presented in (1) can be simplified into a weighted sum rate maximization [11]. The objective function of the simplified problem becomes linear in terms of the instantaneous user's data rate and is given by

$$\max_{\rho_{j,k}} \sum_{j \in \mathcal{J}} \left| U'\left(d_j^{\text{hol}}[n]\right)\right| \cdot R_j[n] = \max_{\rho_{j,k}} \sum_{j \in \mathcal{J}} w_j \cdot R_j[n], \tag{2}$$

where $U'\left(d_j^{\text{hol}}[n]\right) = \left.\frac{\partial U}{\partial d_j^{\text{hol}}}\right|_{d_j^{\text{hol}} = d_j^{\text{hol}}[n]}$ is the marginal utility of user j with respect to its HOL delay at TTI n, w_j is the utility-based weight of the user j given by the marginal utility, and $R_j[n]$ is the instantaneous data rate of user j at TTI n.

We propose to solve the referred problem using a utility-based DRA technique followed by an equal power allocation among the RBs. The proposed DRA is called Delay-based Satisfaction Maximization (DSM) and chooses the user with index $j^\star$ to transmit on RB k in TTI n, so that

$$j^\star = \arg\max_j \{w_j \cdot r_{j,k}[n]\}, \tag{3}$$

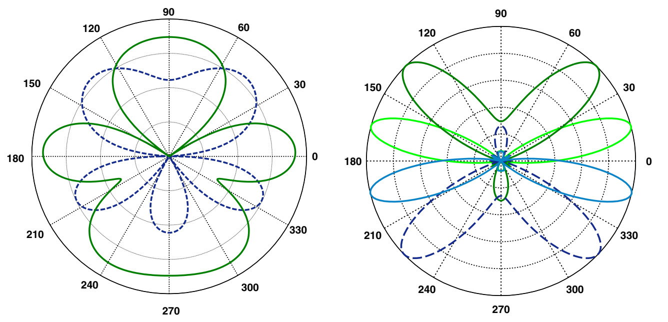
where $r_{j,k}[n]$ denotes the instantaneous achievable transmission rate of user j with respect to RB k at TTI n, and w_j is the utility-based weight factor of user j. If more than one user has the same priority for RB k, a tiebreaker process selects the user with the highest Signal-to-Noise Ratio (SNR). Notice that the DSM technique is not only opportunistic, because it takes into account the wireless channel quality, but also provides a QoS-based resource allocation by means of the users' utility-based weights.

The consideration of a sigmoidal utility function in the resource allocation provides high satisfaction for RT users. The DSM policy uses a sigmoidal utility function based on HOL delay that has the following expression:

$$U\left(d_j^{\text{hol}}[n]\right) = \frac{1}{1 + e^{\sigma\left(d_j^{\text{hol}}[n] - d^{\text{req}}\right)}}, \tag{4}$$

where σ is a non-negative parameter that determines the shape of the sigmoidal function. Notice that this is a decreasing utility function, which means that the higher the HOL delay, the lower the users' utility derived from the network. This function is also centered on a QoS requirement, which is called d^{req} and must be equal to or lower than the RT delay budget.

A sigmoidal utility function means that a given user becomes unsatisfied rapidly if the HOL delay approaches and exceeds the delay requirement. The opposite occurs when the user HOL delay decreases to values lower than the requirement. The utility-based weight, which is the absolute value of the derivative $U'\left(d_j^{\text{hol}}[n]\right)$, is represented by a bell-like function centered at the delay requirement d^{req}. Depending on the values of the DSM delay requirement (central value of the sigmoidal function) and the RT delay budget, there could be some portion of the marginal utility function (abscissa values higher than the RT delay budget) that will be neglected. This is due to the fact that we assume a packet discard procedure where a HOL packet is discarded at the BS if its delay is already higher than the RT delay budget, since this packet would be considered lost at the user terminal anyway.



(a) ORB with $B_k = 2$ beams.

(b) FSB with $B_k = 4$ beams.

Fig. 1. Examples of radiation patterns of ORB and FSB beamforming.

IV. RRA Combined with Spatial Multiplexing

A. Spatial Multiplexing

Fig. 1 shows examples of radiation pattern of ORB with 2 beams and FSB with 4 beams. On one hand, ORB creates very large beams, and so a higher coverage can be obtained. This feature is very useful for systems with a large number of users. Notice that where a given beam presents the maximum gain, there is a null on the other beam. On the other hand, FSB produces narrow and directed beams, which reduces the spatial interference. Notice that these beamforming patterns must be combined with the three-sectored radiation pattern of the BS. More details about how the beamforming vectors are generated by ORB and FSB are given in the following.

1) Orthogonal Random Beamforming: The ORB strategy generates $B_k \leq M_T$ orthogonal random beams on each RB k, where B_k different users can be spatially multiplexed. Random vectors given by $\tilde{\mathbf{w}}_{k,b} \sim \mathcal{CN}(0,1)$ are generated and the beamforming vectors $\mathbf{w}_{k,b}$ in $\mathcal{B}_k$ are obtained by an orthonormalization of $\tilde{\mathbf{w}}_{k,b}$. For $B_k > 1$, the weighting vectors are forced to be orthogonal to each other and to have unit norm, i.e., $\mathbf{w}_{k,b}^H \mathbf{w}_{k,b'} = 0$, if $b \neq b'$, or $\mathbf{w}_{k,b}^H \mathbf{w}_{k,b'} = 1$, if $b = b'$.

Thereby, the interference among beams is reduced along the main direction of each beam, i.e., a terminal will receive a signal with higher power whenever aligned with this direction. Besides, new random beams must be periodically generated, thus allowing the whole cell to be covered and giving equal chance to all terminals to profit from the spatial filtering induced by ORB [4]. Due to the orthogonality condition among beams, there is at most M_T beamforming vectors.

2) Fixed Switching Beamforming: The FSB technique employs fixed steered beams to multiplex several users in space. These beams are formed by applying phase shifts to the individual transmit antenna elements in a uniform linear array, resulting in a evenly distributed arrangement. The desired phase shifts, corresponding to each specific beam, are organized in the phase set $\Theta = \{\theta_1, \ldots, \theta_{M_T}\}$. Therefore, for each phase shift θ_b specified, the weighting vector used to steer the beam b on RB k, is organized as the following steering vector:

$$\mathbf{w}_{k,b} = \frac{1}{\sqrt{M_T}} \left[1 \; e^{j\pi \sin\theta_b} \ldots e^{j\pi (M_T - 1)\sin\theta_b} \right]. \quad (5)$$

Notice that the beams $w_{k,b}$ are not necessarily orthogonal to each other. FSB offers the flexibility to generate a maximum of M_T beams and to choose afterwards a reduced subset of active beams $\mathcal{B}_k$ in order to limit intra-cell interference.

B. Joint Resource Assignment and Beamforming

Based on [4], we consider that the ordering of the beams of the set $\mathcal{B}_k$ is not statistically relevant considering the entire resource assignment process. Therefore, the beams can be processed sequentially, i.e., the algorithms can be applied to beam $b = 1$, then to to beam $b = 2$, and so on.

The scheduling is done on a TTI basis. It is controlled by a priority assignment map $A \in \mathbb{R}^{J \times K \times M_T}$. This map represents the priorities of the users for all RBs and beams, where M_T upper limits $B_k, \forall k$. If more than one user has the same priority for the same RB and beam, a tiebreaker process selects the user with the highest SNR.

An extension of a scheduling algorithm to cope with beamforming techniques was proposed by [4]. Based on that, we adapted our utility-based DRA algorithm. Two modifications intended to limit spatial interference were made:

- **Avoidance of self-interference**: whenever a beam b of RB k is allocated to user j, all the other beams $b' \neq b$ on RB k are blocked to user j. This condition prevents user j from being allocated to multiple beams of the same RB, and so user j does not interfere with himself.
- **Locking of beams/resources**: whenever all B_k beams of the RB k are allocated to users, RB k is withdrawn from the set $\mathcal{K}$ of available RBs. Whenever user j is allocated the beam b of RB k, this beam is blocked to all others users $j' \neq j$. However, the other beams $b' \neq b$ of RB k remain free to be assigned to other users $j' \neq j$. This condition avoids that multiple users be allocated to the same beam of a given RB.

V. Performance Evaluation

In sections V-A and V-B we investigate the performance of the DSM technique with/without the use of ORB and FSB beamforming, respectively. We also compare the joint DSM/beamforming with other classical DRA algorithms found in the literature, such as Rate Maximization (RM) [12], Modified Largest Weighted Delay First (MLWDF) [8], and Urgency and Efficiency Packet Scheduling (UEPS) [9]. Notice that the classical algorithms were also extended to work with ORB or FSB. In section V-C we discuss which is the best beamforming strategy to be used in conjunction with DSM. Analyses are based on system-level evaluations of RT services.

A total number of $M_T = 8$ transmit antennas is considered at the BS for the ORB and FSB cases. We consider different numbers of active beams B_k, which is varied from 1 to 4 in both cases. The simulation parameters are shown in Table I.

The simulation results presented in the following is the percentage of satisfied RT users. If the user's Frame Erasure Rate (FER) is lower than or equal to a requirement, the user is considered satisfied; otherwise it is assumed unsatisfied.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of cells	1
Maximum BS transmit power	1 W
BS antenna radiation pattern	Three-sectored
Cell radius	500 m
UE speed	3 km/h
Carrier frequency	2 GHz
System bandwidth	5 MHz
Sub-carrier bandwidth	15 kHz
Number of RBs	25
Path loss[a]	$L = 128.1 + 37.6 \log_{10} d$
Log-normal shadowing st. dev.	8 dB
Small-scale fading	3GPP Typical Urban
AWGN power per sub-carrier	-123.24 dBm
Noise figure	9 dB
Link adaptation	Link level curves from [10]
Transmission Time Interval	1 ms
RT packet size	256 bits
RT packet interarrival time	2 ms
FER threshold	2%
HOL delay requirement	100 ms
RT delay budget	100 ms
Parameter σ	138.135
Number of transmit antennas	8 (ORB/FSB)
Number of receive antennas	1
Multi-antenna configuration	MU-MISO
Simulation time span	15 s
Number of simulation runs	10

A. ORB Results

The percentage of satisfied users as a function of the system load is depicted in Fig. 2. Notice that the DSM ORB1 has the highest satisfaction values, which surpass those of the Single Input Single Output (SISO) configuration, because the antenna array directivity enhances the SINR. However, when the number of active beams is further increased, the performance of DSM ORB decreases considerably. These results indicate a trade-off between spatial multiplexing and spatial interference when ORB is used, because of the nature of the beams that are generated by this strategy, which are orthogonal, but very wide. Thus, cross-interference between beams can be eliminated only for users perfectly aligned with the main lobes of the random beams. Since this situation is highly improbable, the increased number of beams leads to the scheduling of users that highly interfere with each other, which causes the performance losses shown in Fig. 2.

Let us choose the best ORB configuration ($B_k = 1$ beam), and compare the performance of DSM with other classical RRA techniques in Fig. 3. The algorithms that take into account the HOL delay in their formulations are those ones that provide the highest user satisfaction. The resource allocation criteria of these algorithms are based on the combination of two indicators: a QoS indicator that is a function of the HOL delay, and an efficient indicator that can be the achievable transmission rate (DSM) or the ratio between the transmission rate and the user throughput (MLWDF and UEPS). As can be

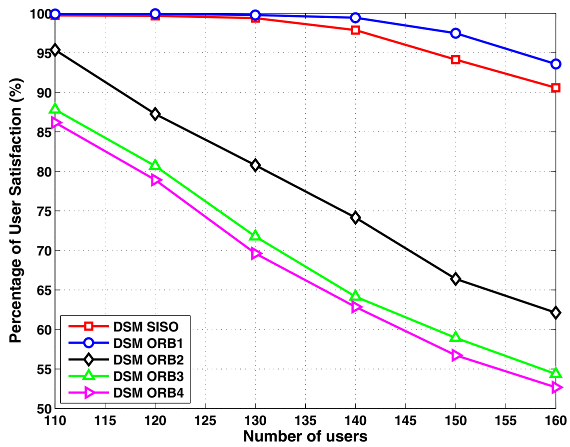


Fig. 2. Evaluation of the DSM technique with ORB.

noticed, the proposed DSM technique achieved its objective of maximizing user satisfaction. The combination of the bell-shaped delay-based indicator and the achievable transmission rate indicator proved to be the best option. Furthermore, its computational complexity is in the same order of the classical algorithms, except RM, which presents the lowest complexity.

B. FSB Results

According to Fig. 4, there is also an optimal number of beams to be used by FSB. In comparison with DSM SISO, the use of one beam in DSM FSB1 is not advantageous. However, when 2 beams are activated, there is a remarkable satisfaction improvement. The use of one additional beam is not beneficial anymore, causing a slight satisfaction degradation. DSM FSB4 degrades the system performance even more, but is still better than DSM SISO. When more beams are used, we still have the benefit of enhanced quality due to the array gain, but this gain is limited by the reduction of the transmit power per beam. Moreover, the spatial multiplexing gain is linear with the number of beams. However, these two advantages are overcome by the interference caused by the overlap of

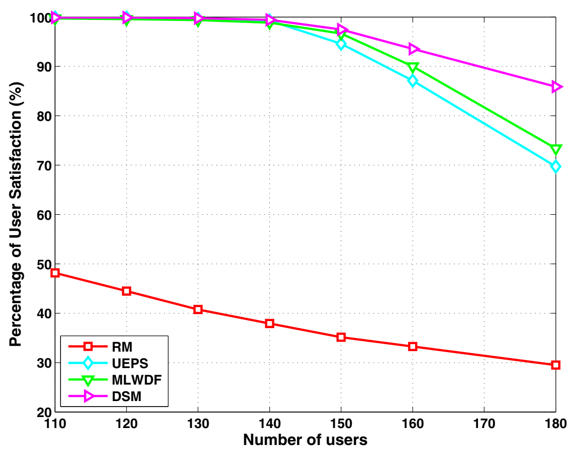


Fig. 3. Evaluation of different RRA techniques using ORB with 1 beam.

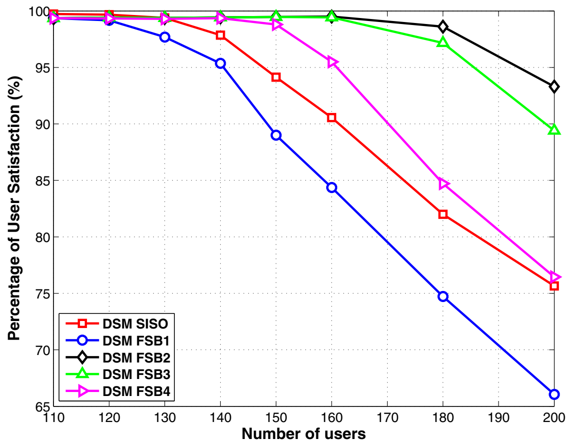


Fig. 4. Evaluation of the DSM technique with FSB.

adjacent beams, which degrades performance.

Choosing the best FSB configuration ($B_k = 2$ beams), and comparing the performance of DSM with RM, MLWDF, and UEPS, we can see that DSM still outperforms the other techniques (see Fig. 5). The reasons behind this behavior were already explained in section V-A for the ORB case.

C. Comparison between ORB and FSB

In this section, we assess the configurations of DSM ORB and DSM FSB that achieve the highest gains in terms of user satisfaction, namely ORB1 and FSB2.

Assessing Figs. 2 and 4, one can notice that DSM FSB2 provides better user satisfaction than both DSM ORB1 and DSM SISO. When the system load is low, the user satisfaction is high for all schemes. As the load increases, the satisfaction of SISO and ORB1 decreases quickly, while FSB2 maintains high satisfaction values. This behavior is a consequence of the DSM FSB resource allocation, which minimizes the interference and exploits efficiently the multi-user diversity and spatial multiplexing. Notice that the relative capacity gains of DSM FSB2 in comparison with DSM ORB1 and DSM SISO,

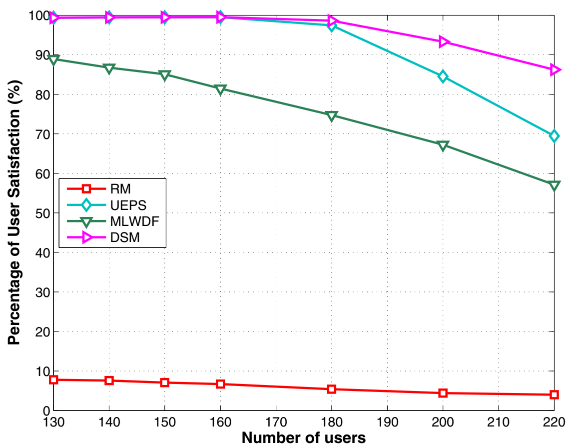


Fig. 5. Evaluation of different RRA techniques using FSB with 2 beams.

in terms of number of users for a satisfaction target of 95%, are 25% and 32%, respectively. DSM ORB1 also obtains a small capacity gain of 5% compared with DSM SISO, as a consequence of the array gain due to antenna directivity.

VI. Conclusions

It is demonstrated by means of system-level simulations that the DSM technique combined with ORB or FSB beamforming is effective towards the objective of user satisfaction maximization. It can also be concluded that the addition of more active beams does not necessarily help DSM to achieve better user satisfaction. There is an optimal number of active beams that achieves the best trade-off between antenna array gain, spatial multiplexing gain and cross-interference among beams.

DSM ORB1 and DSM FSB2 were the combinations that showed the best results. When compared with other RRA techniques using the same beamforming schemes, they presented the highest user satisfaction. When they are compared among each other, it is concluded that FSB is preferred because it provides the highest gains due to reduced interference.

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