Resource Allocation in OFDMA Downlink with Reduced Feedback Overhead

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***Abstract*— Consider the problem of resource allocation on the downlink of a cellular OFDMA system. A fairness constraint is defined by a minimum data rate, a maximum bit-error rate and a maximum outage probability. This paper proposes a low-complexity resource allocation algorithm that requires a reduced feedback-overhead. Under a partial Channel-State Information, we derive the optimal subcarrier and power allocation that provides the best overall outage performance using the lowest possible number of subcarriers. Unneeded subcarriers lend themselves to interference-free use in other cells assuming some inter-cell coordination. We first evaluate the maximum achievable number of users when all subcarriers are used. This defines an upper-bound on system load. Then, for an arbitrary load ratio, we describe the corresponding resource allocation and provide an analytic upper-bound on the achievable outage probability.**

I. INTRODUCTION

Orthogonal Frequency-Division Multiple Access (OFDMA) provides a powerfull solution for current and future wireless systems such as Wifi, WiMax and 4G systems. The flexibility of this modulation and multiple access technique motivates a huge research activity on resource allocation based on cross-layer design [1]. We focus on the downlink of a single-cell system. Efforts were mainly focused on maximizing the system capacity given a total power (zero margin approach) [2], [3] or on minimizing the required total power under minimum rates (adaptive margin approach) [4]. Full *Channel-State Information* (CSI) is usually assumed. In practice, full CSI requires a heavy overhead on feedback channels.

In this paper we propose to minimize the number of active subcarriers under a minimum QoS constraint. Unneeded subcarriers lend themselves to interference-free use in other cells assuming coordination between base stations. The main issue is to propose a practical link adaptation algorithm that requires a low feedback overhead. Thus, we assume a partial CSI and provide the optimal rate, power and subcarrier allocation under different system loads. We also propose a simple CSI quantization scheme and characterize the robustness of the resulting outage performance to CSI accuracy.

II. SYSTEM MODEL

We consider an uncoded OFDMA downlink from a Base Station (BS) to U uniformly-distributed users in a circular cell of radius R. A total power P_{tot} is available for transmission over S subcarriers. The transmitted signal received by user u experiences a frequency-selective slow-fading channel characterized by S i.i.d. random variables $g_{u,s}$ $(s = 1, ..., S)$. These $g_{u,s}$ represent the channel power gains over the different subcarriers. Each coefficient $g_{u,s}$ accounts for a deterministic pathloss $G(r_u)$, that depends on the distance r_u of user u to the BS, in addition to a *log-normal shadowing* $10^{\,0.1\,\xi_{u,s}}$ and to a multipath *Nakagami fading* $\nu_{u,s}$. So, if P_s denotes the transmitted power on subcarrier s, the received *Signal-to-Noise Ratio* (SNR) at the u^{th} user on this subcarrier is

$$\gamma_{u,s} = \frac{P_s\, g_{u,s}}{BN_0} = \frac{P_s}{BN_0}\, G(r_u) 10^{\,0.1\,\xi_{u,s}}\, \nu_{u,s}^2$$

where B is the subcarrier spacing and N_0 is the AWGN power spectral density. The pathloss $G(r_u)$ is the long-term average, known as the *area mean*, of the channel power gain at distance r_u. Thus, the quantity

$$\bar{\bar{\gamma}}_s(r_u) = \frac{P_s}{BN_0}\, G(r_u) \tag{1}$$

represents the *area-mean received SNR* at user u on subcarrier s. The double bar in $\bar{\bar{\gamma}}_s(r_u)$ corresponds to averaging with respect to both shadowing and fading. We assume that $G(r_u)$ follows the *exponent model* [5] defined by

$$G(r_u) = G_0 / r_u^{\alpha} \tag{2}$$

with $G_0 = (c/(4\pi f_c))^2$ (f_c is the center frequency and c is the light speed). The log-normal shadowing $10^{\,0.1\,\xi_{u,s}}$ is the mid-term average gain known as the *local-mean* gain. It is characterized by the *shadowing standard deviation* σ which is the standard deviation of the zero-mean Gaussian random variable $\xi_{u,s}$. We define the *Shadowed SNR* by

$$\bar{\gamma}_s(r_u) = \frac{P_s}{BN_0}\, G(r_u)\, 10^{\,0.1\,\xi_{u,s}}.$$

This $\bar{\gamma}_s(r_u)$ has a log-normal distribution $\mathcal{LN}(\mu_{u,s}, \sigma^2)$ with $\mu_{u,s} = 10 \log_{10} \bar{\bar{\gamma}}_s(r_u)$. From (1) and (2) we get

$$\mu_{u,s} = 10 \log_{10} \frac{P_s\, G_0}{BN_0\, r_u^{\alpha}}. \tag{3}$$

The multipath fading $\nu_{u,s}$ follows a Nakagami-*m* distribution characterized by the *shape factor* $m \geq 1/2$. By combining log-normal shadowing and Nakagami fading, the received SNR $\gamma_{u,s}$ has a *composite Gamma-log-normal* distribution. According to [6], this composite fading can be approximated

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by another log-normal distribution with logarithmic mean and variance given by

$$\tilde{\mu}_{u,s} = \mu_{u,s} - a_m, \tag{4}$$

$$\tilde{\sigma}^{\,2} = \sigma^2 + b_m \tag{5}$$

where the positive constants a_m and b_m can be found in [6]. Thus, the *cumulative distribution function* of the logarithmic SNR $\gamma_{u,s(dB)} = 10 \log_{10} \gamma_{u,s}$ is

$$F_{\gamma_{u,s(dB)}}(\gamma) = \frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\left(\frac{\gamma - \tilde{\mu}_{u,s}}{\tilde{\sigma}\sqrt{2}}\right) \tag{6}$$

where erf(.) is the *error function.*

In this paper, we assume a simple CSI which corresponds to user distance. This is equivalent to say that the BS is able to estimate the pathloss for each user by averaging the received power over dedicated training symbols assuming known transmit power. We consider user distance rather than the channel gain because our approach is closely related to the distribution of users over the cell. Finally, the target QoS is defined for each user by a target data rate D, a target BER ρ and a maximum outage probability ε.

In the next section we derive analytic expressions for the maximum number users that can be served with the target QoS when all subcarriers are used.

III. MAXIMUM ACHIEVABLE CAPACITY

Given the total power P_{tot} and the target QoS (D, ρ, ε), we want to determine the maximum achievable number of users U_{max} as well as the corresponding optimal subcarrier and rate allocation. In this section we assume that the total power P_{tot} is equally divided over the S subcarriers so that

$$P_s = P_{tot}/S. \tag{7}$$

However, this power scheme will be adapted to the system load as shown later in section IV.

A. Rate Allocation

As user distance r_u forms a frequency-non-selective CSI, subcarrier allocation consists in deciding how many subcarriers each user does need in order to achieve the target data rate D. Obviously, this depends on which M-QAM constellation is used on the subcarriers allocated to the user of interest. The maximum number of users correspond to the case where the constellation of the highest possible order is chosen on each subcarrier. But, the choice of constellation is subject to the BER-outage constraint. Let $p_{u,q}$ be the outage probability of user u using the constellation M_q-QAM. We have

$$p_{u,q} = \text{Proba}\left[\, f_{M_q}(\gamma_{u,s}) > \rho \right]$$

where $f_M(\gamma)$ is the function describing the achieved BER versus the SNR γ and the modulation order M. Since this function is decreasing with respect to γ, we have

$$p_{u,q} = \text{Proba}\left[\, \gamma_{u,s} < f_{M_q}^{-1}(\rho) \right]$$

with $f_M^{-1}(\rho)$ being the inverse function of f_M that provides the minimum SNR that an M-QAM constellation needs to achieve a given BER ρ. This outage probability can be expressed using the cumulative distribution function of the logarithmic SNR $\gamma_{u,s(dB)}$ as follows

$$p_{u,q} = F_{\gamma_{u,s(dB)}}\left(10 \log_{10}(f_{M_q}^{-1}(\rho))\right).$$

Using (6) we get

$$p_{u,q} = \frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\left(\frac{10 \log_{10}(f_{M_q}^{-1}(\rho)) - \tilde{\mu}_{u,s}}{\tilde{\sigma}\sqrt{2}}\right) \tag{8}$$

where, according to (3), (4) and (7), we have

$$\tilde{\mu}_{u,s} = 10 \log_{10}\left(\frac{P_{tot}\; G_0}{SBN_0\; r_u^{\alpha}}\right) - a_m.$$

So, the outage probability (8) becomes

$$p_{u,q} = \frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\left(\frac{10 \log_{10} \frac{SBN_0 r_u^{\alpha} f_{M_q}^{-1}(\rho)}{P_{tot} G_0} + a_m}{\tilde{\sigma}\sqrt{2}}\right). \tag{9}$$

For a given M_q, this probability increases with r_u. Therefore, the maximum outage probability constraint $p_{u,q} \leq \varepsilon$ means that each constellation M_q-QAM can be used up to a maximum distance R_q defined by the equation $p_{u,q} = \varepsilon$. We obtain

$$R_q = \left[\frac{(P_{tot}/F)\; G_0}{SBN_0\; f_{M_q}^{-1}(\rho)}\right]^{1/\alpha} \tag{10}$$

with F given by

$$F = 10^{-0.1\,(\tilde{\sigma}\sqrt{2}\;\mathrm{erf}^{-1}(2\varepsilon - 1) - a_m)}. \tag{11}$$

This F represents the power margin that accounts for the effect of shadowing and fading and guarantees an outage probability bounded by ε. The SNR-threshold $f_{M_q}^{-1}(\rho)$ is increasing with M_q (a higher-order modulation requires higher SNR to achieve the same BER). We suppose that the set $\mathcal{M} = \{M_1, M_2, ..., M_Q\}$ of constellations is an ordered set, that is $M_q > M_{q+1}$. So, for the complete set of constellations we have $R_1 < R_2 < ... < R_Q$. Remember that maximizing the achievable number of users requires using for each user the constellation of the highest possible order. Consequently, the M_q-QAM constellation must be allocated to users at distances $r_u \in]R_{q-1}, R_q]$ with $R_0 = 0$. Thus, each constellation M_q-QAM covers an *annular zone* of internal (resp. external) radius R_{q-1} (resp. R_q). This is depicted in Fig. 1 with $Q = 3$ three modulations. In the following, the q^{th} annular zone is called *zone q*. This cell partitioning into different modulation zones defines the optimal rate allocation. The worst-case outage probability is equal to ε and is reached on the boundary of each zone.

Note that the target cell radius R has not been taken into account. Considering R rises the question of coverage feasibility that we treat hereafter.

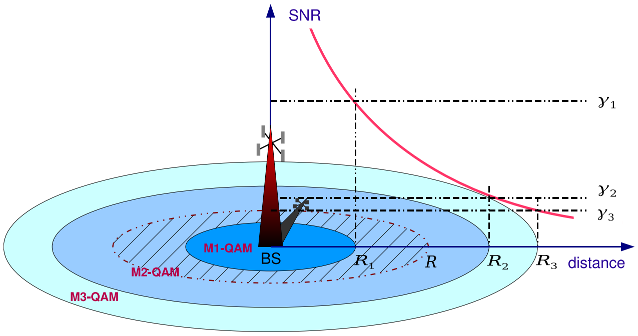

Fig. 1. Modulation zones and SNR thresholds (a feasible case with $Q = 3$, $Z = 2$). SNR thresholds γ_q are defined by $\gamma_q = f^{-1}_{M_q}(\rho)$.

B. Coverage Feasibility Issue

Serving edge users is feasible when the cell radius R is within the range of at least one M-QAM constellation. The ranges of the different constellations are given in (10). Since $R_q < R_{q+1}$, the feasibility is ensured if $R \leq R_Q$. Thus, according to (10) we have the following *feasibility condition*

$$R \leq \left[\frac{(P_{tot}/F)\; G_0}{SBN_0\; f^{-1}_{M_Q}(\rho)} \right]^{1/\alpha} . \tag{12}$$

In the feasible case, depending on the value of R with respect to the R_q's, only a subset of the Q available constellations is needed to achieve the coverage. Let $Z \in \{1, ..., Q\}$ be the index of the lowest-order modulation that we need to serve edge users, i.e. $Z = min\,\{q \in \{1, ..., Q\} : \; R \leq R_q\}$. If Z exists we get $R_1 < ... < R_{Z-1} < R \leq R_Z < ... < R_Q$. In the example of Fig. 1 we have $R_1 < R < R_2$ so that $Z = 2$. Here the SNR curve represents the area-mean SNR (1) divided by the power margin F.

When (12) does not hold, the problem is *unfeasible* because even the lowest-order modulation is not capable of supporting users on the cell boundary. Feasibility can be recovered by increasing the total power or by extending the set $\mathcal{M}$ of available constellations to lower-order ones when it is possible.

In the following, we assume that the feasibility condition (12) is satisfied so that the whole cell is covered by Z annular zones. Based on (10), the radii of these Z zones are given by

$$\mathcal{R}_q = \begin{cases} 0 & q = 0, \\ \left(\frac{G_0\; P_{av}}{\gamma_q\; BN_0\; S} \right)^{1/\alpha} & q = 1, ..., Z-1, \\ R & q = Z. \end{cases} \tag{13}$$

(the external radius of the most-outer zone is replaced by the cell radius R). The following step is to determine how much subcarriers to allocate to each zone or, equivalently, how much subcarriers each user does need to achieve the target data rate D. This will also allow us to calculate the maximum achievable number of users U_{max} that can be provisioned when all subcarriers are used.

C. Subcarrier Allocation and Maximum Capacity

Each subcarrier of those allocated to users in zone q ($1 \leq q \leq Z$), where an M_q-QAM constellation of spectral efficiency $\log_2 M_q$ is used, offers a data rate of $B\;\; \log_2 M_q$. Thus, each user inside zone q needs $D/(B\;\; \log_2 M_q)$ subcarriers. Obviously, the limited number of subcarriers S determines the maximum bearable number of users U_{max}. Under the assumption of uniform user distribution over the cell of radius R, we have a uniform user-density of $U_{max}/(\pi R^2)$ (user/m^2). With the same data rate D per user, this is equivalent to have a *uniform data-rate density* of $U_{max}D/(\pi R^2)$ in bps/m^2. This uniform data-rate density corresponds, in its turn, to a *subcarrier-allocation density* $(subcarrier/m^2)$ in zone q given by $(U_{max}D)/(\pi R^2 B\;\; \log_2 M_q)$. Thus, the number of subcarriers allocated to zone q and denoted S_q is obtained by multiplying this subcarrier-allocation density by the area of zone q, that is

$$S_q = \frac{U_{max}D}{R^2 B}(\mathcal{R}_q^2 - \mathcal{R}_{q-1}^2)/\log_2 M_q. \tag{14}$$

From (14) and the following constraint

$$\sum_{q=1}^{Z} S_q = S$$

we obtain

$$U_{max} = \frac{R^2 BS}{D\; \sum_{q=1}^{q=Z}(\mathcal{R}_q^2 - \mathcal{R}_{q-1}^2)/\log_2 M_q}. \tag{15}$$

Now we substitute (15) back into (14) to get an expression for the *zone-wise subcarrier allocation* as follows

$$S_q = \frac{(\mathcal{R}_q^2 - \mathcal{R}_{q-1}^2)/\log_2 M_q}{\sum_{k=1}^{k=Z}(\mathcal{R}_k^2 - \mathcal{R}_{k-1}^2)/\log_2 M_k}\; S \tag{16}$$

So, equation (15) determines the maximum achievable number of users if all S subcarriers are used. Note that the *achieved-sum rate* is given by the product $U_{max}D$.

In brief, equations (13) and (16) define the optimal rate and subcarrier allocation corresponding to the capacity given by (15). Now the issue is to decide how to allocate system resources when the actual number of users U in the cell is different from the capacity U_{max}. The ratio U/U_{max} can be considered as a *load ratio*. The following section describes our proposed allocation scheme under arbitrary loads.

IV. RESOURCE ALLOCATION UNDER ARBITRARY LOADS

The system is said *fully-loaded* when $U \geq U_{max}$. In this case, only U_{max} users are provisioned and any additional user that requests an access to the service is rejected. Consequently, the optimal rate and subcarrier allocation is still given by (13) and (16). In the under-loaded case ($U/U_{max} < 1$) the number of subcarriers required for zone q becomes

$$\hat{S}_q = \frac{UD}{R^2 B}(\mathcal{R}_q^2 - \mathcal{R}_{q-1}^2)/\log_2 M_q = \frac{U}{U_{max}} S_q.$$

Consequently, the total number of subcarriers required by the Z zones is $\sum_{q=1}^{q=Z}\hat{S}_q = \frac{U}{U_{max}}S$ which is smaller than S.

This means that the consumed power $(P_{tot}/S)\sum_{q=1}^{q=Z}\hat{S}_q = \frac{U}{U_{max}}P_{tot}$ is smaller than P_{tot}. Thus, when the system is underloaded, *the number of unneeded subcarriers* is

$$S_{xs} = \left(1 - \frac{U}{U_{max}}\right) S \tag{17}$$

and *the amount of unneeded power* is

$$P_{xs} = \left(1 - \frac{U}{U_{max}}\right) P_{tot}. \tag{18}$$

If this resource excess is left unused, the outage performance of the served users remains the same as in the fully-loaded case. One can think about exploiting these extra resources in order to improve the achieved performance of the active users. Thus, the unused subcarriers (17) can be distributed over the active users to offer higher data rates. When all subcarriers are used again, the whole total power is consumed as well. Another approach may consists in leaving the S_{xs} subcarriers unused but redistribute the power excess P_{xs} equally over the $S - S_{xs}$ active subcarriers. This boosts the power margin on the active subcarriers and yields a better immunity to fadings. Consequently, the outage performance is enhanced while the data rate per user remains unchanged. In the following, we opt for the second approach. The resulting improvement in outage probability is evaluated hereafter.

When the power excess (18) is redistributed on the $\frac{U}{U_{max}}S$ active subcarriers, the power each active subcarrier gets is

$$\hat{P}_s = \frac{U_{max}}{U} \times \frac{P_{tot}}{S}. \tag{19}$$

By replacing P_{tot}/S in (9) by $\hat{P}_s$ from (19) we obtain

$$\hat{p}_{u,q} = \frac{1}{2} + \frac{1}{2}\,\text{erf}\left(\frac{10\log_{10}\left(\frac{U}{U_{max}}\,\frac{SBN_0 r_u^{\alpha} f_{M_q}^{-1}(\rho)}{P_{tot}G_0}\right) + a_m}{\tilde{\sigma}\sqrt{2}}\right)$$

which provides the new outage probability versus user distance r_u. The *worst-case outage probability* corresponds to the boundary of any modulation zone. So, by replacing r_u in the previous equation by R_q from (10) and using (11) we obtain the following *upper-bound on outage-probability*

$$\hat{p}_{max} = \frac{1}{2} + \frac{1}{2}\,\text{erf}\left(\text{erf}^{-1}(2\varepsilon - 1) - \frac{10}{\tilde{\sigma}\sqrt{2}}\log_{10}\frac{U_{max}}{U}\right) \tag{20}$$

which is lower than the target value ε since $\frac{U_{max}}{U} > 1$.

V. Robustness to CSI Accuracy and Required Overhead

The available CSI, limited to the distances of users, is used by the BS during the rate allocation in order to decide in which modulation zone each user falls. How precise does this CSI need to be? Errors may come from imperfect distance estimation as well as from quantization noise on the CSI feedback channel. Assume that users are sorted according to their actual distances and that imperfect CSI results in a permutation on the indexes of a subset of users belonging to the same modulation zone. This kind of perturbation has no effect on the expected performance since these users continue to get the same resources. On the contrary, some performance degradation may appears when CSI errors shift some users from a modulation zone to another. To improve the immunity of our allocation method to CSI estimation errors, we propose the following quantization scheme for CSI feedback. In fact, all that the BS needs to properly allocate resources is the index of the modulation zone each user belongs to. Assume that the BS broadcasts the modulation zones' radii (13) to all the users in a dedicated frame header and that distances are estimated by users themselves. In this case, each user can find the index of his modulation zone and then feedback this value to the BS on the uplink. This fedback information is simply a discrete value between 1 and Z, the number of modulation zones. So, the feedback occupies about $\log_2 Z$ information bits per user. This approach is equivalent to quantizing the CSI on non-uniform bins which are defined by the zones' radii (13). The resulting robustness in terms of outage performance is evaluated in the following section.

TABLE I

Main parameters' values.

Center frequency f_c	3.5	GHz
Total transmit power P_{tot}	10	W
Number of subcarriers S	256	subcarriers
OFDM symbol duration $T_s = 1/B$	12.8	μs
Noise spectral density N_0	-174	dBm/Hz
Path-loss exponent α	3.6	-
Shadowing standard deviation σ	5	dB
Nakagami parameter m (Rayleigh fading)	1	-
Target data rate D	1	Mbps
Target BER ρ	10^{-3}	bps
Target outage probability ε	0.05	-
Target cell radius R	100	m

VI. Numerical Results

Given the parameter setting in Table I, we find using (11) that the required power margin is $F_{dB} = 10\log_{10}F \simeq 14.8$ dB. Moreover, the feasibility condition (12) is satisfied. From, the attainable ranges of the available modulations $64-QAM, 16-QAM, QPSK, BPSK$ are 45, 68, 106 and 129 m respectively. By comparing these ranges to the target cell radius $R = 100$ m, we find that the coverage is ensured using the first three modulations 64-QAM, 16-QAM and QPSK only. Thus, we have $Z = 3$ modulation zones. From (15), if the 256 subcarriers are used, a maximum number of $U_{max} = 54$ users can be served with the target QoS.

Consider a variable number of users U with $U \leq U_{max}$. In Fig. 2 we compare the outage-probability analytic upper-bound (20) to the simulated outage probability of edge-user for different load ratios. We note that beyond a load ratio of about $U/U_{max} = 0.5$, the upper-bound (20) starts to be loose. This is due to the fact that (20) was derived by approximating the composite Rayleigh-log-normal distribution by an equivalent log-normal one. When the number of users approaches the

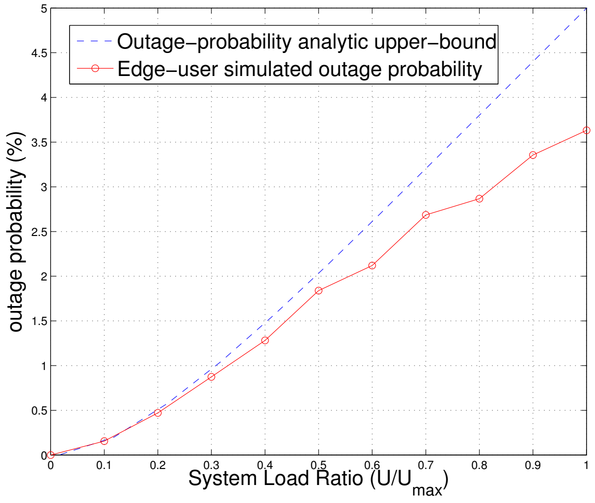

Fig. 2. Edge-user outage probability versus load ratio for log-normal shadowing and Rayleigh fading.

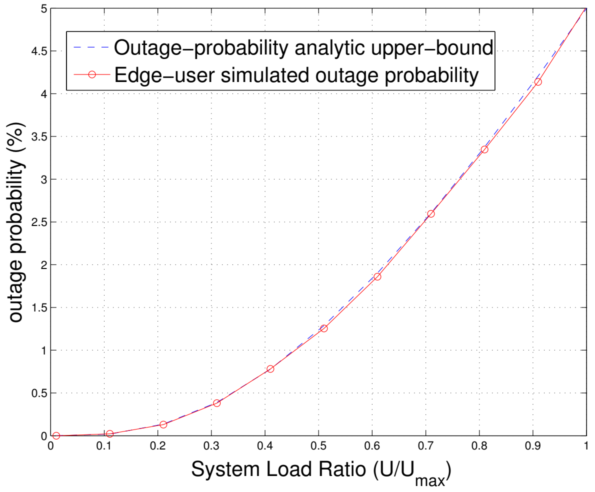

Fig. 3. Edge-user outage probability versus load ratio for log-normal shadowing only.

capacity, the power excess that is distributed over the active subcarriers decreases. Consequently, the actual power margin on each subcarrier decreases also and the accuracy of the composite Rayleigh-log-normal approximation becomes more critical. This can be checked by considering Fig. 3 where the Rayleigh fading is deactivated (log-normal shadowing only) so that the simulated outage probability coincides with the expected upper-bound.

Now, we want to characterize the sensitivity of the overall outage performance to CSI accuracy. Assume that the imperfect CSI is obtained by adding a zero-mean Gaussian error to the user's distance and that the errors for different users are independent. Thus, if r_u is the actual distance of user u, the estimated distance is $\hat{r}_u = r_u + e_u$. The error e_u follows a Gaussian law of standard deviation $\sigma_u = ar_u$ so that the parameter a measures the relative user-distance accuracy.

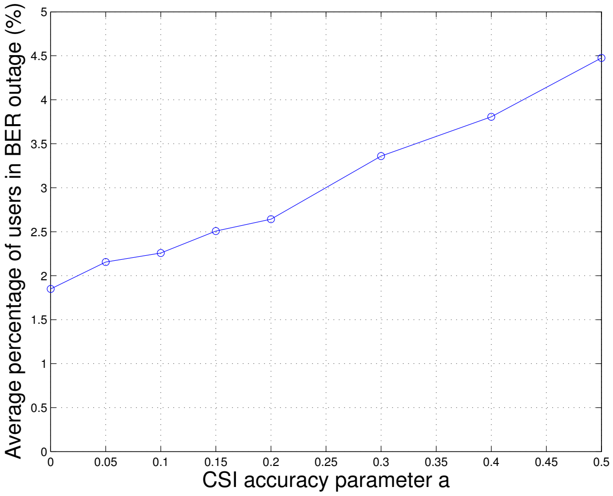

Fig. 4. Effect of CSI accuracy on average percentage of users in outage per frame at full-load ($U = U_{max}$).

We use the *average percentage of users in outage per frame* as an overall performance metric. In Fig. 4, this metric is plotted versus the accuracy parameter a for a fully-loaded system ($U = U_{max}$). We notice that the percentage of users in outage for perfect CSI ($a = 0$) is about 2 $\%$. This percentage does not exceed 4.5 $\%$ even at $a = 0.5$ which corresponds to a significantly-degraded CSI. This shows the robustness of the proposed resource allocation method to user-distance estimation errors.

VII. CONCLUSION

In this paper, we derived an upper-bound on system capacity in terms of number of users in an OFDMA downlink under QoS fairness constraint and a reduced CSI feedback. Depending on the system load, the minimum required number of subcarriers was found as well as the corresponding power and rate allocation that offers the best overall outage performance. Finally, simulations allowed us to validate the analytic results and to characterize the robustness of our approach to CSI estimation errors.

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