Spectral Efficiency Enhancement and Power Control of Smart Antenna Systems

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***Abstract* — In this work we investigate the increase in spectral efficiency in a cellular mobile communications system employing smart antennas at the base station. We analyze two different strategies — SFIR (Spatial Filtering for Interference Reduction) and SDMA (Space Division Multiple Access) — and determine the impact of non–ideal power control.**

Our results indicate that a cluster size of $N_{cl} = 1$ is possible with smart antennas, even in systems with non–ideal power control. The demands on the power control algorithm for an SFIR system are less stringent than for an SDMA system.

The use of SDMA increases the spectral efficiency over SFIR by additional 80%. Furthermore, SDMA adds flexibility to the whole network.

I. Introduction

The increasing demand of capacity of mobile communications systems has spurred the research into new areas. Smart antennas are one of these promising fields. A variety of system concepts [1], algorithms [2], [3], and realizations [4] has been investigated. For a network operator, however, knowledge about the capacity increase achievable by this technology is of decisive importance. Estimates for the spectral efficiency have been published in [5], [6]. In [1] the increase in spectral efficiency of an SFIR–system was determined to be $\sqrt{M}$ over a conventional system, where M denotes the number of antenna elements. For SDMA, a typical efficiency gain of $\sqrt{KM}$ was determined. K was estimated to be equal to three at maximum for $M = 8$.

So far estimates have been based on *mean* values of the CIR (**C**arrier to **I**nterference **R**atio). Since a network operator is interested in the outage probability P_{out} of a system, which should be less than a predefined threshold value $P_{out,th}$, we will investigate the outage probability. Therefore we are not interested in the *mean* CIR (**C**arrier to **I**nterference **R**atio), but rather in the 5%–level of the outage probability, $\text{CIR}_{5\%}$. We will use $P_{out,th} = 5\%$ as a reference value throughout this paper.

We also considered non–ideal power control scenarios to reveal consequences of introducing smart antennas on system performance.

Two possible approaches for introducing smart antennas at the BS (**B**ase **S**tation) of PCSs (**P**ersonal **C**ommunications **S**ystems) are SFIR and SDMA [1]. In the SFIR case only one user is served per traffic channel. The SDMA scenario allows multiple users to be served simultaneously in a simple traffic channel. In [7] we compared these two approaches and determined their potential as well as their requirements.

We have written a flexible simulation tool, where different effects of the mobile radio system can be tested. Some features of this software have been inspired by the simulation tool presented in [8].

The present paper gives estimates of the increase in spectral efficiency for both SFIR and SDMA. Furthermore it focuses on power control issues and determines their requirements and their influences on the system.

II. SFIR

In SFIR only one user per traffic channel is served. The first tier of interfering cells is taken into account for the simulations. The six outer cells are treated as isolated. Each one carries traffic of a randomly located user. For the inner cell also one user is accommodated, but his CIR is determined by the contribution of the six interfering co–channel users. Two different situations might occur:

1. If the CIR of the user in the center cell is below a predefined threshold CIR_Threshold, it is *passed* to another traffic channel. We call this a *handover*.
   Another user located elsewhere within the center cell is selected and his CIR is calculated, which is again compared against the threshold. Depending on its value, the appropriate action ((1) handover, generate new user *or* (2) record the CIR) is taken.

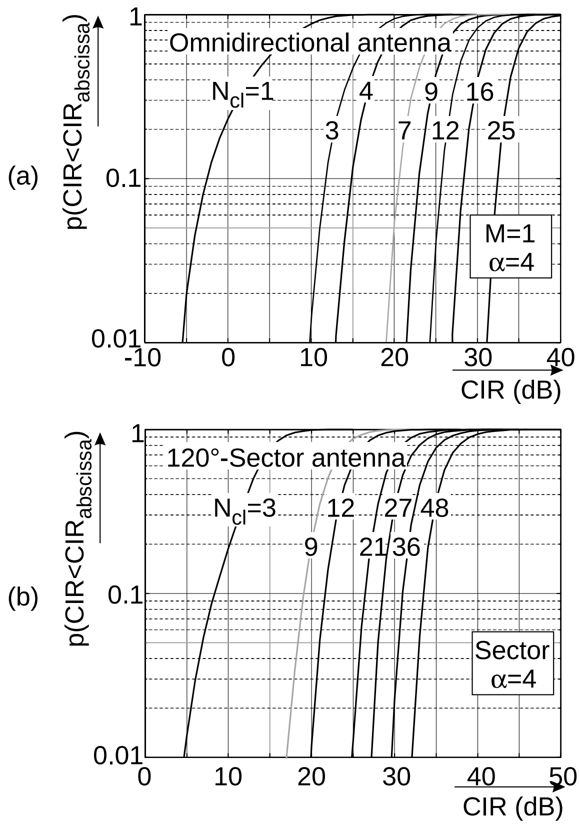

Fig. 1: CDF of the CIR, $p(\text{CIR} < \text{CIR}_{abscissa})$, i.e. the outage probability P_{out}, for (a): a system using omnidirectional antennas, and (b): a system using 120°–sector antennas, with the cluster size N_{cl} as parameter. The curves are read in the following way: (a) For a cluster size of $N_{cl} = 7$ the CIR is less than or equal to 20dB in $P_{out} = 5\%$ of the cases.

2. If its CIR is above the threshold, the user distribution is accepted and the CIR of the user in the center cell is recorded.

This procedure terminates if (1) the CIR of the user in the center cell is above the threshold, CIR_Threshold, or if (2) the maximum number of handovers, MaxHandover, is reached. For Case (2) the last CIR (which is of course below the threshold) is recorded.

As a threshold value for the CIR we assume CIR_Threshold = 9dB + 6dB = 15dB, since 9dB are necessary for proper operation of GSM (**G**lobal **S**ystem for **M**obile communications) and 6dB is a realistic fading margin. As propagation model we use a single–slope curve with pathloss exponent $\alpha = 4$ and a standard deviation of the log–normal fading of $\sigma_{\log} =$ 6dB.

A. Omnidirectional and Sector Antennas

Figures 1a and b show the CDF (**C**umulative **D**istribution **F**unction) of the CIR for a user in the center cell when using omnidirectional or sector antennas. This CDF is equal to the mean outage probability P_{out} averaged over the whole cell. The power control of the system was assumed to be ideal; the antenna is a conventional omnidirectional one.

For customer satisfaction the outage probability averaged over the whole cell should be at maximum $P_{out,th} = 5\%$. Figure 1a tells us that a minimum cluster size of $N_{cl} = 7$ for scenarios with $\alpha = 4$ is necessary to satisfy this requirement.

For sector antennas the cluster sizes necessary to guarantee $P_{out} \leq 5\%$ is $N_{cl} = 9$. Since the cell area of one sector is only $1/3$ than that of the corresponding system using omnidirectional antennas, the spectral efficiency increases by a factor of $7 * 3/9 = 2.33$. Note, however, that we have concomitantly reduced the trunking efficiency by breaking up the trunking pool for a BS using an omnidirectional antenna into three trunking pools for a BS site using three 120°–sector antennas.

B. Smart Antenna

Figure 3 shows the CDF of the CIR for a system using a smart antenna.

If not stated otherwise, we refer to the broadside radiation pattern of an eight–element ULA (**U**niform **L**inear **A**rray) with spacing $d = 0.5\lambda$. The pattern nulls are assumed to be filled up to 20dB below the pattern maximum (**N**ull **D**epth ND=20dB), the FBR (**F**ront–to–**B**ack **R**atio) is also assumed to be 20dB. The filling of the nulls may arise from non–discrete DOAs (**D**irections–**o**f–**A**rrival), and null–steering errors due to DOA estimation errors.

Figure 2 shows the applied antenna pattern that describes the direction–dependent interference suppression (assuming that the wanted user is located at an azimuth of 90°). It is assumed that the maximum of the antenna pattern points into the direction of the user. Co–channel users are then suppressed according to this pattern. We therefore did not assume any specific null–steering that would improve the situation furthermore.

The amazing result of Fig. 3 is that a cluster size of $N_{cl} = 1$ is feasible, i.e. the same group of frequencies can be reused in every cell. (A choice of larger N_{cl} would of course increase the CIR–values, but spectral efficiency would suffer.) Compared to Figure 1 not only the position of the curves, but also their shape has changed. Therefore the increase in *mean* CIR is, in general, not equal to the increase in CIR at the 5%–level of P_{out}.

C. Power Control Errors

Up to now we have based our results on an ideal power control, i.e. the path loss and the lognormal fading are perfectly equalized. Now we investigate

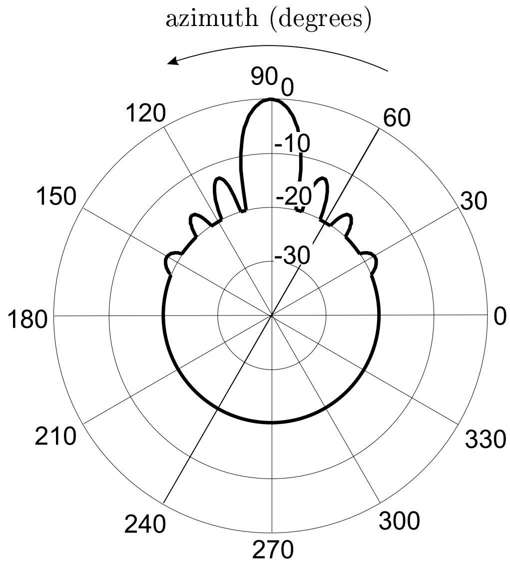

Fig. 2: Antenna pattern of an eight–element ULA with spacing $d = 0.5\lambda$, and null depth and front–to–back ratio of 20dB.

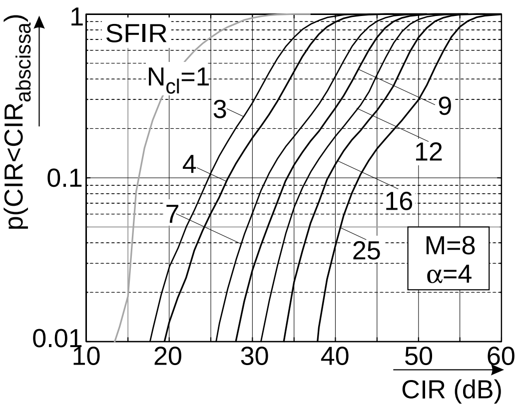

Fig. 3: CDF of the CIR, $p(\text{CIR} < \text{CIR}_{abscissa})$, i.e. the outage probability P_{out}, for a system using three or four ULAs with $M = 8$ at one cell site with the cluster size N_{cl} as parameter.

the influence of power control errors on the outage probability by assuming a Gaussian distributed power control error with standard deviation σ_{PC} (Fig. 4). The curves of Fig. 4 indicate that the influence of power control errors is stronger for smaller values of the propagation exponent α, because then, co–channel interferers are less attenuated. For $\alpha = 4$ ($\alpha = 2$) power control errors up to 10dB (3dB) are not critical for system performance. But it starts to degrade at larger power control errors, $\sigma_{PC} \geq 15$dB (8dB) for $\alpha = 4$ (2).

D. Power Control Strategies

To examine the influence of different power control strategies we also determined system performance with a GSM power control algorithm and without any power

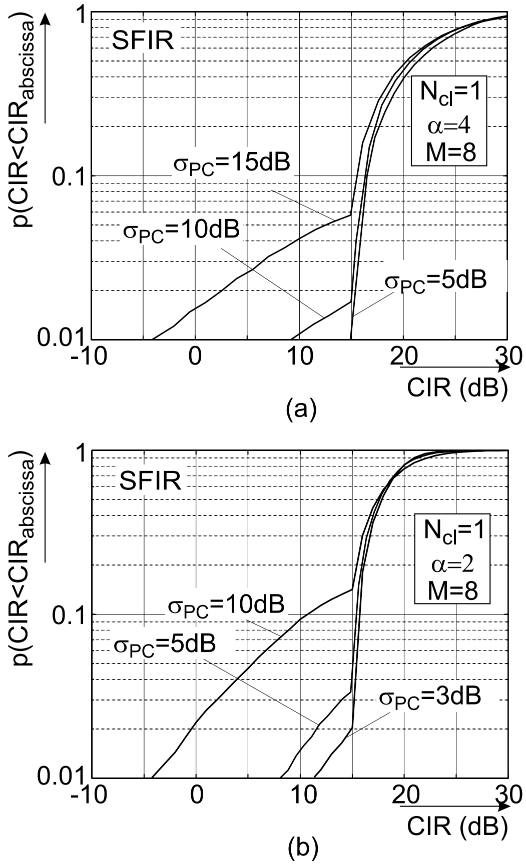

Fig. 4: Influence of power control errors on the CIR. CDF of the CIR, $p(CIR < CIR_{abscissa})$, i.e. the outage probability P_{out}, versus the CIR for an SFIR–system with $N_{cl} = 1$, $M = 8$ with the standard deviation of the power control error, σ_{PC}, as parameter. (a) $\alpha = 4$, (b) $\alpha = 2$.

control. We assumed the **D**ynamic **R**ange, DR, of the power control to be equal to the range of the path loss, i.e. we selected the quotient of the maximum cell radius r_max over the minimum cell radius r_min to satisfy $10\alpha \log(\text{r\_max}/\text{r\_min}) = DR$, where α is the propagation exponent.

Figure 5a shows the outage probability, P_{out}, for the case of GSM power control with the cluster size N_{cl} as parameter. Here we assumed, according to GSM standard, the power control to have 15 steps (2dB per step), giving a dynamic range of $DR = 30$dB. Compared to Fig. 3 the curves become less steep, i.e. for small CIR–values they move slightly to the left, whereas for larger CIR–values they move to the right. The shift is more pronounced for larger cluster sizes.

The same scenario was investigated without power control (Fig. 5b). Here, a similar behaviour is noticed: the curves move remarkably to smaller CIR–values and become less steep. For a cluster size of $N_{cl} = 4$ (25) the loss in $\text{CIR}_{5\%}$ as compared to a system using ideal power control is about 4dB (8dB), while no loss can be

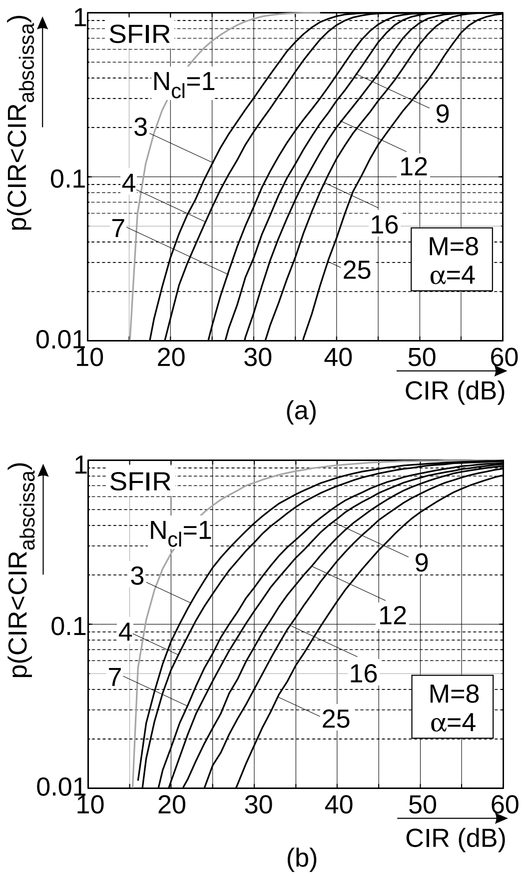

Fig. 5: Influence of power control strategy on the CIR. CDF of the CIR, $p(CIR < CIR_{abscissa})$, i.e. the outage probability P_{out}, versus the CIR for an SFIR–system with cluster size, N_{cl}, as parameter. (a) GSM power control, (b) no power control.

observed for $N_{cl} = 1$.

Independent of the applied power control algorithm a cluster size of $N_{cl} = 1$ suffices to guarantee an outage probability less than 5%. However, we observed an increased number of handovers. This is due the fact that, when an interferer lies in the same direction (seen from the BS of the user) as the user and the CIR is large enough for the case of ideal power control, it might be smaller than the threshold for non–ideal power control, i.e. an additional handover is required. Because these scenarios are less probable with GSM power control algorithm the number of handovers increases only slightly (7% for $N_{cl} = 1$), as compared to the case of no power control (84% more handovers for $N_{cl} = 1$).

III. SDMA

For operation of the cellular system in an SDMA mode multiple users per traffic channel are allowed.

The six outer cells are treated as isolated. In each outer cell as many users as possible are allocated. The

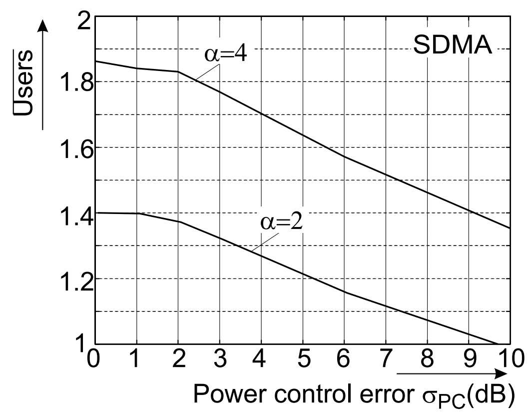

Fig. 6: Influence of power control errors with standard deviation σ_{PC} on the mean number of users.

cell is considered to be fully loaded if either (1) a predetermined maximum number of users, n_MaxUser, is achieved or (2) the number of handovers reaches the value MaxHandover.

For the center cell we consider the interference of the six surrounding co–channel cells. The principle of interference calculation is basically the same as for an isolated cell. As many users as possible are allocated to the channel until the number of handovers is equal to the predefined threshold MaxHandover. Afterwards the number of users in the center cell is recorded for statistical evaluation.

For the following simulation results we assumed a cluster size $N_{cl} = 1$, a maximum number of handovers Max_Handover=6, a pathloss exponent of $\alpha = 4$, and a standard deviation of the log–normal fading of $\sigma_{\log} = 6$dB. The antenna is an eight–element ULA with a null depth of ND=20dB and a front–to–back ratio of FBR=20dB. The CIR–threshold was set to CIR_Threshold=15dB.

A. Ideal SDMA

The mean number of users was found to be $\overline{\text{Users}} = 1.85$ for $N_{cl} = 1$ and $\overline{\text{Users}} = 2.8$ for $N_{cl} = 3$. Therefore the spectral efficiency increases over an SFIR system by about 85% (180%) for $N_{cl} = 1$ ($N_{cl} = 3$).

B. Power Control Errors

Up to now we have only investigated an ideal SDMA processing chain. We will soften this condition here by first analyzing the effect of power control errors. Figure 6 shows the influence of power control errors on the mean number of users, where the error is considered as Gaussian distributed with standard deviation σ_{PC}.

Small power control errors with $\sigma_{PC} \leq 2$dB do not affect the mean number of users remarkably. For $\sigma_{PC} = 3$dB the capacity impairment is about 5% for $\alpha = 4$. Larger power control errors lead to a remarkable capacity decrease, e.g. for $\sigma_{PC} = 6$dB the decrease is

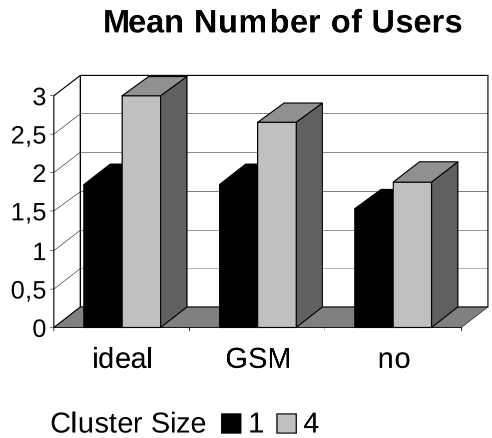

Fig. 7: Mean number of users for ideal, GSM, and no power control for different cluster sizes.

16% for $\alpha = 4$.

C. Power Control Strategies

As in the SFIR case, we also investigated the influence of power control strategies on the system performance.

Figure 7 shows the mean number of users, $\overline{\text{Users}}$, for different power control strategies. For a cluster size of $N_{cl} = 1$ we observe no decrease of $\overline{\text{Users}}$ for the GSM power control strategy compared to ideal power control, whereas with no power control the decrease amounts only to 17%. For a reuse distance of two ($N_{cl} = 4$) we observe larger impairments in the mean number of users. With the GSM power control algorithm the decrease in $\overline{\text{Users}}$ compared to ideal power control is 11%, while we observe a loss of 37% without power control. Note that the impairment of spectral efficiency due to non–ideal power control algorithms is not large, which can be explained by the allowed handovers.

However, the distribution of the power range, Γ, of the accepted users in the same timeslot in the center cell changes significantly. Γ is defined as $\Gamma = 10 \log p_{max}/p_{min}$, where p_{max} (p_{min}) is the maximum (minimum) power of the accepted users in the center cell *before* the application of the power control algorithm.

Figure 8 shows the distribution of the power range, Γ, of the accepted users in the center cell. A small value of Γ means that only users with similar power levels can be served simultaneously in one cell. The cases, where only one user is accepted, which means that $\Gamma = 0$dB, are not included in the distribution. Instead, the percentage that only one user is accepted in the center cell, P_{1User}, is indicated.

Figures 8c and f show that, without any power control, Γ is 5dB at maximum. This comes from the fact that the maximum suppression of co-channel interferers is $ND = FBR = 20$dB, while a CIR–value of CIR_Threshold = 15dB is required for a user to be accepted. The difference of these values gives the maximally allowed ratio of the powers of two accepted users. As a consequence the users has to be grouped into so–called *power classes* [9] with a range of 5dB each, i.e. that for a realistic dynamic range of a cell of about 80dB 16(!) traffic channels for handovers would be necessary. Otherwise, not the whole cell area could be served simultaneously.

For the employment of the GSM or the ideal power control algorithm the spread of Γ is much larger (standard deviation of Γ, $\sigma_\Gamma > 21$dB) than in the case of no power control ($\sigma_\Gamma \approx -3$dB). Here, the requirements for the grouping of users into power classes are less stringent. Although we did not observe a reduction of the mean number of users for the case of GSM power control compared to ideal power control, the distribution of Γ has changed. For the GSM scenario smaller values of Γ became more probable (the mean value of Γ, $\overline{\Gamma}$, is about 8dB smaller than in the case of ideal power control) and situations where $\Gamma > 30$dB nearly vanish. The first statement can be explained due to the inherent power control error of the GSM scenario (maximum error of ± 1dB and lognormal fading), and the second statement comes from the limited dynamic range of the GSM power control of 30dB.

Antenna		**Omni**	**Sector**
Sector antenna		2.3	1
SFIR	$N_{cl} = 3$	2.3	1
	$N_{cl} = 1$	7	3
SDMA	$N_{cl} = 3$	6.4	2.8
	$N_{cl} = 1$	13	5.6

TABLE I
Increase in spectral efficiency for the traffic channels by the application of smart antennas as compared to systems using omnidirectional or sector antennas for a pathloss exponent $\alpha = 4$.

IV. Conclusion

Table I shows the increase in spectral efficiency for both SFIR and SDMA utilizing ideal power control as compared to systems using omnidirectional or sector antennas.

A cluster size of $N_{cl} = 1$ for the traffic channels is possible by using SFIR.

The additional capacity increase of SDMA over SFIR is between 40%–200%, depending on the cluster size N_{cl}. Furthermore, SDMA provides the system with more flexibility. Temporally occuring hot spots in specific locations can be dealt with without making hardware changes to the whole network. The SDMA component needs only to be introduced in such cells where one needs more capacity, whereas SFIR has to be employed in rather large areas to give the wanted capacity increase.

We have assumed that the dynamic range of the ideal power control is large enough to cover the whole dynamic range of the cell. Should this not be the case, the cell has to be divided into several concentric rings, where each one forms a so–called *power class* [9].

We have also assumed that the power control reacts without delay. This is not true in a real GSM system, where the power equalization is delayed. To account for that effect, power control errors can be considered. Our results indicate that an SFIR system can cope with larger power control errors than an SDMA system.

The non–ideal power control strategies give only slightly lower estimates for the spectral efficiency. For the case of SFIR, the spectral efficiency even stays the same. However, we observed an increased number of handovers, which reduces the overall capacity of a network due to an increased signaling load. Additionally, in configurations with larger cluster sizes we observed a reduced quality of the system, i.e. smaller values for $\mathrm{CIR}_{5\%}$.

In the case of SDMA, the spectral efficiency degraded significantly only for systems with no power control. Note, however, that the quality of the power control strategy has significant influence on the channel allocation and handover schemes, since a large number of power classes has to be introduced. This would of course decrease the spectral efficiency of the system.

Sophisticated power control strategies are, especially for SDMA systems, necessary to keep the system complexity low, and to fully exploit the increase in system performance by smart antennas.

V. Acknowledgment

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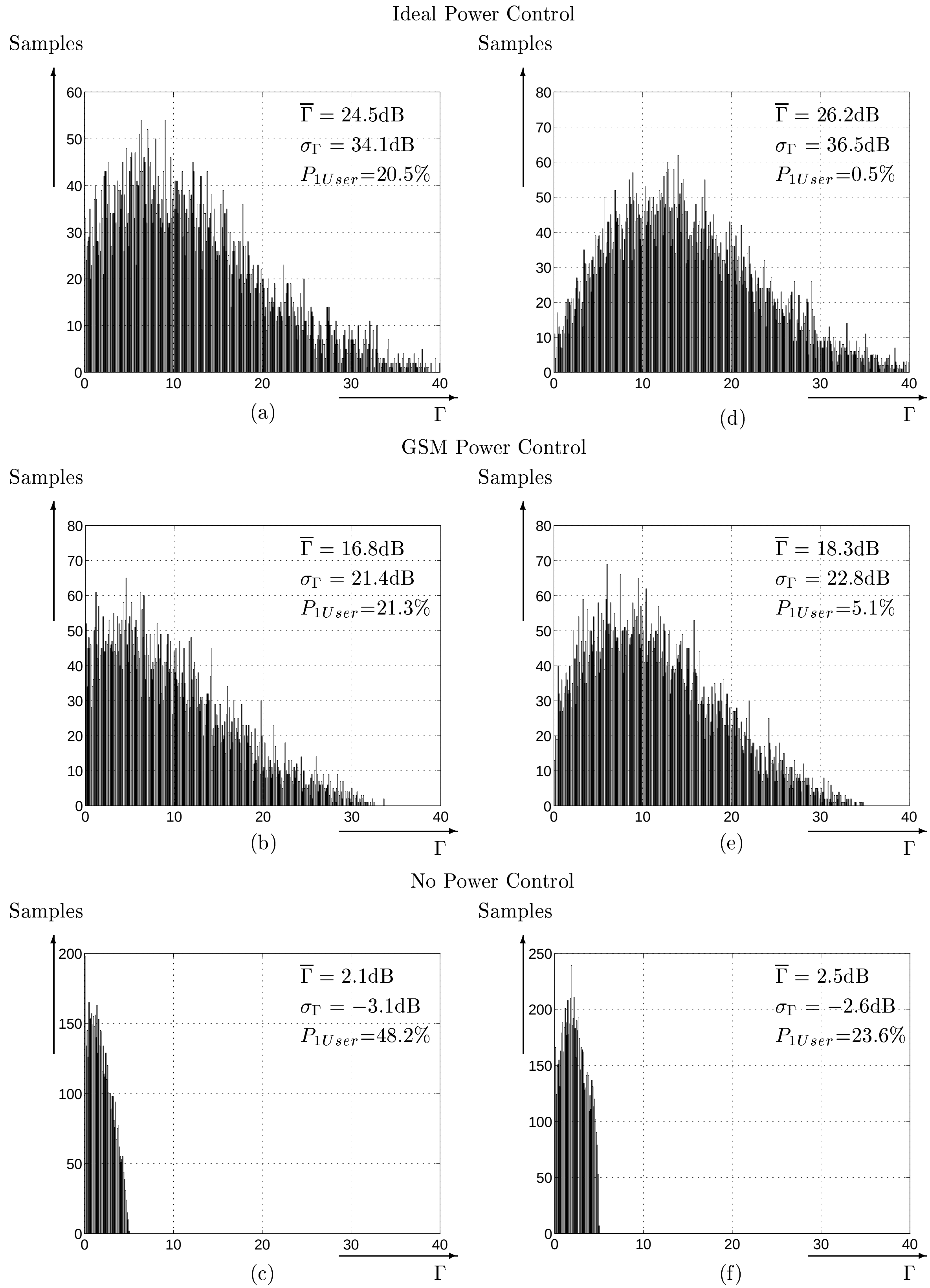

Fig. 8: Distribution of Γ. (a) – (c) for cluster size $N_{cl} = 1$, (d) – (f) for cluster size $N_{cl} = 4$ with ideal, GSM, and without power control, respectively. P_{1User} is the probability that only one user is accepted in the center cell.