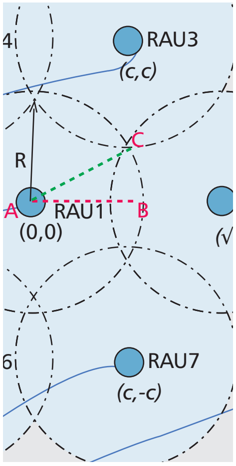
DISTRIBUTED ANTENNA SYSTEM CAPACITY SCALING

DANIEL CASTANHEIRA AND ATILIO GAMEIRO, AVEIRO UNIVERSITY



The authors provide an overview of the main benefits of a DAS in relation to a collocated antenna system. They study the sum-capacity scaling of a multi-user DAS with the number of jointly processed transmit antennas in the downlink.

ABSTRACT

The distributed antenna system concept promises to enhance the capacity and diversity of next-generation wireless communication networks, due to the inherently added micro and macro diversity. In this article we first give an overview of the main benefits of a DAS in relation to a collocated antenna system. Next we study the sum-capacity scaling of a multi-user DAS with the number of jointly processed transmit antennas in the downlink. In a practical system this scaling will have implications on the number of antennas worth jointly processing, since the costs of processing an additional antenna can be higher than the additional benefits obtained. Results show that the most important system property to attain the highest capacity gains is symmetry, and the users that attain the maximum gain are those at cell borders. They also confirm that the main DAS feature that makes possible its gains over the CAS architecture are the additional degrees of freedom/diversity provided by such an architecture, which increase the probability of finding a system state with high symmetry and of each user being near one of the transmit antennas.

INTRODUCTION

In response to the increasing demand for higher spectral efficiencies the multiple-input multiple-output (MIMO) antenna concept has gained a lot of attention in recent years. From theory [1], it is expected that the system capacity will increase far beyond that of single-antenna systems in rich scattering propagation environments. On the other hand, for limited scattering propagation environments, the capacity and diversity order achieved will be limited, due to the existence of strong correlation between channel paths. This is indeed what happens for a collocated antenna system (CAS), in which the antennas are only few wavelengths apart. Intuitively this can be explained by the fact that if the antennas are close together and one of the links has poor quality, the others will have poor quality with high probability, and thus the overall received signal strength will be low. On the contrary, for a system with independent links, if one of the links has poor quality, at least one of the other links will have good quality with a fairly high probability, which increases with the number of considered links. Therefore, to achieve high spectral efficiencies and attain high diversity gains, the channels should be independent. Nevertheless, due to physical limitations at the transceivers, the number of antennas deployed and the degree of channel independence achieved, in a CAS, cannot be high. One possible solution to cope with this problem is to have the mobiles simultaneously communicating with a group of geographically distributed antennas, which are jointly processed at a central point [2]. The key element to achieve this is to have the signals transparently connected to a central unit (CU) (e.g., by fiber) where they are jointly processed. This leads us to the distributed antenna system (DAS) concept, by which not only will capacity and diversity gains be obtained, but also the access distance and transmit power will be reduced, due to the inherent added macro-diversity. In [3] the authors quantify the capacity gains provided by a single-user DAS in the presence of intercell interference, showing that DAS reduces other-cell interference in a multicell environment, and hence significantly improves performance and capacity, especially for users near cell boundaries. When more users are to be served simultaneously, the additional degrees of freedom provided by the DAS architecture can be used to spatially separate users, thus expanding system capacity. Nonetheless, at the mobile terminals the number of antennas is generally low, only one or two. Therefore, from the law of diminishing returns, it is expected that when the number of jointly processed antennas increase, the complexity will increase, but the improvement in throughput may not increase in the same way. As a result, a trade-off between the added complexity/costs and obtained benefits from the joint processing of more transmit antennas must be made. In [4] the authors analyze this trade-off by considering as a measure of network performance the normalized system capacity or, more precisely, the maximum achievable rate per channel use normalized by the number of cooperating remote antenna units (RAUs). Another key performance measure considered in the previous article is the signal-to-interference ratio (SIR). Considering full frequency reuse among RAUs, different cooperation schemes were analytically analyzed. The authors observed that cooperation is not always beneficial; that is, for geographical user positions close to one of the RAUs it is better to use non-cooperative transmission (serve the user with only one RAU), and for cell coverage boundaries cooperation is beneficial. Based on those results, the authors propose to adaptively

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optimize the network operation mode (i.e., the number of cooperative RAUs) to combine the advantages of cooperative and non-cooperative schemes to maximize the system throughput. Results show that adaptive cooperation becomes more significant when shadowing effects increase, with more than 20 percent cell-average gain for up to three RAUs' cooperation. In this article we propose to give an overview of the gains provided by RAUs' cooperation in terms of the ergodic channel sum-capacity in the downlink. In that context we define differential capacity (DCAP) as the increase in ergodic sum-capacity when one additional RAU is connected to the system users, to quantify the gains provided by the processing of one additional RAU at the CU.

We begin in the following section with a description of the system model. Next we give a small overview of the main benefits of DAS over CAS. Then we describe the behavior of the DCAP for the single-user case to introduce the topic. Finally, we access the benefits of the connection of more transmit antennas to the CU for the multi-user case.

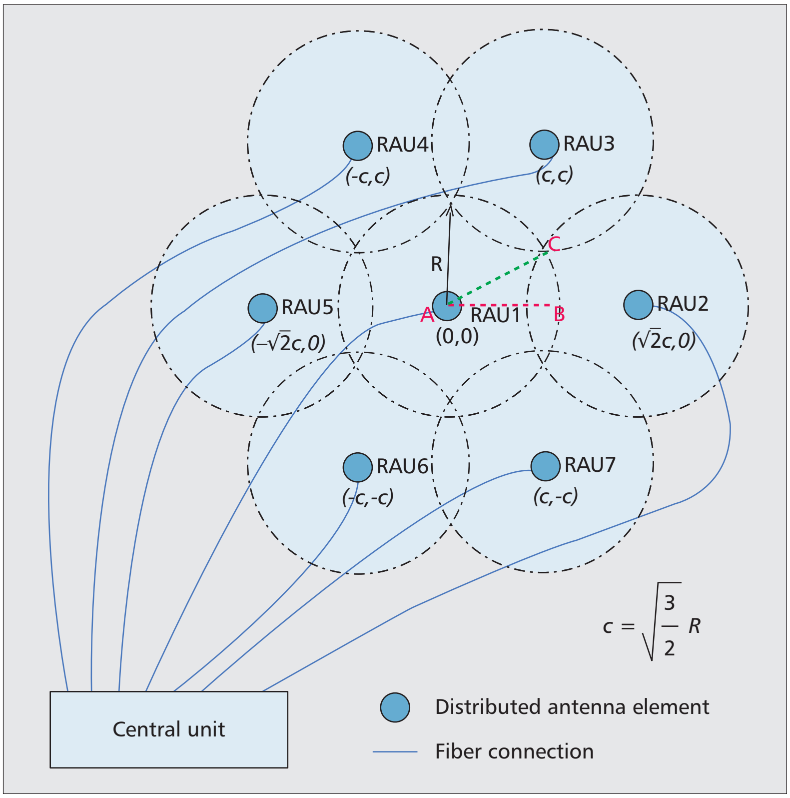

Figure 1. *Distributed antenna system cell.*

CHANNEL MODEL

The multiuser downlink model considered in this article is illustrated in Fig. 1. A CU with M RAUs, each transparently connected to the CU by cable (e.g., fiber), and K single antenna users is considered. Throughout the text it is assumed that the receiver has perfect knowledge of its own channel and that the transmitter has perfect knowledge of all channels for each channel realization. In practice this can be achieved by the use of training data and feedback channels between the CU and the system users. All analysis presented in this article considers, for simplicity, a single cell with all RAUs connected to a single CU, where all signals are jointly processed. Thus, the system is considered to be noise limited. The cable connection is regarded as transparent to the signals transported.

The DAS and CAS have unique channel characteristics. For example, for a DAS there is a significant path loss difference among received paths, as a result of the different access distances, and only a limited number of them influence the actual system performance, due to the high attenuation experienced. It is also this inherent channel asymmetry that increases the probability of each user being near one of the RAUs. On the other hand, for a CAS all received paths experience the same path loss [5, 6], since all transmit antennas are collocated. But the small separation between the transmit antennas also has its drawbacks. It will imply the appearance of correlation between channel paths. In contrast, for a DAS the different scattering properties around each of the RAUs enrich the corresponding channels' statistics, offering channel independence.

To model all the previous stated channel characteristics, a broadcast channel (BC) [7] with M transmit antennas and K users, each with only one receive antenna, is considered as a model for the downlink of a DAS/CAS. For such a system, if no correlation between each user received channel path is considered, user k's received signal can be modeled by

$$y_k = \mathbf{h}_k\mathbf{x} + n_k,\ k = 1, \ldots, K;\ \mathbf{h}_k = \mathbf{h}_k^w\mathbf{R}^{1/2}\boldsymbol{\rho}_k^{1/2}, \quad (1)$$

where $\mathbf{x}$ is the transmitted signal vector, $\boldsymbol{\rho}_k$ is a diagonal matrix where each element i denotes the path loss factor between transmit antenna i and user k, $\mathbf{h}_k^w$ models the microscopic independent Rayleigh fading component, $\mathbf{R}$ represents the correlation between transmit antennas [8], and n_k is additive white Gaussian noise. $\mathbf{R}$ and $\boldsymbol{\rho}_k$ are deterministic. In the following sections no correlation is considered ($\mathbf{R} = \mathbf{I}$), for a DAS, and for a CAS all path losses are regarded as equal ($\boldsymbol{\rho}_k = \mathbf{I}$).

One interesting aspect that can be seen from Eq. 1 is that the effect of path loss asymmetry in DAS is in some sense equivalent to the channel correlation effect in a CAS, as seen in the next sections. However the path loss asymmetries inherent in a DAS can be solved more easily, with careful deployment of the transmit antennas rather than the channel correlation inherent to the CAS, since for a CAS the number of transmit antennas impacts the overall channel correlation effects.

In all results presented in this article, the signal-to-noise ratio (SNR) at a distance of 1000 m from each transmit antenna is assumed to be equal to 0 dB. It is also considered that the RAU connection order is from the closest RAU to the farther one, and that the propagation path loss only depends on the distance between user i and RAU j, d_{ij}, and the path loss exponent α ($d_{ij}^{-\alpha}$), which is considered to be equal to 3. In the next sections on the single-user case, by circular ring we mean a group of antennas with the same mean SNR to the user.

One of the main benefits of DAS over CAS is in terms of power efficiency. This is mainly due to the fact that for a DAS the access distance is reduced, mitigating in that way the path loss effects of the channel onto the transmitted signals.

DAS VS. CAS

In a CAS the jointly processed antennas are only a few wavelengths away from one another; in a DAS they are physically far apart. This physical separation in the DAS implies different scattering properties around each RAU, improving the statistical properties of the channel and offering the necessary channel independence. It is also this inherent channel asymmetry that increases the probability of each user being near one of the RAUs, mitigating in that way the large-scale fading effects, like path loss and shadowing from buildings, increasing the DAS power efficiency. In the following sections we give a brief overview of the power efficiency benefits introduced by a DAS and the impact of the channel correlation and asymmetries on the average bit error rate (BER) performance.

POWER EFFICIENCY

Power efficiency gives a measure of the required power for supporting a given coverage area. One of the main benefits of DAS over CAS is in terms of power efficiency. This is mainly due to the fact that for a DAS the access distance is reduced, mitigating the path loss effects of the channel on the transmitted signals.

To demonstrate the power benefits of DAS over CAS, let us consider a simple example [3]. Consider a distributed cell, as shown in Fig. 1, composed of one central antenna and a tier of six distributed antennas, each with a coverage radius equal to R. This is the same as saying that each distributed antenna has a coverage area equal to $7\pi R^2 - 24(\pi/6R^2 - \sqrt{3}/4R^2) = (3\pi + 6\sqrt{3})R^2$. The radius of a circle with the same area is

$$R\sqrt{3+6\sqrt{3}/\pi}.$$

For a fair comparison with a DAS, consider this circle as the coverage area of a CAS cell [5]. Let us also consider that for a RAU to support a coverage area with radius R, the required power is P. Thus, to support the overall coverage area a total power of $7P$ is needed. On the other hand, for the CAS the needed power is equal to $(3 + 6\sqrt{3}/\pi)^{\alpha/2}P$ if the propagation path loss is assumed to be given by $d^{-\alpha}$, where α is the path loss exponent. In other words, the power efficiency of the DAS is given by $(3 + 6\sqrt{3}/\pi)^{\alpha/2}/7$. For a path loss exponent equal to 3, the DAS power efficiency gain is equal to 3.6 dB and is even higher for bigger path loss exponents. This illustrates the power efficiency benefits of a DAS with respect to a CAS, meaning that a DAS needs a much lower power budget to support the same coverage area.

DIVERSITY/POWER LOSS

To analyze the impact of the channel correlation in a CAS and the path loss asymmetries in a DAS, let us consider as a measure the average BER as well as the downlink of a single-user transmit diversity system with M transmit antennas and one receive antenna. Let us also consider, for simplicity, binary phase shift keying (BPSK) modulation and the high SNR regime. To maximize the received SNR, the signal sent on transmit antenna i is pre-multiplied by a gain α_i. Under those circumstances the optimal gain value is obtained using the maximum ratio transmission (MRT) algorithm. If MRT is used, at the transmitter, the instantaneous received SNR is equal to $\mathbf{h}^w\mathbf{\Lambda}\mathbf{h}^{wH}$, where $\mathbf{\Lambda} = \mathbf{R}^{1/2}\mathbf{\rho}^{1/2}(\mathbf{R}^{1/2}\mathbf{\rho}^{1/2})^H$, and $\mathbf{h}^w$ represents the channel matri, with complex Gaussian distributed entries, zero mean, and variance one. The deterministic matrix $\mathbf{\Lambda}$ can be decomposed using the singular value decomposition, and the corresponding left and right singular vectors integrated into the channel matrix without affecting their distribution, since they are unitary and $\mathbf{h}^w$ is isotropic. Thus, $\mathbf{h}^w\mathbf{\Lambda}\mathbf{h}^{wH}$ follows the weighted chi-square distribution. As a consequence, if $\mathbf{\Lambda}$ is full rank, it is not difficult to verify that the correlation at the transmitter side for a CAS or the path loss asymmetries inherent to a DAS imply a BER power penalty of $|\mathbf{\Lambda}|^{-1/M}$. If, instead, the rank of $\mathbf{\Lambda}$ is equal to $m < M$, the system loses $M - m$ degree of freedom, since $M - m$ channels become linearly dependent.

For a DAS, if one of the channel path losses increases by a factor of 2, the power loss will increase by 3 dB, since the determinant of a diagonal matrix is equal to the product of their diagonal entries. On the other hand, the correlation effects are not as easy to visualize since the correlation matrix is not diagonal, like the path loss matrix. To have better insight into the correlation effects on BER performance, let us consider a CAS with a simplified correlation structure: a correlation r between the channel paths of different transmit RAUs. For such correlation structure the resulting power loss is depicted in Fig. 2. As can be seen from the figure, the power loss experienced by such a system in the high SNR regime increase as the correlation factor (r) increases, but for low values of r the increase is not as sharp as for high values of r. A typical power loss value for moderated correlation ($r = 0.6$) is 2 dB (Fig. 2). Another aspect worth noting is that the power loss starts to saturate when the number of transmit antennas is approximately four. This happens mainly due to the averaging of the power losses corresponding to each of the correlation matrix eigenvalues as M increases, since the power loss in dB is equal to the average of the corresponding eigenvalues of $\mathbf{\Lambda}$ (in dB).

DIFFERENTIAL CAPACITY

In the previous sections a brief overview of the benefits of a DAS over a CAS has been given in terms of power efficiency and diversity. Now we focus on another measure, the channel sum-capacity. More specifically we focus on the system DCAP. The use of DCAP is of interest for the case where the radio resources are dynamically allocated. Assuming centralized management, the CU can then easily decide, as the radio environment changes, whether or not it is worth connecting to an additional antenna.

In a practical system, the scaling of the channel capacity with the number of transmit antennas will have implications on the number of transmit antennas that are worth being jointly processed in a DAS, since the costs of processing an additional antenna can be higher than the additional benefits obtained. Hence, it is important to quantify the benefits introduced by the connection of additional transmit antennas to the system.

Since we consider a noise limited system and also assume a power constraint on each RAU, the system capacity will always increase each time a new antenna is connected to the system users, given that the degrees of freedom available, the signal space dimensions, will also increase. In the following discussions no co-channel or any other type of interference is considered. For a detailed analysis of the capacity for a cellular DAS using cooperative transmission, please refer to [4, references therein]. However, during our analysis on the topic we have verified that a global power constraint at the transmitter (each RAU transmits a signal with power P/M) has similar effects to intercell interference. Indeed, the points where the capacity curves (corresponding to different numbers of cooperating RAUs) cross occur at similar places. However, we do not pursue this topic here.

In the following sections we first quantify the system capacity gains by the connection of additional transmit antennas for the single-user case by resorting to the DCAP definition. For that case, we first give a brief overview of the required background to analyze this scenario. Next we look at a specific distributed antenna deployment to find the points that benefit the most from the connection of additional transmit antennas at the CU and also explore the DCAP sensitivity to SNR variation. Finally, the multiuser case is considered. For the multi-user case we rely mostly on simulations to extend the conclusions drawn from the single-user case.

SINGLE-USER SCENARIO

For the single-user scenario, considering that each RAU transmits a signal with power P, the system capacity is given by the average of the system capacity for each channel realization [1],

$$C_M = \mathbf{E}_{\mathbf{h}}\left[\log_2\left(1+\gamma\right)\right],$$

where $\gamma = P\mathbf{h}\mathbf{h}^H$ and $\mathbf{E}_h$ denotes the expectation over the channel gains. Consequently, the system capacity will only be dependent on the distribution of γ, which is weighted chi-square distributed with $2M$ degrees of freedom, where each weight corresponds to the eigenvalues of the matrix $\mathbf{R}$ or $\boldsymbol{\rho}$ for a DAS and CAS, respectively. As a result, if the eigenvalues are the same for a given DAS and CAS system, the corresponding capacity for the two systems is also the same.

As is well known, the moment generating function (MGF) of the sum of independent random variables is equal to the product of each random variable MGF. With this property in mind, it is not difficult to get a relationship between the distribution of the random variable γ for $M-1$ and M RAUs, respectively [9]. This relationship implies that the DCAP can be expressed by

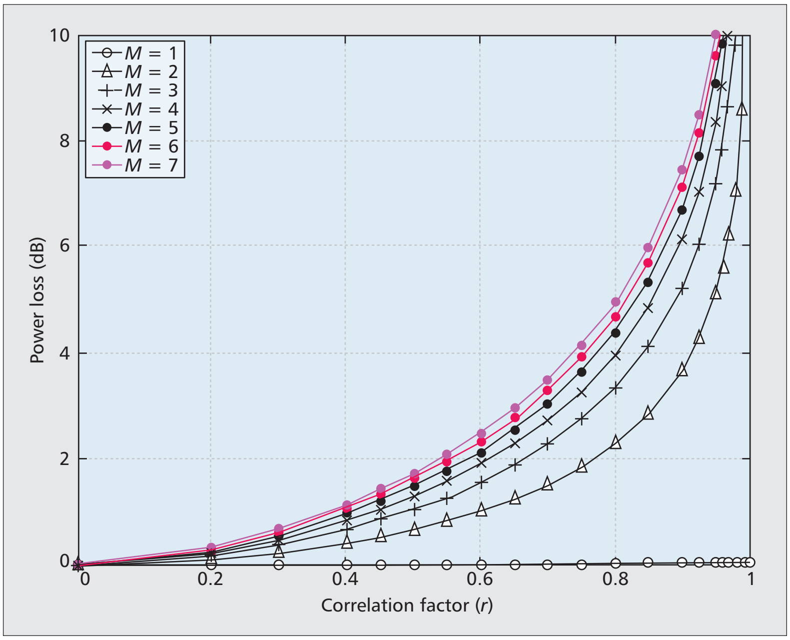

Figure 2. *CAS power loss versus correlation factor (r).*

$$\Delta C_{M-1}^{M} = \lambda_M^{-1}\int_0^{+\infty}\frac{f_{\Gamma_M}\left(\gamma\right)}{1+\gamma}d\gamma \le \frac{\lambda_{M-1}}{\lambda_M}\Delta C_{M-2}^{M-1}, \quad (2)$$

where λ_M and $f_{\Gamma_M}(\gamma)$ denote the inverse of the mean SNR received from antenna M and the Γ_M random variable probability density function, respectively. The bound presented in Eq. 2 was obtained with some manipulations to the exact expression of the DCAP. From the exact expression it is easy to see that, as expected, the gains by the connection of additional RAUs to the user are always positive. However, from the bound, we also verify that the additional amount of gain experienced as more and more RAUs connect to the user decrease with M, even if we allow all the previous connected antennas to continue to transmit a signal with power P to the user.

With the previous exact expression for the DCAP it is not difficult (by taking the derivative of the DCAP for each λ_M and verifying that it is always positive) to assert that the DCAP will be bounded by the DCAP, where all mean link SNRs are equal to the smallest link SNR, which implies that $\Delta C_{M-1}^{M} \le (\lambda_M + M - 1)^{-1} \le (M-1)^{-1}$ (Nats/s/Hz). The bound $1/(M-1)$ can be closely approached if all mean link SNRs are equal and high (higher than 17 dB). As a result, any channel asymmetry in the system, either the path loss (for a DAS) or the correlation (for a CAS), implies smaller capacity gains, since it entails different mean link SNRs. Another way of thinking is that big asymmetries in the system at a given geographical position imply that cooperation is not worth adding the effort of additional processing at the CU due to the diminished expected returns.

To have a better idea of the behavior of the DCAP values, let us start by looking at the DCAP values on representative geographical locations. More specifically, let us evaluate the

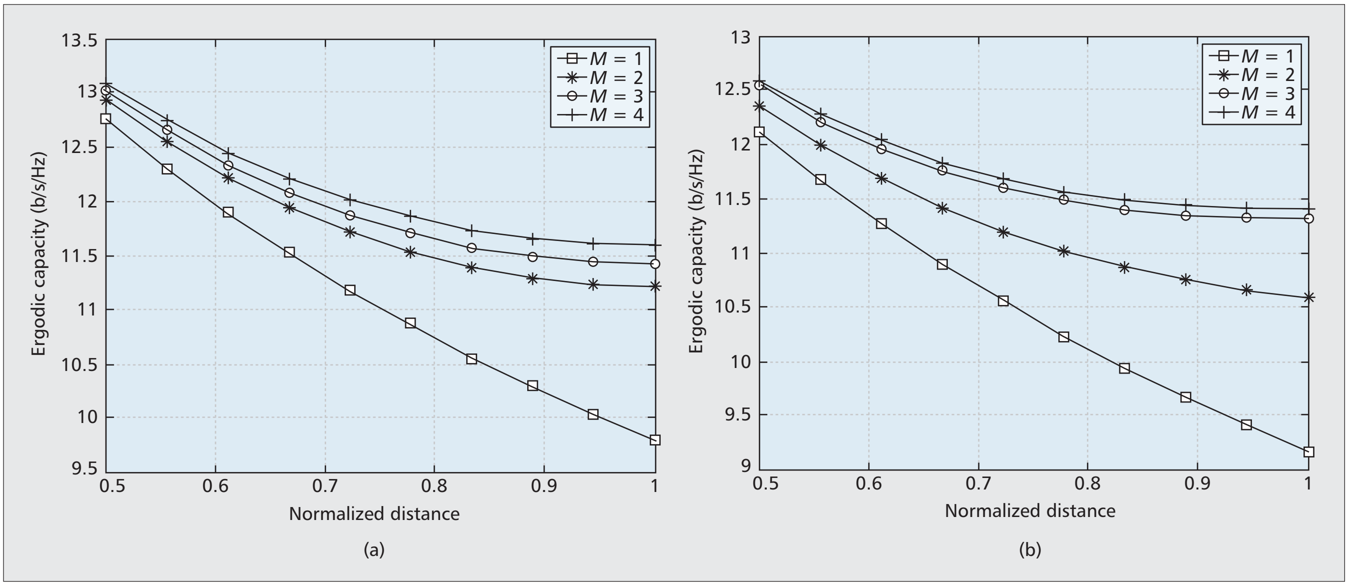

Figure 3. *Ergodic channel capacity for different numbers of transmit antennas, at varying distances from RAU1 (Fig. 1) and for a RAU coverage radius,* $R = 100$ *m: a) capacity variation over red line (Fig. 1); b) capacity variation over green line (Fig. 1). RAU connection order: connect first the closest antennas to the user at each geographical position.*

system capacity, using Eq. 2, first for a user moving from point A to B (red line, Fig. 1) and second for a user moving from point A to point C (green line, Fig. 1), for a DAS. The RAU coverage radius considered was 100 m. As can be seen from Fig. 3, the system capacity always increases, but the amount of gain as *M* increases gets smaller, as expected. The gain becomes larger as we get farther away from RAU1, since the user is getting closer to the boundaries of the coverage area of RAU1 and another RAU, and thus the corresponding mean link SNRs are approaching each other, decreasing the existing asymmetries. A user moving over the red line will only cross the boundary of RAU2 at point B, and thus only the first DCAP value is big in comparison to the other DCAP values. On the other hand, a user moving over the green line will cross two boundaries at the same point (C), and thus the corresponding first two DCAP values are large. The corresponding DCAP values for point (C), one of the points with the highest symmetry, and for two different RAU coverage radii are shown in Fig. 4. In this figure we also plot the bound $1/(M - 1)$, since this is the maximum DCAP any user can get in any position [9], as seen previously. As can be seen from that figure, when the new connected RAU has a mean SNR equal to a previous RAU, like RAU4 and RAU7, the DCAP is approximately equal to the previously connected RAU; and when it changes, the DCAP value also changes, as already seen from Eq. 2. This can be explained by the DCAP ratio ($\Delta C_{M-1}^{M}/\Delta C_{M-2}^{M-1}$) bound, shown in Eq. 2. In a circular ring this upper bound takes the value 1, and thus the DCAP is approximately constant. However, this approximation is not always tight.

To have a better insight into the sensitivity of the DCAP to SNR variation and to verify where the bound shown in Eq. 2 is tight, in Fig. 5 we plot the DCAP ratio for consecutive connected antennas and also the previously stated bound, again for point C. As can be seen from the figure, the DCAP ratio is well approximated by the ratio λ_{M-1}/λ_M; when the new mean SNR is different from the previous one and has *M* increases, the approximation becomes tighter. For a small number of RAUs this approximation is bad, and the DCAP values change even for a circular ring. Thus, one can conclude that a user in a RAU coverage boundary attains the highest DCAP values due to the existence of links with the same or similar mean SNRs.

From the previous analysis it seems that the gains obtained by a DAS can also be obtained for a CAS, since the capacity of the two systems only depend on the eigenvalues of the path loss matrix, for the DAS or of the correlation matrix for the CAS. However, that is not true. This is mainly due to the additional degrees of freedom/diversity available in the DAS. Since for a DAS the eigenvalues change from one geographical position to another, the system macro diversity is high; thus, the probability of finding a system state with high symmetry and corresponding high capacity gains increases. On the other hand, for a CAS the correlation structure is fixed, implying that the corresponding eigenvalues are fixed, and thus no inherent macro diversity is available. Thus, on average, the DAS will have higher capacity gains than a CAS. The same is true for the BER performance analysis.

MULTI-USER SCENARIO

In the previous paragraphs we have studied the DCAP sensitivity to the link's SNR variation for the single-user case. Indeed we have verified that the DCAP is maximized in the high SNR regime and when all antennas have similar link SNRs. Even if that study can provide some useful and interesting insights on the behavior of the DCAP, it is in some way limited, since in a real system more than one user are normally available. Hence, it is important to consider the multi-user case in more detail. However, for the multi-user case the system capacity is not as easy to analyze as it is for the single-user case due to some additional constraints in the transmit covariance matrix and the fact that there is no known closed form solution for this matrix that maximizes the channel sum-capacity. Indeed, to obtain the optimal power allocation matrix an iterative algorithm should be used [10]. However for the high SNR regime and the case of more transmit than aggregate receive antennas, equal power allocation is asymptotically optimal [11]. Since it is also in the high SNR regime that the DCAP is maximized for the single-user case, from now on we only consider the high SNR regime. Hence, as an extension to the single-user scenario, we consider a multi-user scenario with more transmit than aggregate receive antennas. For simplicity, for this scenario we first study the DCAP for the collocated antenna case, considering independent channel paths. Finally, we look at the distributed antennas case.

For the multi-user BC channel, dirty paper coding (DPC) is well known [7] to be the optimal scheme. In the high SNR regime equal power allocation is asymptotically optimal. As a consequence the BC sum-capacity can be approximated by an affine function [11], which is only dependent on the distribution of the logarithm of the determinant of $\mathbf{HH}^H$, where $\mathbf{H}^H = [\mathbf{h}_1^H, \ldots, \mathbf{h}_k^H]$ denote the concatenation of all users' channels.

One aspect that is worth investigating for the multi-user case is the scaling of the DCAP with the number of users. Let us consider first, for simplicity, a CAS without correlation between channels ($\mathbf{R}_{tx} = \rho_k = \mathbf{I}$) and next extend the results to a DAS. For such a system, since $\mathbf{HH}^H$ is K variate complex Whishart distributed with M degrees of freedom, its determinant distribution is equal to the distribution of the product of K chi square random variables; thus, the DCAP for K users and the Mth connected antenna is approximately given by [12]

$$\Delta C_{M-1,K}^{M,K} = \log_2\left(1+\frac{K}{M-K+\beta-1}\right), \qquad (3)$$

where $\beta = \mathrm{Exp}[1 - \delta] - 1$, and $\delta = 0.577215665$ is the Euler constant. From Eq. 3 it is easy to see that the DCAP scales logarithmically with the number of users for the optimal scheme (DPC) if $M - K$ is kept constant. Thus, the gain by the connection of additional RAUs will in some sense saturate, since their increase rate will be smaller and smaller as more users are considered. In that way, the DCAP value we obtain for a small number of users will be only slightly lower than the one for a higher number of users. In fact, it can be observed from Fig. 6 that the DCAP for the multiuser scenario behaves like the one for the single user scenario. For $K = 1$, the curve presented in Fig. 6 is the same as the black curve presented in Fig. 4. The curves presented in Fig. 6 were obtained using Eq. 3.

Indeed, in the single-user case we have seen that the user positions with the highest DCAP values are the ones with highest symmetry with the RAUs. Will this also be true for the distributed case? To investigate that we have studied, in the previous paragraphs, the DCAP for a CAS with uncorrelated channel paths. However, to extend the CAS DCAP results to a DAS, we rely on numerical simulations.

In numerical simulations we have considered a scenario with four uncorrelated transmit antennas (blue circles in Fig. 7) and two users, and have evaluated the respective DCAP values for a high number of uniformly drawn positions.

In the numerical simulation, for the channel model we have considered only path loss and

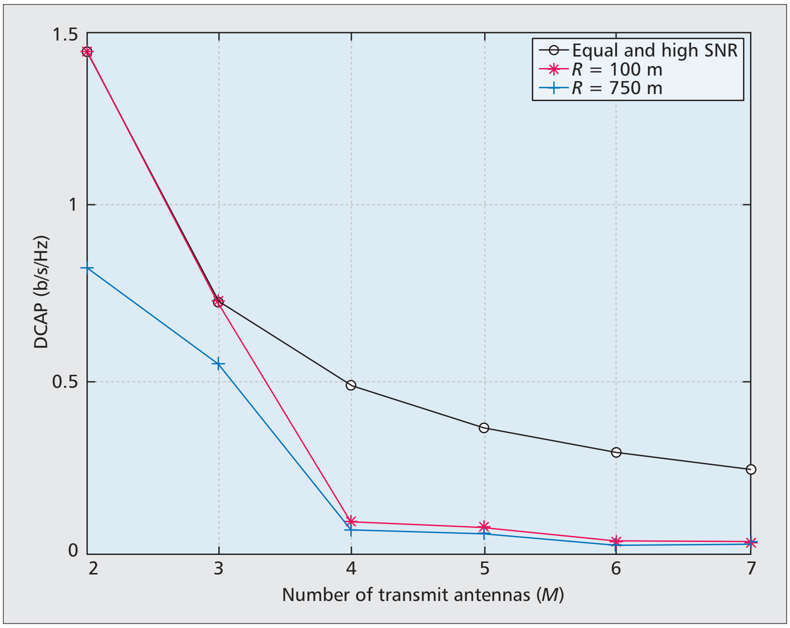

Figure 4. *Exact DCAP values and bound 1/(M - 1) (Nats/s/Hz), for the point C of scenario depicted in Fig. 1, and for two different RAU coverage radii,* R = *100 m and* R = *750 m. RAU connection order: RAU 1, 2, 3, 4, 7, 5, 6.*

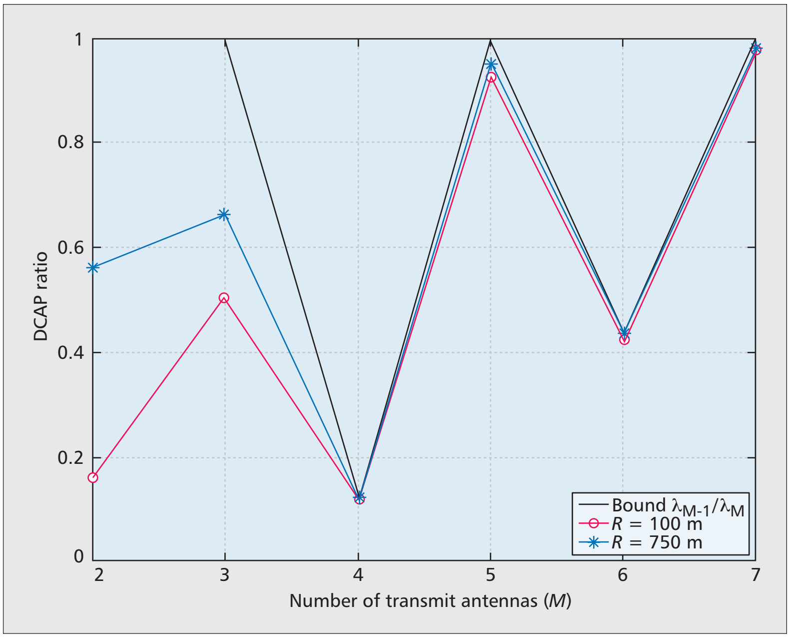

Figure 5. *DCAP variation with respect to M, for the point C of scenario depicted in Fig. 1, and for two different RAU coverage radii,* R = *100 m and* R = *750 m. RAU connection order: RAU 1, 2, 3, 4, 7, 5, 6.*

Rayleigh multipath fading. The users' positions were randomly generated according to a uniform distribution in the [–1, 1] × [–1,1] km square. Ten thousand random positions were generated for each user, and the DCAP was averaged over 10,000 trials. The results from this simulation are shown in Fig. 7. More precisely, we plot in Fig. 7 the users' positions that attain the highest DCAP values when the third antenna is connected to the CU. Each pair of equal black markers represent the positions of each user. As can be seen from the figure, the users' positions with the highest DCAP values are like those in the single user case, in the coverage boundary of each RAU, which define the symmetry lines of the system. The corresponding DCAP value for such positions is very close to that obtained for the uncorrelated CAS, analyzed before.

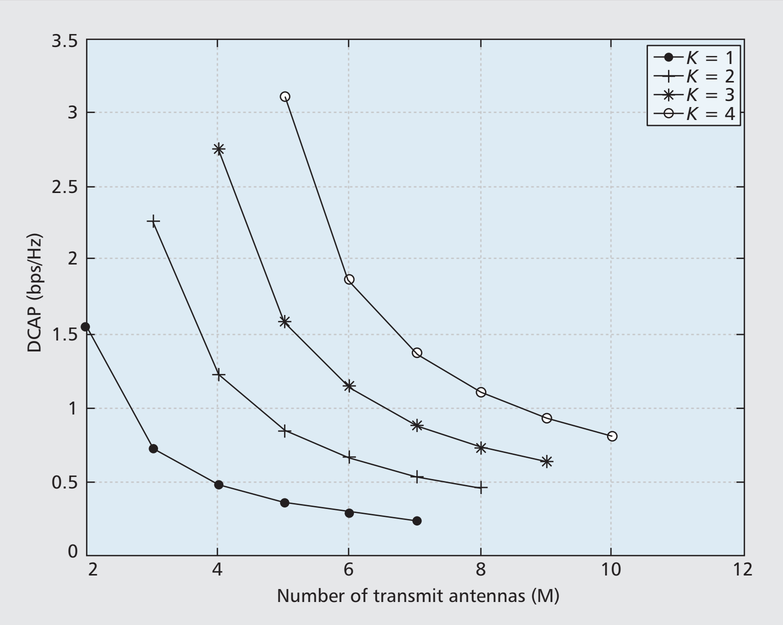

Figure 6. *DCAP values for a multiuser collocated scenario with uncorrelated channel paths for a number of users in the range 1–4, in the high SNR regime.*

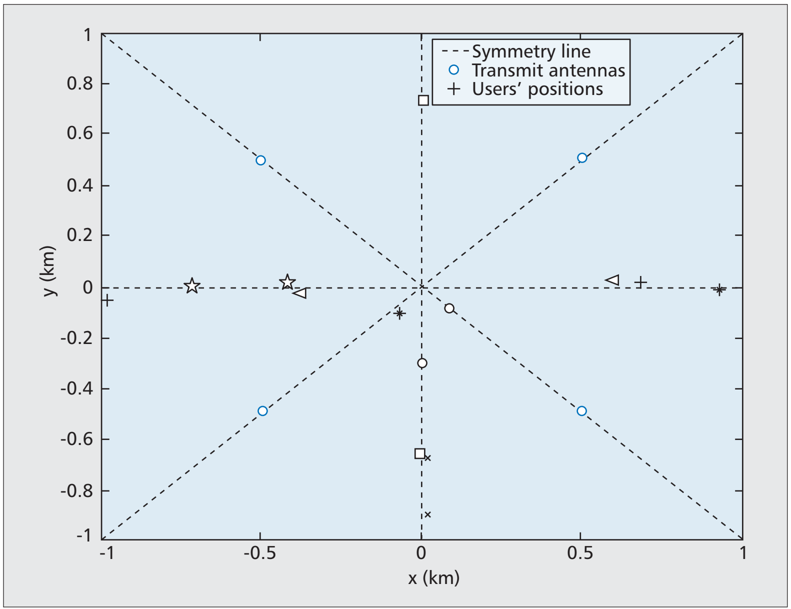

Figure 7. *Users' positions with the highest DCAP values for a DAS with four transmit antennas and two users, when the third RAU is connected to the CU. Each pair of equal black markers represents the positions of each user.*

Thus, the newly connected RAU has the same distribution as the previous one in a similar manner as for the collocated case. Thus, system symmetry again plays an important role in obtaining most of the DCAP gains, just as in the single-user scenario.

DISCUSSION AND CONCLUSION

In this article we have shown that DAS provides an interesting option to CAS because of its power efficiency and diversity. We have considered a differential measure, the DCAP, which can be useful in dynamic radio resource allocation and in the antenna deployment phase. Concerning the DCAP, we have analyzed the benefits of the connection of additional RAUs to the system users of a BC, for both the single-user and multi-user cases. For the single-user case we have analyzed the DCAP limits and its sensitivity to the links' SNR variation, and have also found the user positions that will benefit the most from the connection of additional transmit antennas. For the single-user case we have seen that the most relevant system property to obtain the highest DCAP values is system symmetry. We have also verified that the capacity gains obtained by a DAS in relation to a CAS are mainly due to the additional degrees of freedom provided by the DAS, which increase the probability of finding a user in a state with high symmetry, unlike in the CAS.

For the multi-user case we have verified that the DCAP of a CAS, with uncorrelated channel paths, increases logarithmically with the number of users for the optimal scheme (DPC). For the DAS we have seen, by numerical simulations, that the number of users' positions with the highest DCAP values is small, and their main property is that they are very close to the system symmetry lines defined by the transmit antennas. Thus, symmetry plays, as in the single-user scenario, an important role in the multi-user scenario.

Consequently, one can conclude that the users who will benefit most from the joint processing of additional RAUs in a DAS will be the ones at the cell borders, and that a DAS has power efficiency, diversity, and capacity advantages over a CAS. Consequently, a system architecture based on the DAS concept will be interesting to address the problems encountered in current cellular systems for users at the cell borders.

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REFERENCES

[1] E. Telatar, "Capacity of Multi-Antenna Gaussian Channels," *Euro. Trans. Telecommun.*, vol. 10, 1999, pp. 585–95.

[2] FUTON, "Fibre-Optic Networks for Distributed Extendible Heterogeneous Radio Architectures and Service Provisioning," 2008.

[3] W. Choi and J. G. Andrews, "Downlink Performance and Capacity of Distributed Antenna Systems in a Multicell Environment," *IEEE Trans. Wireless Commun.*, vol. 6, no. 1, Jan. 2007, pp. 69–73.
[4] J. Park, E. Song, and W. Sung, "Capacity Analysis for Distributed Antenna Systems using Cooperative Transmission Schemes in Fading Channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, Feb. 2009, pp.586–92.
[5] J. Wang and L. B. Milstein, "CDMA Overlay Situations for Microcellular Mobile Communications," *IEEE Trans. Commun.*, vol . 43, no. 234, Feb./Mar./Apr. 1995, pp. 603–14.
[6] J. Wang and J. Chen, "Performance of Wideband CDMA with Complex Spreading and Imperfect Channel Estimation," *IEEE JSAC*, vol. 19, no. 1, Jan. 2001, pp. 152–63.
[7] H. Weingarten, Y. Steinberg, and S. Shamai, "The Capacity Region of the Gaussian Multiple-Input Multiple-Output Broadcast Channel," *IEEE Trans. Info. Theory*, vol. 52, 2006, pp. 3936–64.
[8] A. Abouda *et al.*, "Performance of Stochastic Kronecker MIMO Radio Channel Model in Urban Microcells," *17th IEEE PIMRC*, 2006, pp. 1–5.
[9] D. Castanheira and A. Gameiro, "Distributed MISO System Capacity over Rayleigh Flat Fading Channels," *19th IEEE PIMRC*, 2008, pp. 1–5.
[10] N. Jindal *et al.*, "Sum Power Iterative Water-Filling for Multi-Antenna Gaussian Broadcast Channels," *IEEE Trans. Info. Theory*, vol. 51, 2005, pp. 1570–80.
[11] J. Lee and N. Jindal, "High SNR Analysis for MIMO Broadcast Channels: Dirty Paper Coding Versus Linear Precoding," *IEEE Trans. Info. Theory*, vol. 53, 2007, pp. 4787–92.
[12] D. Castanheira and A. Gameiro, "High SNR Broadcast Channel Differential Capacity," *ICT-MobileSummit*, 2009, pp. 1–8.

BIOGRAPHIES

DANIEL CASTANHEIRA (dcastanheira@av.it.pt) received his degree in electronics and telecommunications engineering from Aveiro University, Portugal, in 2007. In October 2007 he started working toward his Ph.D. degree at the Instituto de Telecomunicações — Pólo de Aveiro, Portugal. His current research activities involve interference cancellation techniques and resource allocation for distributed cellular systems.

ATILIO GAMEIRO (amg@ua.pt) received his Licenciatura (five-year course) and Ph.D. from Aveiro University in 1985 and 1993, respectively. He is currently a professor in the Department of Electronics and Telecommunications of Aveiro University, and a researcher at the Instituto de Telecomunicações — Pólo de Aveiro, where he heads a group. His main interests lie in signal processing techniques for digital communications and communication protocols. Within this field he has done work for optical and mobile communications, at the theoretical and experimental levels, and has published over 100 technical papers in international journals and conferences. His current research activities involve space-time-frequency algorithms for the broadband component of 4G systems, and joint design of layers 1 and 2.