Wideband Channel Allocation In Distributed Antenna Systems

Issam TOUFIK and Raymond KNOPP
Institut Eurécom - Mobile Communications Department
2229 route des Crêtes, 06904 Sophia Antipolis, France
Tel: +33.493.008.152 - Fax: +33.493.008.200
Email:{toufik, knopp}@eurecom.fr

***Abstract*— We consider the downlink of a multiuser multi-cell system. Each cell is equipped with multiple antennas transmitting over M parallel channels. We study the benefits of Distributed Antenna arrays on the performance of such systems and the gain on fairness between users offered by this technique,compared to co-located antenna systems. We show that the *Macro-Diversity* introduced by distributed antennas combined with the Max-Min allocation algorithm, not only considerably increases the system Spectral Efficiency but also offers a remarkable enhancement on the Minimum Allocated Rate and thus the fairness between users.**

***Index Terms*— Distributed Antennas, Multi-cell, Multi-user, Fairness.**

I. INTRODUCTION

The promise of future wireless networks is to provide data services at a high bit rate for a large number of users without a corresponding increase in bandwidth or transmit power and if possible with the maximum fairness between users. It is well known that the optimal way to maximize the system throughput is to allocate the available resource to the user with the best channel conditions which is known as Multi-user Diversity [1], [2]. The maximization of the system sum rate with this technique comes at the cost of fairness since users or base station have to wait until their channel is most favorable to transmit. In [3], [4] authors show that for multi-carrier wideband systems, it is also possible to guarantee *Hard Fairness* between a large number of users (The maximum number of users that the system can support) while still achieving high system performance and even approaches the totally unfair allocation Spectral Efficiency. The objective of this study is to investigate how using Distributed Antennas (DA) can effect the performance of such a system especially on terms of fairness.

DA systems was first introduced to solve the problem of coverage for indoor wireless communications (also known as dead spots problem). More recent studies show that DA can bring significant power saving and a considerable increase of system capacity. The basic idea is that Multiple antennas sufficiently separated in space can provide independent shadowing which is also known as Macro-Diversity. Each antenna is connected to a *Central Controller* via a dedicated link, thus the distributed antennas and the central controller represent a macroscopic multiple antenna system. This distributed antenna diversity and shortened distance between users and antennas offer a considerable increase on systems performance [5], [6].

Recently DAS has received researchers attention due to its capacity advantages. However most of the studies consider either single user case or the uplink transmissions ([7]- [10]) and only few papers have treated the multi-user downlink. Authors in [12], [13] analyzed the downlink capacity in terms of multiple-antenna (MIMO) but they did only consider a single-cell environment. Authors in [14] analyzed the system capacity of MIMO multi-cell with distributed antennas for the single user case. In this work we consider the downlink of a multi-user multi-cell system.

The organization of this paper is as follows: We first introduce the system and channel models and the multi-cell antennas architecture in section II while section III describes briefly the allocation strategy. We present numerical results in section IV and finally in section V, we present our conclusions.

II. SYSTEM MODEL AND CELLULAR ARCHITECTURE

We consider the downlink of a multi-cell system involving $\mathcal{C}$ cells with frequency reuse factor F. Each cell is equipped with N_t transmit antennas transmitting over M parallel channels each one of bandwidth W. We assume that each antenna is transmitting at a fixed power P on each channel. The N_t antennas are connected to a Central Controller (Evolution of Radio-Network Controller in UMTS) via a dedicated link: waves, radio over fibers [15], fiber optics or exclusive RF link.

Let K denote the number of users each one having a single receive antenna. The channel between the N_t transmit antennas of cell c and user k on channel m is giving by the $1 \times N_t$ vector $\mathbf{G}_{c,k,m} = \left[\sqrt{L_{c,k}[1]}H_{c,k,m}\left[1\right], ..., \sqrt{L_{c,k}[N_t]}H_{c,k,m}\left[N_t\right]\right]^T$, where $H_{c,k,m}\left[i\right]$ is the channel gain between the i-th antenna and user k on channel m. The channel is assumed stationary for the duration of coded transmission block but may vary from block to block. $\sqrt{L_{c,k}[i]}$ corresponds to Large Scale fading from the i-th antenna of cell c, which includes path loss and shadowing. The path loss is modeled as $(\frac{d_{t,r}}{d_0})^{-\alpha}$, where $d_{t,r}$ is the distance between the transmitter and the receiver, and d_0 is used as a reference point in measurements. α is the pathloss exponent which depends on the environment and

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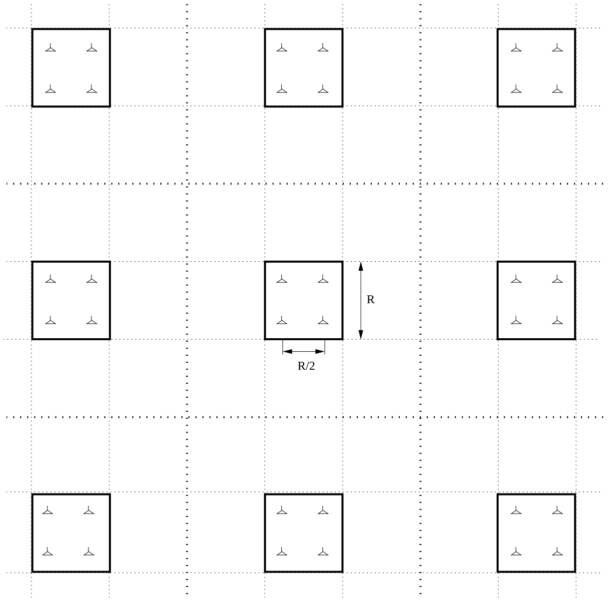


Fig. 1. Example of Distributed Antennas Multi-Cell system for $N_t = 4$ and frequency reuse factor $F = 9$

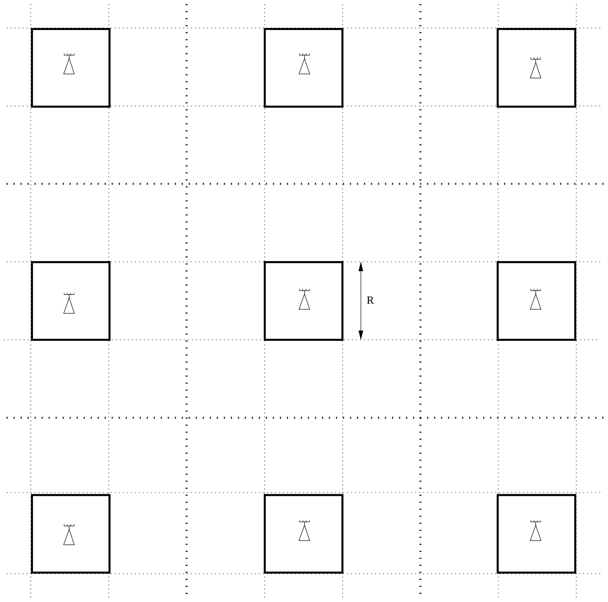
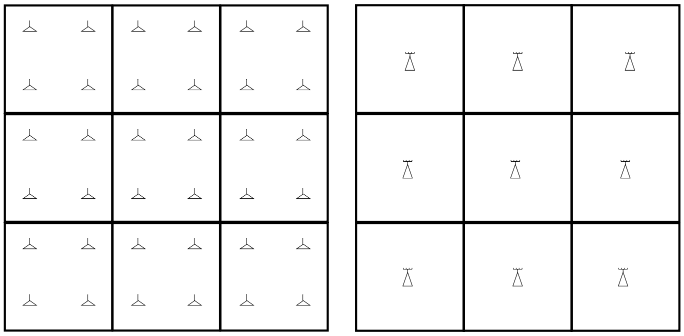


Fig. 2. Example of Co-located Antennas Multi-Cell system for $N_t = 4$ and frequency reuse factor $F = 9$



(a) (b)

Fig. 3. Example of DAS (a) and CAS (b) Multi-Cell systems for $N_t = 4$ and frequency reuse factor $F = 1$

terrain structure and can vary between 2 in free space and 6 in heavily built urban areas. The shadow fading for each user is modeled as an independent log-normal random variable with standard deviation σ_s. The combined large scale fading between user k and antennas i of cell c is given by

$$L_{c,k}[i] = (\frac{d_{i,k}}{d_0})^{-\alpha} 10^{\frac{\chi_i}{10}} \tag{1}$$

where χ_i is a normally distributed random variable with mean zero and variance σ_s^2. The received signal by user k on sub-channel m is then given by

$$Y_{k,m} = \sum_{c=1}^{C} \sum_{i=1}^{N_t} G_{c,k,m}\left[i\right] X_{c,i} + Z_{k,m} \tag{2}$$

where $X_{c,i}$ is the modulated symbol transmitted from the i-th antenna of cell c. $Z_{k,m}$ is the Gaussian channel noise at user k on sub-channel m.

We assume that cells have a square shape of side distance equal to R and we only consider the first tier of eight interfering cells. In the remainder of the paper we consider that cell $c = 1$ is the cell of interest and cells from $c = 2$ to $c = \mathcal{C}$ are interfering cells. Users in the square shape of cell c=0 all depends on this cell (Geometrical assignment to cells).

A. *Distributed Antenna Systems (DAS) cellular Architecture*

In this system, the antennas are located in a $\sqrt{N_t} \times \sqrt{N_t}$ square grid and are equally spaced. N_t is assumed to be a perfect square and the distance between to successive antennas is $\frac{R}{\sqrt{N_t}}$. Examples for such a system are given by figures 1 and 3(a) for $F = 9$ and $F = 1$ respectively.

We assume spatial multiplexing of users. Under the assumption that antenna i^* is assigned to user k on channel m, the received signal can be written as

$$\begin{aligned} Y_{k,m} \quad = \quad & \underbrace{\sqrt{P} G_{1,k,m}[i^*] X_{1,i^*}}_{\text{Desired Signal}} + \underbrace{\sum_{i \neq i^*}^{N_t} \sqrt{P} G_{1,k,m}[i] X_{1,i}}_{\text{Intra-cell Interference}} \\ & + \underbrace{\sum_{c=2}^{\mathcal{C}} \sum_{j=1}^{N_t} \sqrt{P} G_{c,k,m}[j] X_{c,j}}_{\text{Inter-cell Interference}} + Z_{k,m} \end{aligned} \tag{3}$$

Under the assumption of Gaussian signals, the corresponding achievable rate is then given by eq(4)

B. *Co-located Antenna systems (CAS) cellular Architecture*

We assume that all the N_t antennas are located in the center of the cell (Figures 2 and 3(b)). Since the antennas are co-located, the large scale coefficient is the same from a user

$$R_{k,m}\left(i^*\right) = W\log\left(1+\frac{P|G_{1,k,m}[i^*]|^2}{WN_0+\sum_{i\neq i^*}^{N_t}P|G_{1,k,m}[i]|^2+\sum_{c=2}^{\mathcal{C}}\sum_{j=1}^{N_t}P|G_{c,k,m}[j]|^2}\right) \tag{4}$$

$$\begin{aligned} R'_{k,m}\left(i^*\right) &= W'\log\left(1+\frac{P/N_t|G_{1,k,m}[i^*]|^2}{W'N_0+\sum_{c=2}^{\mathcal{C}}\sum_{j=1}^{N_t}P/N_t|G_{c,k,m}[j]|^2}\right) \\ &= \frac{W}{N_t}\log\left(1+\frac{P/N_t|G_{1,k,m}[i^*]|^2}{\frac{W}{N_t}N_0+\sum_{c=2}^{\mathcal{C}}\sum_{j=1}^{N_t}P/N_t|G_{c,k,m}[j]|^2}\right) \end{aligned} \tag{5}$$

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to all antennas in the same cell. The channel vector can be expressed as

$$\mathbf{G}_{c,k,m} = \sqrt{L_{c,k}}\left[H_{c,k,m}\left[1\right],...,H_{c,k,m}\left[N_t\right]\right]^T$$

where the antenna index drops from $L_{c,k}$
In the following we present two transmission schemes for co-located antenna systems. The first attempts to achieve spatial-multiplexing whereas the second is a space-time coding approach.

1) ***Spatial Multiplexing****:* As in the previous section, each user receives signal from one assigned antenna. If antenna i^* is allocated to user k on channel m, the received signal can be written as

$$\begin{aligned} Y_{k,m} &= \underbrace{\sqrt{P}G_{1,k,m}[i^*]X_{1,i^*}}_{\text{Desired Signal}} + \underbrace{\sum_{i\neq i^*}^{N_t}\sqrt{P}G_{1,k,m}[i]X_{1,i}}_{\text{Intra-cell Interference}} \\ &\quad + \underbrace{\sum_{c=2}^{\mathcal{C}}\sum_{j=1}^{N_t}\sqrt{P}G_{c,k,m}[j]X_{c,j}}_{\text{Inter-cell Interference}} + Z_{k,m} && (6) \\ &= \sqrt{PL_{1,k}}\left(H_{1,k,m}[i^*]X_{1,i^*}+\sum_{i\neq i^*}^{N_t}H_{1,k,m}[i]X_{1,i}\right) \\ &\quad + \sum_{c=2}^{\mathcal{C}}\sqrt{PL_{c,k}}\left(\sum_{j=1}^{N_t}H_{c,k,m}[j]X_{c,j}\right)+Z_{k,m} && (7) \\ & && (8) \end{aligned}$$

and the achievable rate is given by eq(4)

2) ***Space Time Coding****:* We assume that a user receives his desired signal from all antennas. For a fair comparison of the different systems and to preserve the number of users and the averaged transmit power per user unchanged, we assume that the bandwidth W of each channel is divided to N_t adjacent but disjoint sub-channels each one of a bandwidth equal to $W' = \frac{W}{N_t}$ (i.e. FDMA in each channel). In such a system, the only interference is the one coming from other cells. The received signal from antenna i^* in sub-channel m is then

$$\begin{aligned} Y_{k,m} &= \underbrace{\sum_{i}^{N_t}\sqrt{\frac{P}{N_t}}G_{1,k,m}[i]X_{1,i}}_{\text{Desired Signal}} \\ &\quad + \underbrace{\sum_{c=2}^{\mathcal{C}}\sum_{j=1}^{N_t}\sqrt{\frac{P}{N_t}}G_{c,k,m}[j]X_{c,j}}_{\text{Inter-cell Interference}} + Z_{k,m} && (9) \\ &= \sqrt{\frac{P}{N_t}L_{1,k}}\sum_{i}^{N_t}H_{1,k,m}[i]X_{1,i} \\ &\quad + \sum_{c=2}^{\mathcal{C}}\sqrt{\frac{P}{N_t}L_{c,k}}\left(\sum_{j=1}^{N_t}H_{c,k,m}[j]X_{c,j}\right)+Z_{k,m} \end{aligned}$$

The corresponding achievable rate, under the assumption of Gaussian signals, is given by eq(5)

III. ALLOCATION

We assume that each user estimates the channel gains and accordingly the achievable rate on each sub-channel, and for each antenna in the case of DAS and CAS with spatial multiplexing, and feeds-back this information to the Central Controller which is responsible of the allocation of antennas and channels to users. The optimal way to do so, in terms of the system throughput, is to allocate each channel and each antenna to the user which will use it the best (i.e. the user with the best channel conditions). It was shown in [3], [4] that it is possible to achieve high system performances and even approaches the totally unfair allocation spectral efficiency even under hard fairness constraint. The proposed Max-Min allocation algorithm guarantees that at any given time instant the minimum SINR allocated (and equivalently the allocated rate) is the best possible among all possible allocations and thus maximizes the minimum allocated rate. In this paper we consider the scheduling of users according to this algorithm. For more details, the reader can refer to [3], [4]. We first consider that there is no cooperation between Central Controllers of different cells. We then investigate the effect of such cooperation in the system performance.

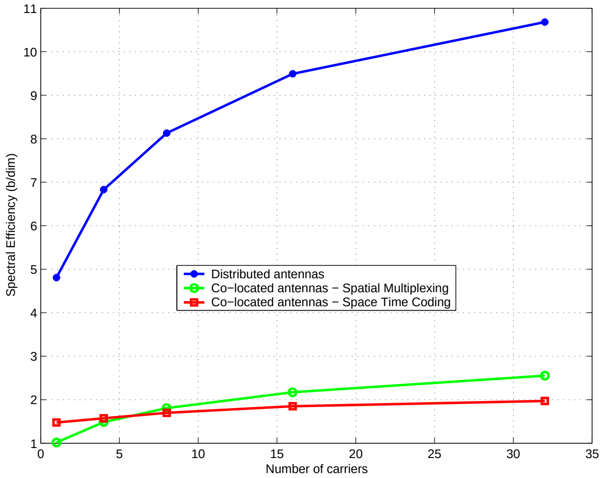

Fig. 4. Spectral Efficiency as a function of M for $N_t = 4$ and $F = 1$.

IV. SIMULATION RESULTS

For all simulations we assumed a Rayleigh fading environment and correlations between frequency channel gains are zero. Although unrealistic, this gives us an idea of the achievable rates as a function of the number of uncorrelated channels (or the approximate number of degrees of freedom of the propagation environment in the available system bandwidth). The Shadow fading for each user is modeled as an independent log-normal random variable with standard deviation $\sigma_s = 10dB$ and the pathloss exponent α is set to 3. The considered value of P is such that a user located in the corner of the cell experiences an average SNR equal to 0dB from an antenna located at the center of the cell. We consider that $K = M.N_t$ which is the maximum number of users that can be supported by the system. We consider cells of side distance $R = 100m$ and the reference distance d_0 is equal to 1m. All users are at a distance greater then d_0 from all antennas.

Figures 4 and 5 represent the Spectral Efficiency (SE), of the three systems presented previously, as a function of the number of channels, for frequency reuse factors $F = 1$ and $F = 3$ respectively. It worth remind that SE is dominated by the rates of close-in users (users close to an antenna), thus these figures can be seen as a representation of performance of this class of users. These figures confirm that distributed antennas offers a considerable gain on system performance and this even under hard fairness constraints. One other remarkable result we should outline is that the system SE decreases with the frequency reuse factor F and a system with factor $F = 1$ outperforms a system with factor $F = 3$ even if in the former, the cell of interest experiences less interferences from the other cells.

Figures 6 and 7 represent the minimum allocated rate as a function of the number of channels M. The minimum rate represents the performance of far-out users (extreme users). This figure shows the remarkable enhancement that

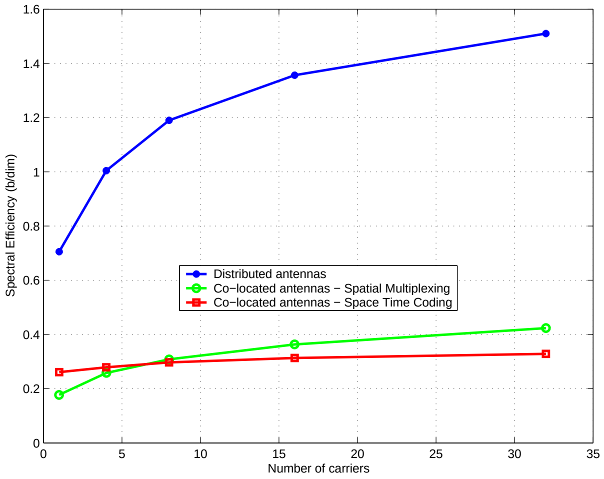

Fig. 5. Spectral Efficiency as a function of M for $N_t = 4$ and $F = 9$.

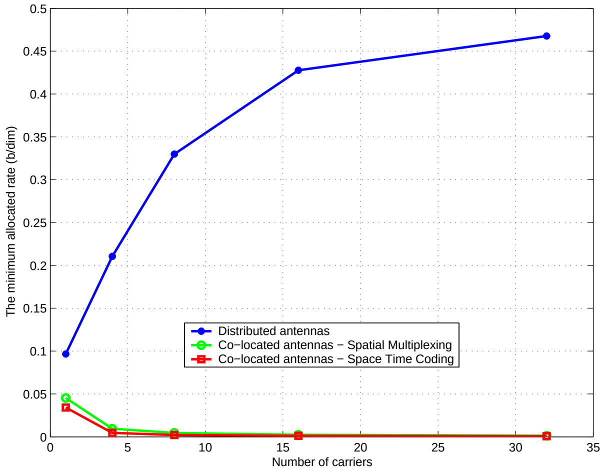

Fig. 6. Minimum Allocated Rate as a function of M for $N_t = 4$ and $F = 1$

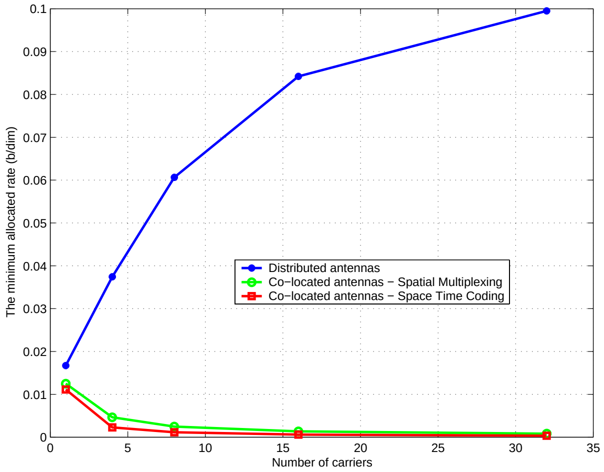

Fig. 7. Minimum Allocated Rate as a function of M for $N_t = 4$ and $F = 9$.

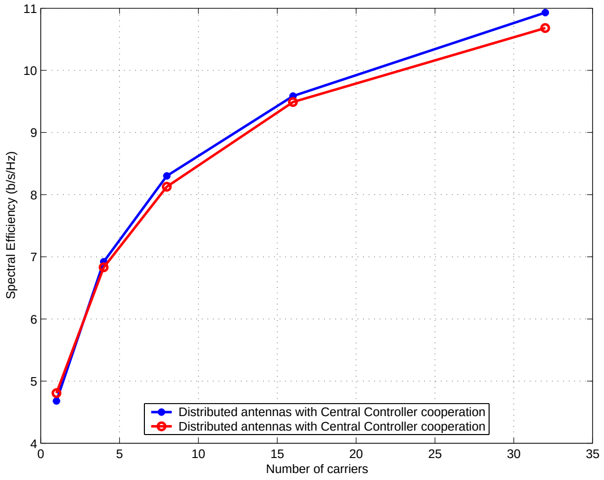

Fig. 8. Spectral Efficiency as a function of M for $N_t = 4$ and $F = 1$

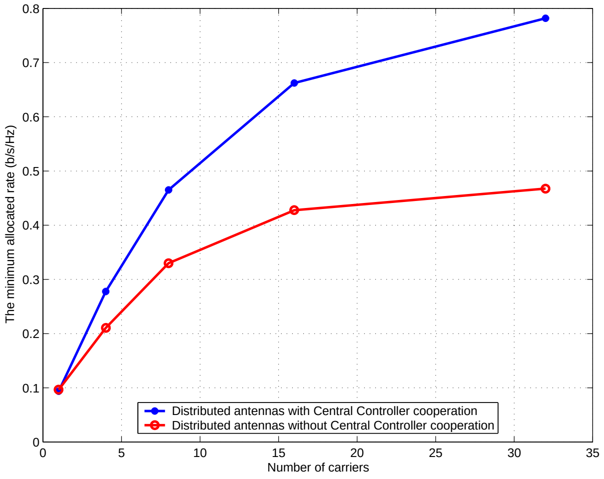

Fig. 9. Minimum Allocated Rate as a function of M for $N_t = 4$ and $F = 1$.

distributed antennas offers on terms of fairness between users compared to both spatial multiplexing and space time coding in co-located antenna systems. The minimum allocated rate increases with the number of channels when distributed antennas are used whereas it converges to zeros in the case of CAS.

Figures 8 and 9 compare respectively the spectral efficiency and the minimum allocated rate for cellular systems with distributed antenna with and without cooperation between Central Controllers of different cells for $F = 1$. The cooperation between the Controllers offer a slight improvement in terms of system spectral efficiency, but the enhancement of the minimum allocated rate is considerable.

V. CONCLUSION

In this paper We compared distributed antenna versus co-located antenna systems and showed the benefits of distributed antennas on terms of fairness between users and the remarkable enhancement of the minimum allocated rate in addition to the gain on Spectral Efficiency. Both close-in and far-out users experiences a considerable increase in their allocated rate when distributed antennas are used.

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