Grassmannian Beamforming for Coordinated Multipoint Transmission in Multicell Systems

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***Abstract*— Wireless communications suffer from the problem of interference, where undesired signals reach the destination and cause its performance to degrade. Several mechanisms have been proposed over the last years to mitigate the interference problem, where Coordinated Multipoint (CoMP) outstands as one of the best approaches to tackle the interference in cellular systems. The main disadvantage of CoMP is the need of high signalling over the system in order to exchange information among the different parties involved in the communication process (eNBs and UEs), that questions its practical benefit for the operators. This paper presents a novel beamforming mechanism that needs for very low signalling among the transmitting base stations, it is a low complexity transmission strategy, the amount of interference to cell edge users is controlled and it offers an outstanding performance. Computer simulations show the data rate enhancement of the proposed CoMP mechanism.**

I. Introduction

The Long Term Evolution (LTE) [1] is one of the most promising technologies that has been recently specified to meet the increasing performance requirements of mobile broadband. LTE has been implemented in several countries with extraordinary results. One of the main challenges within LTE is the data rate for the cell-edge users, that is usually low and decreases the average data rate over the whole system. Its main reason is the intercell interference that cell-edge users suffer. One of the proposed techniques in literature to tackle the interference for cell-edge users is the Coordinated Multipoint (CoMP) [2] that has been recently included in the LTE Release 11 specs [3].

CoMP techniques are mainly divided on the scenario basis, so that CoMP Uplink and CoMP Downlink strategies are available within the literature. LTE specs considers CoMP in both scenarios and within several implementation mechanisms [4]. For CoMP Downlink, the easily implementable Dynamic Point Selection (DPS) enables the cell-edge users to dynamically select the Base Station (BS) that shows better performance, providing a diversity gain for the serviced user. Dynamic Point Blanking (DPB) is an alternative to DPS, where the non serving BSs are asked for small silence periods to decrease the interference to the serviced user. Larger complexity is obtained by the Joint Transmission (JT) mechanism where the BSs cooperate to deliver the information to the user. The higher performance is achieved but at the cost of large complexity and more signalling over the system [2]. The last mechanism within LTE for CoMP is Coordinated Beamforming and Scheduling (CBS) that shows the largest performance but also the highest demands on the system signalling [4].

Therefore, there appears a tradeoff between the higher performance vs. the larger signalling and required feedback. The best scheme is still not clear to the operators, that would like to have the highest performance offered by CBS, while the lowest signalling as requested by DPS. This paper will tackle this challenge and present a scheme that achieves very high performance while very low signalling is required. The proposed strategy is based on Grassmanian Beamforming [5] applied to multicell environments.

One of the major transmission techniques within single cell systems is the *multibeam opportunistic beamforming (MOB)* [6] that shows excellent performance while it only needs for partial channel-state-information at the transmitter (CSIT) so that its required signaling is low. When applied to several adjacent cells, the amount of received interference among the users in the same cell is low, but from other cells is large. Users on the cell-edge suffer from this problem, and some solution is required. MOB scheme generates a number of transmitting beams equal to the number of base station (BS) antennas, but an alternative approach is to generate the beams across all the overlapping BSs and ideally to make them orthogonal among themselves. This is not possible as the degrees of freedom restricts such generation. A possible solution is to generate quasi-orthogonal beams over the neighbour BSs, so that to decrease the interference among their serviced users. Grassmannian packing [7] is the best approach to generate such BS beams, due to its capabilities to generate beams with the highest orthogonality. Grassmannian Beamforming [5] was previously proposed for single cell beamforming to increase the number of serviced users, but no previous design for CoMP has been presented (up the authors' knowledge). Our scheme is denoted as opportunistic grassmannian beamforming over CoMP scenarios (OGB-CoMP).

The rest of this paper is organized as follows, Section II will tackle the system model followed by section III with the mathematical review of Grassmanian theory. Section IV will present the OGB and how to adapt it to CoMP scenarios. Section V displays the simulations results while we close the paper with its conclusions in section VI.

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II. System Model

We focus on a cellular network where a set of M cells are providing service to N users, each one of them equipped with a single antenna. Each BS is equipped with n_t transmitting antennas, and with N greater than n_t. In order to decrease the complexity, each user is only serviced by a single BS, thus a multiple-antenna channel $\mathbf{h}_{[1\times n_t]}$ is considered between each user and its m^{th} serving BS. Let $\mathbf{x}_m(t)$ be the $n_t \times 1$ transmitted vector from the m^{th} BS. Considering that the n^{th} user is scheduled by the m^{th} BS, then its received signal $y_n(t)$ includes the interference from all other ($p \neq m$) BSs as

$$y_n(t)=\mathbf{h}_{n,m}(t)\mathbf{x}_m(t) + \mathbf{h}_{n,p\neq m}(t)\mathbf{x}_{p\neq m}(t) + z_n(t) \quad (1)$$

where $z_n(t)$ is the additive noise whose entries are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance $\sim \mathcal{CN}(0,1)$. A total transmitted power constraint $P_t = 1$ is considered and for ease of notation, the time index is dropped whenever possible.

The channel $\mathbf{h}_{n,m}$ between each of the users and the m^{th} BS follows the specular model [8] for flat fading outdoor channel, which is assumed to keep constant through the coherence time T_c and independently changes between consecutive time intervals. It is defined as

$$\mathbf{h}_{n,m} = \frac{1}{\sqrt{W}} \sum_{w=1}^{W} \alpha_{n,m,w}\mathbf{a}(\theta_{n,w}) \quad (2)$$

where W is the number of paths the signal is assumed to follow from the BS to the n^{th} user. $\theta_{n,w}$ is the angle of incidence of these paths, which are assumed to have gaussian distribution with mean $\overline{\theta_n}$ and angle spread of $AS = \sqrt{E(\left|\theta_{n,w} - \overline{\theta_n}\right|^2)}$. On the other hand, $\alpha_{n,m,w}$ is the gain of the w^{th} path seen by the n^{th} user from the m^{th} BS, which is a complex gaussian distributed random variable that its mean corresponds to the path loss; and $\mathbf{a}(\theta_{n,w})$ is the steering vector defined as:

$$\mathbf{a}(\theta_{n,w}) = \left[1, \exp^{-j2\pi\frac{d\cos(\theta_{n,w})}{\lambda}}, .., \exp^{-j2\pi\frac{(n_t-1)d\cos(\theta_{n,w})}{\lambda}}\right] \quad (3)$$

where d is the distance between the antennas at the BS and λ is the wavelength.

III. Coordinated Multipoint (CoMP)

Coordinated Multipoint (CoMP) transmission [2] is a recently introduced tool in the LTE specs [3] to improve cell edge data rate, coverage and system efficiency. The basic idea of CoMP came from Network MIMO [9] where the cell-edge users can combine the signals that come from several BSs to increase the data rate and the reception quality. All users can benefit from CoMP, but specially cell-edge ones, where the latter is the main concern for CoMP to boost the whole system performance. A coordination and cooperation among the serving BSs is required to enable the combination at the user side. Actually, the main drawback of CoMP is the amount of information (signalling) that has to be exchanged in order to allow the cooperation [4].

This coordination can be simple as in the DPS and DPB techniques that do not require a lot of signalling, but being far from optimality. On the other extreme, the JT and CBS mechanisms need for an excessive amount of signalling while offering very good performance. Several studies [4] have questioned the suitability of the latter mechanisms in practical systems. Commercial operators are free to select the most suitable mechanism for their operation as all cases are optional in the LTE specs [3].

IV. Grassmannian Line Packing

Grassmannian line packing is a mathematical tool to formulate a set of G vectors that pass through the origin, with the minimum maximum (MiniMax) correlation between any two vectors of the set [10]. The correlation indicator between any two vectors $(\mathbf{g}_a, \mathbf{g}_b)$ within this set is obtained as[1]

$$\alpha_{a,b} = \sin(\phi_{a,b}) = \sqrt{1 - |\mathbf{g}_a^H\mathbf{g}_b|^2} \quad (4)$$

with $\phi_{a,b}$ as the angle between the two vectors. Mathematically speaking, Grassmannian packing is the procedure to obtain the set of vectors $\mathbf{G}_{(n_t,G)}= [\mathbf{g}_1, ..., \mathbf{g}_a, \mathbf{g}_b, ..., \mathbf{g}_G]$ with $G > n_t$ such that the MiniMax correlation indicator is formulated as

$$\alpha(\mathbf{G}) = max_{1\leq a,b\leq G}\sqrt{1 - |\mathbf{g}_a^H\mathbf{g}_b|^2} = \sin(\phi_{\min}) \quad (5)$$

where $\phi_{\min}$ is the smallest angle between the vectors in the $\mathbf{G}$ matrix. The smallest angle has the Rankin upper bound [7] that is desired to reach as

$$\alpha(\mathbf{G}) \leq \sqrt{\frac{(n_t-1)G}{n_t(G-1)}} \quad (6)$$

Grassmanian vectors is a generalization of the orthogonal ones, as inspecting last equations we notice that if $n_t = G$ then $\phi_{\min} = 90°$ is obtained as $\alpha(\mathbf{G}) = \sin(\phi_{\min}) = 1$,. Along this paper, we will refer to the Grassmannian vectors only for the case of $G > n_t$, and the orthogonal case when $G = n_t$.

The *tight Grassmannian frames* [10] are the vectors set who present the lowest correlation among all its vectors, and where each vector shows the same cross correlation value to all the other vectors. They are characterized by reaching the Rankin bound (6) with equality for all the generated vectors. This is an important characteristic for transmit beamforming, as we always require transmitting beams with the least interference among each other. Meeting the Rankin bound enables each vector to be formulated with respect to any other vector via the cross correlation indicator between them. As an example, the vector $\mathbf{g}_2$ is formulated through $\mathbf{g}_1$ and the $\alpha_{1,2}$ between them as

$$\mathbf{g}_2 = cos(\phi)\mathbf{g}_1 + sin(\phi)\mathbf{g}_1^{\perp} = \sqrt{1-\alpha_{1,2}^2}\,\mathbf{g}_1 + \alpha_{1,2}\,\mathbf{g}_1^{\perp} \quad (7)$$

where $\mathbf{g}_1^{\perp}$ is the orthogonal vector to $\mathbf{g}_1$. Therefore, $\mathbf{g}_2$ is presented through two orthogonal and statistically independent vectors.

Grassmannian packing has been widely used in off-line codebook design and they have been included in the LTE

[1]Even though the correlation can be expressed as $cos(\phi)$, but to line up with literature [7] we will consider $sin(\phi)$ as the correlation indicator.

codebooks design for the Precoding Matrix Indicator (PMI) [3]. Also they have been proposed for beams generation in multiuser scenarios [5], but to the best of our knowledge, they have not been previously employed for CoMP nor multicell transmission, as the current paper will now show.

V. Opportunistic Grassmannian Beamforming

We will now explain the beamforming transmission scheme by using the Grassmannian vectors, and how it applies to CoMP scenarios in order to decrease the interference among the serviced users in a multicell scenario.

A. OGB procedure

In a non-cooperative approach among the BSs, each BS would transmit with orthogoanl beams that will guarantee zero intracell interference, but an uncontrolled intercell interference. This is specifically critical to cell-edge users that receive the largest intercell interference, and as previously commented, their performance will be low and the whole system data rate will move down. The Grassmannian beams through our OGB-CoMP proposal would tackle the problem from another approach, so that quasi-orthogonal beams are used for transmission over all the cells, where both intracell and intercell interference is generated but in a controlled way. The use of the Grassmannian beams will guarantee the lowest interference possible.

Therefore, one BS generates at each transmission time the Grassmannian vectors for all the M BSs involved in the CoMP process as $\mathbf{G}_{(n_t,G)}= [\mathbf{g}_1, ..., \mathbf{g}_G]$ and it sends the corresponding subset to each BS (i.e., for a scenario with $n_t = 2$, two vectors are sent to each BS) as $\mathbf{G} = [\hat{\mathbf{G}}_1, ..., \hat{\mathbf{G}}_M]$. Therefore, the number of generated beams must be $G = M \times n_t$. Obviously, the signalling over the network is minimal and there is no need to exchange the CSIT for the users (as done in JT and CBS for example). The exchange has to be done each scheduling time that can be a maximum of T_c (20ms in practical systems like LTE). Moreover, the users selection is done simultaneously at all BSs therefore, less overhead is required.

As several users are serviced at the same time by the same BS, the transmitted signal comprises symbols for n_t selected users within the m^{th} BS as

$$\mathbf{x}_m = \sqrt{\frac{1}{n_t}} \sum_{g=1}^{n_t} \mathbf{g}_g \, s_g \tag{8}$$

where $\mathbf{g}_g$ is the Grassmannian beam from $\hat{\mathbf{G}}_m$ which is assigned to the n^{th} user from the m^{th} BS. s_g are the data symbols for each one of the intended users, with $E\{|s_n|^2\} = 1$

In the acquisition step, all the BSs go through the training step to allow users to sequentially calculates the Signal to Noise and Interference Ratio (SINR) for each beam, and feeds back the best value to the BS together with an integer indicating the index of the selected beam. Notice that the interference includes both the intracell and intercell versions. The BS scheduler chooses the user with the largest SINR value to each one of its transmitting beams, and then enters the transmission stage and forwards each intended user its data. Notice that this scheme does not induce any feedback increase compared to orthogonal beamforming [6], as each user is still feeding back a single SINR value.

When transmitting with Grassmannian beams, the SINR for the n^{th} user along the g^{th} beam from the m^{th} cell is

$$SINR_{g,n,m} = \frac{\frac{1}{n_t}\left|\mathbf{h}_{n,m}\mathbf{g}_g\right|^2}{\sum\limits_{p\neq m}^{M} \frac{1}{n_t}\left|\mathbf{h}_{n,p}\mathbf{x}_p\right|^2 + \sum\limits_{u\neq g}^{n_t} \frac{1}{n_t}\left|\mathbf{h}_{n,m}\mathbf{g}_u\right|^2 + 1} \tag{9}$$

where the first term denotes the intercell interference coming from the other $M-1$ cells, while the second term indicates the intracell interference from the other $n_t - 1$ beams. Comparing the SNIR value to its orthogonal counterpart, OGB gives a lower SINR per beam within the same cell. However, when applied to a multicell scenario through our OGB-CoMP proposal, it compensates the increase of intracell interference by a lower intercell interference, and thus more data rate is achieved. The system data rate (DR) is presented as

$$DR = E\left\{\sum_{m}^{M} \sum_{g=1}^{n_t} \log_2(1 + \max_{1\leq n\leq N} SINR_{g,n,m})\right\} \tag{10}$$

Regarded from the interference perspective, expression (9) indicates that a favourable scenario for the application of OGB-CoMP is one with small cross interference terms in the denominator, so that the value of $SINR_{g,n,m}$ does not suffer much from the extra generated beams. Notice that OGB-CoMP is proposed for cellular communications, where the signal goes through outdoor channels that are characterized by small angular spread values [11]. Therefore, OGB-CoMP is expected to offer a very high data rate in practical systems. The simulations will evaluate the OGB-CoMP performance and show the benefit of its application in the different scenarios.

VI. Computer Simulations

The performance of the proposed Grassmannian Beamforming in multicell environment is presented by simulation, where the goal is to display the impact of the several parameters on the total system performance, as well as to compare its behaviour to benchmark orthogonal beamforming scheme in order to realize its improvements. We run Monte Carlo simulations to test for our proposed scheme and 1000 different scenarios are created following the presented system model.

We consider two cells with a full bandwidth reuse. A variable number of users are available in the system and each one is equipped with a single antenna while the BS has two antennas n_t. The two cells are separated by a distance of 5 Km and free-space path loss is assumed, and the system is running an operating frequency of 1 GHz. Considering the outdoor channel with an angle spread of $AS = 5°$, Fig. 1 shows the performance of OGB-CoMP compared to the orthogonal opportunistic beamforming. The behaviour of the schemes is tested under different number of active users, where the superior performance of the OGB-CoMP technique is evident, thanks for its control of the generated intercell interference.

As expected, raising the number of active users makes the simulated sum rate to logarithmically increase thanks to the multiuser gain in the system.

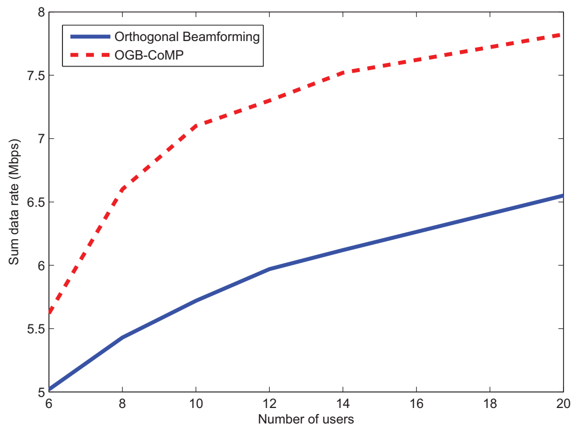

Fig. 1. System sum rate for a variable number of active users in outdoor scenarios with AS=5°.

As shown in Section V, OGB-CoMP performance is enhanced within a low interference scenario where the serviced users show low cross correlations among their channels, to decrease the impact of the interference terms in the SINR formulation in (9), which denotes a dependance on the AS spread value. Practical systems show an AS value in outdoor scenarios in the range $AS = 10° - 25°$ that depends on the number of reflections and obstacles in the scenario [11]. Fig. 2 shows the performance of OGB-CoMP for a variable AS value, where our proposal outperforms the orthogonal beamforming strategy. It can be seen how up to an of $AS = 30°$, value, our proposal outperforms the benchmark technique thus being beyond typical AS values for outdoor channels, which indicates the suitability of our proposal in multicell outdoor systems. The advantage of our scheme is highlighted by the fact that both schemes show the same complexity and they both require the same amount of signalling. Obviously, other CBS and JT strategies would outperform the OGB-CoMP proposal, but at the extent of larger signalling and complexity.

VII. Conclusions

In this paper we tackle a different approach for Coordinated Multipoint (CoMP) strategies in multicell systems to increase the system performance whenever large intercell interference is available. Instead of the JT and CBS proposals for CoMP scenarios, we consider a low complexity beamforming technique that considers the beams generation among several cells, where the beams are generated through the Grassmannian Packing mathematical tool in order to guarantee the lowest interference among the serviced users. Intracell interference is generated but the system compensates through a lower and controlled intercell interference, and obtaining better sum rate performance than the orthogonal beamforming technique. Cell-edge users would be the highest beneficiaries from such

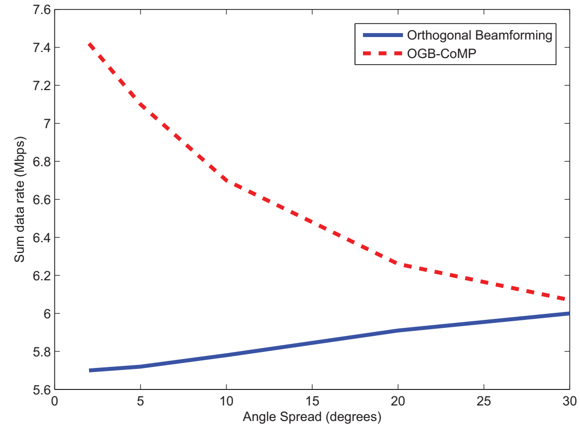

Fig. 2. System sum rate performance for different AS values in a scenario with N=10 users.

transmission strategy as lower they will receive lower intracell interference.

Appendix: An example of a tight Grassmannian frame

This appendix shows an example of a frame that can be used through the presented simulations, where the used Grassmannian frames are obtained through some of the mathematical constructions in [10], or by random search. For the case of $n_t = 3$ and a tight frame with $G = n_t + 1 = 4$ generated beams, $\mathbf{G}$ can be as

$$\mathbf{G} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & i & -1 & -i \\ 1 & -1 & 1 & -1 \\ 1 & -i & -1 & i \end{bmatrix} \quad (11)$$

which shows the same correlation indicator among all the generated beams, with a value of $\sqrt{\frac{8}{9}}$, that matches with the Rankin upper bound in (6).

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