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# Precoder selection scheme based on message-passing approach: a practical perspective

Igor M Guerreiro<sup>1</sup>, Charles C Cavalcante<sup>1</sup> and Dennis Hui<sup>2</sup>

<sup>1</sup> Wireless Telecomm. Research Group, Universidade Federal do Ceará, Fortaleza, Brazil

<sup>2</sup> Ericsson Research, San José, California, USA

E-mail: {igor,charles}@gtel.ufc.br

E-mail: dennis.hui@ericsson.com

**Abstract.** This work addresses a distributed technique to precoding matrices coordination in a multi-cell network. We propose an iterative method based on a message-passing algorithm in factor graphs. Finite precoder codebooks for different MIMO setups are adopted for beam forming purposes. Conversely, practical cellular networks usually solve the precoder selection problem in a non-iterative manner based on the best response method. Nevertheless, this method may not provide a near-optimal solution. For more realistic results, the wireless channel is modeled based on measured data that comprises spatial correlation effects. Evaluations on the potential of such an approach are provided and its performance is compared with the selfish/greedy approach. The capability of reaching the globally optimal solution is evaluated, as well as its performance per iteration. Simulation results for the precoder selection example are presented and discussed, which show that the graph-based technique generally obtains gain in system capacity over both the non-iterative and selfish approaches. Besides, the proposed method usually reaches the global optima in an efficient manner in terms of signaling load.

## 1. Introduction

In a cellular network, each cell usually needs to set a parameter value, such as transmit power and beam direction, preferably in a compatible way with the settings of the neighboring cells, to achieve a certain notion of optimality, e.g. maximizing system throughput [1, 2]. The choice made by one cell on a local parameter often affects the interference level experienced by its immediate neighbors and hence their respective choices made on their local parameters, which in turn would influence the choices made by their neighbors' neighbors. In some cases, the parameter is dynamic and requires coordination to be continually performed. Therefore, a systematic methodology for coordinating the choices of any parameters across the network is desired. Moreover, to facilitate flexible, dense deployment of small base-stations in future cellular networks, there is an increased interest in methods of performing the coordination of parameters among neighboring cells in an autonomous and distributed fashion without a central controller, as any unplanned addition (or removal) of base-stations can substantially alter the system topology and thus the preferred settings.

In this paper, we propose the use of the min-sum algorithm [3] to precoder selection in a distributed way. Different from our work in [4], a discrete set of complex weighting precoding matrices is considered to be coordinated. Such an algorithm can then be applied in order for all nodes, through iterative message exchange with their respective neighboring nodes, to



decide upon the best set of precoders that can collectively maximize the system capacity. It allows each communication node to be indecisive of its own decision until sufficient information is accumulated. The performance of the graph-based method against a greedy approach for coordination of discrete parameters in a wireless communication network is evaluated.

## 2. Problem Formulation

Consider a communication network with  $N$  communication nodes in a multi-cell multiple-input-multiple-output (MIMO) system. A communication node represents a pair of base-station (BS) and its associated user equipment (UE), each one in a cell, where only downlink transmissions are considered. Each BS has  $N_t$  available transmit antennas and each UE has  $N_r$  receive antennas. Let  $p_i$  denote a discrete parameter of the  $i$ th communication node, or simply node  $i$ , whose value is drawn from a finite set  $\mathcal{P}_i$  of  $|\mathcal{P}_i|$  possible parameter values for that node, where  $|\mathcal{P}_i|$  denotes the cardinality of  $\mathcal{P}_i$ , and let  $\mathbf{p} \equiv [p_1 \ p_2 \ \cdots \ p_N]^T$  be a vector collecting all the parameters in the network, where  $p_i \in \mathcal{P}_i$ ,  $i = 1, 2, \dots, N$ . Each parameter  $p_i$  represent a precoding matrix index (PMI) for BS  $i$  indicating which precoder from a predetermined codebook that BS  $i$  should use at a certain radio resource block to transmit signals.

Each node  $i$  is associated with a list  $\mathcal{N}_i$  of proper neighbor nodes (excluding node  $i$ ). Also let  $\mathcal{A}_i \equiv \mathcal{N}_i \cup \{i\}$  denote the neighbor list of node  $i$ . Let  $\mathbf{p}_{\mathcal{A}_i}$  denote the vector of those parameters of nodes in  $\mathcal{A}_i$ . The BS  $i$  transmits vector  $\mathbf{x}_i$  to its associated UE  $i$ . The vector  $\mathbf{x}_i$  is defined as  $\mathbf{x}_i = \sqrt{1/N_s} \mathbf{W}_i \mathbf{s}_i$ , where  $N_s$  is the number of data streams,  $\mathbf{s}_i$  is the  $N_s \times 1$  spatially multiplexed (SM) symbol vector and  $\mathbf{W}_i \in \mathcal{W}$  is the  $N_t \times N_s$  precoding matrix specified by the parameter  $p_i$ . Here,  $\mathcal{W}$  is the finite set of all precoding matrices available for every communication node in the network. In order to index the elements of  $\mathcal{W}$ , assume an index set  $\mathcal{I}$ , which is equivalent to set  $\mathcal{P}_i$ . Due to the lack of space, the matrix formulation of the incoming signal is omitted (please refer to the formulation in [4]).

Our goal is for each node  $i$  to find its own optimal parameter  $p_i^*$ , which is the corresponding component of the optimal global parameter vector  $\mathbf{p}^*$  that minimizes the global metric given by

$$M(\mathbf{p}) \equiv \sum_{i=1}^N M_i(\mathbf{p}_{\mathcal{A}_i}), \quad (1)$$

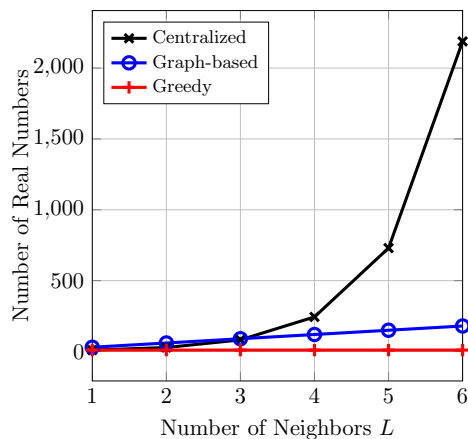
where  $M_i(\mathbf{p}_{\mathcal{A}_i})$  is the local metric of node  $i$  and represents the negative of the data throughput [5, 6] of the cell corresponding to BS  $i$ . It is given by  $M_i(\mathbf{p}_{\mathcal{A}_i}) = -\log \det(\mathbf{I} + |g_{ii}| \mathbf{R}_i^{-1} \mathbf{H}_{ii} \mathbf{W}_i \mathbf{W}_i^H \mathbf{H}_{ii}^H)$ , where  $\mathbf{H}_{ii}$  and  $g_{ii}$  denote the channel and the path gain between BS  $i$  and UE served by BS  $i$ , respectively, and  $\mathbf{R}_i$  denotes the covariance matrix of the noise-plus-interference experienced by the UE served by BS  $i$ .

This problem can be solved through joint optimization, which yields the optimal global parameter vector. A major issue of this approach is its huge computational complexity for large network size. Alternatively, distributed approaches can be adopted, which on one hand often provide sub-optimal solutions through greedy techniques such as non-cooperative games, but on the other hand can provide near-optimal solutions by using message pass in factor graph. In this case, the min-sum algorithm, can then be executed on a factor graph [7, 4], which simply iterates computing and passing messages between nodes. The description of factor graph and the formulation of the algorithm are omitted due to lack of space (please refer to [4]).

## 3. Analysis of Signaling Load and Complexity

A reasonable way to analyze the signaling load involved in the information exchange is to count the number of real numbers which are exchanged by each node. In the message-passing algorithm, each node sends a number of  $|\mathcal{P}| |\mathcal{N}_i|$  real numbers and receives the same amount, per iteration. Let  $\lambda_{\text{ave}}$  be the average number of iterations until convergence and assume  $L = |\mathcal{N}_i|$

tends to be uniform over nodes for large  $N$  in hexagon layout and equals  $N_{\text{hex}}$ . Then, each node exchanges  $I_{\text{GB}} \approx 2(\lambda_{\text{ave}}L|\mathcal{P}|)$ . A greedy technique (e.g. noncooperative game [8]) demands much less information to be exchanged. For instance, each node may exchange only its current own choice (parameter) per iteration, that is,  $I_{\text{G}} \approx 2\lambda_{\text{ave}}$  real numbers. On the other hand, a centralized approach causes a high signaling load over the network. Roughly, each node sends its complete local performance metric and receives its optimal parameter afterwards. That is, each node exchanges  $I_{\text{C}} \approx |\mathcal{P}|^{L+1} + 1$  real numbers.



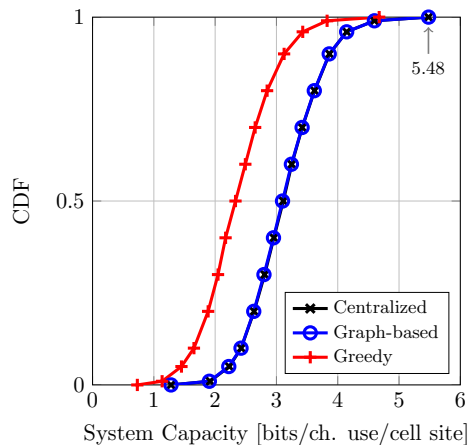
**Figure 1.** Signaling load analysis showing the amount of information exchange per node against the number of neighbors.

Figure 1 shows the amount of real numbers exchanged per node assuming  $\lambda_{\text{ave}}$  equal to five iterations and  $1 \leq L \leq N_{\text{hex}} = 6$ . Clearly, the function  $I_{\text{C}}$  increases exponentially and causes more signaling load than the message-passing algorithm for  $L > 3$ .

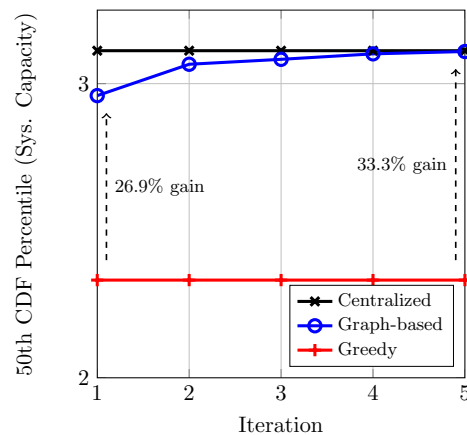
#### 4. Simulation Results

The global metric in (1) is investigated in order to evaluate how it behaves statistically in terms of cumulative distribution functions (CDFs) curves. The graph-based technique is compared with the centralized solution and the greedy approach (formulated as a game [8]). Moreover, the 50th CDF percentile of system capacity is evaluated to realize how much gain each distributed technique obtains over the iterations. The MIMO setup of the  $N = 7$  communication nodes is such that each transmitter has  $N_t = 2$  available transmit antennas,  $N_s = 1$  data streams to be transmitted and each receiver has  $N_r = 1$  receive antennas, and the codebook  $\mathcal{W}$  is as specified in [9]. The signal-to-noise ratio (SNR) equals 20dB and the path loss exponent equals 2 (these simulation parameters and others were taken from [4].)

The graph-based technique appears to reach the optimal solution provided by the centralized approach in terms of system capacity. In Figure 2, the graph-based technique approaches the optimal solution in all the simulation runs, reaching the global optimum in 98% of the cases. That is, the proposed method provides a near-optimal solution. The maximum achievable system capacity is about 5.48 bits per channel use per cell site, reached by both the centralized and the graph-based techniques, while the greedy technique reaches about 4.68 bits per channel use per cell site at the most. As expected, the graph-based technique outperforms the greedy method with a large gain in sum rate. Figure 3 shows the 50th CDF percentile of the curves in Figure 2. The graph-based technique reaches the globally optimum within the first 5 iterations (up to 100 allowed) and the percentage gain obtained over the greedy technique is approximately 33% in system capacity at the fifth iteration. Considering the output at the first iteration, the graph-based approach outperforms the greedy with a percentage gain of about 27% in system capacity. Thus, one may think that the graph-based approach can provide good performance in terms of system capacity even at the very first iteration.



**Figure 2.** Performance analysis in terms of CDF of system capacity.



**Figure 3.** 50th CDF percentile of system capacity against iteration.

## 5. Conclusions

The graph-based method for distributed parameter coordination considers the impact of nodes decisions on their neighboring nodes. That is, the message exchange is only among neighbors. Such a technique reaches the (near) optimal solution at cost of higher signaling load and complexity compared with the greedy solution, but more efficient than the centralized technique for large network size. As for the numerical results, the graph-based technique provides good gains in system capacity over the greedy solution. It is worthwhile to note that the graph-based approach is totally adaptable to any discrete problem of parameter coordination and any network size. As future studies, one may think of working on message-passing scheduling with faster convergence and message exchange with reduced message size.

## Acknowledgments

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