Partial Multi-cell MMSE Vector Combining to Reduce Computational Cost for Massive MIMO Systems

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Abstract—A practical partial multi-cell MMSE (PM-MMSE) combining vector for multi-cell massive MIMO systems is proposed in this work. This new scheme uses only inter-cell channels causing strong interference as partial inter-cell information in the multi-cell MMSE approach. The performance of PM-MMSE is evaluated using channels measured in a two-cell outdoor experiment. In addition, a SIR threshold Γ is introduced as a tradeoff parameter between spectral efficiency and computational cost. For multi-cell scenarios, simulation results show that in a system with 16 cells and 320 users, PM-MMSE is capable of achieving 96% of the M-MMSE spectral efficiency using on average a tenth of inter-cell channel information. For this scenario, PM-MMSE requires only 60% of the total number of multiplications used by M-MMSE.

Index Terms—Combining vector, computational cost, massive MIMO, spectral efficiency.

I. INTRODUCTION

Massive MIMO is one of the most promising new technologies and has shown to improve the spectral efficiency (SE) in both theoretical and real scenarios by serving multiple users at the same time and bandwidth [1]. The huge amount of antennas deployed in each base station (BS) boosts the spectral efficiency by overcoming the effects of fast fading and uncorrelated noise, and on top of that cancelling intra-cell interference with the use of linear precoders or combining vectors [2].

In a multi-cell scenario, during up-link (UL) transmission, a combining vector is used to coherently extract the desired signal from the received one. Different combining vectors, such as, maximum ratio combining (MRC), zero forcing (ZF) and regularized ZF (RZF) take into account only intra-cell information. In contrast, minimum-mean square error (MMSE) combining detectors consider not only intra-cell information but also the corresponding channel estimation errors and inter-cell information. When including inter-cell channels it exhibits the best performance.

Two different MMSE schemes, namely, single-cell MMSE (S-MMSE) and multi-cell MMSE (M-MMSE) detectors are proposed [3]. S-MMSE considers the interference caused by users within the analyzed cell (intra-cell interference), while M-MMSE includes also users from the other cells (intra-cell interference). The ‘optimal’ combining detector is M-MMSE, which maximizes the signal-to-interference-noise ratio (SINR) by suppressing the inter-cell interference with instantaneous inter-cell channel information. For large

systems, the SE gain of M-MMSE versus S-MMSE is up to 84% [3].

Nevertheless, the high computational cost that comes along with the M-MMSE combining vector challenges its implementation specially in large systems. In this work, we propose a new combining vector capable of reducing the computational cost without sacrificing SE. This scheme relies on channel selection based on a SIR heuristic to choose a subset of inter-cell channels with stronger interference to the desired cell. We name this method partial multi-cell MMSE (PM-MMSE) due to the reduced amount of instantaneous inter-cell interference information required to determine the combining vector, and one can easily link this to the reduction in the computation cost. Moreover, the performance of PM-MMSE should be in between S-MMSE and M-MMSE depending on the accuracy in selecting the mentioned subset.

The rest of this paper is structured as follows: Section II describes the channel estimation process along with the SE per user and S-MMSE and M-MMSE combining vectors. Section III details the proposed PM-MMSE combining vector, specifically the inter-cell channel selection algorithm. The framework used to compute the computational cost is explained in Section IV. Section V describes a two-cell experiment setup and a multi-cell simulation system used to validate our proposed scheme. Numerical results are shown in Section VI and finally the main conclusions are summarized in Section VII.

The following notations are used in this paper: $\mathbf{x} \in \mathbb{C}^M$ represents an $M \times 1$ complex vector, $\mathbf{X} \in \mathbb{C}^{M \times N}$ is an $M \times N$ complex matrix. $\mathbf{x}^H$ and $\mathbf{x}^T$ estates a transpose and conjugate-transpose of vector $\mathbf{x}$. $\|\mathbf{x}\|$ is the Euclidean norm of $\mathbf{x}$.

II. CHANNEL ESTIMATION AND SPECTRAL EFFICIENCY

In the following section a detail of our system model is presented, followed by a description of the two state of the art variations of the MMSE combining vector, S-MMSE and M-MMSE.

A. System Model

In this work we consider an UL time division duplex (TDD) system composed of L cells, each cell j has a single BS with M antennas and K_j single antenna users (UEs). The wireless channel between UE i in cell l and BS in cell j is $\mathbf{h}_{li}^j$, with

UE transmission power of p_{li} and average channel gain per antenna given by:

$$\beta_{li}^j = 10 \log_{10} \left\{ \frac{\mathbb{E}\{\|\mathbf{h}_{li}^j\|^2\}}{M_j} \right\}. \quad (\text{dB}) \quad (1)$$

Each UE channel is associated to an individual covariance matrix which contains statistic information about the spatial directions of their signal components and is obtained as follows:

$$\mathbf{R}_{li}^j = \mathbb{E} \left\{ \mathbf{h}_{li}^j \mathbf{h}_{li}^{jH} \right\}. \quad (2)$$

B. MMSE Channel Estimation

During UL training, an orthogonal pilot sequence Φ_{jk} with length τ_p^1 is allocated to each UE k in cell j . Each cell j also experiences pilot interference from $(L-1)$ adjacent cells plus noise $\mathbf{N} \sim \mathcal{N}(0, \sigma_{UL}^2)$, therefore the signal at the receiver is:

$$\mathbf{Y}_j = \sum_{k=1}^{K_j} \mathbf{h}_{jk}^j \Phi_{jk}^T + \sum_{l=1}^L \sum_{i=1, i \neq j}^{K_l} \mathbf{h}_{li}^i \Phi_{li}^T + \mathbf{N}. \quad (3)$$

Once the UL signal reaches a BS, it is correlated with the conjugate of each jk pilot sequence for UE's channels that belong to the analyzed cell j , and the conjugate li pilot sequence for UEs of other cells.

$$\mathbf{y}_{jk}^j = \mathbf{Y}_j \Phi_{jk}^*. \quad (4)$$

If all the pilot sequences for all users in the L cells are orthogonal, $(\Phi_{jk} \perp \Phi_{li})$ a non-pilot contamination scenario is considered and the received signal is decorrelated. In the case of pilot contamination the received signal will contain information with the desired and contaminated channels.

Once pilot decorrelation is carried out we can estimate each UE's channel. In this work the MMSE channel estimation based Theorem 3.1 from [4] is used as follows:

$$\hat{\mathbf{h}}_{jk}^j = \sqrt{p_{jk}} \mathbf{R}_{jk}^j \Psi_{jk} \mathbf{y}_{jk}^j \quad (5)$$

where

$$\Psi_{jk} = \left(\tau_p \sum_{j'k' \in \xi_{jk}} \sqrt{p_{j'k'}} \mathbf{R}_{j'k'}^j + \sigma_{UL}^2 \mathbf{I}_M \right)^{-1}. \quad (6)$$

ξ_{jk} represents the set of users in all L cells that use the same pilot sequence. The noise variance σ_{UL}^2 is obtained through the system signal-to-noise-ratio (SNR). And similar to (2), the covariance error matrix is:

$$\mathbf{C}_{jk}^j = \mathbb{E} \left\{ (\mathbf{h}_{jk}^j - \hat{\mathbf{h}}_{jk}^j) (\mathbf{h}_{jk}^j - \hat{\mathbf{h}}_{jk}^j)^H \right\}. \quad (7)$$

¹ τ_p UL data samples per coherence block are used to transmit a pilot sequence.

C. MMSE Combining Vectors and Spectral Efficiency

After UL pilot training, each BS receives an UL data signal which contains intra and inter-cell interference plus noise. To detect the desired signal for each UE k in cell j a combining vector $\mathbf{v}_{jk}$ is required. Therefore, for a cell j its combining matrix is $\mathbf{V}_j = [\mathbf{v}_{j1} \dots \mathbf{v}_{jK}]$ and its estimated channel matrix

$$\hat{\mathbf{H}}_j^j = [\hat{\mathbf{h}}_{j1}^j \dots \hat{\mathbf{h}}_{jK_j}^j].$$

In this work, we analyze MMSE combining vector schemes as those are capable of maximizing the SINR and therefore increase SE [3]. On one hand, the M-MMSE combining vector uses the channel estimation information from all the users in the system, this scheme enhance the desired signal in the analyzed cell, and suppress all the inter-cell interference and noise.

$$\mathbf{v}_j^M = \left(\sum_{l=1}^L \hat{\mathbf{H}}_l^j \mathbf{P}_l (\hat{\mathbf{H}}_l^j)^H + \sum_{l=1}^L \sum_{i=1}^{K_l} p_{li} \mathbf{C}_{li}^j + \sigma_{UL}^2 \mathbf{I}_{M_j} \right)^{-1} \hat{\mathbf{H}}_j^j \mathbf{P}_j. \quad (8)$$

On the other hand, the S-MMSE scheme considers only its intra-cell channel information, treating the inter-cell information as uncorrelated noise.

$$\mathbf{v}_j^S = \left(\hat{\mathbf{H}}_j^j \mathbf{P}_j (\hat{\mathbf{H}}_j^j)^H + \sum_{k=1}^{K_j} p_{jk} \mathbf{C}_{jk}^j + \sigma_{UL}^2 \mathbf{I}_{M_j} \right)^{-1} \hat{\mathbf{H}}_j^j \mathbf{P}_j. \quad (9)$$

The performance of each combining vector scheme is analyzed as the achievable UL SINR and SE for each UE. Theorem 4.1 in [4] propose an instantaneous SINR which considers channel estimation error in (10) and its SE in (11):

$$\text{SINR}_{jk}^{\text{UL}} = \frac{p_{jk} |\mathbf{v}_{jk}^H \hat{\mathbf{h}}_{jk}^j|^2}{\sum_{l=1}^L \sum_{i=1, i \neq j}^{K_l} p_{li} |\mathbf{v}_{jk}^H \hat{\mathbf{h}}_{li}^i|^2 + \mathbf{v}_{jk}^H \left(\sum_{l=1}^L \sum_{i=1}^{K_l} p_{li} \mathbf{C}_{li}^j + \sigma_{UL}^2 \mathbf{I}_{M_j} \right) \mathbf{v}_{jk}} \quad (10)$$

$$\text{SE}_{jk} = \frac{\tau_u}{\tau_c} \mathbb{E} \left\{ \log_2 \left(1 + \text{SINR}_{jk}^{\text{UL}} \right) \right\}. \quad (11)$$

Where τ_u/τ_c is the portion per coherence block used to transmit UL data.

III. PM-MMSE VECTOR COMBINING

From the previous combining vectors it is noticed that the inter-cell information is treated as *all or nothing*. Despite the fact that M-MMSE considers all inter-cell channels, not all of them contribute to achieve a high spectral efficiency. The proposed PM-MMSE scheme selects only those inter-cell channel with strong interference.

² τ_u is the UL data samples received per coherence block, and τ_c is the total number of samples per coherence block

A. Heuristic Multi-cell Interference

After channel estimation, PM-MMSE algorithm selects all inter-cell UE i in all cells l whose heuristic SIR_{li}^j relative to the analyzed cell j is below a SIR system threshold Γ :

$$\text{SIR}_{li}^j = \max(\hat{\beta}_{jk}^j) - \hat{\beta}_{li}^j \leq \Gamma \quad (\text{dB}) \quad l \neq j. \quad (12)$$

To obtain the SIR_{li}^j in cell j , we first select the UE k in that cell j with the best channel gain to the BS in cell j as a reference signal mainly to normalize the power levels and have a reference point. Note that we could also have chosen the mean power or minimum power in a cell as reference point. We use this reference signal ($\hat{\beta}_{jk}^j$) then to compare the relative power of all other UE in the system using (12). This relative SIR_{li}^j is used as a heuristic to determine if the UE i in cell l should be considered as an inter-cell interferer in the PM-MMSE scheme. A UE is an interferer if it would cause the SIR heuristic to be below a certain threshold.

Along with the selected channels their covariance error matrix and transmission power are also included for further processing in PM-MMSE as it is described in Algorithm 1.

Algorithm 1 Inter-cell interference channel selection, cell j

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1: Select the reference signal  $\hat{\beta}_{jk}^j$ 
2:  $q = 0$ 
3: for  $l = 1 \rightarrow L$  do
Ensure:  $l \neq j$ 
4:   for  $i = 1 \rightarrow K_l$  do
5:     Obtain inter-cell signal  $\hat{\beta}_{li}^j$ 
6:     Obtain  $\text{SIR}_{li}^j$ 
7:     if  $\text{SIR}_{li}^j \leq \Gamma$  then
8:        $\hat{\mathbf{h}}_q^j = \hat{\mathbf{h}}_{li}^j$ 
9:        $\hat{\mathbf{p}}_q^j = \mathbf{p}_{li}^j$ 
10:       $\hat{\mathbf{C}}_q^j = \mathbf{C}_{li}^j$ 
11:       $q = q + 1$ 
12:     end if
13:   end for
14: end for
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The total number of selected channels for cell j is Q^j . Then, the partial multi-cell channel matrix $\hat{\mathbf{H}}^j$ and partial multi-cell power matrix $\hat{\mathbf{P}}^j$ for cell j are presented in (13) and (14).

$$\hat{\mathbf{H}}^j = [\hat{\mathbf{h}}_1^j, \hat{\mathbf{h}}_2^j, \dots, \hat{\mathbf{h}}_{Q^j}^j]^T. \quad (13)$$

$$\hat{\mathbf{P}}^j = \text{diag}(\hat{\mathbf{p}}_1^j, \hat{\mathbf{p}}_2^j, \dots, \hat{\mathbf{p}}_{Q^j}^j). \quad (14)$$

B. Importance of SIR Threshold Γ

Γ is a key parameter for inter-cell interference selection and determines how large the (estimated) interference should be before considering it in PM-MMSE. The SIR threshold could be used as a tradeoff metric between SE and computational cost. So, when $\Gamma \rightarrow -\infty$ no inter-cell channels are considered in PM-MMSE, then $Q \rightarrow 0$ and PM-MMSE $\rightarrow$ S-MMSE. On the other hand, when $\Gamma \rightarrow +\infty$ all inter-cell

channels are considering for PM-MMSE, then $Q \rightarrow (L-1)K$ and PM-MMSE $\rightarrow$ M-MMSE.

C. Partial Multi-cell MMSE combining vector (PM-MMSE)

We categorize the intra and inter-cell interference accounted for PM-MMSE in (15) similar to M-MMSE in (8). The first term is the regular intra-cell interference. Notwithstanding, inter-cell information will be selected according to Algorithm 1. So, in PM-MMSE only Q inter-cell channels and their covariance error matrices are considered as inter-cell information, second term in (15).

IV. COMPUTATIONAL COST

The computational cost is quantified as the number of complex multiplications and divisions³ required per coherence block to compute a desired signal vector. In [4] Lemma B.1 and B.2 describe the number of complex multiplications by each operation used in a MMSE combining vector scheme.

First, $(M^2 + M)K/2$ number of multiplications are required to compute a channel matrix with its transpose conjugate, $\mathbf{H}\mathbf{H}^H$. In Table I we can see that M-MMSE repeats this process L times for all channels in the system, while PM-MMSE add to the analysed cell only Q inter-cell channels. Second, the inverse term of any MMSE combining vector requires $(M^3 + M)/3$ complex multiplications. Finally, the cost between the mentioned inverse term and $\mathbf{H}\mathbf{P}$ is M^2 times the total number of channels considering per combining vector.

Thus, the total number of complex multiplications per coherence block includes $\tau_u MK$ plus the following complex multiplications⁴.

TABLE I
COMPUTATIONAL COMPLEXITY REQUIRED PER COMBINING VECTOR.

M-MMSE	$(3M^2 + M) L \frac{K}{2} + (M^3 - M) \frac{1}{3}$
S-MMSE	$(3M^2 + M) \frac{K}{2} + (M^3 - M) \frac{1}{3}$
PM-MMSE	$(3M^2 + M) \frac{K+Q}{2} + (M^3 - M) \frac{1}{3} + K(L-1)$

Assuming that all channel gains are already known by the system, the operations needed to carry out channel selection in Section III-A contribute only $K(L-1)$ additional complex multiplications when (12) is compute linearly.

V. SIMULATION AND EXPERIMENT SETUP

To analyse the performance of the proposed PM-MMSE combining vector in a two-cell scenario using realistic channel and interference estimates, we carried out an outdoor experiment deployed in the KULeuven massive MIMO testbed.

³Additions and subtractions also contribute to the computational cost, however, their contribution is small and are neglected in this work.

⁴Considering a homogeneous system, with M number of antennas for all BS and K users for all cells.

$$\mathbf{V}_j^P = \underbrace{\left(\hat{\mathbf{H}}_j^P \mathbf{P}_j \left(\hat{\mathbf{H}}_j^P \right)^H + \sum_{i=1}^{K_j} p_{ji} \mathbf{C}_{ji}^j \right)}_{\text{Intra-cell information}} + \underbrace{\left(\hat{\mathbf{H}}_j^P \mathbf{P}_j \left(\hat{\mathbf{H}}_j^P \right)^H + \sum_{q=1}^{Q'} \tilde{p}_q^j \tilde{\mathbf{C}}_q^j + \sigma_{UL}^2 \mathbf{I}_{M_j} \right)}_{\text{Partial Inter-cell information}}^{-1} \hat{\mathbf{H}}_j^P \mathbf{P}_j \quad (15)$$

Fig. 1. Overlook of the symmetric two-cell Massive MIMO outdoor scenario at ESAT KU Leuven. The location of each BS is 21 meters high, separated by 6.5 meters. Each cell supports 18 UEs, which are distributed in 3 rows (2 meters) and 6 columns (1 meter).

While for multi-cell scenarios we used line-of-sight (LOS) massive MIMO simulations.

A. Experiment Setup

The distributed KULeuven massive MIMO testbed used in an outdoor two-cell experiment is described in detail in [5]. This testbed is supported by National Instrument universal software radio peripherals (USRPs) and controlled in real time by the LabVIEW Communications MIMO Application Framework 1.1. [6], operating at 2.61GHz with LTE-TDD standard. The two main components of this system are the distributed BS and fixed UEs.

As a unique feature of this testbed, the 64-antennas from the BS are distributed into two separate patch antenna arrays of equal size. For this experiment, both arrays were placed at the rear windows of KULeuven-ESAT building on the fifth floor at 21 meters high, separated with 6.5 meters from each other and tilted 24°.

The second part of this setup comprises a set of fixed UEs. Those UEs are implemented in a dual-antenna USRP that is capable to transmit two data streams simultaneously. Each stream and antenna are associated to a single UE. In this experiment, we used dipole antennas for each UE, with a TX power of 20dBm. Attached to each dipole antenna was a power amplifier to boost its power for an extra 13dB.

One USRP was placed symmetrically in one of the 18 grid locations on the ground floor at the rear side of KULeuven-ESAT building, facing both BS arrays. This experiment collected the uplink UE's channel in every location and after channel processing we associate 18 users to one BS array, creating a two cells system, as it is shown in Fig. 1. Therefore this system has two homogeneous cells ($L = 2$) with $K = 18$

Fig. 2. Inter-cell SIR for each UE from cell 2 to BS 1. Where the UE in cell 1 row 1 column 4 has the strongest channel gain and is consider as the reference signal based on (12). Notice that a UE in cell 2 giving rise to a SIR of 20dB for the reference user, means that the interference generated by that UE in cell 2 is 20dB larger than the reference signal.

Fig. 3. Inter-cell SIR for each UE from cell 1 to BS 2. Where the UE in cell 2 row 3 column 4 has the strongest channel gain and is considered as the reference signal for SIR in cell 1 based on (12).

and $M = 32$ for each cell. All inter- and intra-cell channels were measured, so we can evaluate inter-cell interference and the performance of M-MMSE using the measured channel database.

1) *Channel collection:* During our experiment, the channel of each UE was collected for 1 OFDMA symbol of 100 sub-carriers every 100ms, during 20 seconds. This channel was treated as raw channel for the following data processing, albeit it was not normalized in any kind, to preserve its path gain.

2) *Data processing:* As a first step during data processing, a fixed noise power was added to all UE, setting each UE's SNR between 30dB to 40dB, depending solely on their channel gain β_{jk} as the UL power p is the same for all of them.

$$\text{SNR}_{jk} = \frac{p\beta_{jk}}{\sigma^2} \quad (16)$$

Once SNR was set, channel estimation process was carried out, continuing with the computation of different MMSE combining vectors and later with SE.

Fig. 4. Average UL SE comparison for different values of Γ for PM-MMSE combining vector, as a function of the number of antennas per BS, applied to our experiment

Fig. 5. Average UL SE per cell, for M-MMSE and PM-MMSE vector combining as a function of the number of antennas (M). In a system with 4, 9 and 16 cells, with $K = 20$ and $\Gamma = 30\text{dB}$.

B. Simulation

To validate the proposed combined vector in larger multi-cell scenarios, this work used different simulations based on the running example and parameters presented in [4], [7], [8]. Those systems are composed by L cells deployed in a square area of 1km^2 using a universal pilot, where L is a square number. Each cell has a single Base Station (BS) which serves K users. And every BS has M antennas, that are deployed next to each other in a uniform linear array (ULA). This simulation uses one-ring channel model for each UE.⁵

VI. NUMERICAL RESULTS

In this section we will first compute the SIR heuristic of each UE in our experiment and plot them according to each UE location. Second we evaluate the impact of the SIR threshold (Γ) on the PM-MMSE performance based on

the data collected in our experiment. Finally with simulation results we assess the performance of the proposed PM-MMSE combined vector in comparison with other MMSE schemes, over SE, area SE and computational cost, for multi-cell scenarios.

A. Experiment results

The SIR heuristic from (12) for each inter-cell UE i is plotted in Fig. 2 and Fig. 3 according to its location. It is noticeable first, that not all the UE contributes with the same SIR, and its value in this specific scenario varies from -5dB to 20dB . Second, as it is expected most of the users which cause strong inter-cell interference or low SIR, giving rise to a negative SIR heuristic, are located next to the adjacent cell. Third, despite that the scenario was deployed symmetrically the inter-cell SIR is not, that due to environmental effects of this particular experiment. Notice that although we compare the power received at BS1 from the neighboring cell with the strongest power from BS1, and still the SIR can be as low as -5dB , meaning that the adjacent has a received power in the neighbouring cell that is 5dB higher.

The key parameter for PM-MMSE is the SIR threshold Γ . To show its impact on SE from our two-cell outdoor experiment, the result is presented in Fig. 4 for M-MMSE, PM-MMSE and S-MMSE combining vectors, under different Γ values. As discussed in Section III-B, small Γ values gives the performance closer to S-MMSE, and high values to M-MMSE. The obtained results show that when $\Gamma = 0\text{dB}$ an average of $Q = 4$ is obtained in PM-MMSE (from a total of 18 inter-cell channels) and its SE increases 25% from S-MMSE. When $\Gamma = 2\text{dB}$ $Q = 9$, and SE approaches 80% of the SE of M-MMSE. From $\Gamma = 5\text{dB}$ ($Q = 12$) and onwards we can see that the remaining inter-cell interference do not impact much to the SE.

B. Simulation results

In the simulation for multi-cell scenarios, users are spread over an area of 1km^2 . Users which are further to the analyzed cell will cause weak inter-cell interference, therefore, Γ will have a higher value compared to the two-cell experiment.

Fig. 5 shows SE between PM-MMSE ($\Gamma = 30\text{dB}$) and M-MMSE for 4, 9 and 16 cells. We can see that when the number of cells increases (also density of users in the same area), the SE reduces because of larger channel estimation errors caused by pilot contamination and an increased of total intra and inter-cell interference. Moreover, when L increases, PM-MMSE is closer to M-MMSE, since the size of the cells are smaller and more inter-cell UEs have a higher SIR below Γ .

In Table II, a numerical comparison for all MMSE combining vectors based on SE and area SE is presented. We can see that PM-MMSE achieves at least 94% of M-MMSE SE when $L = 4$ and 96% when $L = 9, 16$. As was mentioned before, when the number of cells increase the SE per cell is reduced, but also systems with a large number of cells have a better area SE. It is worth to mention that for cases of $L =$

⁵For more details of this simulation and its parameters, we strongly suggest referring to [4], [7], [8].

TABLE II
AREA SPECTRAL EFFICIENCY COMPARISON FOR MULTI-CELL SCENARIOS, WITH $M = 100$, $K = 20$ AND $\Gamma = 30\text{dB}$.

Number of cells	Area per cell [km^2]	SE [bits/s/Hz/cell]			Area SE [bits/s/Hz/ km^2]		
		M-MMSE	PM-MMSE	S-MMSE	M-MMSE	PM-MMSE	S-MMSE
4	0.2500	82.343	77.509	68.752	329.372	310.036	275.008
9	0.0900	62.926	61.340	54.523	699.177	681.555	605.806
16	0.0625	43.778	42.492	37.733	700.448	679.872	603.720

Fig. 6. Total number of inter-cell channels per cell to compute $\mathbf{V}_{\text{M-MMSE}}$ and the average total number of inter-cell channels Q^i used to obtain $\mathbf{V}_{\text{PM-MMSE}}$. For a simulation system with $M = 100$, $K = 20$ and $\Gamma = 30\text{dB}$.

Fig. 7. Total number of complex multiplications per coherence block for M-MMSE, PM-MMSE (with the largest Q) and S-MMSE combining vector, in function of L . Considering $M = 100$, $K = 20$ and $\Gamma = 30\text{dB}$.

9 and 16, the area SE for P-MMSE and M-MMSE are close as well.

Fig. 6, presents the average number of Q inter-cell channels used by PM-MMSE versus the total number of inter-cell channels used by M-MMSE to obtain the SE in Fig. 5 when $M = 100$. We can see that the number of inter-cell channels required by M-MMSE is linear dependent on the number of cells $(L-1)K$. On the contrary, Q increases as a function of K and SIR, and in the case of $L = 16$, Q is around a tenth of the total number of inter-cell channels.

Fig. 7 presents the total number of complex multiplications needed by each combining vector to achieve their SE in Fig. 5. Considering the number of complex multiplications from M-MMSE scheme, and the largest Q value in the system, PM-MMSE reduces the computation up to 40% in a system with 16 cells.

VII. CONCLUSIONS

This paper presents a compelling new vector combining method called PM-MMSE, which uses partial inter-cell information based on inter-cell SIR channel selection. This new scheme is capable of achieving high SE while reducing computational cost. It is worth nothing that in ultra dense scenarios with 16 cells and 320 users, PM-MMSE reaches 96% of the optimal spectral efficiency per cell, using on average a tenth of the total inter-cell channels. As for the computation cost, in the same scenario, PM-MMSE requires only 60% of the total number of multiplications used by M-MMSE. We also propose a SIR parameter, which is used to control the trade-off between computational cost

and spectral efficiency. Multi-cell simulations along with an two-cell outdoor experiment for massive MIMO systems validate the efficiency of the proposed partial multi-cell MMSE combining vector.

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