ENERGY EFFICIENCY-THROUGHPUT TRADE-OFFS IN 5G

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Abstract - *A tractable and realistic CP model for Massive MIMO networks is presented here. This model is used to examine the EE-throughput tradeoff of Massive MIMO and to design a cellular network that achieves maximal EE. Using the model we compare CP of different processing schemes*

***Key Words*: Circuit power CP, Massive MIMO, Energy efficiency, throughput, Uplink Ratio, Downlink Ratio, Base Station, Power Consumption, User Equipment, Minimum Mean Square error, Regularized Zero Forcing, Maximal Ratio Combining, Zero Forcing**

1. INTRODUCTION

CP is based on The PC is mainly determined by the peak throughput and varies very little with the actual throughput of the cell. This is problematic since the number of active UEs in a cell can change rapidly due to changes in user behaviors and the bursty nature of packet transmission. The measurements reported in show that the daily maximum network load is 2–10 times higher than the daily minimum load. Hence, a lot of energy is wasted at the BSs in non-peak hours. A quite remarkable effort has been devoted to reducing the PC of UEs, in order to enhance their battery lifetime

Massive MIMO aims at evolving the coverage tier BSs by using arrays with a hundred or more antennas each transmitting with a relatively low power. This allows for coherent multiuser MIMO transmission with tens of UEs being spatially multiplexed in both UL and DL of each cell. The area throughput is improved by the multiplexing gain. However, the throughput gains provided by Massive MIMO come from deploying more hardware (i.e., multiple RF chains per BS) and digital signal processing (i.e., SDMA combining/precoding) which, in turn, increase the CP per BS. Hence, the overall EE of the network

1.1 Circuit Power Consumption Model

To appropriately evaluate the CP of the UL and DL of Massive MIMO consider the power consumed by digital signal processing, backhaul signaling, encoding, and decoding. A CP model for a generic BS j in a Massive MIMO network is:

$$CP_j = \underbrace{P_{FIXj}}_{\text{Fixed Power}} + \underbrace{P_{TCj}}_{\text{Transceiver Chains}} + \underbrace{P_{CEj}}_{\text{Channel Estimation}} + \underbrace{P_{C/Dj}}_{\text{Codind Decoding}} + \underbrace{P_{BHj}}_{\text{Backhaul}} + \underbrace{P_{SPj}}_{\text{Signal Processing}}$$

where $P_{FIX,j}$ is a constant quantity accounting for the fixed power required for control signaling and load-independent power of backhaul infrastructure and baseband processors. Furthermore, P_{TCj} accounts for the power consumed by the transceiver chains, P_{CEj} for the channel estimation process (performed once per coherence block), $P_{C/Dj}$ for the channel encoding and decoding units, P_{BHj} for the load dependent backhaul signaling, and P_{SPj} for the signal processing at the BS. Note that neglecting the power consumed by transceiver chains, channel estimation, precoding, and combining was previously the norm in multiuser MIMO. More precisely, the small numbers of antennas and UEs, before Massive MIMO was introduced, were such that the CP for all those operations was negligible compared to the fixed power

A) Transceiver Chains

P_{TCj} of cell j can be quantified as

$$P_{TCj} = \underbrace{M_j P_{BSj} + P_{LOj}}_{\text{BS Circuit Components}} + \underbrace{K_j P_{UEj}}_{\text{UE Circuit Components}}$$

where P_{BSj} is the power required to run the circuit components attached to each antenna at BS j (which has to be multiplied by the number of antennas Mj) and P_{LOj} is the power consumed by the LO. The term P_{UEj} accounts for the power required by all circuit components

B) Coding and Decoding

In the DL, BS j applies channel coding and modulation to K_j sequences of information symbols and each UE applies some practical fixed-complexity algorithm for decoding its own received data sequence. The opposite is done in the UL. The term $P_{C/Dj}$ accounting for these processes in cell j is thus proportional to the number of information bits that is transferred and can be quantified as

$$P_{C/Dj} = (P_{COD} + P_{DEC})\, TR_j$$

where TR_j stands for the throughput (in bit/s) of cell *j*, while P_{COD} and P_{DEC} are the encoding and decoding powers (in W per bit/s), respectively

C) Backhaul

The backhaul is used to transfer UL and DL data between the BS and the core network, and can be either wired or wireless depending on the network deployment. Looking jointly at the UL and DL, the load-dependent backhaul term P_{BHj} in cell *j* is computed as

$P_{BHj}=P_{BT}.TR_j$

where P_{BT} is the backhaul traffic power (in W per bit/s), which is, for simplicity, assumed to be the same for all cells in the network.

D) Channel Estimation

The UL channel estimation is carried out using the MMSE estimator

$$P_{CE,j} = \frac{3B}{\tau_c L_{BS}} K_j . \left(M_j \tau_p + M_j^2 \right)$$

where K_j is the number of UEs in cell j and τ_p is the pilot sequence length, typically chosen such that $\tau_p \geq \max_l K_l$.

E) Receive Combining and Transmit Precoding

To compute the power $P_{SP,j}$ consumed by BS $_j$ for receive combining and transmit precoding.

$$P_{SP,j} = \underbrace{P_{SP-\frac{R}{T},j}}_{\frac{\text{Reception}}{\text{Transmission}}} + \underbrace{P_{SP-C,j}^{UL}}_{\text{Computing combining}} + \underbrace{P_{SP-C,j}^{DL}}_{\text{Computing precoding}}$$

where $P_{SP-R/T,j}$ accounts for the total power consumed by UL reception and DL transmission of data signals (for given combining and precoding vectors) whereas $P_{SP-C,j}^{UL}$ and $P_{SP-C,j}^{DL}$ are the powers required for the computation of the combining and precoding vectors at BS $_j$, respectively

F) UL Reception and DL Transmission

CP for reception and transmission is the same irrespective of the choice of combining and precoding schemes.

$$P_{SP-R/T,j} = \frac{3B}{\tau_c L_{BS}} M_j K_j (\tau_u + \tau_d)$$

G) Computation of the Combining/Precoding Vectors

$$P_{SP-C,j}^{DL} = \frac{4B}{\tau_c L_{BS}} M_j K_j$$

$$P_{SP-C,j}^{UL} = \frac{7B}{\tau_c L_{BS}} K_j$$

2. METHODOLOGY

Parameter	Value set 1	Value set 2
1.Fixed power: P_{FIX}	10W	5W
2.Power for BS LO: P_{LO}	0.2W	0.1W
3.Power per BS antennas: P_{BS}	0.4W	0.2W
4.Power per UE: P_{UE}	0.2W	0.1W
5.Power for data encoding: PCOD	0.1 W/(Gbit/s)	0.01 W/(Gbit/s)
6.Power for data decoding: P_{DEC}	0.8 W/(Gbit/s)	0.08 W/(Gbit/s)
7.BS computational efficiency: L_{BS}	75 Gflops/W	750Gflops/W
8.Power for backhaul traffic: P_{BT}	0.25 W/(Gbit/s)	0.025 W/(Gbit/s)

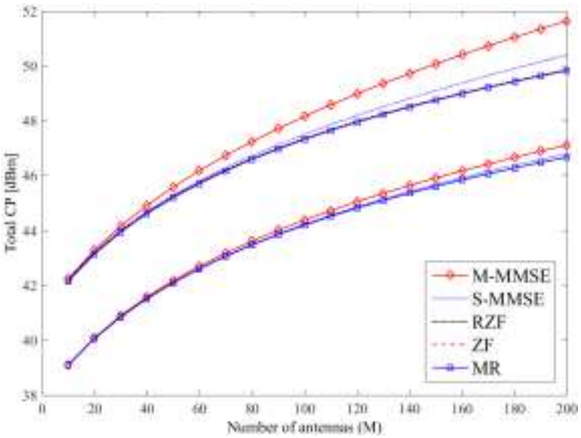
Table-1: Comparison of CP with Different Processing Schemes

We will compare the CP consumed with different combining/precoding schemes. There are M antennas at each BS and K UEs in each cell. The values of M and K will be changed and specified in each figure. The pilot reuse factor is f = 1, such that each pilot sequence consists of τ_p = K samples. The number of samples per coherence block that is used for data is $\tau_c - \tau_p = 190-K$, whereof 1/3 is used for UL and 2/3 for DL. This yields $\tau_u = 1/3\,(\tau_c - \tau_p)$ and $\tau_d = 2/3\,(\tau_c - \tau_p)$. We consider UL and DL transmit powers of 20 dBm per UE (i.e., $p_{jk} = \rho_{jk}$ = 100 mW). The Gaussian local scattering with ASD $\sigma_\phi = 10^\circ$ is used as channel model. The throughput of cell j for computing the consumed power for backhaul, encoding, and decoding is obtained using the UL and DL SE expressions

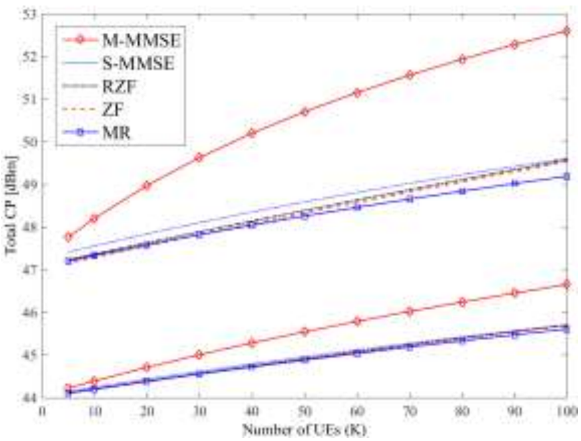
Scheme	value set 1	value set 2
M-MMSE	65.48 W	27.42 W
S-MMSE	56.35W	26.51W
RZF	54.43W	26.32W
ZF	54.43w	26.32W
MR	53.96W	26.37W

Table 2 : Parameters in the CP model. Two different set of values are exemplified.

Table 2: CP per cell with M = 100 and K = 10 for different schemes and the two sets of values reported in Table 1.



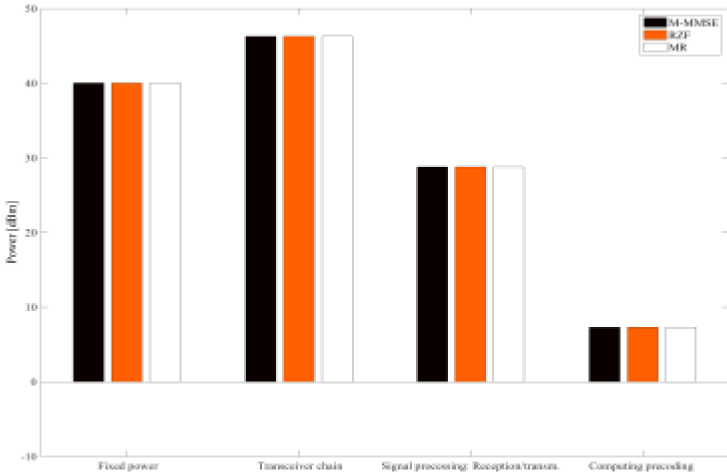
a) Total CP for K = 10 and varying M



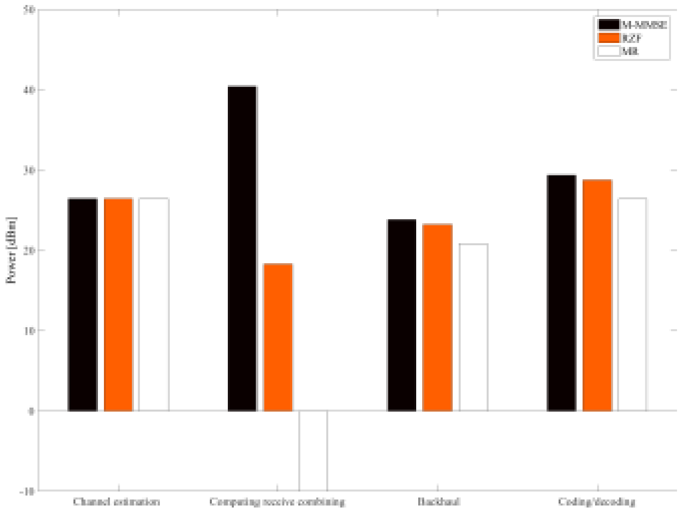
b) CP for M = 100 and varying K.

Figure 1: Total CP per cell of both UL and DL The two sets of CP parameter values reported in Table1 are considered.

Figure 1 illustrates the total CP per cell for the combined UL and DL scenario with different combining/precoding schemes.. The highest CP is required by M-MMSE, followed by S-MMSE. For Value set 1, S-MMSE reduces the CP by 0.5%–25% since inter-cell channel estimates are not computed. Note, however, that M-MMSE provides higher SE than S-MMSE. For Value set 2, the CP required by M-MMSE is only 0.1%–7% higher than with S-MMSE. This is mainly due to the increased computational efficiency. RZF and ZF consume less CP. Compared to M-MMSE, when M = 100, this reduces the CP by 17% for Value set 1 and by 4% for Value set 2. MR only provides a substantial complexity reduction compared to RZF and ZF when the number of UEs is very large. When M = 100 and let K vary from 10 to 100. The CP increases with the number of UEs, but with a smaller slope than when M is changed (especially for Value set 2). We see that for Value set 1 the CP required by M-MMSE is 8%–100% higher than with S-MMSE. This CP increase reduces to 2%–25% CP for Value set 2.



(a)

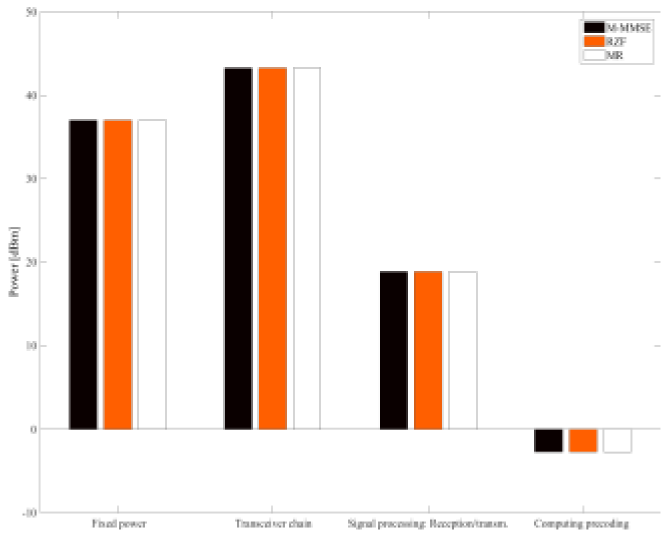


(b)

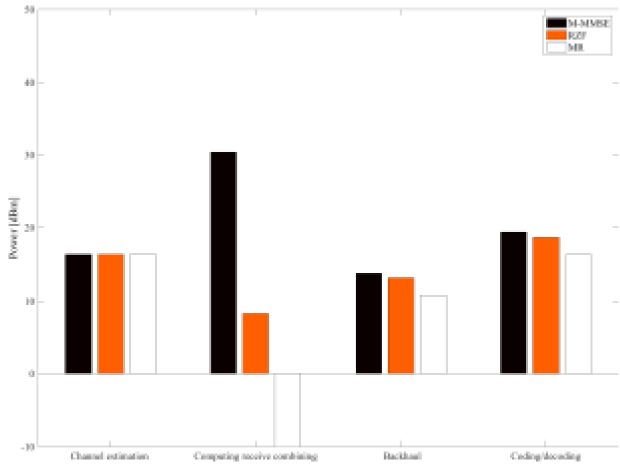
Figure 2: Breakdown of the CP per cell when using the first set of values in Table 1 with M-MMSE, RZF or MR.

A setup with K = 10 UEs and M = 100 BS antennas per cell is considered Figure 2 shows that CP contributed by the fixed power, transceiver chains, signal processing for UL reception, DL transmission, and precoding computation are the same for all schemes. These four terms contribute as illustrated in Figure 2a and require a total of 47.23dBm, which is the majority of the total CP. The largest CP is required by transceiver chains, followed by the fixed power. The signal processing required for UL reception and DL transmission of data consumes around 28.8 dBm, while the smallest part is the computation of precoding vectors, roughly 7 dBm.

The breakdown of the CP required by the different processing schemes for channel estimation, computation of receive combining vectors, backhaul, and encoding/decoding is reported in Figure 2b. The CP consumed by intra-cell channel estimation is approximately 26dBm (440 mW) and independent of the processing scheme. The CP for computing the receive combining vectors depends on the scheme and the highest CP is required by M-MMSE, for which it is approximately 40dBm (10.96 W). Together with the consumed power by channel estimation, they account for 91% of the CP required by M-MMSE for performing the operations considered in Figure2b. A substantially lower CP would be required by M-MMSE with the EW-MMSE estimator, which reduces the computational complexity by 45%–90% by not exploiting the correlation between antenna elements.



(a)



(b)

Figure 3: Breakdown of the CP per cell when using the second set of values in Table 1 with M-MMSE, RZF or MR. A setup with K = 10 UEs and M = 100 BS antennas per cell is considered. Note that the vertical axis is in dBm.

Figure 3 shows the CP terms with Value set 2 in Table 1. Compared to Figure 2a, the CP common to all schemes (accounting for the fixed power, transceiver chains, and signal processing) is reduced by 50%. Computing the receive combining vectors with M-MMSE still represents the most power-consuming operation in Figure 3b, though in this case it requires only 30 dBm rather than 40 dBm, which corresponds to a 90% reduction. Quantitively speaking, the CP required for all the operations of Figure 3b is roughly 31 dBm with M-MMSE, 21.6 dBm with RZF, and 20 dBm with MR.

3. Tradeoff between Energy Efficiency and Throughput

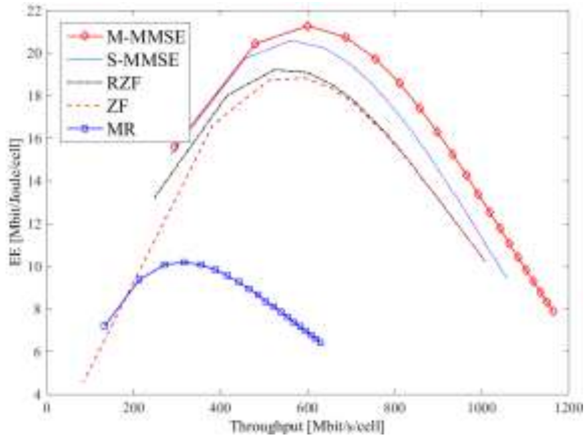
The tradeoff between EE and throughput, using the CP model introduced in the previous section and the two sets of CP values reported in Table1. Now we concentrate on the throughput of the Massive MIMO network to emphasize that one cannot carry out EE analysis without specifying the bandwidth . There are M antennas at each BS and K UEs in each cell. The values of M and K will be changed and specified in each figure. The pilot reuse factor is f = 1, such that each pilot sequence consists of τ_p = K samples. The number of samples per coherence block used for UL and DL are $\tau_u = 1/3\,(\tau_c - \tau_p)$ and $\tau_d = 2/3\,(\tau_c - \tau_p)$, respectively. We consider UL and DL transmit powers of 20dBm per UE (i.e., $p_{jk} = \rho_{jk}$ = 100 mW). The Gaussian local scattering with ASD $\sigma_\phi = 10^{\circ}$ is used as channel model.

$$EE_j = \frac{TR_j}{ETP_j + CP_j}$$

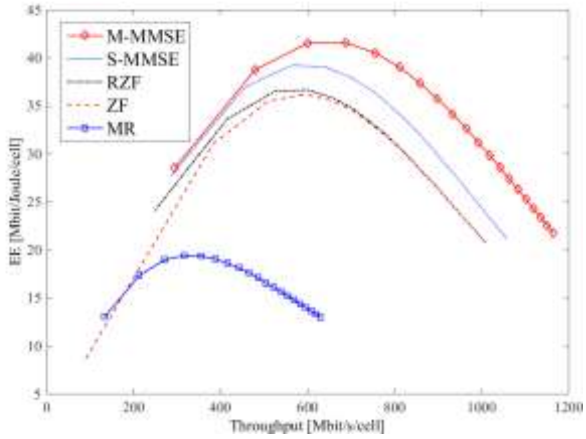
where ETP_j denotes the ETP of cell *j*. This term accounts for the power consumed by the transmission of the pilot sequences as well as of UL and DL signals:

$$EPT_j = \underbrace{\frac{\tau_p}{\tau_c}\sum_{k=1}^{K_j}\frac{1}{\mu_{UE,jk}}p_{jk}}_{EPT\ for\ pilots} + \underbrace{\frac{\tau_u}{\tau_c}\sum_{k=1}^{K_j}\frac{1}{\mu_{UE,jk}}p_{jk}}_{EPT\ in\ the\ UL} + \underbrace{\frac{1}{\mu_{BS,j}}\frac{\tau_d}{\tau_c}\sum_{k=1}^{K_j}p_{jk}}_{EPT\ in\ the\ DL}$$

where $\mu_{UE,jk}$ $(0 < \mu_{UE,jk} \leq 1)$ is the PA efficiency at UE k in cell j and $\mu_{BS,j}$ $(0 < \mu_{BS,j} \leq 1)$ is that of BS j. The EE and throughput tradeoff of different schemes will be compared with the assumption of $\mu_{UE,jk} = 0.4$ and $\mu_{BS,j} = 0.5$.



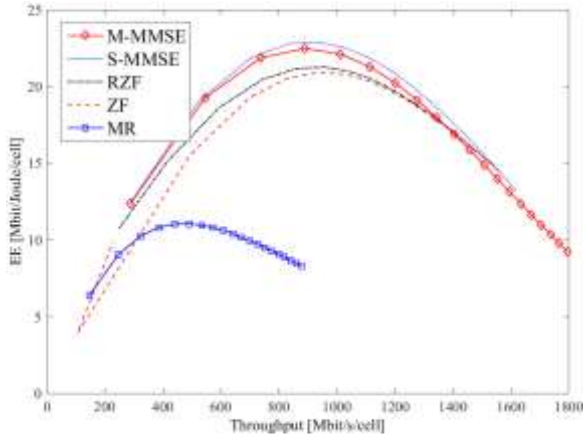
(a) K = 10 with the first set of values in Table 1



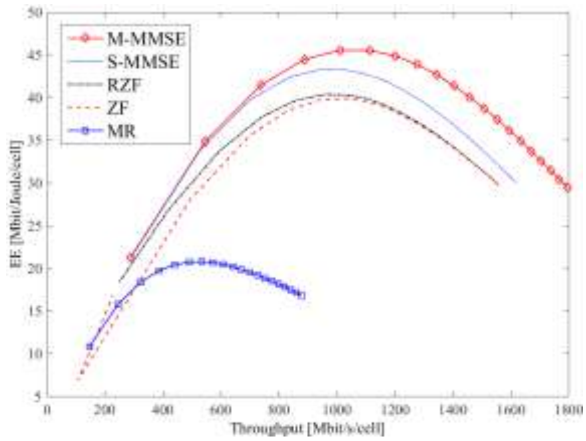
(b) K = 10 with the second set of values in Table 1

Figure 4: EE versus throughput. The hardware parameters are modeled as in Table1. The different values of throughput are achieved varying M from M = 10 to M = 200, in steps of 10.

Notice that all schemes allow to jointly increase the EE and throughput. M-MMSE provides the highest EE for any value of throughput. Figure 4 illustrates the EE as a function of the average throughput per cell with all processing schemes. The different throughput values are achieved with K = 10 UEs and by letting the number of BS antennas vary from M = 10 to M = 200, in steps of 10. The two sets in Table 1 are considered. We notice that the EE is a unimodal function of the throughput for all schemes and both sets of CP values. This implies that we can jointly increase the throughput and EE up to the maximum EE point, but further increases in throughput can only come at a loss in EE. The curves are quite smooth around the maximum EE point; thus, there is a variety of throughput values or, equivalently, numbers of BS antennas that provide nearly maximum EE. M-MMSE provides the highest EE for any value of the throughput, followed by S-MMSE. MR has the lowest performance. This shows that, in the considered setup, the additional computational complexity of M-MMSE processing pays off both in terms of SE and EE.



(a) K = 20 with the first set of CP values in Table 1



(b) K = 20 with the second set of CP values in Table 2

Figure 5: EE versus throughput . The hardware parameters are modeled as in 1. The different values of throughput are achieved by varying M from M = 20 to M = 200, in steps of 10.

Compared to results of Figure 4, we see that increasing K improves the EE of all schemes.

Scheme	EE, set 1	EE, set 2	Area throughput
M-MSE	20.73 Mbit/Joule	41.53 Mbit/Joule	11 Gbit/s/km^2
RZF	19.07 Mbit/Joule	36.63 Mbit/Joule	9.6 Gbit/s/km^2
MR	10.18 Mbit/Joule	19.38 Mbit/Joule	5.07 Gbit/s/km^2

a) ith K = 10 and M = 40 (the results are summarized from Figure 4)

b) With K = 20 and M = 60 (the results are summarized from Figure 5)

Table 3: Maximal EE per cell with the two sets of CP values in Table 1 for M-MMSE, RZF and MR.

Scheme	EE, set 1	EE, set 2	Area throughput
M-MMSE	21.27 Mbit/Joule	45.5 Mbit/Joule	17.82 Gbit/s/km^2
RZF	21.24 Mbit/Joule	40.35 Mbit/Joule	15.33Gbit/s/km^2
MR	11.04 Mbit/Joule	20.7 Mbit/Joule	7.84 Gbit/s/km^2

The corresponding area throughputs are also reported with S-MMSE, RZF, and ZF, and thus counteracts the SE gain of using M-MMSE. Different observations can be made for the second set of CP values as we can see from Figure 5b. In this case, the general trends are the same of Figure4, where M-MMSE provides the highest EE and throughput. Moreover, increasing the number of UEs per cell has a positive effect on the EE of all schemes, which is larger for any throughput value. Unlike with K = 10 in Figure 4b, wherein the maximal EE was achieved at M = 30 or 40, with K = 20 we see that M = 50 or 60 provides the highest EE. Table 3b summarizes the results of Figure 5 for M-MMSE, RZF, and MR with M = 60

4: CONCLUSIONS

1. Realistic CP models are needed to evaluate the PC for different numbers of antennas and UEs. The modeling complexity makes a certain level of idealization unavoidable, but a fairly accurate polynomial CP model was developed n to account for the dissipation in analog hardware, digital signal processing, backhaul signaling, and channel estimation. The model depends on a variety of fixed parameters that were kept generic in the analysis. Typical values are given in Table 1. The MR scheme has the lowest CP, while the interference suppressing schemes, such as RZF and M-MMSE, require higher CP.

2. Massive MIMO allows to jointly increase the EE and throughput, as compared to a system with few antennas. M-MMSE provides the highest EE for any throughput value only when more energy-efficient hardware is used. MR achieves the lowest EE. RZF provides a good tradeoff between EE and throughput.

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