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Massive MIMO: Achievable Energy Efficiency for 5G systems with Multi-user Environment

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***Abstract:** Massive Multi-Input and Multi-Output (MIMO) antenna system potentially provides a promising solution to improve energy efficiency (EE) for 5G wireless systems. The aim of this paper is to enhance EE and its limiting factors are explored. The maximum EE of 48 Mbit/Joule was achieved with 15 user terminal (UT)s. This problem is related to the uplink spectral efficiency with upper bound for future wireless networks. The maximal EE is obtained by optimizing a number of base station (BS) antennas, pilot reuse factor, and BSs density. We presented a power consumption model by deriving Shannon capacity calculations with closed-form expressions. The simulation result highlights the EE maximization with optimizing variables of circuit power consumption, hardware impairments, and path-loss exponent. Small cells achieve high EE and saturate to a constant value with BSs density. The MRC scheme achieves maximum EE of 36 Mbit/Joule with 12 UTs. The simulation results show that peak EE is obtained by deploying massive BS antennas, where the interference and pilot contamination are mitigated by coherent processing. The simulation results were implemented by using MATLAB 2018b.*

***Index Terms:** Base station, Channel state information. Energy efficiency, Multi input and multi output, Spectral efficiency,.*

I. INTRODUCTION

Future wireless networks demand high-speed data in a dense urban environment under an interference scenario. Massive multi-input and multi-output (MIMO) is the fundamental solution to achieve high spectral efficiency (SE) and data rate by deploying more antennas at the base station (BS). To meet these requirements, the networks need to be developed with high energy efficient [1-3]. Since power consumption (PC) of the system greatly deals with economic and societal concerns. Massive MIMO has evolved substantially over the past few decades and has seen an accelerating trend of technical advances particularly in multi-user communication. The future information and communication technology (ICT) industry should require low PC to support high data rates. New methods and technologies must be designed to attain high energy efficiency (EE) in the fifth generation (5G) networks. Since a large number of Internet-of-Things (IoT) devices and host of inter-connected networks will co-exist on a single platform.

The critical challenge of a cellular network is to improve 1000× area throughput with an annual traffic growth rate of 41%-59% over the next 20 years [4]. The network load grows daily 3-10 times higher than the minimum network load reported in [5]. It is recommended to implement novel methods and technologies to be designed to minimize PC. To meet the requirements of urban high dense networks, small cells and massive MIMO are considered as the most promising technologies to achieve high SE and EE [6]. The first technology deploys hundreds of small dipole antennas and fits on the flat-television screen. In massive MIMO, array gain reduces transmit power by using coherent processing, where the multiplexing gain allows high area throughput. From the last decade, more research has done on EE perspective of a system, which is related to the cost-benefit ratio. The EE of a system is defined as the ratio of area SE to the transmit power plus circuit power as follows,

$$EE = \frac{ASE}{P_{tx} + p_c}$$

Massive MIMO combines with small cells also improve the area throughput but the combined technology increases hardware cost and complexity. The EE maximization has been achieved with UL EE by minimizing [7] the superimposed pilot signals in the DL. Realistic circuit PC and path loss models were proposed [8] to achieve maximal EE. By operating power amplifiers towards saturation region and reducing the peak to average power ratio also improve the EE. The SE and EE are improved by optimizing cell density and frequency spectrum [9]. Optimization of pilot signals also improves the EE [10] with the predefined quality of service and total power budget. Reference signal power control [11] plays an important role to maximize the EE in the UL massive MIMO systems. Scaling laws of EE is analyzed [12] with large BS antennas, and spatial channel correlation. Reducing interference [13] is more effective to gain maximum EE by using spatially dynamic power control in device-to-device networks. Deploying large BS antennas by using scalable optimal power transfer efficiency model was proposed [14] to improve the EE. The optimization of EE is achieved without knowledge of circuit PC [15] by large BS antennas. The EE is an increasing function of the number of BS antennas and UTs in the DL massive MIMO [16]. These works do not provide how EE is influenced by BS antennas and UTs. Similar simulation results were demonstrated for the optimal BS antennas and UTs [17] for UL, similarly [18] also derived for the UL and DL.

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These results report the optimization of the hardware parameters for the realistic PC model, where the EE changes non-linearly with simulation parameters. In this paper, we mainly focused on the optimization of EE in the UL perspective.

A.Problem formulation

The main contribution of this work is summarized as follows, The EE is achieved by using more number of BS antennas. We also demonstrated the limitations and challenges to achieve optimized EE. The EE increases exponentially with BS antennas and the maximum number of UTs. We mainly demonstrated the impact of circuit PC on EE by analyzing the parameters as transceiver chains, coding/decoding, signal processing. Hardware-impairments increase with the number of BS antennas.This research paper was structured as follows, the proposed massive MIMO system model demonstrated in Section 2. The optimization of the EE was presented with UL in section 3. The Simulation results were compared with the EE versus BS antennas and UTs in section. 4. Finally, the conclusion is presented. Here, $[.]^T$ and E {.} represent transpose and expectation.

II. PROPOSED SYSTEM MODEL

In this section, the proposed UL cellular system model is presented in fig.1. Here, the UTs are distributed with Poisson point process (PPP) in the urban dense heterogeneous network. Similarly, the BSs also scattered as PPP per unit area with density β.

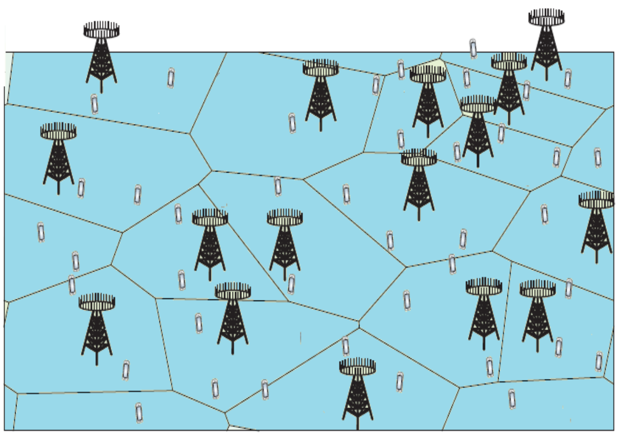

Fig.1 Proposed cellular system model

A. Channel Model

The UT in the cell is denoted by k, which is connected to the BS by using Rayleigh distributed presented [19] under a non-line-of-sight environment. We consider each UT k is connected to the BS i in a cell n is represented as h_{nik}.

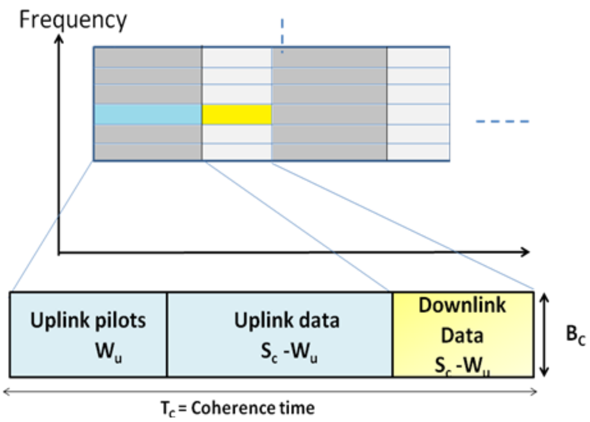

Fig.2 Proposed frame structure

Here, the proposed frame model is shown in Fig.2. In each frame, time-frequency resources are arranged into blocks. Here, each block is designed with coherence time T_c Seconds and coherence bandwidth and B_c Hz. The total transmitting symbols per frame is presented by $T_s = T_c B_c$. Where B_c is very small compared with coherence bandwidth of UTs. Where L_c denotes a coherence block length and W_u number of pilot symbols. The channel assumed as constant over T_c. The channel response between UT k, and the BS i in a cell $n \in N$ is presented by

$$h_{nik} \cong CN(0, z^{-1} d_{nik}^{-\frac{\alpha}{2}} I_M) \qquad (1)$$

Where $h_{nik} \in C^N$ is distributed as Rayleigh with non-line-of-sight propagation. Where I_M denotes the identity matrix with size $M \times M$ and α represents pathloss exponent. Here, d_{nik} denotes the distance between the BS and UT. The DL is estimated with received CSI in the UL by using channel reciprocity. Here, z defines the path loss at a distance of 1 km. This distance accounts as the reference model to estimate the channel path loss independently based on propagation distance. Power control provides a promising solution in the UL channel estimation of massive MIMO systems. It is essential to avoid the impact of near-far blockage, where the strong signals from the nearby UTs interfere with weak signals far from the BS. The power transmitted from the UT k to cell n is given by

$$p_{nk} = \rho z d_{nk}^{-\alpha} \qquad (2)$$

Here, $\rho \geq 0$ is a power control parameter and d_{nk} denotes the distance from UT k to the cell n .The mean value of transmitted power at the UT k in a cell n is given by

$$E\{p_{nk}\} = \rho z E\{d_{nk}^{-\alpha}\} = \rho z \frac{\Gamma(\frac{\alpha}{2}+1)}{\pi\beta^{\frac{\alpha}{2}}} \qquad (3)$$

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B. Channel Estimation

The channel acquisition needs knowledge of CSI in the UL by using coherent processing. In order to estimate the channel, W_u out of L_c symbols were assigned for pilot signaling, where the remaining were used for data. These pilot symbols were shared among the cells with pilot reuse pattern $\lambda = \frac{W_u}{K} \geq 1$. This leaves to design the system with $\lambda K = W_u \leq L_c$. Since the pilot reuse pattern designed with $\frac{K}{W_u}$ and, $K \leq W_u$. This means that increasing of pilot symbols reduces the effective utilization of SE. The received signal at the BS is presented as

$$Y_0 = \sum_{i=1}^{K} \sum_{j=1}^{N} \sqrt{P_{ij}} [\sqrt{1-\varepsilon^2} S_{ij} + e_{ij}] h_{ij} + \sum_{i=1}^{K} \sum_{l}^{N} \sqrt{P_{li}} [\sqrt{1-\varepsilon^2} S_{li} + e_{li}] h_{lij} + n_0 \quad (4)$$

Here, $\sqrt{1-\varepsilon^2}$ factor denotes distortion of desired signal power with range $0 \leq \varepsilon < 1$. where e_{ij} denotes UL distortion noise and n_0 account noise at the receiver with variance σ^2.

III. ENERGY EFFICIENCY OPTIMIZATION

The optimization of the EE can be obtained by the SE and power consumption of hardware parameters. The SE defined as the number of bits /Sec/Hz. We consider maximum ratio combining (MRC) at the BS in the UL. It is well suited for small cells and massive MIMO networks. The signal received at the BS with MRC is given by

$$\vartheta \log_2 (1+\gamma) \quad (5)$$

Where $\vartheta = \left(1 - \frac{\lambda K}{W_u}\right)$ denotes the pilot overhead and γ is a signal to interference plus noise ratio (SINR).

The ergodic capacity can be calculated by taking the mean value of Eq. (5) with locations of UTs and BS density. The lower bound SE by using Minimum mean square estimation (MMSE) is given as

$$\overline{SE} = \vartheta \log_2 (1+\bar{\gamma}) \quad (6)$$

Where $\bar{\gamma}$ represents an average SINR. Here, the average SINR is scaled by factor M. Since the array gain increases with coherent processing , and M.

A. SE and EE Formulation

We consider the EE in the UL with SE and PC per unit area (Joule/symbol/km^2). The SE per unit area (Bit/Hz/km^2) is presented as follows,

$$SE/area = \beta K \, \overline{SE} \quad (7)$$

To meet the specifications of PC per unit area, we concentrate on the transmitted power at the UT with power control policy as,

$$\frac{w_u - (\lambda K - 1)}{w_u} E\{p_{nk}\} = (1-\vartheta)\rho z \frac{\Gamma\left(\frac{\alpha}{2}+1\right)}{\pi \beta^{\frac{\alpha}{2}}} \quad (8)$$

Each UT requires one pilot symbol $w_u - \lambda K$ symbols in the coherence block for transmission. The PC per unit area not only depends on the transmitted power but also power utilization in signal processing, hardware, backhaul signaling. We calculated the other overhead parameters such as PC due to supply losses and cooling. Recent works highlight the detailed models that account all the factors related to the area PC. We considered the total PC is the contribution of radiated power, static PC, BS transceiver chain, PC due to signal processing and UT. The PC per unit area was given as follows,

$$PC/area = \overbrace{\beta(1-\vartheta)\frac{\rho z}{\eta} E\{p_{nk}\} K}^{radiated\ power} + \overbrace{A_0}^{stastic\ PC} + \overbrace{A_1 K + C_1 M K}^{signal\ processing\ PC\ and\ UT} + \overbrace{C_0 M}^{BS\ tranceiver\ PC} + \overbrace{D.SE/area}^{area\ SE\ with\ constant} \quad (9)$$

Where η denotes the efficiency of the power amplifier. The constant D in Eq. (9) represents the PC in the coding and decoding process, which is proportional to the number of bits in the coding process. We consider the hardware parameters and desired frame length to obtain the optimized parameters. The maximization of EE constraint to maximum $\bar{\gamma}$ was expressed as follows,

$$EE(\vartheta) = \left(\frac{SE(\vartheta)}{PC(\vartheta)}\right) \quad (10)$$

Where $\vartheta = (\lambda, \beta, M, K,)$

To achieve high SE, there is a constraint on $\bar{\gamma}$. Since $\bar{\gamma}$ is increased by decreasing the EE.

B. Optimization of BS antennas and UTs

An alternating optimization algorithm is presented [20] with PC and hardware parameters that account the optimization parameters**.** We consider a Novel alternating optimization algorithm to achieve desired performance and increase the EE asymptotically in each iteration. It converges to achieve maximal EE with hardware PC and propagation parameters. This algorithm well performed and guaranteed for local and global maximum. The novel alternating optimization was presented with stepwise as follows,

Novel alternating optimization algorithm

Step.1 Start
Step.2 Initialize hardware parameters
Step.3 Find the optimum M and K
Step.4 Find the optimum M for fixed K
Step.5 Find the optimum K for fixed value M
Step.6 Repeat step 4 and step5 to achieve global maximum
Step.7 End

It can be considered as a quasi-concave function with a global maximum. The objective of this alternating algorithm is to select desired M and K. It also explains how PC of hardware parameters affects the EE. It reveals that K increases with A_0 and decreases with A_1, C_0 , and C_1. Whereas, M decreases with C_0 and C_1, but increases with A_0 and A_1.

It turns out that the BS antennas and UTs must be turned on. Since the scaling of hardware parameters increases the total PC per unit area.

To summarize, maximization of EE problem in Eq. (10) has been obtained by using the following steps

a) Select the pilot reuse factor λ to meet average SINR constraint.

b) Consider the BS density $\beta \to \infty$, and $\gamma \to 0$.

c) To maximize the EE use the alternating optimization algorithm that generates optimized M and K.

d) Finally, obtain the optimized solution with real values, which satisfy the maximal EE problem. The optimization of EE deals with achieving maximal EE with circuit PC parameters and propagation characteristics.

IV. SIMULATION RESULTS AND DISCUSSION

Table I. Simulation parameters

S.No	Parameters	Value
1	Coherence bloclk length	500
2	Path-loss exponent	3.8
3	Power amplifier efficiency	0.4
4	Propagation loss at (1 KM)	131 DB
5	Symbol time	$\frac{1}{10^8}$[S/symbol]
6	Power Coding/decoding	1.12×10^{-9} [Joule/Bit]
7	Stastic PC	10 W
8	Circuit PC per UT	0.05 W
9	Circuit PC per BS antenna	0.25 W
10	PC per signal processing	1.5×10^{-10} W
11	Noise variance	10^{-21} W

In this section, the simulation results were presented with BS antennas and UTs. The simulation parameters were reported in Table.1 and similar parameters presented in [21]. The simulation results validate the EE expressions demonstrated in section. III. We mainly highlight how EE changes with the number of BS antennas and UTs. The simulation parameters are obtained with a bandwidth of 100 MHz. Here, the coherence block length is assumed as S=500, (B_c=100 kHz and T_c= 5 ms) and path loss exponent γ =3.8.

The simulation results were presented and compared by using linear processing algorithms. We demonstrated the effect of increasing BS antennas and UTs on the EE. It validates from the section.III that the EE maximization problem is obtained when antennas at the BS tends to infinite, that is $M \to \infty$. The asymptotic results obtained by the application of large BS density. We described how large BS density needs to be varied to achieve the optimized EE. For each numerical value of M, the other simulation parameters were optimized. The payload data are encoded with 4 bits/symbol. The simulation results were presented by using the 64-quadrature amplitude modulation (QAM) with 3/4 code rate. The simulation parameters were performed using MATLAB 2018a. The transmitted power per user $P_u = 10$ dB for the UL channel estimation. We compared the simulation results with MRC and MMSE schemes. The EE optimization is achieved with massive BS antennas and UTs.The simulation results were performed by using an alternating optimization algorithm. The EE was explored in Fig.3 with MRC for a given UTs by varying the BS antennas. The EE is increasing with BS antennas and the number of UTs. The maximum EE of 35 Mbit/Joule was achieved with MRC scheme by using M=100 and K=10.

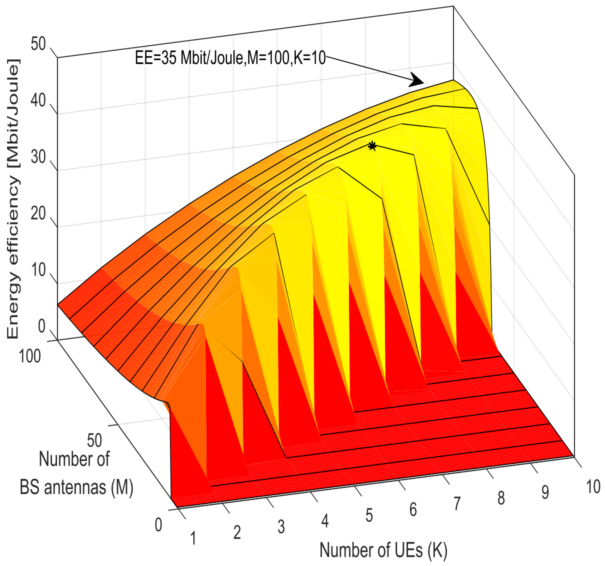

Fig.3. EE in (Mbit /Joule) Vs BS antennas and UTs with MRC

Fig.4 shows a pie diagram of the PC per unit area. It provides different power parameters with global optimum values in the PC model. Here, the transmitted power parameters are not included. Since transmit power is negligible, as compared to circuit PC. The major contribution of PC parameters is the BS transceiver chains C_0M and the static circuit power A_0. These parameters considered as the most dominating than the others to design the system hardware more spectral and energy efficient.

The simulation results can be changed with different values of PC parameters and power constraints of the hardware.

The circuit PC of 19% is achieved due to signal processing and UT. The BS transceiver PC is 42% of the total PC, which is slightly higher than static PC and area SE. Hence the static PC achieves 33 %, which is 9% less than BS transceiver PC.

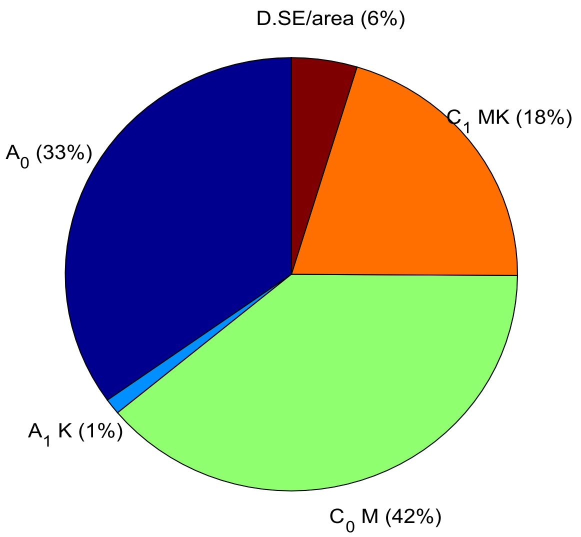

Fig.4. PC parameters per unit area with MRC

Finally, the PC of 6% is achieved by the SE per unit area. We noticed that the PC due to BS transceiver chains was observed with high value. Interestingly, the PC due to signal processing was identified with low value than the other parameters shown in Fig.4. The optimization of EE in Eq. (10) is demonstrated by using simulation results with Fig.5, and Fig.6. The major observations were obtained from the simulations in Fig.5.Firstly, it is noticed that EE is a function of the BS antennas. The EE is highly improved by increasing the BS density a large value; resulting in small cell densification is the potential solution to achieve maximal EE. However, the EE saturates to a constant value when M reaches a large value. The Fig.5 illustrates lower bound EE of 36 Mbit /Joule with MRC scheme, and (M, K) = (100, 12), which is considered as the global optimum value of the EE. We noticed the following observations from the simulation results. Firstly, the EE curve is flat at the global optimum regime. Secondly, the insight behind this result is that reduction of inter carrier interference (ICI) in urban dense deployments by reducing pilot contamination and channel estimation error. The ICI is mitigated with the MRC scheme. Since SE is highly decreased with large ICI. We noticed that the optimum EE was achieved with MRC scheme, which was designed with less computational complexity, and easy to implement the massive MIMO system. Fig.6 shows the upper bound EE with the alternating optimization algorithm. The starting point of the curve was (K, M) = (15, 100). This algorithm requires 4 iterations to converge and reaches to peak EE of 48 Mbit/Joule, which provides peak SE of 32.51 Gbit/s/km^2. The final real-valued solution is given by (K, M) = (15, 48). The EE curve is quite flat at the global optimum point, since it converges at the global maximum. It has been identified that the obtained EE is 10 Mbit/Joule higher than the results presented in [20]. Fig5 and Fig.6 were obtained from the Eq. (10) with optimization parameters. We considered three SINR constraints as $\gamma = \{3, 7, 15\}$. The EE is calculated in all three cases by using upper and lower bound SE analysis. It is observed that the EE curves provide substantially smoother surface when the EE reaches to the maximal value.

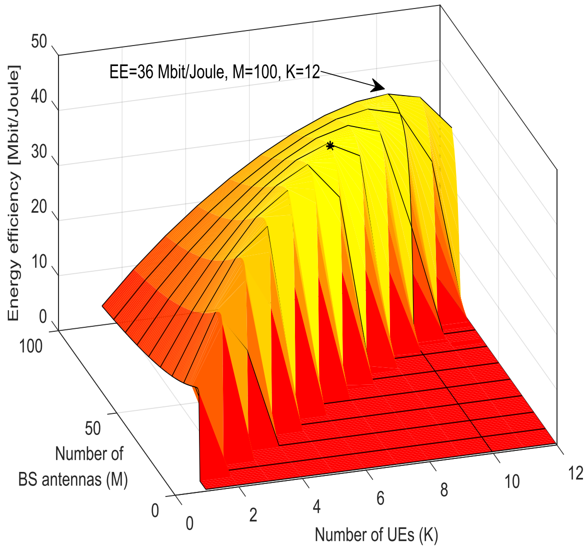

Fig.5. EE in (Mbit /Joule) Vs BS antennas and UTs with MRC

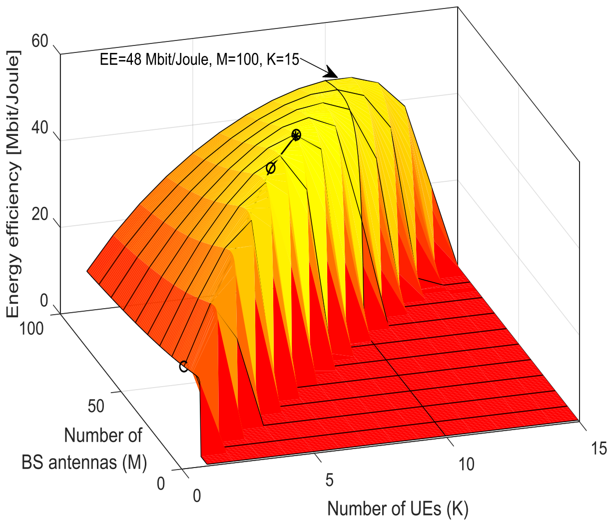

Fig.6. EE in (Mbit/Joule) Vs BS antennas and UTs with MMSE.

The simulation results were compared and summarized in Table. II by using MRC, and MMSE schemes. The MMSE scheme provides the EE of 48 Mbit/Joule, which is higher than the MRC method, since the reduction of circuit PC of the BS. It is also noticed that the MMSE achieves high SE of 32.51 Gbit/s/km^2 per unit area.

The MRC scheme is demonstrated with low EE of 35 Mbit/Joule, and SE of 23.68 Gbit/s/km^2, but it requires less computational complexity compared with MMSE. Since the circuit PC increases with large values of M and K in MMSE scheme.

Table II. Comparison of EEs

Scheme	Number of UT's with M=100	EE Bits/S/Hz	Proposed EE Mbit/Joule
MRC	12	3[24] 9.8[20] 12[22]	36
MMSE	15	1.3[23], 3.8[24], 36 [20],	48

We observe that the MMSE scheme can potentially increase both EE and SE per unit area when high energy efficient hardware is implemented in the massive MIMO system. The intuition behind these results is that the EE increases with BS antennas and UTs by using MMSE scheme. But, the MMSE requires more computational complexity, which multiplexes more UTs, and increases the network infrastructure. The simulation results also validate that the EE greatly decreases with increasing γ. It motivates the system should be designed with the desired SINR for a practical user perspective. Since the maximization of EE is spectrally inefficient without considering target SINR. Fig.7 illustrates how total PC is divided into different parts of the BS in the massive system. The BS contributes 60% of total PC, while the remaining 15% PC account by the core infrastructure and 25% for mobile switching equipment. The most prominent portion of the PC is contributed by the process of power amplification at the BS. But the array gain can reduce the PC by deploying with hundreds of BS antennas. The circuit PC of 23 % is contributed by the signal processing and UT. The BS transceiver PC accounts for 38% of the total PC, which is slightly higher than static PC and area SE. Hence the static PC obtains 35%, which is 3% less than BS transceiver PC. Finally, the PC due to SE per unit area achieves only 4% of total PC. We observed that the PC of BS transceiver chains was identified with high value. But, the PC the signal processing was with low value than the other PC parameters shown in Fig.7.The BSs were deployed to serve more UTs distribution to achieve maximal EE.

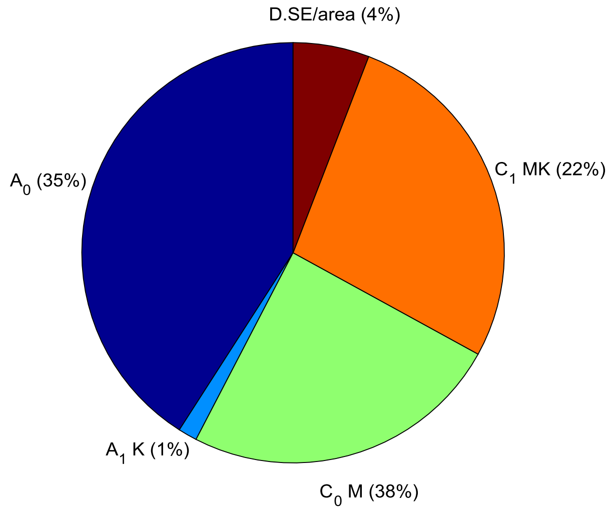

Fig.7. PC parameters per unit area with MMSE

A. Maximization of EE with UT

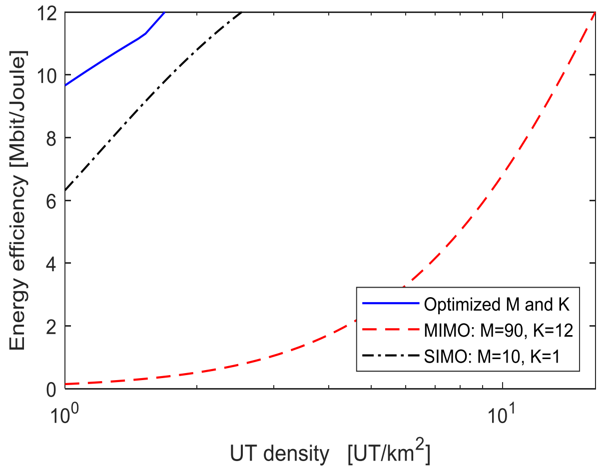

Fig.8. Energy efficiency Vs UT density

We implemented the proposed system to support K UTs in each BS. The average UT defines the number of UTs is $K\beta$ per km^2. Hence the average BS density is equal to β. It reveals that the increasing BS density also serving many UTs per km^2. The UT density is calculated numerically as follows,

$$\delta = K\beta \qquad (11)$$

It is being a function of BS density and product of K times β. Several prominent results have been observed from METIS project [25] for future wireless networks. Firstly, the UT density is ranging from $\delta = 100$ (for rural area) and $\delta = 10^5$ (in a high dense urban area). This range might be changed for different values of BS density. Secondly, we noticed some important observations that the EE of BS is changing with UT density is shown in Fig.8. Here, the curves were simulated with target SINR γ =3.

The following important observations were taken into consideration from Fig.9. Firstly, the system parameters such as M, K, β, λ, and γ with the UT density. Secondly, the EE is not depending on UT density for a large value of δ.

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Since the EE reaches into saturation when δ is large. It reveals that the value of $\delta \geq 2$ for SIMO, and $\delta \geq 100$ for fixed massive MIMO presented in [25]. It is identified that the UT density linearly varies with BS density when the BS antennas are equal to the UT density. It motivates to turn on and off the BS to minimize the PC. It is observed that the maximum EE is achieved for fixed massive MIMO when the BS antennas and UT configuration given by (M, K) = (90, 12).

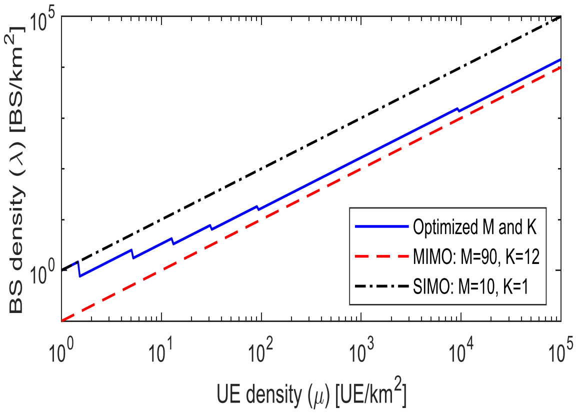

Fig.9. BS density Vs UT density

V. CONCLUSION

Small cells and network densification were the promising solutions to improve the EE of the massive MIMO system. To achieve high EE, cell densification was proposed by deploying many BSs antennas and distributed as a Poisson point process. We derived closed-form solution and tractable Shannon SE expressions with lower bound for PC in the network. The maximization of EE was observed as a function of the density of BSs, pilot re-use factor, and network densification. This problem is related to the uplink SE with upper bound for future wireless networks. The optimization of variables presented with closed-form expressions. The simulation results were demonstrated for only UL by using channel reciprocity. The DL was estimated due to the duality nature of DL/UL. The peak EE was achieved by using cell densification and small cells. We noticed that the transmitted power was negligible compared with the circuit PC. The maximum EE of 48 Mbit/Joule was achieved with MMSE scheme and 15 UTs. The MRC achieves maximum EE of 36 Mbit/Joule with 12 UTs. We observed that the MMSE scheme outperforms than the MRC method by comparing the EEs. The circuit power highly dominates, as compared to the transmission power, for wireless networks that deploy with high UT densities. The EE can be improved by integrating the BSs with massive multi-user MIMO. By improving the EE to an optimized value, leads to provide substantial gain to future networks, it is likely reducing the BS density.

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