Energy Efficiency Comparison of Massive MIMO and Small Cell Network

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***Abstract*—In this paper, we compare the average energy efficiency (EE) of massive MIMO system and small cell network (SCN) under the conditions of identical user density, antenna density and data rate requirements, where the uplink and downlink training overhead as well as multi-cell power control are taken into account. Our analysis shows that the average transmit power of SCN decreases faster than massive MIMO as the antenna density increases. Moreover, massive MIMO achieves a higher average EE than SCN if its power consumption except the power for transmitting data is very low or the data rate requirement is very high. Considering that in SCN with large number of base stations (BSs) the opportunity for turning some BSs into idle mode is higher, massive MIMO exhibits higher EE only if its circuit power of each active antenna is lower than that for each antenna at an idle small BS. If antenna idling is allowed for massive MIMO, massive MIMO will be more energy efficient than SCN when the former has smaller circuit power for each idling antenna.**

***Index Terms*—Energy efficiency, massive MIMO, small cell network, training overhead.**

I. Introduction

Massive multiple-input multiple-output (MIMO) and small cell network (SCN) are two promising technologies to support the explosively increasing data traffic in 5G systems, which are commonly believed to be able to provide both high spectral efficiency (SE) and energy efficiency (EE) [1, 2].

There exist many valuable works analyzing the EE of massive MIMO and SCN recently. The EE of SCN was analyzed in [3], which shows that increasing the base station (BS) density will improve the EE only when the circuit power consumption is less than a certain threshold. The analytical results are concise and explicit, but the BS was assumed always transmitting with its maximum power [3], which is not necessarily optimal in terms of EE. The SE-EE relationship of massive MIMO was analyzed in [4], where the impact of circuit power on the SE-EE relationship was shown with closed-form expressions, but only single-cell scenarios without inter-cell interference (ICI) were considered.

In a multi-cell cellular network, the analysis of EE for the two technologies is rather involved, due to the complicated impact of ICI and multi-cell power control on EE. As a first attempt, we compared the multi-cell EE of the two technologies via simulations in [5]. In general, SCN enjoys more opportunities for BS idling, which increases SE and EE via reduced ICI and circuit power, respectively. However, compared to massive MIMO, smaller array gain in SCN leads to a higher transmit power, leading to degraded SE and EE. On the other hand, SCN brings users closer to BSs and results in smaller path loss, which increases the SE and EE via reduced transmit power. On the contrary, massive MIMO has less opportunities for BS idling, but with larger array gain and severer path loss. When training overhead is considered, the time-frequency resources for data transmission are less for massive MIMO than SCN, because in massive MIMO a BS serves more users. In this paper, we strive to analyze and compare the EE of the two technologies. For a fair comparison, we consider identical antenna and user density in a multi-cell network. Given zero-forcing beamforming (ZFBF) and dynamic power control, we analyze the average transmit power and EE, and compare the average EEs of massive MIMO and SCN under different configurations that satisfy different data rate requirements from the users.

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II. System and Power Consumption Models

A. System Model

Consider a downlink multi-cell network consisting of N_M non-coordiated hexagonal macro cells, covering an area $\mathcal{A}$ with radius D_0. To model massive MIMO and SCN in a unified framework, we define N, K, M and D as the number of BSs in a macro cell, the numbers of users and antennas in a cell, and the cell radius, respectively. For massive MIMO, M_0 antennas are co-located at a macro BS (MBS), which serves K_0 users uniformly located in a macro cell with radius $D_M \triangleq \frac{D_0}{\sqrt{N_M}}$, i.e., the area $\mathcal{A}$ includes N_M macro cells, i.e., N=1, K=K_0, M=M_0, and D=D_M. For SCN, M_0 antennas in a macro cell are distributedly deployed in N_S hexagonal small cells each with radius $D_S \triangleq \frac{D_M}{\sqrt{N_S}}$, and K_0 users are served by their closest small BSs (SBSs), i.e., N=N_S, K is random and $0 \leq K \leq K_0$, M=$\frac{M_0}{N_S} \triangleq M_S$, and D=D_S.

We consider a time-division duplexing (TDD) system, where uplink channel estimation is assumed perfect without pilot contamination and used for computing downlink precoding based on channel reciprocity. A block Rayleigh fading channel is considered, where channels are constant within a time-frequency coherence block. T channel uses in a coherence block are split into three phases. The uplink training phase occupies KT_u channel uses, in which K users send orthogonal uplink training signals each with T_u channel uses. The downlink training phase occupies T_d channel uses, in which the BS broadcasts the training signal to assist the users to estimate the precoded equivalent downlink channels. The remaining $T - KT_u - T_d$ channel uses are employed in the downlink data transmission phase. Note that massive MIMO has larger training overhead than SCN because a MBS usually serves more users than a SBS, which leads to higher uplink training overhead.

Suppose that all users are served in the same time-frequency resources and the interference outside $\mathcal{A}$ can be neglected. The received signal of UE_k served by BS_b can be expressed as

$$y_{bk} = \sum\nolimits_{i=1}^{N_M N} \sum\nolimits_{j=1}^{K_i} \sqrt{p_{ij} r_{ibk}^{-\alpha}} \frac{\mathbf{h}_{ibk}^H \mathbf{w}_{ij}}{||\mathbf{w}_{ij}||} x_{ij} + n_{bk},$$

where α is the path-loss exponent, r_{ibk} and $\mathbf{h}_{ibk} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_M)$ are the distance and channel vector from BS_i to UE_k that is served by BS_b, $\mathcal{CN}(\mathbf{m}, \mathbf{\Sigma})$ denotes the complex Gaussian distribution with mean $\mathbf{m}$ and covariance matrix $\mathbf{\Sigma}$, p_{ij}, $\mathbf{w}_{ij}$ and $x_{ij} \sim \mathcal{CN}(0,1)$ are the transmit power, precoding vector and data symbol from BS_i to UE_j served by BS_i, K_i is the number of users served by BS_i, and $n_{bk} \sim \mathcal{CN}(0, \sigma^2)$ is the white Gaussian noise at UE_k.

We assume that all users require the same data rate, R_u, which can be satisfied by controlling transmit power as follows

$$B \log_2 \left(1 + \frac{p_{bk} r_{bbk}^{-\alpha} \left| \frac{\mathbf{h}_{bbk}^H \mathbf{w}_{bk}}{||\mathbf{w}_{bk}||} \right|^2}{\sum_{i=1, i\neq b}^{N_M N} \sum_{j=1}^{K_i} p_{ij} r_{ibk}^{-\alpha} \left| \frac{\mathbf{h}_{ibk}^H \mathbf{w}_{ij}}{||\mathbf{w}_{ij}||} \right|^2 + \sigma^2} \right) = R_u, \quad (1)$$

where B is the system bandwidth.

B. Power Consumption Model and Energy Efficiency

Apart from the transmit power to satisfy the data rate requirements given in (1), the hardware components at the BS to support transmission also consume nonnegligible power. Based on [6] and [7], the power consumption model at the BS for both massive MIMO and SCN can be expressed as

$$P_{sum} = \rho(P_{Tt} + P_{Td}) + M P_{sp}(K) + M P_{ca}, \quad (2)$$

where $P_{Tt} = \frac{T_d P_{max}}{T}$ and $P_{Td} = \frac{(T - KT_u - T_d) P_{tx}}{T}$ respectively denote the transmit power of the BS at downlink training and data transmission phases, P_{max} and P_{tx} are respectively the maximum transmit power and total power for transmitting data to multiple users, ρ is the reciprocal of power amplifier efficiency, P_{ca} is the circuit power at each active antenna, $P_{sp}(K) = \frac{B}{T \eta_C}(KT_u \log_2(KT_u) + 2(T - KT_u)K + (K + K^2))$ is the power for channel estimation and precoding, and η_C is the power efficiency of computing measured in flops/W.

When a BS has no users to serve, the BS is turned into idle mode and the power consumption becomes $P_{sum} = M P_{ci}$, where P_{ci} is the circuit power for each idle antenna. Then, the average EE per BS can be expressed as

$$\overline{\mathrm{EE}} = \frac{\frac{T - \overline{K}_a T_u - T_d}{T} \overline{K} \cdot R_u}{\mathrm{Pr}_a(\rho(P_{Tt} + \overline{P}_{Td}) + M(\overline{P}_{sp} + P_{ca})) + (1 - \mathrm{Pr}_a) M P_{ci}}, \quad (3)$$

where $\overline{K}$ and $\overline{K}_a$ are respectively the average number of users in a cell and in an active cell, Pr_a is the probability of a BS being active, $\overline{P}_{Td}$ is the average transmit power of an active BS taken over small-scale, large-scale channels and the number of users K, and $\overline{P}_{sp}$ is the average value of $P_{sp}(K)$ taken over K. Because the probability of all users locating outside a cell, i.e., a BS being idle, is $\left(\frac{N-1}{N}\right)^{K_0}$, we have $\mathrm{Pr}_a = 1 - \left(\frac{N-1}{N}\right)^{K_0}$. For massive MIMO, we have $\mathrm{Pr}_a = 1$ with $N = 1$.

III. Average Energy Efficiency Analysis

In this section, we first analyze the average transmit power $\overline{P}_{Td}$, then compare the average EE of massive MIMO and SCN, and finally investigate the EE of massive MIMO when antenna idling is allowed.

A. Average Transmit Power Analysis

We consider dynamic power control among multiple cells to satisfy the data rate requirement of every user. From (1), the average transmit power can be derived as

$$\begin{aligned}\mathbb{E}_{r,\mathbf{h}}\{p_{bk}\} &= \gamma_0 \left(\mathbb{E}\left\{ \sum_{i=1, i\neq b}^{N_M N} \sum_{j=1}^{K_i} p_{ij} r_{ibk}^{-\alpha} g_{ijbk} \right\} + \sigma^2 \right) \mathbb{E}\left\{ \frac{r_{bbk}^{\alpha}}{g_{bk}} \right\} \\ &\triangleq \gamma_0 \left(\bar{p} \cdot \bar{I} + \sigma^2 \right) \overline{S^{-1}}, \end{aligned} \quad (4)$$

where $g_{ijbk} \triangleq \left| \frac{\mathbf{h}_{ibk}^H \mathbf{w}_{ij}}{||\mathbf{w}_{ij}||} \right|^2$ and $g_{bk} \triangleq \left| \frac{\mathbf{h}_{bbk}^H \mathbf{w}_{bk}}{||\mathbf{w}_{bk}||} \right|^2$ are respectively the gains of the equivalent interfering and desired channels, $\gamma_0 = 2^{\frac{R_u}{B}} - 1$ is the required signal-to-interference plus noise ratio (SINR), $\bar{p}$ is the average transmit power of interfering BSs to a user, $\bar{I} \triangleq \mathbb{E}\left\{ \sum_{i=1, i\neq b}^{N_M N} r_{ibk}^{-\alpha} \sum_{j=1}^{K_i} g_{ijbk} \right\}$ denotes the average ICI normalized by transmit power, and $\overline{S^{-1}} \triangleq \mathbb{E}\left\{ \frac{r_{bbk}^{\alpha}}{g_{bk}} \right\}$ is the expectation of the reciprocal of the signal power.

Remark 1: When the data rate requirements are different for multiple users, the average transmit power in (4) becomes $\mathbb{E}\{p_{bk}\} = \mathbb{E}\{\gamma_0\}(\bar{p}\bar{I} + \sigma^2)\overline{S^{-1}}$, which will not affect the subsequent conclusions.

As shown in [2], $\mathbf{h}_{ibk}$ is independent from $\mathbf{w}_{ij}$, and the equivalent interfering channel gain $g_{ijbk} \sim \exp(1)$ for $i \neq b$ with $\exp(1)$ denoting the exponential distribution with unit mean. Then, the normalized average ICI can be derived as

$$\bar{I} = \mathbb{E}_{r,\mathbf{h}} \left\{ \sum_{i=1, i\neq b}^{N_M N} r_{ibk}^{-\alpha} \sum_{j=1}^{K_i} g_{ijbk} \right\} = (N_M K_0 - K) D^{-\alpha} I(L), \quad (5)$$

where $I(L) \triangleq \frac{2}{\pi(L^2+L)} \sum_{n=1}^{L} n \int_{(2n-1)^2}^{(2n+1)^2} x^{-\frac{\alpha}{2}} \arccos\left(\frac{4n^2-1}{4n\sqrt{x}} + \frac{\sqrt{x}}{4n}\right) dx$, $L = \lceil \frac{\sqrt{N_M N} - 1}{2} \rceil$ represents the number of rings of interfering BSs in $\mathcal{A}$, and $\lceil \cdot \rceil$ is the ceiling function.

Similarly, we can derive $\overline{S^{-1}}$ as

$$\overline{S^{-1}} = \mathbb{E}_{r,\mathbf{h}} \left\{ \frac{r_{bbk}^{\alpha}}{g_{bk}} \right\} = \frac{D^{\alpha}}{(1 + \frac{\alpha}{2})(M - K)}, \quad (6)$$

where $\mathbb{E}_{\mathbf{h}}\{\frac{1}{g_{bk}}\} = \frac{1}{M-K}$ [2]. Due to space limitation, the detailed derivations for (5) and (6) are omitted.

Since all BSs in massive MIMO or SCN have the same antenna configuration and circuit power, all users are uniformly distributed and require the same data rate, and all the channels are identically and independently distributed, the power consumptions of all BSs are statistically identical. Therefore, the average transmit power in (4) is the same as the average transmit power of interfering BSs to a user, $\bar{p}$. According to (2) and (4), the average total transmit power can be derived as

$$P_{Td}(K,M)=\frac{(T-KT_u-T_d)}{T}K\overline{p}(K,M)=\frac{(T-KT_u-T_d)K\sigma^2}{T((\gamma_0\overline{S^{-1}})^{-1}-\bar{I})}$$
$$=\frac{(T-KT_u-T_d)K\sigma^2D^\alpha}{T((M-K)\frac{1+\frac{\alpha}{2}}{\gamma_0}-(N_MK_0-K)a(N))}, \quad (7)$$

where $a(N)=I(\lceil\frac{\sqrt{N_MN}-1}{2}\rceil)$ and $I(\cdot)$ is defined in (5).

For typical scenarios, the number of antennas at the MBS or the number of SBSs in a macro cell are very large, i.e., the antenna density is high. Therefore, in the following we analyze the asymptotic EE when $M_0, N_S \to \infty$ and $M_S = \frac{M_0}{N_S}$ is a constant. When N_S is large, the number of users in an active small cell approaches one. According to (7), the asymptotic average total transmit power in massive MIMO, $\overline{P}_M$, and in SCN, $\overline{P}_S$, can be obtained as

$$\lim_{M_0\to\infty}\overline{P}_M=\lim_{N_S\to\infty}\frac{(T-K_0T_u-T_d)K_0\sigma^2D_M^\alpha}{T((N_SM_S-K_0)\frac{1+\frac{\alpha}{2}}{\gamma_0}-(N_M-1)K_0a(1))}=0,$$

$$\lim_{N_S\to\infty}\overline{P}_S=\lim_{N_S\to\infty}\frac{(T-T_u-T_d)\sigma^2D_M^\alpha}{T(N_S^{\frac{\alpha}{2}}((M_S-1)\frac{1+\frac{\alpha}{2}}{\gamma_0}-(N_MK_0-1)a(N_S)))}=0,$$

where $a(N_S)$ is a decreasing function of N_S. The results indicate that the average transmit power reduces to zero eventually, and power of SCN decays faster with the growth of antenna density than massive MIMO systems when $\alpha \geq 2$.

Observation 1: For the same antenna density, SCN is more efficient in reducing the transmit power than massive MIMO.

B. Average Energy Efficiency Analysis

For massive MIMO, $K = K_0$ is a constant, then the average EE can be obtained from (7) and (3) as

$$\overline{\text{EE}}_M = \frac{\frac{T-K_0T_u-T_d}{T}K_0R_u}{\rho P_{Td}(K_0,M_0)+P_{0,M}}, \quad (8)$$

where $P_{0,M}\triangleq\rho\frac{T_dP_{max,M}}{T}+M_0(P_{sp}(K_0)+P_{ca,M})$ is the power consumption independent with the data rate requirements.

For SCN, the number of users in a small cell, K, is random, which leads to both random transmit and circuit powers. Therefore, to obtain the average EE from (3), we need to compute the average power $\overline{P}_{Td}$ and $\overline{P}_{sp}$. To this end, we first compute the average number of users in a small cell and in an active small cell as $\overline{K} = \frac{K_0}{N_S}$ and $\overline{K}_a = \frac{\overline{K}}{\text{Pr}_a}$, respectively. Then we approximate $\overline{P}_{sp} \approx P_{sp}(\overline{K}_a)$ and $\overline{P}_{Td} \approx P_{Td}(\overline{K}_a, M_S)$. Finally, the average EE in SCN can be expressed as

$$\overline{\text{EE}}_S = \frac{\frac{T-\overline{K}_aT_u-T_d}{T}\frac{K_0}{N_S}R_u}{\text{Pr}_a\rho P_{Td}(\overline{K}_a,M_S)+P_{0,S}}, \quad (9)$$

where $P_{0,S} \triangleq \text{Pr}_a(\rho\frac{T_dP_{max,S}}{T}+M_S(P_{sp}(\overline{K}_a)+P_{ca,S}))+(1-\text{Pr}_a)M_SP_{ci,S}$ is the power consumption independent from data transmission.

Next, we analyze the EE gain of massive MIMO over SCN, which is defined as $\text{EG} = \frac{\overline{\text{EE}}_M}{\overline{\text{EE}}_S}$.

1) EE Gain versus Data Rate Requirement: According to (7), the average transmit power increases with the required SINR γ_0. Because $P_{Td}>0$ in (7), we have $\gamma_0<\frac{1}{\overline{S^{-1}}\cdot\bar{I}}\triangleq\gamma_{max}$, where the maximum SINR γ_{max} for massive MIMO and SCN are respectively $\gamma_{max,M}$ and $\gamma_{max,S}$. It can be proved that the ratio $\frac{\gamma_{max,M}}{\gamma_{max,S}}$ is an increasing function with N_S and $\frac{\gamma_{max,M}}{\gamma_{max,S}}=1$ when $N_S=1$. Then, $\frac{\gamma_{max,M}}{\gamma_{max,S}}\geq 1$ holds for $N_S \geq 1$, i.e., the maximum achievable data rate of massive MIMO is higher than SCN.

When R_u approaches the maximum achievable rate of SCN, $R_{max,S}$, the EE gain of massive MIMO over SCN is $\lim_{R_u\to R_{max,S}}\text{EG} = \lim_{P_{Td}(\overline{K}_a,M_S)\to\infty}\text{EG} = \infty$.

When R_u approaches zero, the transmit power can be neglected, and the average EE gain is

$$\text{EG}_0 \triangleq \lim_{R_u\to 0}\text{EG} = \frac{(T-K_0T_u-T_d)N_SP_{0,S}}{(T-\overline{K}_aT_u-T_d)P_{0,M}}. \quad (10)$$

It reflects the ratio of powers except transmitting data consumed at massive MIMO and SCN, which only depends on the system configurations.

Remark 2: After some derivations we can show that

- $0 < \text{EG}_0 < 1$: there exists R_{eq} such that $\text{EG}=1$ when $R_u = R_{eq}$, $\text{EG}<1$ when $R_u<R_{eq}$ and $\text{EG}>1$ when $R_u>R_{eq}$;
- $1 < \text{EG}_0 < 1+G$: there exist R_{eq1} and R_{eq2} such that $\text{EG}=1$ when $R_u = R_{eq1}$ or R_{eq2}, $\text{EG}>1$ when $R_u < R_{eq1}$ or $R_u > R_{eq2}$, and $\text{EG}<1$ for $R_{eq1} < R_u < R_{eq2}$;
- $\text{EG}_0 > 1+G$: $\text{EG}>1$ for any R_u,

where G is a constant dependent on the system configurations and we can prove that $0 < G < \frac{P_{Td}(K_0,M_0,\gamma_{max,S})}{P_{0,M}}$.

2) EE Gain versus Antenna Density: For fixed data rate requirements, when the antenna density goes to infinity, i.e., M_0 or $N_S \to \infty$, the asymptotic EE gain can be derived as

$$\text{EG}_a \triangleq \lim_{M_0,N_S\to\infty}\text{EG}=\frac{(T-K_0T_u-T_d)P_{ci,S}}{(T-T_u-T_d)(P_{sp,M}(K_0)+P_{ca,M})}. \quad (11)$$

It shows that for high antenna density, the circuit power dominates and the transmit power is negligible. If the per-antenna power consumption of an idle SBS is zero, i.e., $P_{ci,S}=0$, EG_a becomes zero. In addition, we know that $\text{EG}_a>1$ when $P_{sp,M}(K_0)+P_{ca,M} < \frac{T-K_0T_u-T_d}{T-T_u-T_d}P_{ci,S} \leq P_{ci,S}$.

Observation 2: Massive MIMO achieves a higher EE than SCN asymptotically if the circuit power consumption at each active antenna in massive MIMO is lower than the circuit power consumption at each idle antenna in SCN.

C. Average EE of Massive MIMO with Antenna Idling

In previous analysis, we only consider BS idle mode in SCN and antenna idling is not allowed for massive MIMO. In this subsection, we assume that some antennas at the MBS can also be turned into idle mode. In this case, the average EE of massive MIMO can be obtained from (3) as

$$\overline{\text{EE}}_M=\frac{\frac{T-K_0T_u-T_d}{T}K_0R_u}{\rho(P_{Td}(K_0,M_a)+P_{Tt})+M_a(P_{sp}(K_0)+P_{ca})+(M_0-M_a)P_{ci}},$$

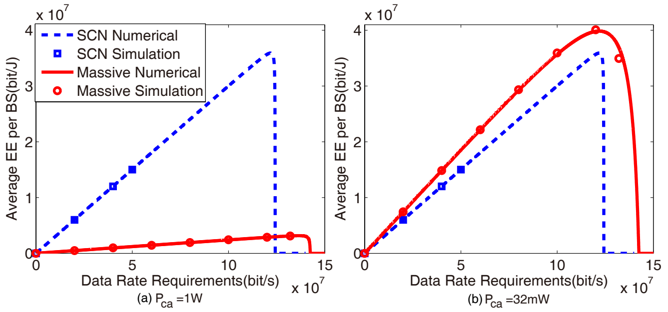

Fig. 1. Average EE versus data rate requirements. The per-antenna circuit power in massive MIMO is P_{ca} = 1 W or 32 mW. The number of SBSs and antennas in a macro cell are $N_S = 91$ and $M_0 = 364$, respectively.

where $K_0+1 \leq M_a \leq M_0$ is the number of active antennas at the MBS.

For a fair comparison, we consider that the number of active antennas at a MBS is the same as the total number of antennas at all active SBSs in a macro cell, i.e. $M_a = M_S N_S \mathrm{Pr}_a$. In this case, the asymptotic EE gain as antenna density approaches infinity can be derived as

$$\mathrm{EG}_a = \lim_{M_0, N_S \to \infty} \mathrm{EG} = \frac{(T - K_0 T_u - T_d) P_{ci,S}}{(T - T_u - T_d) P_{ci,M}}. \quad (12)$$

Observation 3: When antenna idling is allowed for massive MIMO, massive MIMO will be asymptotically more energy efficient than SCN when the circuit power at each idling antenna in massive MIMO is smaller than that in SCN.

IV. Numerical and Simulation Results

In this section, we evaluate the analytical analysis via simulations, and compare the average EE of massive MIMO with SCN. The system bandwidth is set as 20 MHz. The noise variance is -95 dBm. The area $\mathcal{A}$ with seven macro cells is simulated while only the performance of the central macro cell is considered. 10 users are uniformly dropped in a macro cell with radius 250 m, which are served by the MBS or the nearest SBSs. Other simulation parameters are given in Table I. The data rate requirements are identical for all users.

TABLE I
Simulation Parameters

Parameters	Massive MIMO	SCN
ρ [8]	1/0.388	1/0.08
P_{max} [8]	40 W	1 W
η_C [9]	12.8 Gflops/W	5 Gflops/W
P_{ca} [6, 9]	1 W or 32 mW	0.1 W
P_{ci}	500 mW or 20 mW	80 mW
Path loss [10]	$35.3{+}37.6\log_{10} d$ dB	$30.6{+}36.7\log_{10} d$ dB
M	$M_0 = M_S N_S$	$M_S = 4$
T=round($T_C B_C$)	1305, coherence time T_c=2.17 ms for 30 km/h moving speed and 3.5 GHz carrier, coherence bandwidth B_c=300 kHz for suburban area	
T_u [11]	9.69	
T_d [11]	24.2	

In Fig. 1, the numerical results are obtained from (8) and (9), and the simulation results are obtained based on the iterative power control proposed in [12], which computes the transmit powers at all BSs to satisfy the data rate requirements of all users in non-coordinated cellular network. We consider the

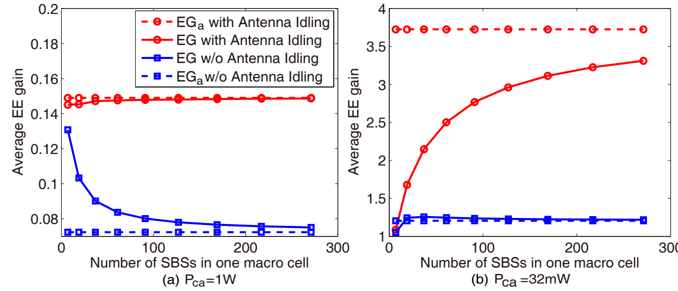

Fig. 2. Average EE gain versus the number of SBSs in a macro cell. R_u = 10Mbit/s, and the number of active antennas is $M_S N_S \mathrm{Pr}_a$.

maximum transmit power constraint in the simulations, therefore one can observe that only some data rate requirements can be supported for a 5% outage probability. We can see that the achievable rate for massive MIMO is higher than SCN. The simulated EEs overlap with the numerical results, indicating that the numerical analysis are accurate.

When per-antenna circuit power is large, we have $\mathrm{EG}_0 < 1$. We can see that the average EE of massive MIMO is higher than SCN only for high data rate requirements, as analyzed in Section III.B. When per-antenna circuit power is small enough, say P_{ca} = 32 mW that is not variable in existing BSs, we have $\mathrm{EG}_0 \gg 1$. In this case, we can see that massive MIMO is more energy efficient for all data rate requirements, which is consistent with the analytical results.

In Fig. 2, the impact of number of SBSs in one macro cell (that reflects the antenna density) on the EE gain is shown. When P_{ca} in massive MIMO is large, e.g., 1 W, EG is always smaller than 1, which means that massive MIMO is less energy efficient than SCN. For small P_{ca} in massive MIMO, e.g., 32 mW, EG approaches the asymptotic EE gain EG_a given in (11) and (12), and is larger than 1, indicating a higher EE of massive MIMO. As shown in Figs. 2(a) and 2(b), the EE gains considering antenna idling at MBSs are larger than that without antenna idling.

V. Conclusions

In this paper, we compared the average energy efficiency (EE) of massive MIMO and small cell networks (SCNs), given identical user density, antenna density and data rate requirements, where power control between the non-coordinated BSs as well as the uplink and downlink training overhead were considered. Our results show that the average transmit power of SCN reduces faster with the growth of antenna density than massive MIMO. Massive MIMO is more energy efficient than SCN when the power consumption except the power for transmitting data in massive MIMO is small or the data rate requirement is large. When the antenna density is very large, the average EE of massive MIMO is higher than SCN if the circuit power of each active antenna in massive MIMO is less than that of each idle antenna in SCN. If antenna idling is allowed for massive MIMO, massive MIMO will achieve higher EE than SCN when the former consumes lower circuit power at each idling antenna.

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