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Impact of Circuit Intake Power on the Spectral Energy Efficiency of Massive MIMO With Channel Estimation Errors

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ABSTRACT The influence of circuit intake power on Spectral Energy Efficiency (S.E.E) of massive Multiple-Input-Multiple-Output (MIMO) under the existence of channel estimation errors is examined using Zero-Forcing (ZF) linear pre-coding scheme. The system model which includes new defined total intake power involving the transmit power of amplifiers and the circuit power intake of the analog devices is developed. To analyze the impact of circuit intake power on S.E.E, the S.E.E with and without circuit intake power is investigated and presented after formulating a closed-form expression of S.E.E that incorporates new defined power model. Our investigation reveals that, the impact of circuit intake power is very significant when Base Station (BS) is arrayed with large number of antennas. Using the new S.E.E closed-form formula, derived from our new defined power intake model, the S.E.E is evaluated when the number of BS antennas (M) rises and it is observed that, S.E.E behaves like a concave function. The same results for S.E.E are also observed when transmit power increases. We conclude that, it is easy to get maximum S.E.E using a small number of BS antennas and optimal transmit power, when circuit power intake is included in the power consumption model. When transmit power totally dominates the circuit intake power, the maximum S.E.E is obtained only when all antennas are used (meaning maximum S.E.E is obtained when the number of BS antennas becomes very large). The numerical results reveal the importance of circuit intake power on optimizing S.E.E of massive MIMO under the presence of channel estimation errors.

INDEX TERMS Spectral energy efficiency (S.E.E), channel estimation errors, circuit intake power, downlink transmit power, zero-forcing pre-coder, massive MIMO.

I. INTRODUCTION

Relying on multiple-input multiple-output (MIMO) related technologies well developed, the spectral efficiency (S.E) gets solidly promoted to meet the incredible growth requirement of wireless data traffic. Meanwhile, energy efficiency (E.E) is a key feature in improving the next generation of mobile system as the telecommunication sector contributes towards the total carbon footprint [1]. These facts make Spectral Energy Efficiency (S.E.E) to be a special and unique perspective on wireless communication system profiling.

Currently, some new technologies are proposed for the coming age of wireless networks. Massive MIMO technology [2], [3], in which large number of antennas are mounted at the base station (BS) to serve considerable amount of users, offers an extensive array of spatial multiplexing gain [4], [5]. Massive MIMO technology is an actual approach to enhance throughput of wireless network without requiring additional bandwidth or power transmission. In reality, massive MIMO is able to offer greater S.E and S.E.E in comparison to present Fourth-Generation (4G), and thus paving the path to the coming Green Fifth-Generation (5G) candidate.

S.E.E enhancement has turned out to be the key 5G benchmark and can be calculated as the ratio between S.E (is the total number of bits transmitted per unit bandwidth) and total power intake (which is the sum of transmit power and circuit intake power) [6]. It is affected by numerous

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factors like S.E (which contains channel estimation errors), transmitted and circuit consumption power, number of BS antennas, number of users, and network architecture. Massive MIMO technologies are mostly attractive in their ability to simultaneously reduce the transmit power at both users and BSs [7]. Enormous amount of power is exhausted in BS, because BSs are the leading power-consuming parts of wireless communication networks [8], [9]. Therefore, minimizing the transmit power of base station is a practical strategy for reducing BS power intake, hence paving the way to enhance overall S.E.E. Furthermore, S.E.E improvement is attained at the low circuit consumption power due to the use of linear pre-coding systems, particularly zero-forcing (ZF) and maximum-ratio-transmit (MRT) that can attain an optimal spectral efficiency [10].

There are several contributions regarding S.E.E and circuit intake power. Authors in [11], came with an idea of optimizing energy efficiency by fixing the ratio of number of BS antennas (M) to that of users (K), but it is not possible to attain optimal S.E.E without considering the impact of circuit intake power. Moreover, power intake increases not only because of the transmitted power, but also due to the presence of power intake of analog devices like oscillators, mixers, and power amplifiers [12]. In [13], the authors observed that energy efficiency can only be optimal if and only if $M \rightarrow \infty$ without considering the presence of circuit power consumption. As per [14], exact modeling of the total intake power is of major significance in achieving the consistent guiding principles for S.E.E optimization in terms of number of BS antennas and that of users. The influence of number of BS antennas on the S.E.E was widely discussed in different ways [15]–[20]. The effect of transmit power on the energy efficiency was widely explained [21]–[23]. The effect of power allocation on maximizing E.E was clearly studied [24] under perfect Channel State Information (CSI). However, in their analysis, the authors didn't consider the impact brought by circuit intake power on maximizing E.E. The optimal precoding for optimization of S.E.E under power constraints for massive MIMO in the uplink transmission was studied clearly in [15], [25]. In [26], the authors used jammer's pre-coding to obtain the target E.E using minimum consumption power but their results revealed the optimum jamming power was almost equal to the transmit power of the BS. Similarly, in [27], the authors noted that for a large number of users, the optimal number of BS antennas required also becomes massive because it is essential to use substantial array antennas to recompense for the enlarged user interference. Generally, allocating radio resources efficiently (e.g., power, antennas, and number of users) plays an essential part in the improvement of massive MIMO performance. Thus, massive MIMO has become a research interest now for performance analysis and optimization.

The analysis and optimization of E.E in massive MIMO are clearly studied in several fading networks [28]–[33]. Authors in [33], analyzed the influence of transmit power, number of BS antennas and that of users on E.E, however their analysis considered only perfect CSI with the assumption that circuit intake power was fixed. The authors in [34], examined the impact of number of BS antennas and number of users on maximization of E.E, but their study assumed transmit power to be constant and divided equally among users. Most sound outcomes of the above works were obtained with perfect CSI, an assumption which is surely not achievable in reality. For instance, when pilot symbols are employed in channel estimation, Gaussian errors may occur because of time-frequency gap between the signal and pilot [35]. As a result, from hypothetical and practical perspectives, it is imperative to count on how the S.E.E performance deteriorates as a result of imperfect CSI. The effect of imperfect CSI on the Signal-Interference-Noise-Ratio (SINR) spreading, ergodic sum rate and Bit Error Rate (BER) was examined in the past. For instance, authors in [36], investigated the BER under varying conditions of speeds and jamming-noise ratios, and found that increasing the speed raised the BER induced by the eavesdropper. However, most of the works in [37]–[39] did not concern how the estimation errors can impact the S.E.E. So, the impact of channel estimation errors as well as circuit intake power should not be ignored in the analysis of S.E.E of any system. Therefore, the number of BS antennas, downlink transmit power and the circuit intake power needs to be comprehensively considered so as to attain an optimized S.E.E.

Many articles researched the trade-off between S.E.E and S.E but most of them based on perfect CSI. For example, the authors in [40], found that maximum E.E is obtained when the optimal number of BS antennas serves a fixed number of users under perfect CSI. The authors in [41], found a way to optimize E.E-S.E tradeoff under perfect CSI by minimizing the total power consumption and maximizing the channel capacity. Obviously, their theoretical analyses were purely based on ideal assumptions. With perfect CSI, the authors in [42], examined the relationship between E.E and S.E in a downlink transmission, and discovered that the E.E-S.E relationship is quasi-concave function. They further developed an algorithm for sub-optimal resource allocation by making full use of the E.E-S.E trade-off conclusion. In [43], the authors exploited the trade-off between E.E and S.E by balancing the power consumption and the bandwidth which is called resource efficiency for downlink transmission.

In this paper, we deal with the impact of circuit intake power on the S.E.E of massive MIMO system under the existence of channel estimation errors. By focusing on the essential part of analysis we adopt a ZF linear pre-coding scheme in our paradigm transmission link. We carry out analyses under three different scenarios, one is when downlink transmit power totally dominates the circuit intake power, another is when there are both circuit intake power and transmit power, and lastly when circuit intake power totally dominates the transmit power. Both scenarios considered with the presence of channel estimation errors using ZF precoder. The contributions offered in this paper include:

- We refine a new power intake model which incorporates total power intake by amplifiers (P_{PA}) and circuit intake power (P_{cir}) of various analog devices, which helps us to arrive comfortably in formulating a closed-form expression of S.E.E for massive MIMO using ZF linear precoding scheme under imperfect CSI. We then present the analytical impact of the circuit intake power on the S.E.E for massive MIMO.

- Three cases of evaluation are considered. In the first case, the evaluation is carried out when both circuit intake power and downlink transmit power are considered in the new refined power intake model. The second case is when downlink transmit power (P_{d}) totally dominates circuit intake power. In the third case, circuit intake power totally dominates downlink transmit power. In the presence of P_{cir}, mathematical analysis proves that S.E.E is a concave function of M and downlink transmit power, because S.E.E first increases with M and P_{d}, until it reaches a certain optimal point where it starts to decrease as M and P_{d} keep increasing. When transmit power totally dominates the circuit intake power the maximum S.E.E is obtained only when all antennas are used. However, when circuit intake power totally dominates the transmit power, the maximum S.E.E is obtained with a small number of BS antennas.
- We then incorporate S.E.E -Spectral efficiency relation with circuit intake power variation to find out how P_{cir} has profound impact on S.E.E-S.E relationship. We finally investigate and analyze the S.E.E in the presence as well as in the absence of P_{cir} by using Monte Carlo simulations. Based on the new refined total power intake model, analytical and simulations results show the importance of circuit intake power-downlink transmit power trade-off in the maximization of S.E.E.
- The findings from this paper lays a framework/guiding principles for coming researchers when designing the total power consumption model to whether include circuit intake power or ignore it during optimization of S.E.E.

The remaining parts are structured as follows. System model is stated in section II which also includes derivation of expression for spectral efficiency after deriving SINR for ZF pre-coding scheme. S.E.E problem is formulated in section III which leads to the analysis of the impact of circuit intake power on the S.E.E. Numerical results and discussions are explained in section IV, and section V presents our conclusion.

II. SYSTEM MODEL

In this paper, we consider downlink massive MIMO systems with M antennas serving K users in the Time Division Duplex (TDD) mode, in which the uplink and downlink share similar channel resource at various time so as to make the BS capable of estimating the channel from recognized pilots from users.

If we assume S_k. to be the signal symbol transmitted to k^{th} user in which $E\left\{|S_k|^2\right\} = 1$ and $H \in, \mathbb{C}^{M\times k}$ stands for channel matrix between BS and user, and H holds *i.i.d* Gaussian distributed property (with zero-mean and unity-variance). We can also let $F \in, \mathbb{C}^{M\times k}$ represent a linear precoder matrix. The transmitted $M \times 1$ pre-coded signal is given by:

$$x = \beta F s, \tag{1}$$

in which $s = [s_1, s_2, s_3, \cdots, s_k]^T$ holds original signal symbol of K users and β bounds the total-power of all arrays for the P_d to totally hinge on s, so that β remains designated to assure the average total-power $E\left\{\|x\|^2\right\} = P_d$ which fluctuates depending on the type of linear pre-coder. The received signal is now:

$$y = Hx + n = H\beta F s + n. \tag{2}$$

Equation (2) holds for perfect CSI but it can also be transformed to represent imperfect CSI because the main distinguishing factor is only the existence of estimation errors. Channel estimation is always complicated in the sense that it generates estimation errors which makes the channel imperfect like the one in equation below:

$$\widetilde{H} = H + \xi, \tag{3}$$

where $\widetilde{H}$ is channel estimate matrix and $\xi = \widetilde{H} - H$ is the error matrix in which H and ξ are not correlated.

Elements of error matrix ξ have the variance of

$$\varepsilon^2 = E\left\{\left[H_{ij}\right]^2 - \left[\tilde{H}_{ij}\right]^2\right\}, \tag{4}$$

where the scalar $\varepsilon \in [0, 1]$ is the reliability of channel accuracy estimate, for $\varepsilon = 0$, the CSI is perfect (i.e., no channel errors) but for $\varepsilon = 1$ the channel is totally imperfect.

By applying Moore-Penrose pseudo-inverse, the ZF precoder matrix is

$$F = \widetilde{H}^{\dagger} = \widetilde{H}^H(\widetilde{H}\widetilde{H}^H)^{-1}. \tag{5}$$

The pre-coded signal is then:

$$x = \beta F s = \beta \widetilde{H}^{\dagger} s = \beta \widetilde{H}^H(\widetilde{H}\widetilde{H}^H)^{-1} s. \tag{6}$$

By applying convergence of $\widetilde{H}\widetilde{H}^H/_M$ to I (I being identity matrix), β can now be written as:

$$\beta = \sqrt{\frac{P_d/\sigma_s^2}{tr\left(\widetilde{H}\widetilde{H}^H\right)^{-1}}} = \sqrt{\frac{P_d/\sigma_s^2}{\sum_{k=1}^{K} 1/\delta_k^2}}, \tag{7}$$

in which δ_k is singular K^{th} of $\widetilde{H}$ and σ_s^2 is signal power, consequently, the received signal is now expressed as:

$$y = Hx + n = H\beta\widetilde{H}^{\dagger} s + n \tag{8}$$

But $H = \tilde{H} - \xi$, so substituting H,

$$y = \widetilde{H}\beta\widetilde{H}^{\dagger} s - \xi\beta\widetilde{H}^{\dagger} s + n = \widetilde{H}\widetilde{H}^{\dagger}\beta s - \xi\beta\widetilde{H}^{\dagger} s + n. \tag{9}$$

By using Haar Matrices theory for unitary square matrix as in [44], pp. 31, $\widetilde{H}\widetilde{H}^{\dagger} \approx 1$ thus:

$$y = \beta s - \xi\beta\widetilde{H}^{\dagger} s + n, \tag{10}$$

where $\xi\beta\widetilde{H}^{\dagger}s$ stands for interference, which is not completely canceled and n stands for noise term. The auto-correlation matrix of the interference plus noise signal matrix is:

$$\Re_{i+n} = E\left[\left(-\xi\beta\widetilde{H}^{\dagger}s+n\right)\left(-\xi\beta\widetilde{H}^{\dagger}s+n\right)^{H}\right],$$

$$\Re_{i+n} = \beta^2\sigma_s^2 E\left[\xi\widetilde{H}^{\dagger}\left(\widetilde{H}^{\dagger}\right)^{H}\xi^{H}\right]+I,$$

$$\Re_{i+n} = \beta^2\sigma_s^2\varepsilon^2 tr\left(\Sigma^{-2}\right)I+I = \left(P_d\varepsilon^2+1\right)I, \quad (11)$$

where ε is estimation error and $\tilde{H}$ is attained from singular value decomposition (SVD) [45], that is, $\widetilde{H} = U\Sigma V^H$ and the matrix ξ remain constant.

SINR of user k is then given by:

$$SINR_k^{ZF} = \frac{\beta^2\sigma_s^2}{\left(P_d\varepsilon^2+1\right)} = \frac{P_d/\sigma_s^2}{tr\left(\widetilde{H}\widetilde{H}^H\right)^{-1}} \times \frac{\sigma_s^2}{P_d\varepsilon^2+1},$$

$$SINR_k^{ZF} = \frac{P_d}{\left(P_d\varepsilon^2+1\right)tr\left(\widetilde{H}\widetilde{H}^H\right)^{-1}}. \quad (12)$$

Definition 1: The Ergodic sum rate R_{sum} is well-defined from Shannon theorem $R_k = K\log_2(1+SINR_k)$ *as:*

$$R_{sum} = K\log_2\left(1+\frac{P_d\varepsilon^2(M-K)}{K\left(P_d\varepsilon^2+1\right)}\right). \quad (13)$$

Proof: Please refer to Appendix A.

The spectral efficiency (S.E) is defined from the ergodic sum rate as:

$$S.E = \left(1-\tau/T\right)R_{sum}, \quad (14)$$

in which τ represents symbols transmitted per coherence interval (T) and T is defined in terms of the total number of symbols transmitted. Substituting (13) into (14) we get:

$$S.E = \left(1-{}^{\tau}/_{T}\right)K\log_2(1+SINR), \quad (15)$$

where by SINR is defined in equation (12).

III. SPECTRAL ENERGY EFFICIENCY MODEL AND ANALYSIS

The massive MIMO technology is adopted to enhance the ergodic-sum-rate or to decrease P_d subject to the growth of M antennas by using the benefits of massive antennas. In this section, the spectral energy efficiency model is developed with respect to the total power consumption model.

Definition 2: Spectral energy efficiency is defined as the ratio of spectral efficiency to the total consumed power (number of bits transferred in the channel per joule of energy with an overhead pilots being considered), and is symbolically defined as:

$$S.E.E = \frac{S.E}{P_{tot}}, \quad (16)$$

where P_{tot} is the total consumption power obtained from the sum of the total power intake by amplifiers (P_{PA}) and circuit consumption power (P_{cir}) in which now $P_{tot} = P_{PA}+P_{cir}$.But based on [46] the power intake by amplifiers is written as:

$$P_{PA} = \frac{P_d}{\eta(1-\varsigma)}, \quad (17)$$

in which η denotes power amplifier efficiency, ς is the antenna feeder lossy factor and P_d is the downlink transmit power. Furthermore, based on [47],

$$P_{cir} = M(P_{dac}+P_{mix}+P_{filt})+2P_{syn} + K(P_{\ln a}+P_{filr}+P_{mix}+P_{adc}+P_{ifa}), \quad (18)$$

where P_{dac} and P_{adc} are power values for Digital to Analogue and Analogue to Digital converters respectively, P_{filt} and P_{filr} are power values for active filters in the transmitter and the receiver respectively, P_{mix} is power value for mixer, P_{ifa} is an intermediate frequency amplifier power value, P_{syn} is the frequency synthesizer power value and $P_{\ln a}$ is the power value for the low noise amplifier.

For simplification, we can denote, $P_0 = P_{dac}+P_{mix}+P_{filt}$, $P_1 = P_{\ln a}+P_{mix}+P_{ifa}+P_{adc}$ and $P_2 = 2P_{syn}$, then:

$$P_{cir} = MP_0+KP_1+P_2. \quad (19)$$

So the closed form expression for $S.E.E$ from equation (16) becomes:

$$S.E.E = \frac{S.E}{P_{PA}+P_{cir}} = \frac{(1-\tau/T)K\log_2(1+SINR)}{P_{PA}+MP_0+KP_1+P_2}, \quad (20)$$

$$S.E.E = \frac{(1-\tau/T)K\log_2(1+SINR)}{P_d/\eta(1-\varsigma)+MP_0+KP_1+P_2}. \quad (21)$$

Because $P_{PA} = \frac{P_d}{\eta(1-\varsigma)}$ and $SINR = \left(\frac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}\right)$, substituting these parameters in equation (20) we get;

$$S.E.E = \frac{(1-{}^{\tau}/_{T})K\log_2\left(1+\frac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}\right)}{\frac{P_d}{\eta(1-\varsigma)}+MP_0+KP_1+P_2}. \quad (22)$$

As it can be seen, equation (22) is the ultimate closed-form formula for the spectral energy efficiency in which, it is possible to see that the S.E.E varies with M antennas, K users and the transmit power P_d.

A. THEORETICAL ANALYSIS OF SPECTRAL ENERGY EFFICIENCY WITH CIRCUIT POWER INTAKE

In this case, the assumption is based on both circuit intake power and transmit power being existent as presented in equation (22), and from there we can formulate an optimization equation based on both parameters M, K and P_d as presented in equation (23)

$$\max_{M,\,Pd\geq 0, M>K} S.E.E = \max_{M,\,Pd\geq 0, M>K}\left(\frac{(1-{}^{\tau}/{}_{T})K\log_2\left(1+\frac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}\right)}{\frac{P_d}{\eta(1-\varsigma)}+MP_0+KP_1+P_2}\right). \tag{23}$$

In the presence of P_{cir}, the core objective is to solve equation (22) by finding the optimal spectral-energy-efficiency with respect to either M antenna or P_{d} and also if possible the effect of K on S.E.E under imperfect CSI.

The optimization formula in equation (22) is discrete, so an iterative search may be employed to find the optimal solution of the problem. As it is too complex to make such a search strategy, some variables must be kept constant to solve such an optimization problem and mathematical analysis and derivation is employed to find the optimum values of the varying parameter that maximizes S.E.E.

Definition 3: Lambert function abbreviated by $W(x)$ is defined as $x = W(x)\,e^{W(x)}$ for all $x \in \mathbb{C}$.

Lemma 1: Consider the problem formulation

$$\max_{z>-a/b} \frac{g\log(a+bz)}{c+dz}, \tag{24}$$

where $a \in \mathbb{R}$, $c \geq 0$, and $b, d, g > 0$, the equation (24) has a unique solution of

$$Z^{opt} = \frac{e^{W\left(\frac{bc}{de}-\frac{a}{e}\right)+1}-a}{b}, \tag{25}$$

where Z^{opt} is the optimum value of z obtained from objective function in (25) and stands for natural number.

Proof: Please refer to Appendix B

Lemma 2: Lambert function $W(x)$ increases for $x \geq 0$ and obeys the inequalities

$$e\frac{x}{\ln(x)} \leq e^{W(x)+1} \leq (1+e)\frac{x}{\ln(x)}, \quad \text{for } x \geq e. \tag{26}$$

Lemma 2 is straightforwardly obtained from the inequalities in [48] and means that $e^{W(x)+1} \approx x$ for small x and $e^{W(x)+1} \approx x$ for large x.

By having lemma 1 and Lemma 2, we can now find the optimal S.E.E of massive MIMO when some of the settings or parameters are fixed or assumed to be constant.

1) IMPACT OF M ON S.E.E ANALYSIS

The optimum value of M antennas is easily obtained from the theorem that follows.

Theorem 1: From the $S.E.E$ optimization problem, for given values of P_d, K and estimation error (ε).

$$S.E.E = \max_{M>K}\left(\frac{(1-{}^{\tau}/{}_{T})K\log_2\left(1+\frac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}\right)}{\frac{P_d}{\eta(1-\varsigma)}+MP_0+KP_1+P_2}\right), \tag{27}$$

is easily solved by the optimum equation for M provided by:

$$M^{opt} = \frac{K(P_d\varepsilon^2+1)e^{W\left(\frac{P_d\varepsilon^2(P_d/\eta(1-\varsigma)+KP_1+P_2)}{eP_0K(P_d\varepsilon^2+1)}-\frac{1}{e(P_d\varepsilon^2+1)}\right)+1}-K}{P_d\varepsilon^2}. \tag{28}$$

Proof: Refer to Appendix C.

M^{opt} is in practicable region $K \leq M < \infty$ because objective function in (27) is concave and is always zero when $M = 0$ or $M \rightarrow \infty$. Theorem 1 gives an insight into how the number of antenna M helps on reaching the optimum S.E.E. As seen and with the help of Lemma 2, for enlarging S.E.E, M needs increasing sub-linearly as the transmit power P_{d} keeps increasing. And when P_{d} grows large, the growth of M ought to be linear so as to push S.E.E higher. Similar phenomenon occurs when taking into account channel estimation error, although its impact is relatively minor. M affects S.E.E in a non-monotonic way as shown in equation (27), which implies the existence of optimal value of M. Theorem 1, presents a simple closed-form formula that maximizes the S.E.E by finding the optimal value of M. Binary search algorithm gives the chance for determining the optimal value of M, so as to attain the maximum S.E.E. Another observation from the solution in equation (28), is that the circuit power coefficients of P_1 and P_2 play a supporting role exponentially pulling optimal antenna number of M^{opt} higher.

Furthermore considering the impact of M on S.E.E, we can see from equation (20) that M affects both S.E and the total intake power. Because S.E increases as M increases while total intake power increases linearly as M increases (from $P_{cir} = MP_0 + KP_1 + P_2$), M affects S.E.E directly as it affects S.E and P_{tot} which are important parameters in S.E.E. Nevertheless as it can be noted on equation (20), the S.E.E function is a quasi-concave with the number of BS antennas because it first increases with M and after reaching a certain optimal point it starts to decrease as M keeps increasing. So through analyzing the properties of S.E.E we can easily obtain the monotonicity of S.E.E, $\lim_{M\to 0} S.E.E \approx 0$ as and also

$$\lim_{M\to 0} S.E.E \approx \frac{(1-{}^{\tau}/{}_{T})K\log_2\left(1/P_d\varepsilon^2+1\right)}{P_d/\eta(1-\varsigma)+KP_1+P_2}$$

which means that the S.E.E first increases as M increases and then after reaching a certain maximal point there will be a decrease in S.E.E as M keeps increasing as shown in the two equations above, the same analysis applies for the number users.

2) IMPACT OF P_{d} ON S.E.E ANALYSIS enumerate

With the constant M, K and ε, the optimization problem for S.E.E is given by:

$$S.E.E = \max_{Pd\geq 0,}\left(\frac{(1-\tau/T)K\log_2\left(1+\frac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}\right)}{P_d/\eta(1-\varsigma)+MP_0+KP_1+P_2}\right), \tag{29}$$

which can be solved by first changing the maximization problem into a function. Let it be $f(P_d)$, then:

$$f(P_d) = \frac{K(1-\tau/T)\log_2(1+\frac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)})}{P_d/\eta(1-\varsigma)+MP_0+KP_1+P_2}. \quad (30)$$

Differentiating with respect to P_d, we get

$$f'(P_d) = \frac{\left(\varepsilon^2(M-K)\times\kappa_2-(1-{}^{\tau}/_{T})\times\kappa_1\times\kappa_3\right)}{\kappa_1\times\kappa_2}, \quad (31)$$

where

$$\begin{cases}\kappa_1 = \ln(2)K(P_d\varepsilon^2+1)(K+P_d\varepsilon^2M),\\ \kappa_2 = \dfrac{P_d}{\eta(1-\varsigma)}+KP_1+P_2+MP_0,\\ \kappa_3 = \ln(1+\dfrac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}).\end{cases}$$

As it can be seen in equation (31), the denominator is always positive, so, we concentrate on the numerator. If we let the numerator to be $h(P_d)$, then

$$h(P_d) = \varepsilon^2(M-K)\times\kappa_2-(1-{}^{\tau}/_{T})\times\kappa_1\times\kappa_3. \quad (32)$$

To find optimal $P_{\rm d}$, we take another derivative of $h(P_d)$ This yields the following formula:

$$h'(P_d) = a_1-(a_2+a_3\times\kappa_3), \quad (33)$$

where

$$\begin{cases}a_1 = \varepsilon^2(M-K)\dfrac{1}{\eta(1-\varsigma)},\\ a_2 = K(1-\tau/T)\varepsilon^2(M-K),\\ a_3 = \varepsilon^2(M-K)+2P_d\varepsilon^4M).\end{cases}$$

It can be seen that $h'(P_{\rm d}) < 0$, which means that $f(P_{\rm d})$ is a decreasing function of $P_{\rm d}$. Therefore $h(\infty) \leq h(P_d) \leq 0$. So the function $f(P_{\rm d})$, increases first and then decreases as P_d grows to infinity. Thus, the spectral energy efficiency initially increases then decreases as P_d increases as shown in equations 34 and 35.

$$\lim_{Pd\to 0} S.E.E = \lim_{Pd\to 0}\left(\frac{(1-{}^{\tau}/_{T})K\log_2\left(1+\dfrac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}\right)}{\frac{P_d}{\eta(1-\varsigma)}+MP_0+KP_1+P_2}\right)\approx 0. \quad (34)$$

As seen when P_d is very small, the S.E.E approaches zero and when $P_d\to\infty$, the S.E.E gives the same value as when $P_d\to 0$ as shown in equation 35 below.

$$\lim_{Pd\to\infty} S.E.E = \lim_{Pd\to\infty}\left(\frac{(1-{}^{\tau}/_{T})K\log_2\left(1+\dfrac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}\right)}{\dfrac{P_d}{\eta(1-\varsigma)}+MP_0+KP_1+P_2}\right)\approx 0. \quad (35)$$

Also, from equation (32), it is revealed that the $P_{\rm d}$ increases with M to optimize the S.E.E, and for circuit consumption power, which is multiple of M, the same explanation is shared. So, in general, when the $P_{\rm d}$ is massive, it is obligatory to employ many BS antennas to maximize S.E.E, however, with low transmit power, increasing M may cause a reduction in S.E.E.

To attain the optimum transmit power that can maximize the S.E.E, we let $h(P_d) = 0$ and the following equation is obtained:

$$\varepsilon^2(M-K)\times b_1-b_2\times b_3 = 0,$$

where

$$\begin{cases}b_1 = (\dfrac{P_d}{\eta(1-\varsigma)}+KP_1+MP_0+P_2),\\ b_2 = K(1-{}^{\tau}/_{T})(P_d\varepsilon^2+1)(K+P_d\varepsilon^2M)\\ b_3 = \ln(\dfrac{P_d\varepsilon^2M+K}{K(P_d\varepsilon^2+1)}).\end{cases}$$

If we let $Q(P_d) = \varepsilon^2(M-K)\times b_1$ and $Y(P_d) = b_2\times b_3$ then: $Q(P_d)$ and $Y(P_d)$ have a single crossing point, which can only be obtained by using iterative algorithm to attain the optimal solution.

3) CROSS ITERATION ALGORITHM FOR M and $P_{\rm d}$

Equations (28) and (32) provide closed-form expressions for optimizing spectral energy efficiency by optimizing M and P_d separately under the condition that the other parameters are fixed. So, we propose an algorithm that computes optimal values of M and P_d as shown in iteration 1 and 2. For iteration 1 it begins with the initialization of the variables for P_d,with the controlling counter in the form of ξ and $\Delta(P_d)$, while for the case of M in iteration 2,we initialize lower value (l), and upper value (u) in which middle value (mid) is the average between lower value and the upper value [i.e. $mid = (u+l)/2)$]. The lower value has an initial value of 1 whereas the upper value is given according to the number of iterations the algorithm will take. The S.E.E that is attained by using M antennas is denoted by $S.E.E(M)$. This is shown clearly in Algorithm 1.

B. THEORETICAL ANALYSIS OF SPECTRAL ENERGY EFFICIENCY WITHOUT CIRCUIT POWER INTAKE

In this case, the assumption is based on the fact that $P_{\rm d}$ totally dominates the circuit intake power in the sense that the circuit intake power is so minimal that it can be neglected during analysis.

1) IMPACT OF M ON S.E.E ANALYSIS

From the concept of total consumption power (P_{tot}) which is equivalent to the sum of P_{PA} $(P_{PA} = P_d/\eta(1-\varsigma))$ and $P_{\rm cir}$, when $P_{\rm d}$ totally dominates the $P_{\rm cir}$, the total consumption power becomes approximately equal to transmit power as shown in the coming equations:

TABLE 1. Showing system parameters and values used during simulations.

Circuit block parameter	Value used in simulation
P_{mix}	30.3mW
P_{ifa}	3mW
$P_{\ln a}$	20mW
P_{syn}	50mW
P_{filt}	2.5mW
P_{filr}	2.5mW
η	38%
T	400-800
B	10kHz

From $P_{tot} = P_d / \eta(1-\varsigma) + P_{cir}$.But in this case, $P_d \gg P_{cir}$ i.e. $P_{cir} \approx 0$ (this means that $P_0 \approx P_1 \approx P_2 \approx 0$) then $P_{tot} \approx P_d / \eta(1-\varsigma)$. Thus from the following formula: $M^{opt} = \frac{K(P_d\varepsilon^2+1)e^{W_K}-K}{P_d\varepsilon^2}$, where

$$W_K = W\left(\frac{P_d\varepsilon^2(P_d/\eta(1-\varsigma)+KP_1+P_2)}{eP_0K(P_d\varepsilon^2+1)} - \frac{1}{e(P_d\varepsilon^2+1)}\right)+1$$

and when substituting $P_0 \approx P_1 \approx P_2 \approx 0$ into above equation we get the optimal M: $M^{opt\ without\ P_{cir}} = \frac{K(P_d\varepsilon^2+1)e^{W_{K_1}}-K}{P_d\varepsilon^2}$, where

$$W_{K_1} = W\left(\frac{P_d\varepsilon^2(\frac{P_d}{\eta(1-\varsigma)}+K\times 0+0)}{e\times 0\times K(P_d\varepsilon^2+1)} - \frac{1}{e(P_d\varepsilon^2+1)}\right)+1$$

$$M^{opt\ without\ P_{cir}} \approx \frac{K(P_d\varepsilon^2+1)e^{W(\infty)+1}-K}{P_d\varepsilon^2} \approx \infty. \tag{36}$$

From above, it can be seen that when P_d totally dominates the P_{cir} there is no optimal value of M which can give a maximum S.E.E. It can also be noted in equation (36) where the optimum S.E.E is obtained only when $M \to \infty$ meaning that the circuit intake power has a very big impact on S.E.E.

The values of P_{dac} and P_{adc} are not shown in Table 1 because they are not constant and they usually change depending on the dynamic nature of the block themselves. Instead we present how to get them in appendix D.

2) IMPACT OF P_d ON S.E.E ANALYSIS

For the case of P_d dominating circuit intake power, in a sense total consumption power is totally dominated or equal to transmit power. Increasing P_d will have a detrimental impact on S.E.E, while the lower the transmit power the better the S.E.E. So when $P_d \to \infty$ while other parameters are kept constant the S.E.E will be decreasing approaching to zero and when P_d is very small there will be an increase in S.E.E. In both cases the impact of estimation channel errors is considered.

Algorithm 1 Search for Optimal Values of P_d and M

Step 1: **Initialization** P_d, Ψ and $\Delta(P_d)$, l, u and mid of M
Step 2: **Iteration for** P_d
  repeat
    if $Q(P_{dk}) - Y(P_{dk}) > \Psi$
      $P_{dk} = P_{dk} - \Delta(P_d)$
    else
      $P_{dk} = P_{dk} + \Delta(P_d)$
    end if
      $P_{dk+1} = P_{dk}$
    until $|Q(P_{dk+1}) - Y(P_{dk+1})| < \Psi$
Step 3: **Iteration for** M
  while $(u - l) > 1$
    if $S.E.E(u+1) > S.E.E(mid)$
      $l = mid + 1$
    else if $S.E.E(mid+1) < S.E.E(mid)$
      $u = mid$
    else
      break;
  end while
  if $(u - l = 1)$
    $S.E.E^* = \max(S.E.E(l), S.E.E(u))$
  else
    $S.E.E^* = S.E.E(mid)$
  end if
Step 4: Optimal values of P_d **and** M
  If $|Q(P_{dk+1}) - Y(P_{dk+1})| < \Psi$ or $S.E.E^* = \max(S.E.E(l), S.E.E(u))$ or $S.E.E^* = S.E.E(mid)$
    return (P_d, M) as (P_d^{opt}, M^{opt})
  else
    Go to step 2
End

Note that, There is also a case when the circuit intake power totally dominates P_d($P_{cir} \gg P_d$) in the sense that total consumption power becomes approximately equal to P_{cir} i.e. $P_{tot} \approx P_{cir}$. In this case the S.E.E will decrease with an increase in the circuit power. Therefore, increasing P_{cir} will cause degradation on S.E.E which means that P_{cir} has very positive impact on S.E.E because of being energy efficient as it uses a small amount of power to have large S.E.E.

IV. RESULTS AND DISCUSSION

In this part, results are provided in several aspects to find how circuit intake power affects the spectral energy efficiency (S.E.E) under imperfect CSI using zero-forcing linear pre-coding scheme. The parameters for simulations for the case of circuit consumption power are provided in Table 1. The results are obtained through simulations using MATLAB where Monte Carlo simulations are carried out to quantify

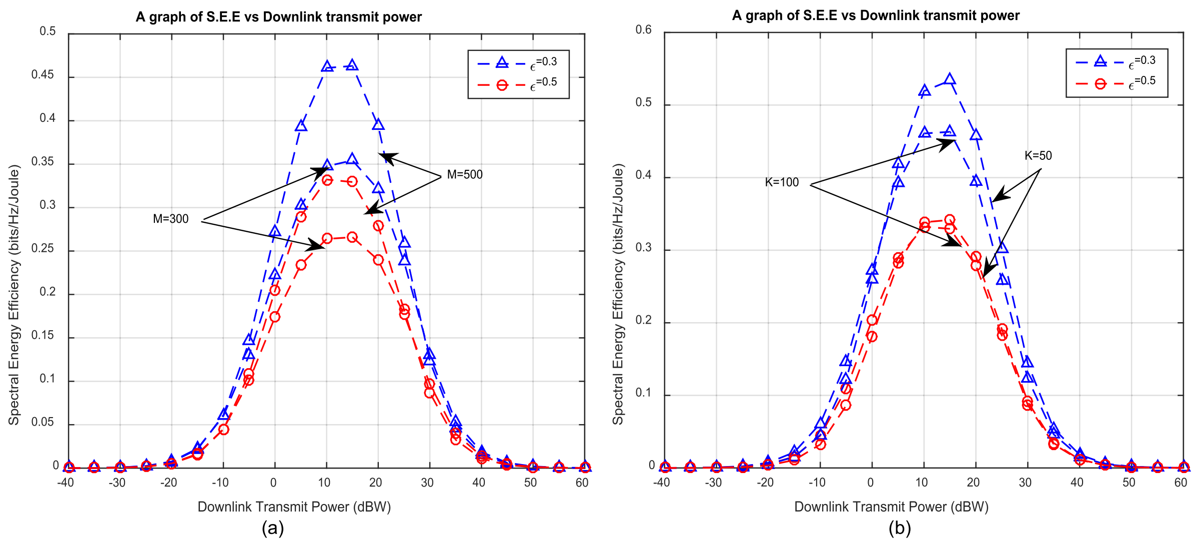

FIGURE 1. **A graph of S.E.E against P_d with (a) varying M (b) varying K in the existence of estimation errors.**

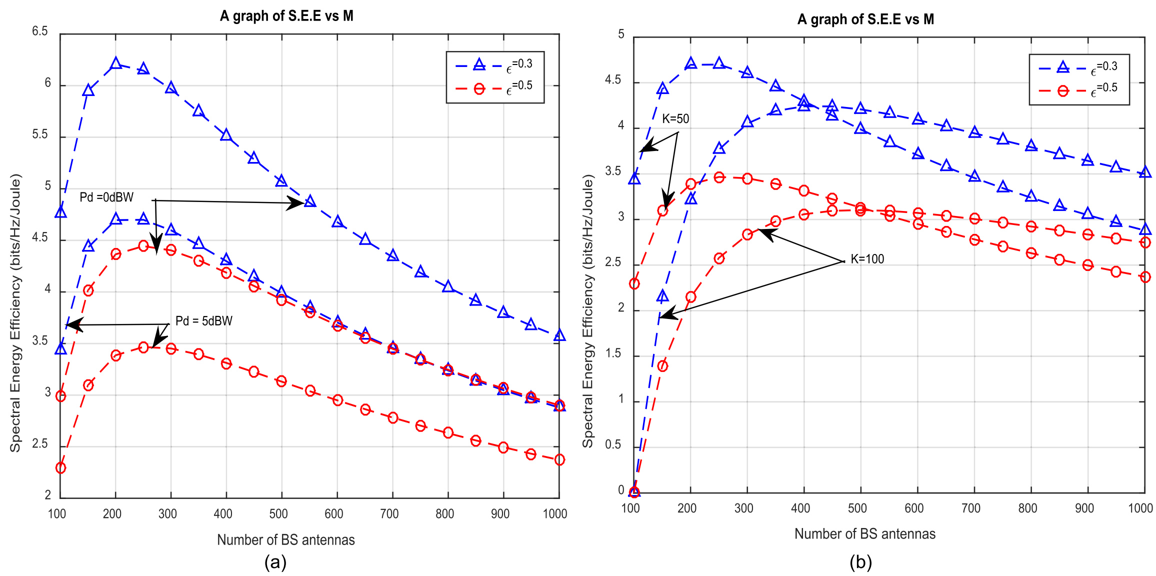

FIGURE 2. **A graph of S.E.E against M with (a) varying P_d (b) varying K in the presence of circuit intake power.**

the theoretical analysis. As shown in Fig. 1(a), a plot of S.E.E against downlink transmit power is generated in the vicinity of channel errors with M being a varying variable between 300 and 500, while the number of users is limited to 50. It is observed that the S.E.E starts to increase with the increase in P_d until it reaches a certain point assumed as an optimal point where the S.E.E starts to decrease despite the increase in P_d. This means that in the presence of circuit intake power, it is easy to get an optimum S.E.E compared to when P_{cir} is neglected as observed in the previous cases above. Furthermore, as observed in the plot, the large number of BS antenna serving fixed or restricted number of users has a positive impact on the S.E.E compared to the one with a small number of BS antennas. For example, for estimation error of 0.3 with M being 500, the optimal S.E.E is noted to be approximately 0.47 bits/Hz/Joule at P_d of 9.8dBW, compared to approximately 0.35 bits/Hz/Joule when $M = 300$ at P_d of 14.7dBW. So it can be deduced that the S.E.E always approaches to zero in both cases when there is very small P_d as well as when there is very large P_d. This also happens when there is circuit intake power in which more BS antennas are needed for improving the S.E.E. However, this causes another problem in additional circuit complexity that can eventually result in energy inefficiency.

In Fig. 1(b), the S.E.E approximately approaches zero when the P_d is either too small or too large. It can be observed that when P_{cir} is equivalent to or dominates the P_d, more BS antennas could increase S.E.E, but excessive BS antennas contribute to additional circuit complications and consequently reduce the energy efficient. Conversely, when K increases with M serving those users being restricted it is witnessed that the S.E.E tends to decrease compared to when there are fewer users being served by the same amount of BS antennas.

Generally, the S.E.E tends to increase at a normal rate with an increase in P_{d} but then decreases after reaching the maximum value despite the continued increase in P_{d}, as shown in Fig. 1(b). As it is perceived also for K when P_{d} is low the large K tends to contribute an improved S.E.E until it reaches a certain value of P_{d} where the small K outweighs the large K, and the same applies after the maximum S.E.E is obtained, when P_{d} grows large, the small K being served by restricted M antennas tends to have a lower S.E.E compared with large K. Likewise, the channel estimation errors are constantly giving an improved S.E.E when it is small compared with when it is large.

In the presence of circuit consumption power, the S.E.E is observed to first increase as the number of BS antennas increases until it reaches an optimal number of BS antenna (where the maximum S.E.E is obtained) then from there it starts to decrease as M increases. So, in the presence of circuit intake power the increase in M does not necessarily cause an increase in S.E.E as presented in Fig. 2 (a) where the concave shaped S.E.E means there is an increase as well as a decrease as M rises. Therefore the maximum point for S.E.E is easily obtained with a small M (for example the S.E.E is found to be approximately 6.25bits/Hz/Joule when $M = 200$ at an estimation error of 0.3 and $P_{\mathrm{d}} = 0$dBW, while the S.E.E is found to be 4.48bits/Hz/Joule when $M = 250$ at estimation error 0.3 which means that optimum S.E.E is attained when estimation error is small at the same time it is obtained when M is not so large) compared with some literatures which concludes that the maximum S.E.E is obtained with large values of M. As also observed the small amount of transmit power is found to give superior S.E.E compared to large amount of P_{d} which in terms of energy efficiency is better by using right hand thumb rule, the lower the transmit power the better the energy efficiency.

Furthermore, the smaller the channel estimation error the better the S.E.E. Meanwhile, the impact of users on S.E.E is. A graph of S.E.E vs presented in Fig. 2(b), as it can be seen and interpreted, the S.E.E is found to increase first with an increase in M until it reaches a certain optimal point where it starts to decrease as M increases.

As the number of users' increases there is an exceptional observation in the S.E.E as M increases compared to previous results where there is a decrease in S.E.E as K rises and M increases. Increasingly, as estimation errors decrease the S.E.E has a better value in comparison to large estimation errors.

Fig. 3 presents a relationship between S.E.E and the number of users being served by $M = 300$ in the presence of circuit intake power under imperfect CSI. As it can be perceived, there is an optimum value of S.E.E reached when

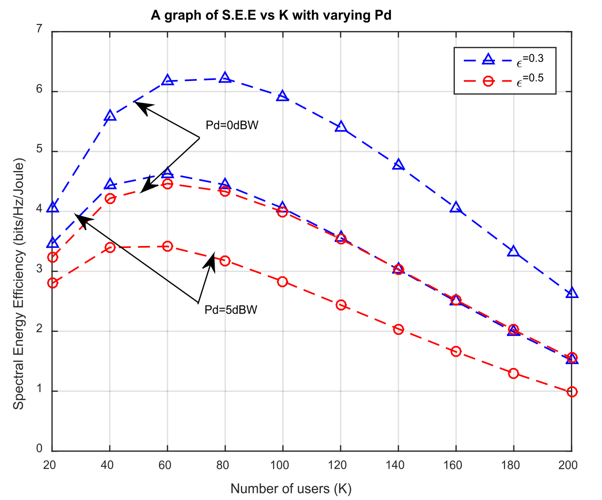

FIGURE 3. A graph of S.E.E against P_{d} with (a) varying M and (b) varying number of users in the absence of P_{cir}.

a small number of users are served by constant number of BS antennas (in our case $M = 300$).

The S.E.E in Fig. 3 form a concave shape with the number of users. As it can be seen there is first an increase in S.E.E when rises up to an optimal point where the S.E.E starts to decrease as increases. In turn means, it is possible to get optimum S.E.E when circuit intake power is incorporated in the total intake power model compared with when circuit intake power is neglected in that power model. Furthermore, downlink transmit power is found to have an impact on the S.E.E as observed, in the sense that the small amount of transmit power contributed to the better value of S.E.E in comparison with the large amount of transmit power.

As seen in Fig. 4, a graph of S.E.E is plotted against P_{d} when circuit intake power is totally dominated by P_{d}.

As depicted in Fig. 4 (a), there is an exponential decrease in the S.E.E as P_{d} increases, large portion of transmit power is in the denominator which particularly coincides with the theoretical analysis as S.E.E is inversely proportional to P_{d} (so as P_{d} increases the S.E.E is automatically expected to decrease and the vice-versa holds true). Accordingly, the presence of the small estimation errors accounts for the large and improved values of S.E.E compared with large estimation errors as shown in the graph with blue plots. Besides, the large M serving limited K is found to have positive impact on the S.E.E compared with small number of BS antennas.

As indicated in Fig. 4 (b), the S.E.E is better when there is a small amount of transmit power (P_{d}) but with P_{d} increasing the S.E.E starts to decrease drastically until it approximately approaches to zero for whatever increased value of P_{d}. As for the impact of K on the S.E.E, the small number of users which are served by large M has better S.E.E than the large number of users being served by the same M. Moreover, the small values of estimation errors gives an improved S.E.E compared with large estimation errors.

Fig. 5 shows the association between S.E.E and M in the existence of channel errors with varying downlink transmit

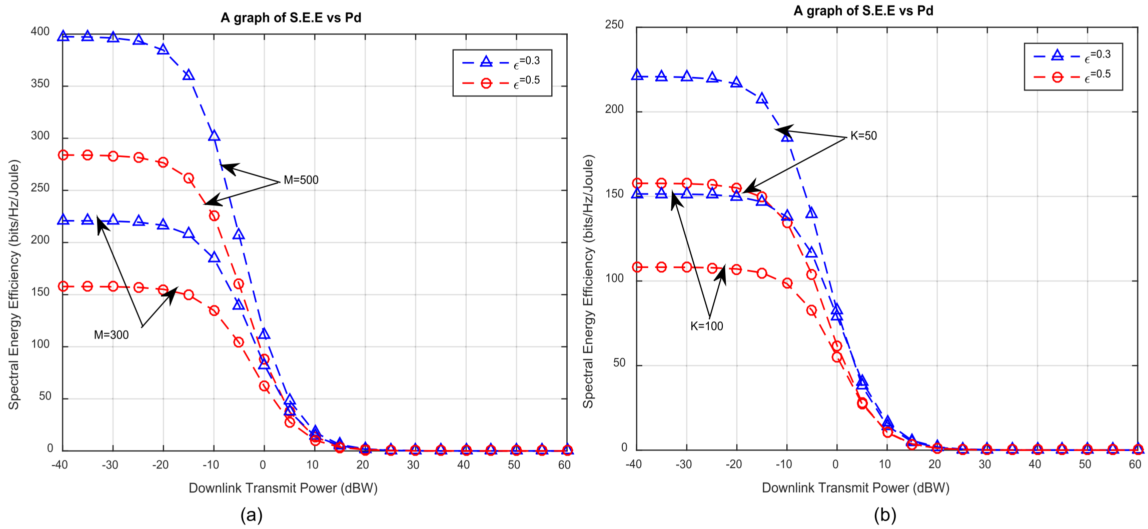

FIGURE 4. A graph of S.E.E against M with (a) varying P_d and (b) varying number of users when P_d totally dominates the P_{cir}.

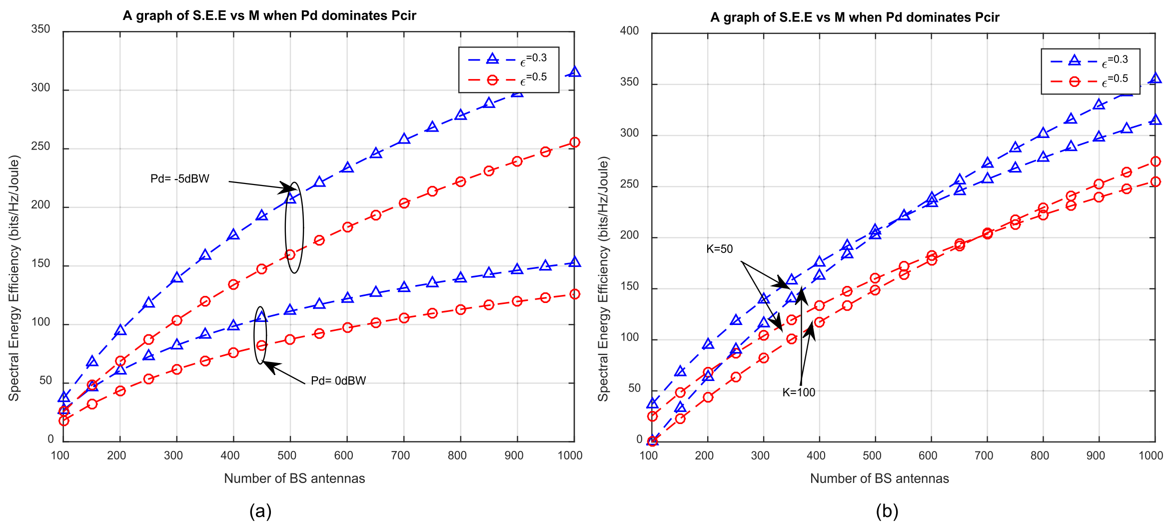

FIGURE 5. A graph of S.E.E against M with (a) varying P_d and (b) varying number of users when P_d totally dominates the P_{cir}.

power as displayed in Fig. 5(a). The S.E.E increases as M increases which makes it difficult to have an optimal value of S.E.E for a certain amount of M because the S.E.E is always increasing as long as M increases. This means that the presence of P_{cir} helps a lot to optimize the S.E.E with some reasonable amount of M compared with its absence. Additionally, the lower the downlink transmit power the larger values of S.E.E compared with large amount which in turn is better for energy efficiency systems. Furthermore, for the case of estimation errors, the lower the value of the estimation error as shown in Fig. 5 (a), the better the S.E.E which means that as the channel becomes cleaner with very few errors the S.E.E behaves like that of perfect CSI.

Furthermore, as witnessed in Fig. 5(b), the S.E.E increases as M increases which makes it very difficult to obtain the optimal value of S.E.E with the selected M because the maximum S.E.E will be obtained with a large number of M. In the case of K, the fewer the users being served by appreciable M the larger the S.E.E compared with large K, but as M increases, the large K outweighs the small number of users as observed. This means when M grows large say up to infinity it is capable of serving the large number of users efficiently and effectively, hence providing better and improved S.E.E.

As shown in Fig. 6(a), the S.E.E tends to decrease with an increase in P_{cir} but as observed with large M serving the fixed K, the S.E.E tends to have improved values compared with when M is small. Accordingly, the lower the estimation errors the larger the S.E.E. For example when $\varepsilon = 0.3$ and $M = 500$ the S.E.E is recorded to be approximately 3000bits/Hz/Joule, but when $M = 300$ the S.E.E is found to be approximately 1800bits/Hz/Joule. Essentially, it can be easily deduced that the S.E.E decreases logarithmically when

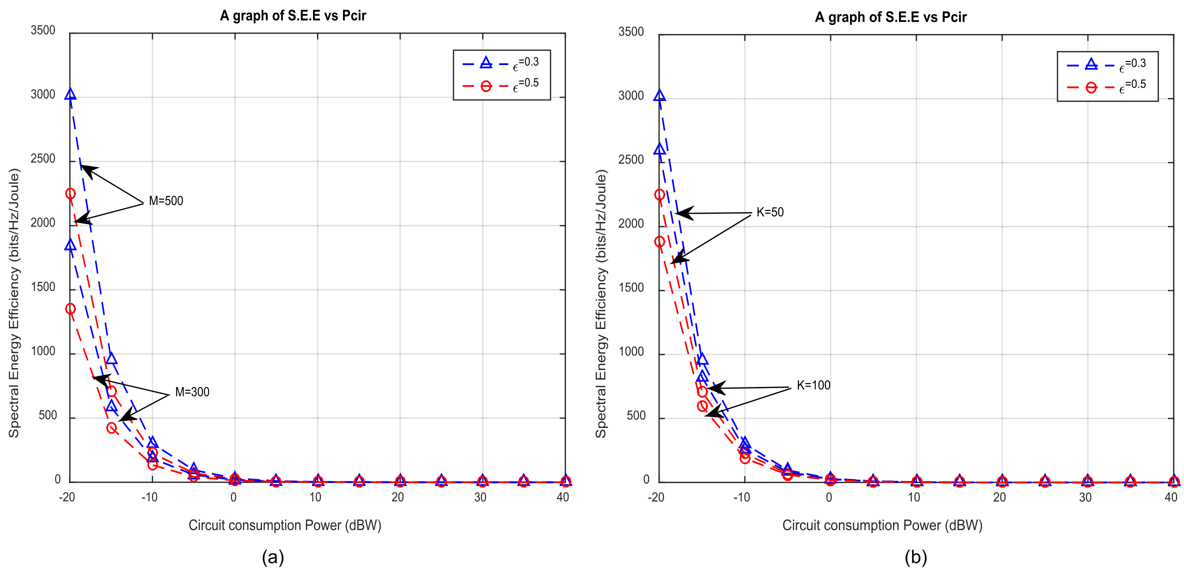

FIGURE 6. **Showing a plot of S.E.E against P_{cir} with (a) variation of M (b) variation of the number of users.**

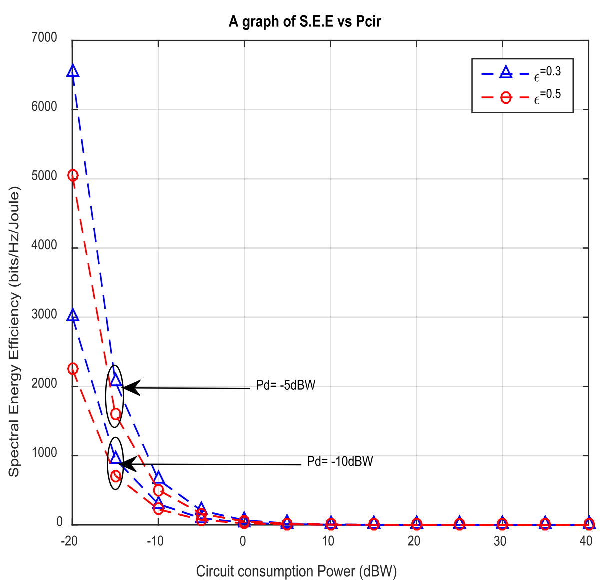

FIGURE 7. **Showing a plot of S.E.E against P_{cir} with varying P_d when P_{cir} totally dominates P_d.**

P_{cir} keeps increasing and this continues until a certain value of P_{cir} is reached, where no matter what value of estimation error or number of BS antennas is, the S.E.E remains constant as seen in the graph when P_{cir} is approximately 40dBW, and all these variations takes place when K is fixed to 50. As illustrated in Fig. 6(b), the S.E.E tends to decrease with an increase in P_{cir} when it happens that P_{cir} totally dominates P_d and furthermore the large K, which is served by the same M has a negative impact on the S.E.E as seen on the graph. For instance when K is 100 the S.E.E at $\varepsilon = 0.3$ is recorded to be approximately 2650 bits/Hz/Joule compared to that of 3016 bits/Hz/Joule when K is taken to be 50. So, this means that when fewer users are served with large portion of BS antennas the S.E.E tends to be improved because every user in the scheduled coherence time gets enough energy signal compared to when there are more users who receive equally small amount of energy signal. The lower the estimation errors are, the better the S.E.E is obtained compared to the large values of channel estimation errors.

Furthermore, as displayed in Fig. 7, the relationship between S.E.E and P_{cir} is depicted with varying P_d in which M is restricted to 500 while K being served by those BS antennas is limited to 50. It can be noted that the S.E.E decreases logarithmically with an increase in P_{cir} until S.E.E approaches zero as P_{cir} keeps increasing. Nonetheless, for the case of transmit power, the larger the transmit power is, the better values of the S.E.E are obtained compared to the small P_d.

However, this is not energy efficient for massive MIMO because some better values of S.E.E can be obtained with small transmit power. Nevertheless, as P_{cir} keeps increasing the difference between large transmit power and small transmit power can be ignored since the S.E.E becomes approximately the same for very large P_{cir}. Likewise, the small values of estimation errors are found to give better S.E.E compared to large values as shown.

The variation of S.E.E against S.E with varying circuit intake power in the presence of channel estimation errors using ZF linear pre-coding scheme is presented in Fig. 8. As it can be observed, the impact of P_{cir} on the S.E.E-SE tradeoff is well illustrated with being 100, $K = 30$ and channel estimation error being 0.5, P_{cir} is assumed to be fixed. As indicated in Fig. 8, the small values of P_{cir} have a good contribution in achieving good S.E.E, furthermore for the fixed P_{cir}, an increased S.E causes a decrease in S.E.E.

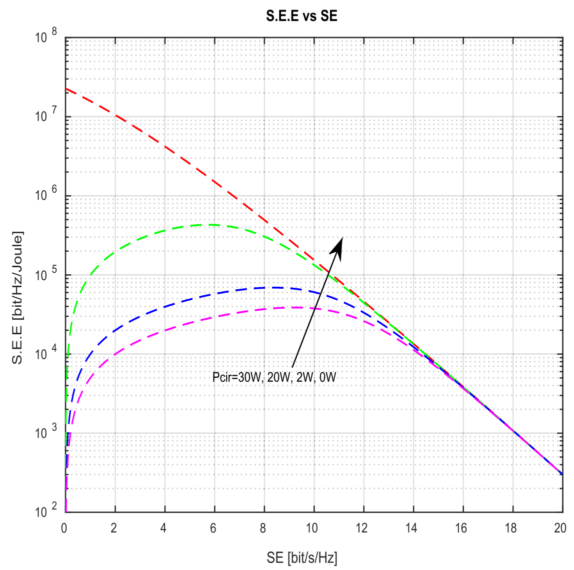

FIGURE 8. A graph of S.E.E against spectral efficiency in the varying conditions of P_{cic}.

By assuming $P_{cir} = 0$W, there is a gradual decrease in S.E.E as S.E increases as shown in the graph with red line. However when P_{cir} increases, let say $P_{cir} = 2$W, there is first an increase in S.E.E with an increase in S.E up to an optimal point from which the S.E.E begins to decrease as S.E keeps increasing as it can be spotted in Fig. 8 with green line. It behaves like unimodal function whereby the function tends to increase first with certain input values and after reaching an optimal point the function starts to decrease as input value keeps increasing. Furthermore, when P_{cir} is approximately equal to zero as shown with red line, the S.E.E tends to decrease as S.E increases which means that P_{cir} has positive impact on the S.E.E, so the presence of P_{cir} tends to have idealistic values of S.E.E with respect to the values of S.E.

Fig. 9 shows the three-dimension S.E.E surface for varying values of M and K in the presence of circuit intake power under imperfect CSI. As it can be observed, there is an optimal S.E.E value marked by a star, which is only obtained when circuit intake power is included in the total intake power model, but when circuit intake power is not included in the model it is very difficult to get an optimal. Showing a 3-Dimension graph of S.E.E against and alue of S.E.E as it can be observed in Fig. 5 in which the value of S.E.E grows large as number of BS antennas grows. Furthermore, as observed in Fig. 2, the surface is concave and the maximum S.E.E value is obtained with considerable number of BS antennas serving reasonable number of users in the presence of circuit intake power.

Fig. 10 shows the association between S.E.E and M when circuit intake power totally dominates downlink transmit power in the presence of channel error estimates. As it can be observed, S.E.E tends to increase first with M up to an optimal point where it starts to decrease as M keeps increasing. Thus, S.E.E forms a concave shape with M and the maximum

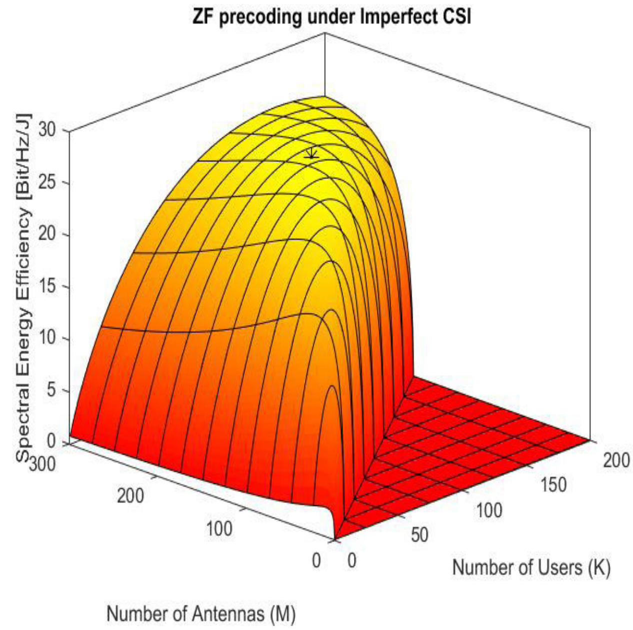

FIGURE 9. Showing a 3-Dimension graph of S.E.E against M and K in the presence of circuit intake power.

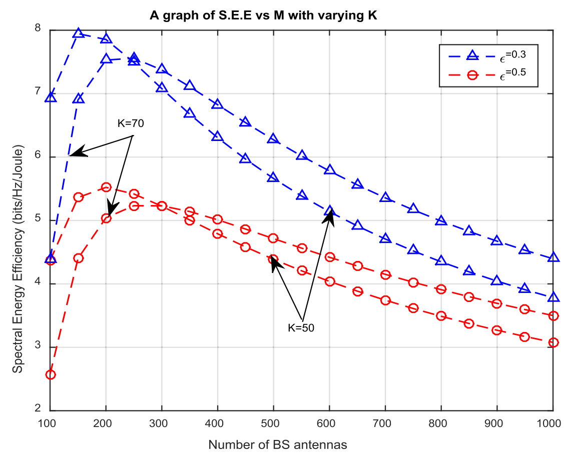

FIGURE 10. A graph of S.E.E against M with varying K when P_{cir} totally dominates d_P.

S.E.E occurs when small number of BS antennas are applied in comparison with large number of BS antennas. Furthermore, for the case of number of users, it can be observed that fewer users tend to give maximum possible S.E.E compared to more users being served by the same number of BS antennas. For instance when $M = 150$ and $K = 50$, the maximum S.E.E obtained is approximately 7.9bits/Hz/Joule for an estimation error of 0.3. But when $= 70$ for the same M and estimation error, the S.E.E is noted to be approximately 6.9 bits/Hz/Joule.

On the other hand, when keeps increasing, the large number of users tends to give better S.E.E compared to the small number of users. For example at $M = 1000$, $K = 50$ and estimation error of 0.3, the S.E.E is noted to be approximately

3.8 bits/Hz/Joule, while when $K = 70$ for the same value of M and estimation error, the S.E.E is approximately 4.45 bits/Hz/Joule. Accordingly, the lower the estimation error the better the S.E.E.

V. CONCLUSION

In this work, we evaluated the impact of circuit power intake on the spectral energy efficiency of massive MIMO in the existence of estimated channel errors with Zero-forcing linear pre-coder being the pre-coding scheme used during evaluation. Based on the new refined total power intake model which comprises of transmit power of the amplifiers and circuit intake power from various analog devices, we formulate closed-form expression for spectral energy efficiency which helps us to evaluate the impact brought by circuit intake power on S.E.E. We evaluated S.E.E in the presence and in the absence of circuit intake power to see what happens to the S.E.E when circuit intake power is ignored. As discussed in the previous section, when circuit intake power is taken into consideration it is very simple to attain maximum S.E.E by using a small number of BS antennas compared with when it is ignored. But when circuit intake power is totally dominated by transmit power, it is not possible to get an optimized S.E.E with fewer antennas as the maximum S.E.E will be obtained only when all antennas are used which interprets the importance of circuit intake power on optimizing S.E.E. Furthermore it is noted that when circuit intake power totally dominates P_{d}, the S.E.E tends to decrease exponentially as circuit intake power increases. It is the same case when P_{d} totally dominates the circuit intake power. This indicates the importance of circuit intake power-downlink transmit power trade-off in the optimization of S.E.E.

Therefore, this study exposes the importance of circuit intake power in evaluating the S.E.E. For the case of channel estimation errors, it is noted that the lower the estimation channel errors are, the better S.E.E is obtained, which means that our model works perfectly in the environment with channel errors.

APPENDIX A

From $R_{sum} = \sum_{k=1}^{K} E\{R_k\}$ Where $E\{.\}$ means the expectation of the achievable rate and

$$R_k = \log_2(1 + SINR_k)$$

$$R_{sum} = KE\left\{\log_2\left(1 + \frac{P_d}{(P_d\varepsilon^2 + 1)\, tr\left(\widetilde{H}\widetilde{H}^H\right)^{-1}}\right)\right\}$$

By Jensen inequality,

$$R_{sum} \le K\log_2\left(1 + \frac{P_d}{(P_d\varepsilon^2 + 1)}E\left\{\frac{1}{tr\left(\widetilde{H}\widetilde{H}^H\right)^{-1}}\right\}\right) \quad (37)$$

Using identity from [44], $E\left\{tr\,(W)^{-1}\right\} \approx K/c\,(M-K)$, where $c \cong \varepsilon^2$, $W \triangleq \widetilde{H}\widetilde{H}^H$ and $W \sim W_k(m, I_m)$ is $K \times K$ Wishart matrix having $M(M > K)$ degrees of freedom, so usually $E\left\{tr\,(W)^{-1}\right\} \approx K/\varepsilon^2\,(M-K)$, then substituting in R_{sum} we will arrive at the required result of equation (13)

APPENDIX B

Lemma 1: The objective function $f(z) = \frac{g\log(a+bz)}{c+dz}$, is a quasi-concave because the level sets $S_\alpha = \{z : f(z) \ge \alpha\} = \{z : \alpha(c+dz) - g\log(a+bz) \ge 0\}$ are firmly convex for $\alpha \in \mathbb{R}$ according to the lemma in [49]. If there is optimum, point z^{opt} such that $g'(z^{opt}) = 0$, this implies that z^{opt} is the maximum value, and the function is rising for $z < z^{opt}$ and decreasing for $z > z^{opt}$. To find the optimum values, we differentiate $f(z)$ and then equate to zero to find the points i.e. $f'(z) = 0$ $f'(z) = \frac{b(c+dz)}{\ln(2)(a+bz)} - d\frac{\ln(a+bz)}{\ln(2)} = 0$ By eliminating the non-zero denominator values of $f'(z)$ and other terms that cancel out. The equation above can be modified as: $\frac{(bc-ad)}{a+bz} - d(\ln(a+bz)+1) = 0$ or

$$\frac{(bc-ad)}{a+bz} = d(\ln(a+bz) - 1). \quad (38)$$

If we let $x = ln(a+bz) - 1$ in which $a + bz = e^{x+1} = e^x e$ and substitute into (38), we will have $\frac{(bc-ad)}{e^x e} = dx \rightarrow \frac{(bc-ad)}{de} = xe^x$

But from $e^{x+1} = a + bz$, then $z = \frac{e^{x+1}-a}{b}$.

APPENDIX C

From Lemma 1, we are required to find the value, which will optimize the problem in equation (27), by assuming M to be real-valued, by comparing the coefficients of Lemma 1 with equation (38) below:

$$S.E.E = \frac{(1 - {}^{\tau}/_{T})K\log_2\left(1 + \frac{P_d\varepsilon^2(M-K)}{K(P_d\varepsilon^2+1)}\right)}{\frac{P_d}{\eta(1-\varsigma)} + MP_0 + KP_1 + P_2}. \quad (39)$$

From which we get:

$$a = \frac{1}{P_d\varepsilon^2 + 1},\ b = \frac{P_d\varepsilon^2}{K(P_d\varepsilon^2+1)},\ c = \frac{P_d}{\eta(1-\varsigma)} + KP_1 + P_2,\ d = P_0,$$

e is the natural number and $g = K(1 - \tau/T)$, so substituting these coefficients in equation (14), then M^{opt} in equation (16) will be obtained.

APPENDIX D

Power consumption parameters P_{dac} and P_{adc} are calculated from the approximations in [50], as follows:

$P_{dac} = \theta(P_s + P_{dyn})$ where P_s is the static intake power and P_{dyn} is the dynamic intake power while θ is just the correcting factor and in this model $\theta = 1$ but $P_s \approx \frac{1}{2}V_{dd}I_0(2^{n_1} - 1)$ where V_{dd} the voltage is supply and I_0 is the current source.

$P_{dyn} = n_1 C_p(2B + f_{cor})V_{dd}^2$ where C_p is the parasitic capacitance, f_{cor} is the corner frequency and B is the bandwidth, so

$$P_{dac} = \theta\left(\frac{1}{2}V_{dd}I_0(2^{n_1} - 1) + n_1 C_p(2B + f_{cor})V_{dd}^2\right)$$

and

$$P_{adc} = \frac{3V_{dd}^2 L_{\min}(2B + f_{cor})}{10^{-0.1525n_2 + 4.838}},$$

in this paper, the following parameters are used to compute the values of P_{dac} and P_{adc}: $V_{dd} = 3\text{V}, f_{cor} = 1\text{MHz}, n_1 = n_2 = 10, L_{\min} = 0.5\mu m, B = 10\text{kHz}, I_0 = 10\mu A$ and $C_p = 1\text{pF}$.

CONFLICT OF INTEREST

The authors declare no any conflict of interest.

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