Power Consumption Evaluation in Random Cellular Networks

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***Abstract*—Recently, issues of power consumption at base stations (BSs) in wireless cellular networks have attracted great interest in both research communities and the industry. In this paper, we investigate the BS power consumption in multiple-input single-output (MISO) Poisson-Voronoi tessellation (PVT) random cellular networks. Taking into account the inter-cell interference, the impact of the traffic demands of users and the spatial traffic intensity on the BS power consumption are jointly considered for MISO PVT random cellular networks. Furthermore, the power consumption required at the BS in a typical PVT cell is modeled through characteristic functions. Simulation results are employed to evaluate the BS power consumption and the performance of the random cellular networks.**

***Index Terms*—Poisson-Voronoi tessellation (PVT); random cellular networks; power consumption; multi-antenna; inter-cell interference.**

I. Introduction

With the rapid development of wireless mobile communications, over 1,200,000 new base stations (BSs) are deployed yearly. And the cost of powering the mobile communication devices amounts to more than 50% of a service provider's overall expenses [1]. In order to alleviate the severe energy shortage and environment pollution, it is a global consensus to improve energy efficiency and reduce carbon emissions. Toward this end, the global information and communication technology (ICT) industry has initialized research on energy efficiency standards [2], [3]. As an important resource in wireless communications, how to reduce the energy consumption in cellular networks in the framework of optimizing or maintaining the system capacity as well as the quality of service (QoS) of users is a great challenge for future cellular networks.

Current research reveals that the energy consumption at BSs accounts for the majority energy consumption (around 80% [4]) in cellular networks. Since the power consumption at BSs are mainly determined by the traffic demand of users and the co-channel interference, the modeling of spatial traffic load and interference is critical in investigating the power consumption at BSs.

In practical cellular networks, the traffic distribution is in general not uniform across space and time dimensions. To investigate the power consumption at BSs, self-similarity and burstiness are the two key features that should be taken into account for traffic distributions. In general cellular networks, the wireless resources (including power) are usually allocated based on the worst-case scenario [5], i.e., the resources are allocated to support the peak traffic demand in the cellular network. This result leads to a waste of resources when there is a low traffic demand in the cellular network. To solve this problem, an opportunistic scheme was proposed in [6] to shut down BSs that are not active. Further studies were presented in [7], where some typical topologies in cellular networks were evaluated and an energy saving of 25-30% could be achieved by shutting down BSs that are not active. However, the above work only considered simplistic scenarios, where the random distribution of traffic across space and time dimensions was not accounted. In this paper, by employing the Pareto distribution to model the burst traffic load of users, a reasonable traffic model is used to evaluate the BS power consumption in PVT random cellular networks.

Various co-channel interference models have been proposed recently. Analytical expressions for the instantaneous and second order distributions of the interference were derived by Yang and Pertropulu [8]. Salbaroli and Zanella derived the characteristic function of co-channel interference in a finite Poisson field of interferers [9]. In [10], the co-channel interference statistics in a Poisson field of interferers was characterized based on a unified framework. However, random network scenarios where only single antenna equipped at the BS was considered in the above work. In this paper, taking into account the path-loss, shadowing and fading effects in wireless channels, we attempt to build a modeling of the interference in MISO random cellular networks. Furthermore, different from the regularity hexagon topology with simple wireless channel conditions, we consider a PVT random cellular network topology in this paper. In view of the random locations of users and BSs, we adopt statistic models, e.g. Poisson point

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process (PPP), in the modeling and evaluation the BS power consumption in random cellular networks. The objective of this paper is to characterize the BS power consumption in PVT random cellular networks based on the spatial traffic intensity and co-channel interference.

The rest of this paper is organized as follows. A brief introduction of multi-cell PVT random cellular networks is described in Section II. Then a power consumption model of the MISO PVT random cellular networks is presented in Section III, where the transmission power required at BSs is derived. Based on the proposed model, numerical results are analyzed in Section IV to evaluate effects of critical parameters on the BS power consumption. Finally, Section V concludes the paper.

II. System Model

To simplify the modeling and simulation, Mobile stations (MSs) are assumed to be equipped with only one antenna. BSs equipped with $N_T \in [1, \cdots)$ antennas are located randomly in an infinite plane $\mathbb{R}^2$. Besides, users' motions are isotropic and relatively slow, such that during an observation period, e.g., a time slot, the relative positions of MSs and BSs are assumed to be stationary. Then, the locations of MSs and BSs can be modeled as two independent Poisson point processes [11], which are denoted as $\Pi_M = \{x_{Mi}, i = 0, 1, 2, \cdots\}$, $\Pi_B = \{y_{Bk}, k = 0, 1, 2, \cdots\}$, where x_{Mi} and y_{Bk} are two-dimensional Cartesian coordinates, denoting the locations of the ith MS as $\mathcal{MS}_i$ and the kth BS as $\mathcal{BS}_k$, respectively. The corresponding intensities of the two Poisson point processes are $\lambda_M \geq 0$ and $\lambda_B \geq 0$. Moreover, only downlinks of cellular networks are considered in this paper.

For a traditional cellular network, assume that a MS associates with the closest BS, which would suffer the least path loss during wireless transmissions. Moreover, every cell is assumed to include only one BS and a few MSs. Then the cell boundary, which can be obtained through the "Delaunay Triangulation" method by connecting the perpendicular bisector lines between each pair of BSs, splits the plane $\mathbb{R}^2$ into irregular polygons that correspond to different cell coverage areas. Such stochastic and irregular topology forms a so-called Poisson-Voronoi tessellation [12]. An illustration of PVT cellular network is depicted in Fig. 1, where each cell is denoted as $\mathcal{C}_k$ $(k = 0, 1, 2, \cdots)$. According to the Palm theory [11], the geometric characteristics of any cell $\mathcal{C}_k$ with the kth BS centered at location y_{Bk} coincide with that of a *typical* PVT cell $\mathcal{C}_0$ where $\mathcal{BS}_0$ locates at a fixed position. This feature implies that the analytical results for a *typical* PVT cell $\mathcal{C}_0$ can be extended to the whole PVT cellular network.

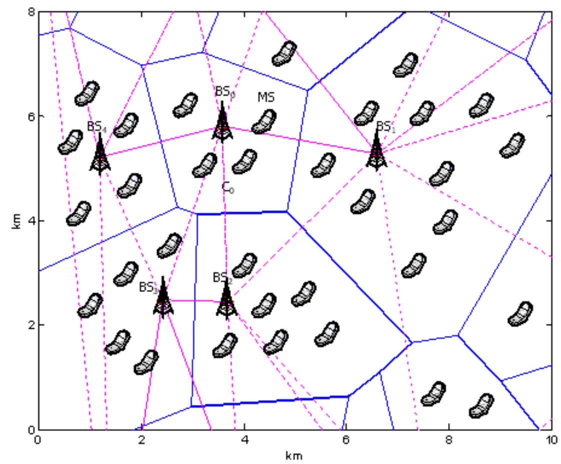

Fig. 1. Illustration of PVT cellular structure.

III. Power Consumption Modeling of MISO PVT Cellular Networks

A. Signal Transmission Processes

The propagation effects of path loss, shadowing and Rayleigh fading are considered in wireless channels. The received signal at the user $\mathcal{MS}_0$ in $\mathcal{C}_0$ is defined as

$$y_0 = \sqrt{P_0}\mathbf{h}_0\mathbf{x}_0 + \sum_{i=1}^{\infty}\sqrt{P_i}\mathbf{h}_i\mathbf{x}_i + \mathbf{n}, \tag{1}$$

where P_0 is the transmission power from $\mathcal{BS}_0$ and $P_i\,(i = 1, 2, 3, \cdots)$ is the interfering transmission power from the ith interfering $\mathcal{BS}_i$. Moreover, P_0 and $P_i\,(i = 1, 2, 3, \cdots)$ are assumed to be independently and identically distributed (i.i.d.). $\mathbf{n}$ is the additive white Gaussian noise (AWGN) vector. $\mathbf{x}_0$ is the desired signal vector and $\mathbf{x}_i\,(i = 1, 2, 3, \cdots)$ is the interfering signal vector with N_T degrees, all these signals are governed by a circularly symmetric complex Gaussian distribution, whose covariance matrix is $\mathbf{Q}_j = E\left\{\mathbf{x}_j\mathbf{x}_j^H\right\}, (j = 1, 2, 3, \cdots)$, where H is the conjugate transpose operation, and the trace of the matrix $\mathbf{Q}_j$ is assumed to be $tr\left\{\mathbf{Q}_j\right\} = 1$. $\mathbf{h}_0$ is the desired channel matrix between $\mathcal{BS}_0$ and $\mathcal{MS}_0$, $\mathbf{h}_i\,(i = 1, 2, 3, \cdots)$ is the interference channel matrix between $\mathcal{BS}_i\,(i = 1, 2, 3, \cdots)$ and $\mathcal{MS}_0$.

To simplify the derivation, assumed that the BS power is equally allocated to every antenna in the BS. In this case, all transmission signal covariance matrixes are defined as $\mathbf{Q}_0 = \mathbf{Q}_i = \frac{1}{N_T}\mathbf{I}_{N_T}, (i = 1, 2, 3, \cdots)$, where $\mathbf{I}_{N_T}$ is the $N_T \times N_T$ unite matrix. Furthermore, the desired signal covariance at $\mathcal{MS}_0$ is $P_0\mathbf{h}_0\mathbf{Q}_0\mathbf{h}_0^H = \frac{P_0}{N_T}\mathbf{h}_0\mathbf{h}_0^H = \frac{P_0}{N_T}\sum\limits_{n=1}^{N_T}|h_{0,n}|^2$ and the interfering signal covariance at $\mathcal{MS}_0$ is $P_i\mathbf{h}_i\mathbf{Q}_i\mathbf{h}_i^H = \frac{P_i}{N_T}\mathbf{h}_i\mathbf{h}_i^H = \frac{P_i}{N_T}\sum\limits_{n=1}^{N_T}|h_{i,n}|^2, (i = 1, 2, 3, \cdots)$, where $|h_{0,n}|$ and $|h_{i,n}|$ are the elements of $\mathbf{h}_0$ and $\mathbf{h}_i$, respectively. Without considering the additional transmission power for interruption in downlinks, and neglecting the noise at MSs, the capacity of wireless channel is assumed to be equal to the average spatial traffic intensity at $\mathcal{MS}_0$, which is formulated as follows

$$B_W \cdot \log_2(1 + \frac{P_0 \sum_{n=1}^{N_T} |h_{0,n}|^2}{P_i \sum_{n=1}^{N_T} |h_{i,n}|^2}) = \rho(x_{MS_0}), \tag{2}$$

where B_W is the bandwidth allocated for $\mathcal{MS}_0$. $\rho(x_{MS_0})$ is the spatial traffic intensity at $\mathcal{MS}_0$ in the PVT cell $\mathcal{C}_0$. Considering that the impact of noise is obviously less than the impact of interference on the downlink capacity in cellular networks, the noise is ignored in (2).

B. Interference Model of $\mathcal{MS}_0$

Every BS in the PVT cellular network is equipped with N_T antennas. The signal transmitted from every antenna is assumed to be passed through independent frequency flat-fading channels, and experienced the independent pass loss, Nakagami fading and Gamma shadowing [13]. In this case, the path loss effect transmitted from the nth $(n \in [1, N_T])$ antenna integrated at the interfering $\mathcal{BS}_i$ to $\mathcal{MS}_0$ is denoted as $r_i{}^{-\sigma}, (i = 1, 2, 3, \cdots)$, where r_i is the Euclid distance between the interfering $\mathcal{BS}_i$ and $\mathcal{MS}_0$, σ is the path loss exponent. The Nakagami fading effect is denoted as $z_{i,n}\,(i = 1, 2, 3, \cdots; n = 1, 2, ..., N_T)$. The Gamma shadowing effect is denoted as $w_i\,(i = 1, 2, 3, \cdots)$.

Assumed that interference is transmitted from adjacent BSs in the infinite plane $\mathbb{R}^2$, the aggregated interference at $\mathcal{MS}_0$ is expressed as

$$\begin{aligned} N_{0-equal} &= \sum_{i \in \Pi_{Inf}} P_i \sum_{n=1}^{N_T} |h_{i,n}|^2 \\ &= \sum_{i \in \Pi_{Inf}} P_i \frac{1}{r_i{}^{\sigma}} w_i \left(\sum_{n=1}^{N_T} |z_{i,n}|^2 \right), \end{aligned} \tag{3a}$$

Let $T_i = w_i \sum_{n=1}^{N_T} |z_{i,n}|^2$,

$$N_{0-equal} = \sum_{i \in \Pi_{Inf}} P_i \frac{1}{r_i{}^{\sigma}} T_i, \tag{3b}$$

where $\Pi_{Inf} = \{y_{Ii}, i = 0, 1, 2, \cdots\}$ is the set of active interfering BSs in the infinite plane $\mathbb{R}^2$ and y_{Ii} is the locations of the ith interfering BS $\mathcal{BS}_i$. Based on the assumption of BSs distribution in a PVT cellular networks, Π_{Inf} can be viewed as an independent thinning process on the BS Poisson point process Π_B. Thus, Π_{Inf} still is a Poisson point process with intensity λ_{Inf}, which generally satisfies $0 \leqslant \lambda_{Inf} \leqslant \lambda_B$.

The Euclid distance between the interfering $\mathcal{BS}_i$ and $\mathcal{MS}_0$ is denoted as $r_i = \|y_{Ii} - x_{M0}\|$. When the location of $\mathcal{MS}_0$ is assumed as the original node or the fixed node, the distribution of $\|y_{Ii} - x_{M0}\|$ has the same distribution of $\|y_{Ii}\|$ based on the Slivnyak theory [11]. Furthermore, (3b) is expressed as

$$N_{0-equal} = \sum_{i \in \Pi_{Inf}} \frac{P_i T_i}{r_i{}^{\sigma}} = \sum_{i \in \Pi_{Inf}} \frac{P_i T_i}{\|y_{Ii}\|^{\sigma}}. \tag{4}$$

Let $T_{i,n} = w_{i,n}|z_{i,n}|^2$ and $T_{i,n}$ follows the Generalized-K distribution(K_G) based on results in [14]. The sum of N_T gamma random processes with the same parameter m is also a gamma distribution with parameter $N_T m$. Therefore, $T_i = w_i \sum_{n=1}^{N_T} |z_{i,n}|^2$ is governed by a K_G distribution, whose probability density function (PDF) is expressed as

$$\begin{aligned} f_{T_i}(y) &= \frac{2\left(\frac{m\lambda}{\Omega}\right)^{\frac{N_T m + \lambda}{2}}}{\Gamma(N_T m)\Gamma(\lambda)} y^{\frac{N_T m + \lambda - 2}{2}} \\ &\cdot K_{\lambda - N_T m}\left(2\sqrt{\frac{m\lambda y}{\Omega}}\right), (y > 0, i = 1, 2, 3...), \end{aligned} \tag{5}$$

where m is the Nakagami shaping factor, $\Omega = \sqrt{(\lambda+1)/\lambda}$ is the signal average received power experienced Nakagami fading channels, $\lambda = 1/(e^{(\sigma_{dB}/8.686)^2} - 1)$ is a constant, σ_{dB} is the shadowing deviation [13], $\Gamma(\cdot)$ is the Gamma function, $K_{\lambda - N_T m}(\cdot)$ is the modified Bessel function of the second kind with order $\lambda - N_T m$.

Let $Q_i = P_i T_i, (i = 1, 2, 3...)$ (P_i and T_i are independently each other), and the PDF and characteristic function of Q_i are denoted as $f_Q(q)$ and $\Phi_Q(\omega)$, respectively. Based on the Campbell theorm for a marked Poisson point process [11] [10], the characteristic function of $N_{0-equal}$ is derived as follows

$$\begin{aligned} &\Phi_{N_{0-equal}}(\omega) = E\left\{e^{j\omega \cdot N_{0-equal}}\right\} \\ &= \exp\left(-2\pi\lambda_{Inf} \iint \left(1 - e^{j\omega \frac{q}{r^{\sigma}}}\right) f_Q(q) dq r dr\right) \\ &= \exp\left(-2\pi\lambda_{Inf} \int_r \left[1 - \Phi_Q\left(\frac{\omega}{r^{\sigma}}\right)\right] r dr\right) \\ &= \exp\left\{-\delta|\omega|^{\frac{2}{\sigma}} \left[1 - j\beta \mathrm{sign}(\omega) \tan\left(\frac{\pi}{\sigma}\right)\right]\right\}, \end{aligned} \tag{6a}$$

where $E\{\cdot\}$ denotes an expectation operation, $\mathrm{sign}(\omega)$ is a sign function, and

$$\begin{aligned} \delta &= \lambda_{Inf} \frac{\pi\Gamma\left(2 - \frac{2}{\sigma}\right)\cos\left(\frac{\pi}{\sigma}\right)}{1 - \frac{2}{\sigma}} E\left(Q_i{}^{\frac{2}{\sigma}}\right) \\ &= \lambda_{Inf} \frac{\pi\Gamma\left(2 - \frac{2}{\sigma}\right)\cos\left(\frac{\pi}{\sigma}\right)}{1 - \frac{2}{\sigma}} E\left(P_i{}^{\frac{2}{\sigma}}\right) E\left(T_i{}^{\frac{2}{\sigma}}\right), \\ &(i = 1, 2, 3...). \end{aligned} \tag{6b}$$

Moreover, $N_{0-equal}$ is simply denoted to follow a stable process as $N_{0-equal} \sim Stable\left(\alpha = \frac{2}{\sigma}, \beta = 1, \delta, \mu = 0\right)$.

Based on (5) and Table of Integrals in [15], $E\left(P_i{}^{\frac{2}{\sigma}}\right)$ is further derived as follows

$$E\left(P_i{}^{\frac{2}{\sigma}}\right) = \left(\frac{m\lambda}{\Omega}\right)^{-\frac{2}{\sigma}} \frac{\Gamma(\lambda + \frac{2}{\sigma})\Gamma(N_T m \frac{2}{\sigma})}{\Gamma(N_T m)\Gamma(\lambda)}, (i = 1, 2, 3...). \tag{7}$$

C. Transmission Power Consumption on Downlinks

To simplify the derivation, let $Z = \frac{P_0 \sum_{n=1}^{N_T} |h_{0,n}|^2}{N_{0-equal}} = \frac{P_0 \sum_{n=1}^{N_T} \frac{1}{r_0{}^\sigma} w_0 |z_{0,n}|^2}{N_{0-equal}}$. Furthermore, the transmission power consumption P_0 from $\mathcal{BS}_0$ to $\mathcal{MS}_0$ is expressed as

$$P_0 = \frac{N_{0-equal} \cdot Z \cdot r_0{}^\sigma}{T_0}, \tag{8}$$

where $T_0 = \sum_{n=1}^{N_T} w_0 |z_{0,n}|^2$, r_0 is the Euclid distance between $\mathcal{BS}_0$ and $\mathcal{MS}_0$, w_0 is the shadowing between the every antenna of $\mathcal{BS}_0$ and $\mathcal{MS}_0$, $|z_{0,n}|$ is the Nakagami fading between the nth antenna of $\mathcal{BS}_0$ and $\mathcal{MS}_0$.

To evaluate the impact of self-similar traffic load on downlinks transmission power, the spatial traffic intensity $\rho(x_{MS_0})$ at $\mathcal{MS}_0$ is assumed to be governed by a Pareto distribution with infinite variance in our study. Moreover, the spatial traffic intensity of all MSs is assumed to be i.i.d.. Then, a PDF of $\rho(x_{MS_0})$ is given by

$$f_\rho(x) = \frac{\theta \rho_{min}^\theta}{x^{\theta+1}}, (x \geq \rho_{min} > 0), \tag{9}$$

where $\theta \in (1, 2]$ reflects the heaviness of the distribution tail. When the value of heaviness index θ is closer to one, the distribution tail of spatial traffic intensity becomes heavier. This result implies slower decaying in the tail of PDF curve and more burstiness in the defined traffic load. Parameter ρ_{min} represents the minimum traffic rate preserved for MS's QoS guarantee. Based on (2) and $f_\rho(x)$, the PDF of variable Z is derived as

$$\begin{aligned} f_Z(z) &= \frac{dF_\rho\left(B_W \log_2(1+Z)\right)}{dz} = \frac{\theta \rho_{min}^\theta B_W{}^{-\theta}}{\ln 2 \cdot (1+z)} \\ &\cdot \left(\log_2(1+z)\right)^{-\theta-1}, \left(z > z_0 = 2^{\rho_{min}/B_W} - 1\right). \end{aligned} \tag{10}$$

As a consequence, the PDF of r_0 is derived as

$$\begin{aligned} f_{r_0}(r) &= \frac{dPr\{r_0 \leqslant r\}}{dr} = \frac{d\{1 - Pr\{r_0 \geq r\}\}}{dr} \\ &= -\frac{dPr\{r_0 \geq r\}}{dr} = -\frac{d\left(\frac{\left(\lambda_B \pi r^2\right)^0 e^{-\lambda_B \pi r^2}}{0!}\right)}{dr} \\ &= 2\pi\lambda_B r e^{-\pi\lambda_B r^2}, \end{aligned} \tag{11}$$

where $Pr\{r_0 \geq r\}$ is the probability of the event: there is no BS in a circle where the original node is x_{M0} and the radius is r [16].

Furthermore, the PDF of $r_0{}^\sigma$ is derived as follows

$$f_{r_0}^\sigma(r) = \frac{1}{\sigma} r^{\frac{2}{\sigma}-1} \cdot 2\pi\lambda_B e^{-\pi\lambda_B r^{2/\sigma}}. \tag{12}$$

Let $X = \frac{Z \cdot r_0{}^\sigma}{T_0}$ and denote the PDF of random variable X as $f_X(x)$. Moreover, the PDF of random variable T_0 is denoted as $f_{T_0}(y)$, which has the similar expression as $f_{T_i}(y)$. Based on (6a), (10), (12) and $f_{T_0}(y)$, the characteristic function of P_0 is derived as

$$\begin{aligned} \Phi_{P_0}(\omega) &= \int_x \Phi_{N_{0-equal}}(\omega x) \cdot f_X(x) dx = \int_x \Phi_{N_{0-equal}}(\omega x) \\ &\cdot \left(\iint_{z,y} \frac{y}{z} f_Z(z) f_{r_0}^\sigma(\frac{xy}{z}) f_{T_0}(y) dz dy\right) dx \\ &= \iint_{y,z} \frac{\pi\lambda_B}{G(\omega) z^{2/\sigma} y^{-2/\sigma} + \pi\lambda_B} f_{T_0}(y) f_Z(z) dy dz, \end{aligned} \tag{13a}$$

with

$$G(\omega) = \delta|\omega|^{\frac{2}{\sigma}} \left[1 - j \cdot \mathrm{sign}(\omega) \tan\left(\frac{\pi}{\sigma}\right)\right]. \tag{13b}$$

D. Power Consumption model at BS

It is assumed that all wireless downlinks are assigned appropriate transmission power to satisfy the required traffic rate, then the required total BS transmission power in a typical PVT cell $\mathcal{C}_0$ is given by

$$\mathcal{P}_{\mathcal{C}0} \overset{def}{=} \sum_{x_{Mi} \in \Pi_M} P_k \cdot \mathbf{1}\{x_{Mi} \in \mathcal{C}_0\}, \tag{14}$$

where P_k is the transmission power from $\mathcal{BS}_0$ to the user $\mathcal{MS}_k$. $\mathbf{1}\{\cdots\}$ is an indicator function, which equals to 1 when the condition inside the bracket is satisfied and 0 otherwise.

P_k is assumed to be an i.i.d.. The PDF and characteristic function of P_k are denoted as $f_P(p)$ and $\Phi_P(\omega)$, respectively. Based on the Campbell theorem for a marked Poisson point process [11], the characteristic function of $\mathcal{P}_{\mathcal{C}0}$ is derived as follows

$$\begin{aligned} &\phi_{\mathcal{P}_{\mathcal{C}0}}(\omega) \\ &= E\left\{\exp\left[\iint_{x,p} \left(e^{j\omega p} - 1\right) f_P(p) dp \cdot \mathbf{1}\{x \in \mathcal{C}_0\} 2\pi\lambda_M x dx\right]\right\} \\ &= \exp\left[-2\pi\lambda_M \int_0^\infty \left(1 - \phi_P(\omega)\right) \cdot E\left(\mathbf{1}\{x \in \mathcal{C}_0\}\right) x dx\right], \end{aligned} \tag{15}$$

Based on (11), we get the result of $E\left(\mathbf{1}\{x \in \mathcal{C}_0\}\right) = e^{-\pi\lambda_B x^2}$. Substituting this result into (15)

$$\begin{aligned} &\phi_{\mathcal{P}_{\mathcal{C}0}}(\omega) \\ &= \exp\left[-2\pi\lambda_M \int_0^\infty \left(1 - \phi_P(\omega)\right) \cdot e^{-\pi\lambda_B x^2} x dx\right] \\ &= \exp\left[-\frac{\lambda_M}{\lambda_B}\left(1 - \phi_P(\omega)\right)\right] \\ &= \exp\left[-\frac{\lambda_M}{\lambda_B}\left(1 - \phi_{P_0}(\omega)\right)\right]. \end{aligned} \tag{16}$$

However, due to the fact that an infinite demand for transmission power is required by a BS to satisfy all traffic rates in wireless downlinks, the required total BS transmission power is approximate infinity. Considering that perfect power control is an ideal case, a maximal BS transmission power threshold P_{max} is configured in this paper. In this case, some wireless downlinks will be interrupted when required total BS transmission power exceeds the maximal BS transmission power threshold. Therefore, the practical total BS transmission power in a typical PVT cell $\mathcal{C}_0$ can be further derived by "truncating" $\mathcal{P}_{\mathcal{C}0}$ in the interval $(0, P_{max}]$, whose PDF is given as

$$f_{\mathcal{P}_{\mathcal{C}0\_\mathrm{real}}}(x) = \begin{cases} f_{\mathcal{P}_{\mathcal{C}0}}(x)/F_{\mathcal{P}_{\mathcal{C}0}}(P_{max}), & x \le P_{max}; \\ 0, & x > P_{max}. \end{cases} \tag{17a}$$

with

$$F_{\mathcal{P}_{\mathcal{C}0}}(P_{max}) = \int_0^{P_{max}} f_{\mathcal{P}_{\mathcal{C}0}}(x)dx, \tag{17b}$$

where $f_{\mathcal{P}_{\mathcal{C}0}}(x)$ is the PDF of $\mathcal{P}_{\mathcal{C}0}$, which can be numerically calculated by its characteristic function in (16).

Then, the average practical total BS transmission power is derived as

$$\begin{aligned} E(\mathcal{P}_{\mathcal{C}0\_\mathrm{real}}) &= \int_0^{P_{max}} x \frac{f_{\mathcal{P}_{\mathcal{C}0}}(x)}{F_{\mathcal{P}_{\mathcal{C}0}}(P_{max})} \\ &= \frac{1}{F_{\mathcal{P}_{\mathcal{C}0}}(P_{max})} \int_0^{P_{max}} x f_{\mathcal{P}_{\mathcal{C}0}}(x)dx. \end{aligned} \tag{18}$$

IV. Simulation Results and Performance Analysis

Based on the proposed BS power consumption model, the effect of some parameters on the BS total transmission power of PVT cellular networks are numerically analyzed in this section. Default simulation parameters are configured as follows: Nakagami shaping factor $m = 1$, shadowing deviation $\sigma_{dB} = 6$, path loss exponent $\sigma = 4$ [17]; the number of BS transmission antennas is configured as $N_T = 4$; the heaviness index $\theta = 1.8$ and the minimum rate with the channel bandwidth B_W is normalized as $\rho_{min} = 2.5 bits/s/HZ$, then the minimum SINR is configured as $Z_{min} = 24.49$ [18]; the moment of transmission power is configured as $E(P_i^{\frac{2}{\sigma}}) = 10^{-2}W$ [19]; the BS intensity is configured as $\lambda_B = 1/(\pi \cdot 800^2)m^{-2}$; the intensity ratio of MSs to BSs is configured $\lambda_M/\lambda_B = 30$; the intensity of interfering links is configured as $\lambda_{Inf} = 0.9\lambda_B$; the maximal available transmission power at BS is configured as $P_{max} = 40W$ [20].

Fig. 2 illustrates the realistic total BS transmission power with respect to SINR under different number of BS transmission antennas. It is shown that the realistic total BS transmission power increases with an increase of SINR. When the values of SINR is fixed, the realistic total BS transmission power decreases with an increase of the antenna number N_T.

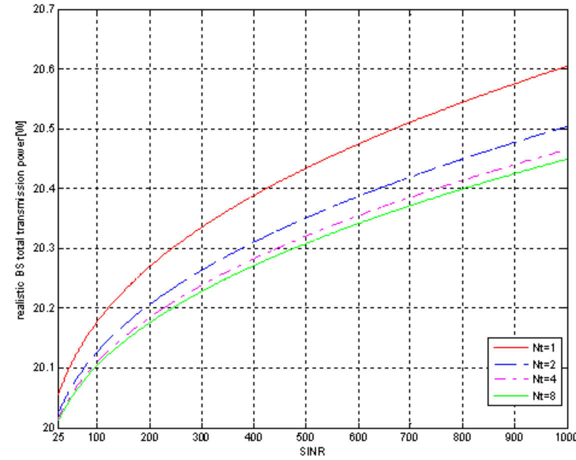

Fig. 2. The realistic total BS transmission power with respect to SINR under different number of BS transmission antennas.

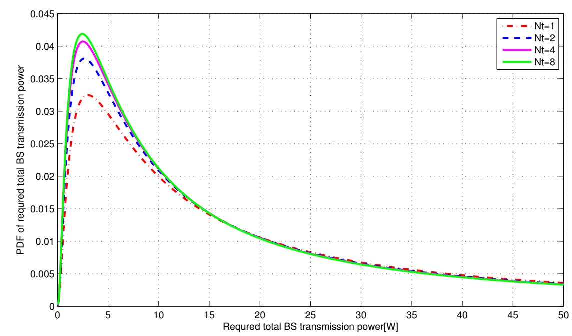

Fig. 3. The PDF of required total BS transmission power under different number of BS transmission antennas.

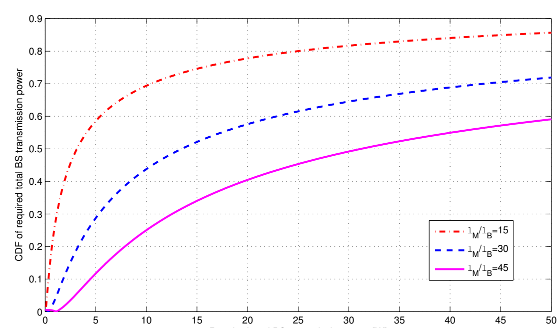

Fig. 4. The CDF of required total BS transmission power under different intensity ratios of MSs to BSs.

The PDF of required total BS transmission power under different number of BS transmission antennas is illustrated in Fig. 3. The curves in Fig. 3 show that the probability mass is shifted to the left with an increase of transmission antenna number. This result indicates that a lower transmission power is implemented with a larger number of transmission antennas

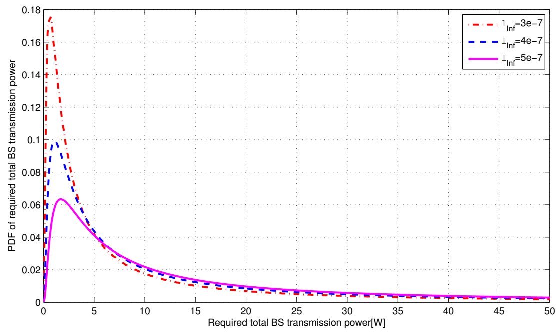

Fig. 5. The PDF of required total BS transmission power under different interfering link intensities.

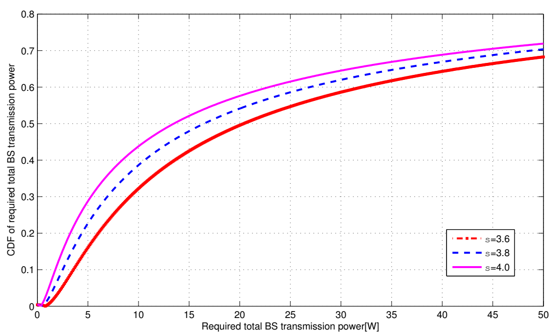

Fig. 6. The CDF of required total BS transmission power under different path loss exponents.

at BS.

The CDF of required total BS transmission power under different intensity ratios of MSs to BSs is illustrated in Fig. 4. The curves in Fig.4 show that the probability mass is shifted to the right with an increase of intensity ratios of MSs to BSs λ_M/λ_B. This is due to the fact that an increasing intensity ratio of MSs to BSs will result in an increase of total BS transmission power.

The PDF of required total BS transmission power under different interfering link intensities is illustrated in Fig. 5. The curves in Fig. 5 show that the probability mass is shifted to the right with an increase of interfering link intensity λ_{Inf}. This result indicates that an additional BS power consumption is transmitted to compensate for the corresponding SINR degradation with an increase of interfering link intensity.

The CDF of required total BS transmission power under different path loss exponents is illustrated in Fig. 6. The curves in Fig. 6 show that the probability mass is shifted to the right with a decrease with path loss exponent. This result indicates that the larger transmission power is required with the lower path loss exponent due to increasing interference.

V. Conclusion

Based on PVT random cellular network scenarios, a power consumption model of BS with multi-antennas is proposed. Moreover, the impact of co-channel interference and spatial traffic density on the BS power consumption are analyzed for PTV random cellular networks. Numerical results have shown the impacts of critical parameters on the BS power consumption, including the number of BS antennas, intensity ratio of MSs to BSs, interfering link intensity and path loss exponents in PVT random cellular networks. Our analysis indicates the BS power consumption can be optimized by trade-off these critical parameters. In the future, we plan to investigate the BS power consumption model for MIMO PVT random cellular networks.

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