ON THE PERFORMANCE OF CLOUD RADIO ACCESS NETWORKS USING MATÉRN HARD-CORE POINT PROCESSES

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ABSTRACT

In this paper, the performance of a cloud radio access network (CRAN) is analysed, which consists of multiple randomly distributed remote radio heads (RRHs) and a macro base station (MBS). Different from previous works on CRAN where Poisson Point Process (PPP) is used to model spatial distribution of RRHs, a more realistic Matérn Hard-core point process (MHCPP) model is adopted in this work. To compare system performance of CRAN when different transmission strategies are used, two RRH selection schemes are adopted including 1) the best RRH selection (BRS) and 2) all RRHs participation (ARP). Considering downlink transmission, the outage probability and system throughput of CRAN are analytically characterized. The presented results demonstrate that compared to PPP model, the presence of hard-core distance will increase outage probability. Furthermore, the BRS scheme is more energy-efficient than the ARP scheme. Moreover, it is shown that the hard-core distance has a more significant impact on systems with higher intensity of PPP distributed candidate points and in large hard-core distance regime increasing the intensity of candidate points can only provide a small improvement in outage performance.

Index Terms— Cloud radio access networks, Matérn Hard-core point process, remote radio heads, stochastic geometry.

1. INTRODUCTION

Cloud radio access networks (CRANs) have recently triggered enormous research interest as potential network architectures for 5G wireless networks to provide increased network capacity, energy efficiency, reduced network capital expenditure (CAPEX) and operating expenses (OPEX) [1–5]. In CRAN system, a central location/data centre works with multiple remote radio heads (RRHs) by connecting through optical fibre and the users are served by the RRHs. Replacing the baseband units in the current system by the central data centre improves the power efficiency significantly. Meanwhile, the cost of the system is lowered due to the use of simpler RRHs [4].

The distributed antenna system (DAS) where each RRH is equipped with single antenna has been studied and analyzed in [6–9]. The ergodic capacity of such system was investigated in [6, 8] whereas the spectrum efficiency was studied in [7] and the energy efficiency was analyzed in [9] by antenna selection strategy. However, all these works only considered that the RRHs were located at fixed regular locations. The ergodic capacity of a multi-cell PPP distributed RRHs system was studied in [10] where the authors showed that the system provided better cell-edge performance and higher capacity in a user-centric configuration. Recently, the single nearest and N-nearest RRH association strategies were presented and the ergodic capacity of CRAN was studied in [11] where the locations of RRHs were modeled as a PPP. However, the authors of [11] only derived the approximation of ergodic capacity in high SNR regime.

Nevertheless, the assumption in the previous works that the RRHs are equipped with single antenna and are distributed as PPP is inconsistent with the actual scenario. Therefore, we have considered a more general and realistic scenario in this paper where the macro base station (MBS) and all RRHs are equipped with multiple antennas. Moreover, instead of considering PPP, all RRHs are randomly distributed according to a Matérn Hard-core point process (MHCPP) [12]. In the MHCPP, the points are selected from a standard PPP, but there is a minimum distance requirement for all points. Since the spacial correlations are considered, MHCPP can better capture the distribution of RRHs in practical scenario. In [13], performance of random carrier-sense multiple access (CSMA) wireless networks was analyzed by considering classical HCPP and modified HCPP models while the transmitters and receivers were considered in pairs and the distance between each pair of transmitter and receiver was assumed to be fixed. In [14], PPP, HCPP and Strauss process (SP) were used to model the locations of BSs in real cellular networks obtained from a public database while their fitness was compared through coverage probability. In addition, the authors showed that HCPP and SP models led to significantly more accurate results than the PPP, commonly used in previous works.

Considering various benefits of HCPP compared to PPP, we use HCPP to model the distribution of RRHs in CRANs. Different from previous works where HCPP is simply approximated with a homogeneous PPP of the same intensity (e.g. [15]), we propose a new approach which uses homogeneous PPP of a higher intensity and probability of classifying candidate points to approximated HCPP. The outage probability of the two different transmission schemes is studied and compared while expressions of throughput are provided. Analytical results are verified by Monte Carlo simulations.

2. SYSTEM MODEL

We consider a downlink CRAN system as shown in Fig. 1 where a user, U, with single antenna is served by a central intelligence unit (also referred to as MBS) and a group of RRHs. The locations of RRHs are assumed to obey a MHCPP, Φ_M, with intensity λ_M and a minimum distance r_d between different RRHs, which is generated from a corresponding homogeneous PPP Φ_P with intensity $\lambda_P = \frac{-1}{\pi r_d^2}\ln(1-\pi r_d^2\lambda_M)$ [16]. In this work, we denote all points in Φ_P as candidate points and all candidate points are randomly ordered. A RRH is denoted as the ith RRH if the RRH is located at the ith candidate point. The locations of RRHs are obtained by applying the thinning rules to Φ_P. For a candidate point $x \in \Phi_P$, an independent mark $m_x \sim \mathcal{U}[0,1]$ is associated to x. The candidate point x is

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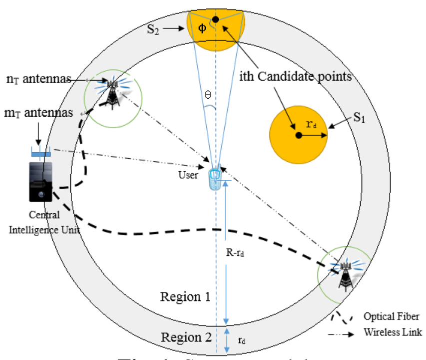

Fig. 1. System model

retained in Φ_M (i.e. x is selected as the location of a RRH) if and only if (iff) it has the lowest mark compared to all candidate points in the circle centered at x with radius r_d. The MBS is equipped with m_T antennas, whereas each RRH has n_T antennas. Without loss of generality, the MBS is assumed to be located on the edge of the circular region $\mathcal{D}$[1]. The channels between the ith RRH and the user U can be expressed as

$$\mathbf{g}_i = (g_{i,1}, \ldots, g_{i,n_T})^T \quad (1)$$

where $g_{i,t}$ is the channel gain between the tth antenna of ith RRH and the user. Considering Rayleigh fading in this system, $g_{i,t}$ can be modeled as a complex Gaussian random variable with zero mean and unit variance, i.e. $g_{i,t} \sim \mathcal{CN}(0,1)$. The received signal at the user from the ith RRH is given by

$$y_i = \frac{\mathbf{g}_i^T}{r_i^\alpha}\mathbf{x}_i + n \quad (2)$$

where $\mathbf{x}_i \in \mathbb{C}^{n_T \times 1}$ and y_i are the transmitted and received signals. We assume that the available transmit power at each RRH is P, i.e., $\mathrm{E}\left[\mathrm{tr}(\mathbf{x}_i^\dagger \mathbf{x}_i)\right] \le P$. The white Gaussian noise is denoted by n, i.e. $n \sim \mathcal{CN}(0, N_0)$. The path loss is represented by $\frac{1}{r_i^\alpha}$, where r_i is the distance between the user and the ith RRH, and α is the path loss exponent[2]. As all candidate points are independently and uniformly distributed in $\mathcal{D}$, the p.d.f. of r_i can be presented as

$$f_{r_i}(x) = \frac{2x}{R^2}, \quad 0 \le x \le R. \quad (3)$$

Meanwhile, the channels between the user and the MBS are denoted as $\mathbf{g}_0 = (g_{0,1}, \ldots, g_{0,m_T})^T$.

3. PERFORMANCE ANALYSIS

It is assumed that the MBS and all RRHs transmit using MRT. To analyse the performance of RRHs, the p.d.f. of the distance between a generic RRH and the user should be obtained. However, the locations of RRHs are assumed to follow a HCPP and it is not trivial to obtain the p.d.f. of the distance between a generic RRH and the user. Because of this, it is worthwhile to notice that candidate points, which meet the hard-core distance requirement, and RRHs share the same statistical characteristics. Therefore, instead of focusing on the statistical characteristics of a generic RRH in Φ_M, it is preferable to analyse the statistical characteristics of a candidate point in Φ_P.

3.1. BRS

In the BRS scheme, only the RRH or the MBS which has the best channel is selected for transmission.

3.1.1. *Outage probability*

As mentioned earlier, candidate points, which meet the hard-core distance requirement, share the same statistical characteristics with RRHs. Instead of deriving the outage probability of RRHs in Φ_M, it is preferable to consider the outage probability of candidate points in Φ_P.

Since the locations of RRHs are selected from candidate points, when the ith candidate point has been eliminated (i.e. no RRH is located at the ith candidate point), the outage probability of this candidate point equals to 1. Thus, the overall outage probability of the ith candidate point can be expressed as

$$\mathcal{P}_i(z) = \int_0^R f_{r_i}(r)\left(Pc(r)\mathcal{P}_{\gamma_i|r}(z) + (1 - Pc(r))\right) dr \quad (4)$$

where $Pc(r)$ is the probability to classify a candidate point in Φ_P as a point in Φ_M (i.e. a candidate point is selected as a location of a RRH) and $\mathcal{P}_{\gamma_i|r}(z)$ is the conditioned outage probability of the ith RRH when the distance to the user is fixed to r. The expression of $Pc(r)$ is given by the following *Lemma*.

Lemma 1: When there are N candidate points, the probability that a candidate point is selected as a location of a RRH can be expressed as (5), where $S_2 = \theta R^2 - r_i R \sin(\theta) + \phi r_d^2$, r_i is the distance from the ith candidate point to the user U, $\theta = \arccos\left(\frac{R^2 + r_i^2 - r_d^2}{2 r_i R}\right)$ and $\phi = \arccos\left(\frac{r_i^2 + r_d^2 - R^2}{2 r_i r_d}\right)$.

Proof. It is defined that two points are neighbors iff the distance between them is less than the hard-core distance r_d. It can be observed from Fig. 1 that a candidate point can be a neighbor of the ith candidate point iff it is located in region S (S_1 or S_2), i.e. the probability that two candidate points are neighbors is $P_{nei} = \frac{S}{\pi R^2}$. We denote the distance between the ith candidate point and the center of the circular region as r_i, then the area of S can be written as

$$S(r_i) = \begin{cases} S_1 = \pi r_d^2 & 0 \le r_i \le R - r_d \\ S_2 = \theta R^2 - r_i R \sin(\theta) + \phi r_d^2 & R - r_d < r_i \le R \end{cases} \quad (6)$$

If the ith candidate point has n neighbors, then the probability that it has the lowest mark is $P_m = \frac{1}{n+1}$. Since it is assumed there are N candidate points in the circular region, the probability that the ith candidate point is classified as a point in Φ_M is

$$Pc(r_i) = \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{1}{n+1} \left(\frac{S(r_i)}{\pi R^2}\right)^n \left(1 - \frac{S(r_i)}{\pi R^2}\right)^{N-n-1}.$$

Using the expression of $S(r_i)$ in (6), the expression of $Pc(r_i)$ can be obtained as shown in (5) and *Lemma* 1 is proved. □

The channel gain between the ith RRH and the user can be expressed as

$$\gamma_i = \frac{\|\mathbf{g}_i\|^2}{r_i^\alpha} = \frac{\sum_{j=1}^{n_T} g_{i,j}^2}{r_i^\alpha}. \quad (7)$$

For a fixed r_i, since $g_{i,j} \sim \mathcal{CN}(0,1)$, $\gamma_i r_i^\alpha = \sum_{j=1}^{n_T} g_{i,j}^2$ follows the gamma distribution $\Gamma(n_T, 1)$. Therefore, $\mathcal{P}_{\gamma_i|r_i}(z)$ can be obtained as

$$\mathcal{P}_{\gamma_i|r_i}(z) = \frac{\nu(n_T, z r_i^\alpha)}{(n_T - 1)!} \quad (8)$$

where $\nu(n,x) = \int_0^x t^{n-1} e^{-t} dt$ is the lower incomplete gamma function [17, Eq. (8.350)].

It can be noticed from (5) that $Pc_2(r)$ is dependent on r, therefore it is not trivial to derive an exact expression of $\mathcal{P}_i(z)$. Assuming $R >> r_d$, the approximated outage probability of the ith candidate point is given by Proposition 1.

[1]The MBS is placed on the edge of the circular region to ensure that the user will still be served when there is no RRH in the circular region.

[2]Note that normally the distance $r_i \gg 1$ in realistic scenarios. Because of this, we approximate the the path loss $\frac{1}{1+r_i^\alpha}$ by $\frac{1}{r_i^\alpha}$ for the sake of mathematical tractability, without compromising on the fundamental performance insights of the system.

$$Pc(r_i) = \begin{cases} Pc_1(r_i) = \sum_{n=0}^{N-1} \frac{\binom{N-1}{n}}{n+1} \left(\frac{r_d^2}{R^2}\right)^n \left(1 - \frac{r_d^2}{R^2}\right)^{N-n-1} & 0 \le r_i \le R - r_d \\ Pc_2(r_i) = \sum_{n=0}^{N-1} \frac{\binom{N-1}{n}}{n+1} \left(\frac{S_2}{\pi R^2}\right)^n \left(1 - \frac{S_2}{\pi R^2}\right)^{N-n-1} & R - r_d < r_i \le R \end{cases} \quad (5)$$

Proposition 1. *When $R >> r_d$, the outage probability of the ith candidate point can be approximated as*

$$\tilde{\mathcal{P}}_i(z) = 1 - \frac{2Pc_1(r)}{R^2} \sum_{k=0}^{n_T-1} \frac{\nu(k+\frac{2}{\alpha}, zR^\alpha)}{k!\alpha z^{\frac{2}{\alpha}}}. \quad (9)$$

Proof. When $R >> r_d$, $Pc_2(r_i) \approx Pc_1(r_i)$. Substituting the expressions of $\mathcal{P}_{\gamma_i|r_i}(z)$ and $Pc(r_i)$ into (4) and solving the resulting integral by using the series representation $\nu(s,x) = \sum_{n=0}^{\infty} \frac{(-1)^n x^{s+n}}{n!(s+n)}$ to yield (9). □

The outage event occurs when all channels of both the MBS and the RRHs are in outage. Therefore, the overall outage probability for the BRS scheme can be expressed as

$$\mathcal{P}_{BRS}(\epsilon) = \sum_{N=0}^{\infty} \mathcal{P}_{\gamma_0(\epsilon)} \left(\tilde{\mathcal{P}}_i(\epsilon)\right)^N \frac{\mu^N e^{-\mu}}{\Gamma(N+1)} \quad (10)$$

where $\mathcal{P}_{\gamma_0}(z)$ is the outage probability of the MBS, $\epsilon = \frac{2^{\mathcal{R}}-1}{\rho}$, $\mathcal{R}$ is the data rate, ρ is the transmitted power over receiver noise and $\mu = \frac{-R^2}{r_d^2} \ln(1 - \pi r_d^2 \lambda_M)$. For the MBS, $\mathcal{P}_{\gamma_0}(z)$ can be obtained by substituting $n_T = m_T$ and $r_i = R$ into (8), and given by

$$\mathcal{P}_{\gamma_0}(z) = \frac{\nu(m_T, zR^\alpha)}{(m_T-1)!}. \quad (11)$$

3.1.2. Throughput

The throughput for the BRS scheme is written as

$$\mathcal{R}_{BRS} = \log_2(1+\varrho)(1 - \mathcal{P}_{BRS}(\epsilon)) \quad (12)$$

where ϱ is the receive SNR at the user. Assuming $R >> r_d$, substituting the expressions of $\mathcal{P}_{BRS}(\epsilon)$ and $\varrho = \epsilon\rho$ into (12) to yield

$$\mathcal{R}_{BRS} = \mathcal{R}\left(1 - \sum_{N=0}^{\infty} \mathcal{P}_{\gamma_0}(\epsilon) (\mathcal{P}_i(\epsilon))^N \frac{\mu^N e^{-\mu}}{\Gamma(N+1)}\right) \quad (13)$$

where $\mathcal{R} = \log_2(1+\varrho)$ and the expressions of $\mathcal{P}_i(\epsilon)$ and $\mathcal{P}_{\gamma_0}(\epsilon)$ can be found in (9) and (11).

3.2. ARP scheme

3.2.1. Outage probability

In this scheme, all RRHs and the MBS are selected to form a distributed antenna array for transmission. Therefore, the outage event will occur if the overall SNR from the MBS and the RRHs is in outage.

Assuming there are N candidate points in Φ_P, the overall channel gain at the user can be given by

$$\gamma = \gamma_0 + \sum_{i=1}^{N} \gamma_i = \gamma_0 + \gamma_{sum} \quad (14)$$

where γ_0 is the channel gain of the MBS, γ_i is the channel gain of the ith candidate point and $\gamma_{sum} = \sum_{i=1}^{N} \gamma_i$. Outage occurs when γ is less than a pre-defined threshold ϵ, i.e.

$$\mathcal{P}_{ARP}(\epsilon|N) = Pr(\gamma < \epsilon) = \int_0^\epsilon f_{\gamma_0}(z) \int_0^{\epsilon - z} f_{\gamma_{sum}}(y) dy dz \quad (15)$$

where $f_{\gamma_{sum}}(\cdot)$ and $f_{\gamma_0}(\cdot)$ are the p.d.f.s of γ_{sum} and γ_0.

The PDF of γ_{sum} can be obtained as

$$f_{\gamma_{sum}}(y) = \mathcal{L}^{-1}\left\{\left(\int_0^\infty e^{-sx} f_{\gamma_i}(x) dx\right)^N\right\} \quad (16)$$

where $f_{\gamma_i}(\cdot)$ is the p.d.f. of γ_i. It is worth to note that it is not trivial to obtain the expression of $f_{\gamma_{sum}}(y)$ by using the exact expression of $f_{\gamma_i}(z)$. Therefore, the approximation in high SNR regime is preferable. Assuming there are N candidate points in Φ_P, the approximation of outage probability for ARP scheme is given in the following proposition.

Proposition 2. *Assuming there are N candidate points, $R >> r_d$ and in high SNR regime, the approximation of outage probability for the ARP scheme is given by* (17)*, where $\sum_{1\sim M}^{n}$ is the shorthand notation for $\sum_{n_1=0}^{\infty} \sum_{n_2=0}^{\infty} \cdots \sum_{n_M=0}^{\infty}$, $T = \sum_{l=1}^{M} n_l$ and*

$$\varphi(n) = \frac{(-1)^n}{n!}(n_T + n - 1)! \frac{R^{\alpha(n_T+n)}}{(n_T+n)\alpha + 2}. \quad (18)$$

Proof. Assuming $R >> r_d$, the approximated PDF of γ_i $\widetilde{f}_{\gamma_i}(z)$ can be derived and written as

$$\widetilde{f}_{\gamma_i}(z) = \int_0^R \frac{2r}{R^2} \frac{r^{\alpha n_T} z^{n_T-1}}{(n_T-1)!} e^{-zr^\alpha} Pc_1(r) dr + (1 - Pc_1(r))\delta(z)$$

where $\delta(z)$ is the Dirac delta function. In high SNR regime, $z \to 0$, $\widetilde{f}_{\gamma_i}(z)$ can be rewritten as

$$\widetilde{f}_{\gamma_i}(z) = \frac{2Pc_1(r)}{(n_T-1)!} \sum_{n=0}^{+\infty} \frac{(-1)^n}{n!} z^{n_T+n-1} \frac{R^{\alpha(n_T+n)}}{\alpha(n_T+n)+2} + (1 - Pc_1(r))\delta(z). \quad (19)$$

By doing Laplace transform of $\widetilde{f}_{\gamma_i}(z)$ and then doing inverse Laplace transform of $\mathcal{L}(f_{\gamma_{sum}}(y)) = \left(\mathcal{L}(\widetilde{f}_{\gamma_i}(z))\right)^N$, the p.d.f. of γ_{sum} can be obtained and shown as

$$f_{\gamma_{sum}}(y) = \sum_{M=0}^{N} \binom{N}{M} \left(\frac{2Pc_1(r)}{(n_T-1)!}\right)^M (1 - Pc_1(r))^{N-M} \sum_{1\sim M}^{n} \prod_{l=1}^{M} \varphi(n_l) \frac{y^{n_T M + T - 1}}{(n_T M + T - 1)!}. \quad (20)$$

The p.d.f. of γ_0 can be derived from (11) and expressed as

$$f_{\gamma_0}(z) = \frac{R^{\alpha m_T}}{(m_T-1)!} z^{m_T-1} e^{-zR^\alpha}. \quad (21)$$

Substituting the expressions of $f_{\gamma_{sum}}(y)$ and $f_{\gamma_0}(z)$ in (15), and solving the resulting integral to yield (17). □

$$\mathcal{P}_{ARP}\left(\epsilon|N\right) = \frac{1}{(m_T-1)!}\sum_{M=0}^{N}\binom{N}{M}\left(\frac{2Pc_1(r)}{(n_T-1)!}\right)^M (1-Pc_1(r))^{N-M}\sum_{1\sim M}^{n}\frac{\prod_{l=1}^{M}\varphi(n_l)}{(n_T M+T)!}$$
$$\sum_{q=0}^{Mn_T+T}\binom{n_T M+T}{q}(-1)^q\epsilon^{n_T M+T-q}\frac{\nu(m_T+q,\epsilon R^\alpha)}{R^{\alpha q}}. \quad (17)$$

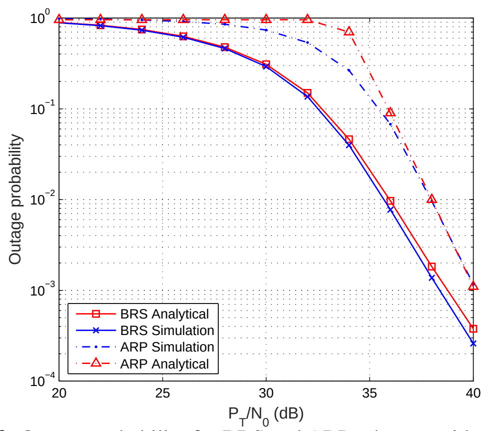

Fig. 2. Outage probability for BRS and ARP schemes with the same total transmit power.

Since N is a Poisson distributed RV, when $R >> r_d$ and in high SNR regime, the approximation of outage probability for the ARP scheme is written as

$$\mathcal{P}_{ARP}\left(\epsilon\right) = \sum_{N=0}^{\infty}\mathcal{P}_{ARP}\left(\epsilon|N\right)\frac{\mu^N e^{-\mu}}{\Gamma(N+1)}. \quad (22)$$

3.2.2. Throughput

The throughput for the ARP scheme can be given by

$$\mathcal{R}_{ARP} = \log_2(1+\varrho)(1-\mathcal{P}_{ARP}(\epsilon)) \quad (23)$$

where ϱ is the receive SNR at the user. Assuming $R >> r_d$ and in high SNR regime, substituting the expressions of $\mathcal{P}_{ARP}(\epsilon)$ and $\varrho = \epsilon\rho$ into (23) to yield

$$\mathcal{R}_{ARP} = \mathcal{R}\left(1-\sum_{N=0}^{\infty}\mathcal{P}_{ARP}\left(\epsilon|N\right)\frac{\mu^N e^{-\mu}}{\Gamma(N+1)}\right) \quad (24)$$

where $\mathcal{R} = \log_2(1+\varrho)$ is the required data rate at the user and the expression of $\mathcal{P}_{ARP}\left(\epsilon|N\right)$ is given in (17).

4. NUMERICAL RESULTS

In this section, unless otherwise specified, we assume $R = 100$ m, $r_d = 10$ m, $n_T = 2$, $m_T = 3$, $\alpha = 2$, $\mathcal{R} = 1$ bits per channel use (BPCU) and $N_0 = 1$.

Fig. 2 illustrates the outage probability for BRS and ARP schemes versus the ratio of total transmit power to noise power with HCPP intensity $\lambda_M = \frac{1-e^{-0.06}}{100\pi}$ (i.e. the corresponding $\lambda_P = 6/(10000\pi)$). In ARP scheme, it is assumed that the total power, P_T , is equally distributed among the MBS and the RRHs. As can be readily observed, the outage probability decreases when P_T/N_0 is increasing. This is obvious as higher transmit power improves the performance of the system. Meanwhile, it is worth to notice that when the same total transmit power is consumed, the

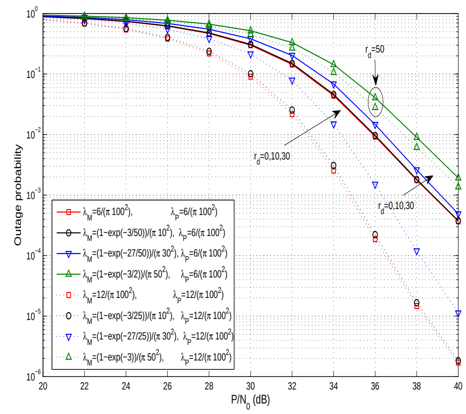

Fig. 3. Outage probability for BRS scheme with different hard-core distance r_d.

BRS scheme outperforms the ARP scheme. The results show that when limited total transmit power is assumed, the user can have better service by using fewer RRHs.

Fig. 3 plots the outage probability of BRS scheme with different hard-core distance r_d and HCPP intensity λ_M. When $r_d = 0$, we know that $P_c(r) = 1$, i.e. the HCPP converges to PPP. It shows that for a fixed intensity of candidate points, the outage probability of BRS scheme increases with the increasing of hard-core distance r_d. This is because increasing r_d will reduce the number of RRHs in the circular region. Since $\lambda_M = \frac{1-e^{-\pi r_d^2\lambda_P}}{\pi r_d^2}$, for a large r_d (e.g. $r_d = 50$ m), $\frac{1}{\pi r_d^2}$ becomes dominant and increasing the intensity λ_P only provides a small improvement on outage performance. Also, the difference of the outage probabilities for PPP model and HCPP model increases when there are more candidate points in the circular region (λ_P is larger).

5. CONCLUSION

In this paper, we have analyzed the performance of CRAN with multiple randomly distributed RRHs and a MBS, based on more realistic Matérn Hard-core point process (MHCPP) model. The performance of two downlink RRH selection schemes, namely, best RRH selection and all RRHs participation was investigated and analytical expressions for the outage probability, and throughput were obtained. Simulation and analytical results showed that the best RRH selection scheme is more power-efficient than all RRHs participation scheme. It is further shown that outage probability increased with the hard-core distance and systems with higher intensity of candidate points suffered more significant loss of outage performance. Moreover, it is illustrated that in large hard-core distance regime, increasing the intensity of candidate points can only provide a small improvement on outage performance. Future research directions may include extension of this work on the uplink side.

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