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Capacity Analysis of Coordinated Multipoint Reception for mmWave Uplink with Blockages

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***Abstract*— We consider an uplink coordinated multi-point (CoMP) transmission from a user served by multiple base stations (BSs) which are connected to each other via a central unit (CU). We model the millimeter-wave communication link with Nakahami-m fading and random blockage. In this paper, we investigate the impact of blockage on the system ergodic capacity and try to find analytical formulation which can be useful in future optimization problems such as power control and resource allocations. The system performance is analyzed by deriving the probability density function of the received signal and finding closed form solution of ergodic capacity. Finally, the analytical results are compared with simulations and the impact of blockage is studied numerically. Numerical results show the efficiency of using CoMP in capacity improvement and reducing the blockage effect, as well as necessity of considering the blockage effect in performance analysis.**

I. Introduction

Millimeter-wave (mmWave) communications is one of the main enabling technologies for 5G and Beyond mobile networks due to abundance of unused frequency bands in this spectrum. However, due to challenges such as high path loss and blockage, ultra-dense deployment of base stations (BSs) is required to improve the coverage. The further discussion of the above is given in [1], [2] and references therein. An efficient strategy to tackle adverse effects of mmWave communications is coordination among small cells by employing coordinated multi-point (CoMP) systems which is necessary to reduce handoff and inter-cell interference. The CoMP systems are employed in 4G LTE-A (see, e.g., [3]–[5]), especially for cell-edge users improvement. They will be also featured in 5G systems as a part of the cloud-radio access networks (C-RAN) architecture (see, e.g., [6], [7]). Despite the great potential of CoMP based mmWave cellular communications, there are many key technical challenges need to be addressed [5], [8], [9].

The performance of CoMP system has been investigated in the literature. For instance, in [10], the outage probability of joint processing CoMP using maximum ratio transmission was presented. The capacity analysis for CoMP transmission over fading channels is also studied in a number of work such as [4] and [11], in which downlink and uplink scenarios were considered, respectively. Moreover, the devices in mmWave bands are equipped with a number of antennas [5], [7], [12], [13]. This is justified by the small wavelength, which makes it possible to fit several antennas onto a mobile device. One of the main barriers in employing mmWave bands for outdoor cellular communication is their sensitivity to blockage due to poor penetration through concrete, water, foliage, and other common material [14]. The experimental measurements in [15] show that mmWave transmissions can experience significant blockages that are not well-modeled in 3GPP models. This calls for statistical models of a blockage event (see, e.g., [16]–[19]). However, joint study of tractable fading models and blockage models are not considered in these papers.

In this paper, we treat mmWave communication over access links, for which we employ the analytical Nakagami-m channel model (similar to [20]–[24]) concatenated with a random blockage model. The proposed concatenated channel model is useful because of number of reasons. Firstly, one of the main characteristics of the mmWave channels is their sensitivity to the blockage, compared to lower frequency bands such as ultrahigh frequency (UHF) or microwaves, and thus, the effect of blockage should be considered. Secondly, it takes into account the impact of the line-of-sight (LoS) component which is essential in high frequency mmWave bands due to their high path-loss characteristic. Thirdly, it is based on an analytical model which is mathematically tractable unlike most of mmWave channel models. Moreover, in order to reduce the impact of a blockage, here we consider the use of a CoMP system. In this paper, we derive closed form solution for the probability density function (PDF) of the analytical channel, which is used in uplink CoMP transmission. Using the derived PDF, the ergodic capacity is obtained. Numerical results show the efficiency of CoMP as an architecture to handle blockages and in capacity improvement, as well as necessity of considering blockage effect in performance analysis.

II. System Model and Channel Description

Similar to [20]–[22], we assume Nakagami-m model for mmWave based access links. Hence, the effect of LoS and non-line of sight (NLoS) can be taken into account. For example, considering integer values for m, in the worst case of $m = 1$, we have no LoS component, which is corresponding to Rayleigh fading channel. However, in mmWave band, due to the high path-loss degradation, the role of LoS component is more effective, which can be modeled by assuming $m > 1$. In this paper, we assume each link can have different Nakagami parameter m_i, where i is access link index, and by changing values of m_i, access links can be either LoS oriented (higher

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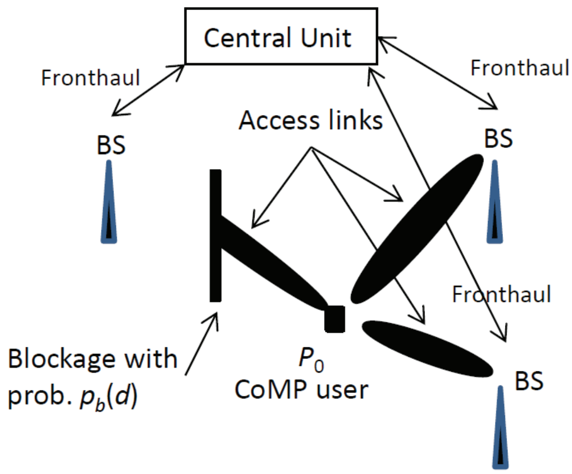

Fig. 1. The system model of a CoMP-based mmWave uplink system controlled by the central unit with possibility of random blockage.

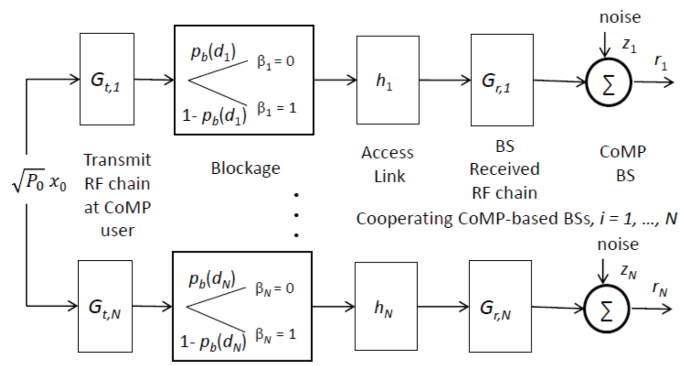

Fig. 2. The block diagram of system model of a CoMP-based mm-Wave uplink system. For detection, the received signals r_i's are sent to the central unit via reliable fronthaul links.

values of m_i) or NLoS oriented (lower values of m_i). Thus, different degree of LoS/NLoS components can be considered for each access link. From [25, Eq. (2.26)], we have

$$K_i = \frac{\text{LoS Power of Link } i}{\text{NLoS Power of Link } i} = \frac{\sqrt{m_i^2 - m_i}}{m_i - \sqrt{m_i^2 - m_i}}. \quad (1)$$

where for large values of m_i, we have $K_i \approx 2m_i$.

Next, we consider the effect of blockage which is prominent in mmWave bands. The blockage occurs when a random object or barrier interrupt the mmWave communication link. Similar to [16], [17], we assume the binary blockage over the ith access link, modeled by a Bernoulli distribution with parameter of

$$p_b(d_i) = 1 - e^{-b\, d_i}, \quad (2)$$

where d_i is the distance between the user and the i-th associated BS and parameter b depends on the density and the average size of the blockages, and $1/b$ determines the average coverage of mmWave link in the network. Thus, with probability of $p_b(d_i)$, the blockage occurs over the access link i. This model provides a reflection of blockage possibilities inherent in mmWave communication, where the blockage parameters are characterized by some random distributions. Other blockage models are used in [14], [15], [18], [19].

Now, consider an uplink CoMP system consisting of a CoMP user and multiple BSs around the user. The CoMP system is deployed with error-free fronthaul links connected to a central network controller unit in the area called central unit (CU). As shown in Fig. 1, the CoMP user broadcasts its message to N BSs in it vicinity.

Both BSs and CoMP user are equipped with multiple antennas in order to apply analogue beamforming. Thus, each user has multiple beams aligned to the associated BSs. Since mmWave communication is used, the use of beamforming is essential to tackle the effect of high pathloss due to high frequency. In addition, beamforming reduces the impact of interference from nearby devices. The assumption of multiple antennas for the CoMP user is also feasible in mmWave scenarios due to small size antenna requirement of the order of wavelength. We assume CoMP user antennas are divided into N groups, and each group is connected to a RF chain. We assume that the RF chain i, $i = 1, 2, \cdots, N$, creates a single beam directed toward the ith BS. The antenna directions are adjusted before data transmission phase for both transmitter and the receivers. Hence, the maximum antenna gains (main lobe gain) $G_{t,i}$ and $G_{r,i}$, $i = 1, 2, \cdots, N$, are achievable at the ith RF chain of the user and BS i, respectively. Note that BS associations and beamwidth alignments are done at the CU, which consists of both data collection center and network controller unit for signaling purposes.

The CoMP user transmits the message x_0 in a given time, toward N associated BSs (see Fig. 1). The ith access channel linking the user to BS i is Nakagami-m distributed and is denoted by h_i. The average power gain of the channel is denoted by $\Omega_i = \mathbb{E}\{|h_i|^2\}$ which depends on the inverse of path-loss.

The received signal at the ith associated BS at a given time is expressed as

$$r_i = \sqrt{P_0\, G_{t,i} G_{r,i}}\, h_i\, \beta_i\, x_0 + z_i, \quad (3)$$

where P_0 denotes the average transmission power from the user, since we assume normalized message, i.e., $\mathbb{E}\{|x_0|^2\} = 1$. In addition, β_i is a Bernoulli random variable with parameter $p_b(d_i)$ where d_i is the distance between the user and the ith BS. This models the random blocking, i.e., $\beta_i = 1$ with probability of $1 - p_b(d_i)$ when there is no blockage, and otherwise, we have $\beta_i = 0$. We assume each message transmission time is equal to channels coherent time. Therefore, we assume both channel coefficients h_i's and blockage variables β_i's are fixed during each transmission time and change independently for next messages. In (3), z_i denotes circularly symmetric complex zero-mean white Gaussian noise with variance of σ^2 at BS i. The block diagram illustrated in Fig. 2 summarizes the different blocks signal traverses from a typical user to the mm-Waves CoMP BS.

Next, we have a data collection phase, in which the signals from associated BSs are sent to the CU via ideal fronthaul link, as shown in Fig. 1. This assumption can be justified

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by employing high capacity fiber optic links or high capacity mmWave links with strong LoS components. The assumption of non-ideal fronthaul can be an interesting extension to this work (see, e.g., [27]). Finally, the user's message is decoded at the CU.

III. Ergodic Capacity Analysis

In this section, we evaluate the ergodic capacity of the system mentioned in the previous section. From (3), the instantaneous SNR at the ith BS can be written as

$$\mathrm{SNR}_i = \beta_i \, \gamma_i, \ \text{for } i = 1, \cdots, N. \tag{4}$$

where $\gamma_i = \frac{P_0 \, G_{t,i} G_{r,i}}{\sigma^2}|h_i|^2$, with the average value of $\bar{\gamma}_i = \frac{P_0 \, G_{t,i} G_{r,i}}{\sigma^2}\Omega_i$, where $\Omega_i = \mathbb{E}\{|h_i|^2\}$. Since we assume access channels are modeled by independent Nakagami-m channels concatenated with random blockage, γ_i is a Gamma distributed random variable with the average $\bar{\gamma}_i$ and Nakagami parameter of m_i. Assuming integer values for m_i, the distribution of γ_i becomes Erlang and its cumulative distribution function (CDF) can be expressed as

$$F_{\gamma_i}(\gamma; m_i) = 1 - e^{-\frac{\gamma}{\bar{\gamma}_i} m_i} \sum_{k=0}^{m_i - 1} \frac{1}{k!} \left(\frac{\gamma}{\bar{\gamma}_i} m_i \right)^k, \ \text{for } \gamma \geq 0, \tag{5}$$

for $i = 1, \cdots, N$.

Next, we consider the cooperation among multiple BSs at the receiving side. When received signals are related to the same information source, they can be summed up constructively, and we have cooperative communications at the CU (see Fig. 1). Thus, we consider the case that we have multiple BSs cooperatively transmitting their received data toward a single CU terminal. Note that this is a practical assumption since in mmWave access communications, we have a high chance of link interruption due to the blockage effect. The value of blockage probability $p_b(d_i)$ could be high in practice due to the large distance or high density of obstacles. The aggregated SNR at the CU that is combined by error-free fronthaul links is given by

$$\gamma_N^b = \frac{1}{N} \sum_{i=1}^{N} \beta_i \, \gamma_i, \tag{6}$$

and the coherent detection of the uplink user message is done at the CU by employing the maximum ratio beamforming (MRB) combining scheme.

Here, we evaluate the system ergodic capacity as performance metric. In order to find the capacity expression, we need to find the PDF of aggregated SNR stated in (6).

Proposition *1:* The PDF of $\gamma_N^b = \frac{1}{N} \sum_{i=1}^{N} \beta_i \gamma_i$ is given by a nested finite weighted sum of Gamma distributions plus a spike at $\gamma = 0$, i.e.,

$$f_N^b(\gamma) = q_0 \, \delta(\gamma) + N \sum_{n=1}^{N} \sum_{i=1}^{n} \sum_{k=1}^{m_i} q_n \Lambda_{n,i,k} \, f_{\gamma_i}(N\gamma; k), \tag{7}$$

for $\gamma \geq 0$, and zero otherwise, where $f_{\gamma_i}(\gamma; k) = \frac{k^k \, \gamma^{k-1}}{\bar{\gamma}_i^k \, (k-1)!} e^{-\frac{\gamma}{\bar{\gamma}_i} k}$ and q_n is the probability of number of access links which are not blocked and has the Poisson binomial distribution, where $q_0 = \prod_{i=1}^{N} p_b(d_i)$, and for $n = 1, \cdots, N$, we can use the following recursive formula [28]

$$q_n = \frac{1}{n} \sum_{i=1}^{n} (-1)^{i-1} q_{n-i} \sum_{j=1}^{N} \left(\frac{1 - p_b(d_j)}{p_b(d_j)} \right)^i. \tag{8}$$

In addition, weights $\Lambda_{n,i,k}$ can be recursively obtained using the following formula:

$$\Lambda_{n,i,m_i - k} = \frac{1}{k} \sum_{j=1}^{k} \sum_{q=1, q \neq i}^{n} \frac{m_q}{\bar{\gamma}_i^j} \left(\frac{1}{\bar{\gamma}_j} - \frac{1}{\bar{\gamma}_q} \right)^{-j} \Lambda_{n,i,m_i - k + j}. \tag{9}$$

with

$$\Lambda_{n,i,m_i} = \frac{\bar{\gamma}_i^{m_i}}{\prod_{h=1}^{n} \bar{\gamma}_h^{m_h}} \prod_{j=1, j \neq i}^{n} \left(\frac{1}{\bar{\gamma}_j} - \frac{1}{\bar{\gamma}_i} \right)^{-m_j}. \tag{10}$$

Proof: The proof is given in Appendix I. ■

Note that the discrete mass probability in $f_N^b(\gamma)$ at $\gamma = 0$, i.e., q_0, is due to the fact that we combined the continuous random variable γ_i with discrete random variable of blockage. In addition, if we assume equal blockage probability for access links, i.e., $p_b(d_i) = p_b$, for $i = 1, \cdots, N$, q_n becomes binomial distribution, $q_n = \binom{N}{n} (1 - p_b)^n p_b^{N-n}$.

Next, we investigate the achievable data rate for uplink CoMP system with cooperative reception. Considering normalized bandwidth, using (6), the normalized achievable instantaneous rate of the primary user is $\log_2\left(1 + \gamma_N^b\right)$. Thus, the ergodic capacity of the system is given as

$$\begin{aligned} \bar{C}_{\text{MRB}} &= \mathbb{E}\{\log_2\left(1 + \gamma_N^b\right)\} = \int_0^\infty \log_2\left(1 + \gamma\right) f_N^b(\gamma) d\gamma \\ &= \sum_{n=1}^{N} \sum_{i=1}^{n} \sum_{k=1}^{m_i} q_n \Lambda_{n,i,k} C_{i,k}, \end{aligned} \tag{11}$$

where $C_{i,k} = N \int_0^\infty \log_2\left(1 + \gamma\right) f_{\gamma_i}(N\gamma; k) d\gamma$ and we used the fact that $\int_0^\infty \log_2\left(1 + \gamma\right) \delta(\gamma) d\gamma = 0$. Using [29, Eq. (47)], we have

$$\begin{aligned} C_{i,k} &= N \int_0^\infty \log_2\left(1 + \gamma\right) f_{\gamma_i}(N\gamma; k) d\gamma \\ &= \frac{k^k \, N^k}{\bar{\gamma}_i^k \, (k-1)!} \log_2 e \int_0^\infty \ln\left(1 + \gamma\right) \gamma^{k-1} e^{-\frac{N\gamma}{\bar{\gamma}_i} k} d\gamma \\ &= \log_2(e) \, e^{\frac{kN}{\bar{\gamma}_i}} \sum_{j=1}^{k} E_j\left(\frac{kN}{\bar{\gamma}_i}\right) \end{aligned} \tag{12}$$

where $E_j(x) = \int_1^\infty e^{-x\alpha}/\alpha^j \, d\alpha$ is the exponential integral function of order j, for $j = 0, 1, 2, \cdots$, and positive x [30].

Combining (7), (11), and (12), we have

$$\begin{aligned} \bar{C}_{\text{MRB}} &= \sum_{n=1}^{N} \sum_{i=1}^{n} \sum_{k=1}^{m_i} q_n \, \Lambda_{n,i,k} \, C_{i,k} \\ &= \sum_{n=1}^{N} \sum_{i=1}^{n} \sum_{k=1}^{m_i} q_n \Lambda_{n,i,k} \log_2(e) \, e^{\frac{kN}{\bar{\gamma}_i}} \sum_{j=1}^{k} E_j\left(\frac{kN}{\bar{\gamma}_i}\right). \end{aligned} \tag{13}$$

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Next, we calculate the ergodic capacity for the special case that access channels have similar parameters. Using (12) and assuming identical distributions $f_{\gamma_i}(\gamma;k)=f(\gamma;k)$, it can be shown that

$$\bar{C}_{\text{MRB}}^{\text{iden}}=\sum_{n=1}^{N}\binom{N}{n}(1-p_b)^n p_b^{N-n}\int_0^\infty \log_2(1+\gamma)\, f(N\gamma;mn)d\gamma$$
$$=\sum_{n=1}^{N}\binom{N}{n}(1-p_b)^n p_b^{N-n}\log_2(e)\, e^{\frac{mN}{\bar{\gamma}}}\sum_{j=1}^{mn}E_j\left(\frac{mN}{\bar{\gamma}}\right). \quad (14)$$

In order to find more tractable formulas for ergodic capacity, in the following, we find upper and lower bounds.

1) Upper-bound: By using the Jensen's inequality, an upper-bound for ergodic capacity in (11) is given by

$$\bar{C}_{\text{MRB}} \le \log_2\left(1+\mathbb{E}\{\gamma_N^b\}\right), \quad (15)$$

where

$$\mathbb{E}\{\gamma_N^b\}=\int_0^\infty \gamma\, f_N^b(\gamma)d\gamma$$
$$=N\sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k}\int_0^\infty \gamma\, f_{\gamma_i}(N\gamma;k)d\gamma$$
$$=\sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k}\frac{k^k N^k}{\bar{\gamma}_i^k (k-1)!}\int_0^\infty \gamma^k e^{-\frac{N\gamma}{\bar{\gamma}_i}k}d\gamma$$
$$=\frac{1}{N}\sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k}\,\bar{\gamma}_i \quad (16)$$

where we used [31, 3.351] to find the integral. Hence, we have

$$\bar{C}_{\text{MRB}} \le \log_2\left(1+\frac{1}{N}\sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k}\,\bar{\gamma}_i\right). \quad (17)$$

We also calculate an upper bound of ergodic capacity for the special case that access channels have similar parameters. Thus, in this case, using (15) and (16), the closed-form solution can be obtained as

$$\bar{C}_{\text{MRB}}^{\text{iden}} \le \log_2\left(1+\frac{1}{N}\sum_{n=1}^{N}\binom{N}{n}(1-p_b)^n p_b^{N-n}\, n\,\bar{\gamma}\right). \quad (18)$$

2) Lower-bound: A lower-bound on the ergodic capacity in (16) can be calculated by the fact that $\log_2(1+ae^x)$ is a convex function with $a>0$. Thus, applying Jensen's inequality, we have

$$\bar{C}_{\text{MRB}} \ge \log_2\left(1+\exp\left(\mathbb{E}\{\ln\gamma_N^b\}\right)\right), \quad (19)$$

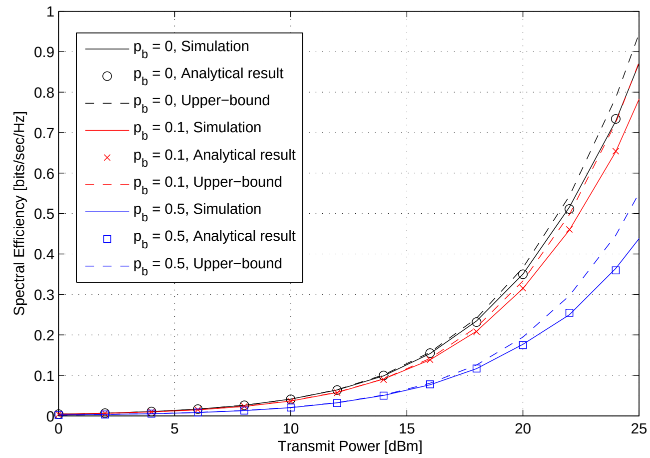

Fig. 3. The ergodic capacity curves versus the transmit power for a single channel modeled by concatenation of Nakakagami-m and binary blockage model with different parameters of the blockage probability p_b.

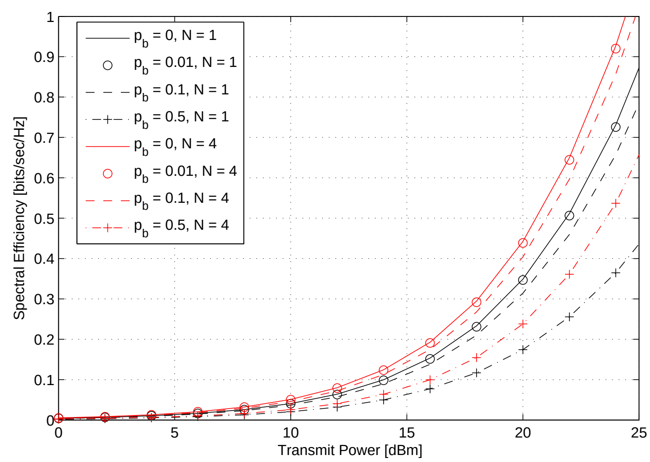

Fig. 4. The ergodic capacity curves versus the transmit power for Nakagami-Blockage channels with different parameters of the blockage probability p_b, in an uplink CoMP with $N=4$.

where

$$\mathbb{E}\{\ln \text{SNR}_{\text{MRB}}\}=\int_0^\infty \ln(\gamma)\, f_N^b(\gamma)d\gamma$$
$$=N\sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k}\int_0^\infty \ln(\gamma)\, f_{\gamma_i}(N\gamma;k)d\gamma$$
$$=\sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k}\frac{k^k N^k}{\bar{\gamma}_i^k (k-1)!}\int_0^\infty \ln(\gamma)\,\gamma^{k-1} e^{-\frac{N\gamma}{\bar{\gamma}_i}k}d\gamma$$
$$=\sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k}\left[\sum_{j=1}^{k-1}\frac{1}{j}-c-\ln\left(\frac{kN}{\bar{\gamma}_i}\right)\right] \quad (20)$$

where [31, 4.352] and $c\approx 0.577$ is the Euler's constant.

IV. Numerical Results

In this section, we present numerical results to demonstrate the performance of analytic results derived in Section III. We used simulations based on Monte Carlo method to verify the correctness of our analytic results. For simulation, the block fading model is used, and simulation result is averaged over 3'000'000 transmitted symbols (channel realization trials). We assume operating frequency of 28 GHz, Nakagami parameter $m = 2$, antenna main-lobe gain of 18 dB, and path-loss of $L = 70 + 10\alpha \log_{10}(d_i)$ in dB, where $\alpha = 2.9$ is the path-loss exponent [15]. The fixed geometry is also assumed for deployment of BSs in order to focus more on the impact of blockage. Thus, we consider the case of $d_i = 400$ meter, for $i = 1, \cdots, N$. The maximum transmit power of 25 dBm is also considered. For noise power, we have [14]

$$\sigma^2 = -174\text{dBm/Hz} + 10\log_{10} W + \text{noise figure of 10 dB}, \tag{21}$$

where W is the uplink channel bandwidth. Based on 3GPP Release 15, bandwidth should be in the range of 50 MHz to 300 MHz for higher frequencies (FR2), above 24 GHz. Thus, we assume $W = 100$ MHz.

In Fig. 3, the ergodic capacity performance of single-input-single-output (SISO) Nakagami-Blockage channels versus the transmit power, under different blockage probability values of $p_b = 0, 0.1, 0.5$, modeled by a binary Z-channel, are investigated. The curves are based on normalized capacity or spectral efficiency with the unit of bits/sec/Hz. As it can be seen, the blockage can degrade the system capacity. For example, it is shown that at spectral efficiency of 0.4, around 4 dBm more transmit power is required when there is blockage with probability of 0.5, compared to a system with no blockage. Furthermore, the correctness of closed-form formulas derived in the previous section are confirmed in Fig. 3 by comparing them to simulation results.

In Fig. 4, we consider a CoMP uplink network consisting of N equidistance cooperating BSs. Due to the blockage effect and other impairments, in reality, multiple number of BSs should cooperate to transmit the data to serve the user. Thus, in Fig. 4, we investigate the effect of multiple BSs transmission by using CoMP on the system capacity. It can be observed that using more cooperating BSs, i.e., $N = 4$, we can significantly improve the spectral efficiency for different values of blockage probabilities $p_b = 0.01, 0.1, 0.5$, specially for high SNR conditions. Please note that a high number of associated BSs is not recommended due to high signaling cost and the limited number of antennas deployed at the user. Since our main goal is deriving tractable and insightful formulas that can be used in future work for optimization purposes, we have not studied the effect of signaling needed for beam-alignment, scheduling, channel estimation, synchronization, etc. The idea of using CoMP to tackle blockage effect is similar to nervous systems in which due to low probability of vesicle release [32], many synapses are employed to cooperatively carry a single message.

V. Conclusion

This paper has analyzed the problem of blockage-impaired wireless communication in mmWave bands. We have considered an uplink scenario in which the reception diversity is enhanced by having a CoMP in the infrastructure. We have used a Nakagami-m channel model concatenated with a random blockage model. We have derived a closed form solution of the ergodic capacity. In addition, more tractable formulas as upper and lower bounds were found that can be used in future for optimization problems. The numerical results show that blockage can have a significant impact on the performance, while the diversity offered by CoMP is very beneficial for mitigating this impact. The idea of using CoMP to tackle blockage effect is similar to nervous systems in which due to low probability of vesicle release, many synapses are employed to cooperatively carry a single message. In the future work, we will consider different ways of combining the uplink transmissions in the CoMP setup, based on the availability of channel state information. Another natural extension is to complement this study with the downlink CoMP transmissions, as well as joint uplink/downlink transmission with Dynamic TDD. The study of the system with signaling constraints can be an interesting extension of this work.

Appendix I
Proof of Proposition 1

The CDF of γ_i is given as in (5). The total number of unblocked access links can be written as $N_0 = \sum_{i=1}^{N} \beta_i$. For a fixed value of N_0, called n, the sum of independent Erlang-distributed random variables, with different parameters $\bar{\gamma}_i$, $i = 1, \cdots, N$, and of order m_i, i.e., $\sum_{i=1}^{n} \gamma_i$, is given by [33, Eq. (9)]

$$F_{\text{sum}}(\gamma|n) = \sum_{i=1}^{n}\sum_{k=1}^{m_i} \Lambda_{n,i,k} F_{\gamma_i}(\gamma; k), \tag{22}$$

where weights $\Lambda_{n,i,k}$ can be calculated using (9)-(10). Since N_0 is the summation of independent Bernoulli variables β_i's with different parameters, $p_b(d_i)$, N_0 will have a Poisson binomial distribution with the following probability mass distribution $\text{P}\{N_0 = n\} = q_n$, $n = 0, \cdots, N$, where q_n is defined in (8). Hence, using the law of total probability, the CDF of $\sum_{i=1}^{n} \beta_i\gamma_i$ can be written as

$$\begin{aligned} F_{\text{sum}}(\gamma) &= \sum_{n=0}^{N} \text{P}\{N_0 = n\} F_N(\gamma|n) \\ &= q_0 + \sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k} F_{\gamma_i}(\gamma; k). \end{aligned} \tag{23}$$

The PDF of $\sum_{i=1}^{n} \beta_i\gamma_i$ can be simply obtained by derivative of its CDF given by

$$f_{\text{sum}}^{b}(\gamma) = q_0\,\delta(\gamma) + \sum_{n=1}^{N}\sum_{i=1}^{n}\sum_{k=1}^{m_i} q_n \Lambda_{n,i,k}\, f_{\gamma_i}(\gamma; k) \tag{24}$$

Finally, the PDF of of $\gamma_N^b = \frac{1}{N}\sum_{i=1}^{N}\beta_i\gamma_i$ is given by $f_N^b(\gamma) = N\, f_{\text{sum}}^b(N\gamma)$ as stated in (7), where we used the fact that $\delta(N\gamma) = \frac{\delta(\gamma)}{N}$.

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