Performance Analysis of Large Intelligent Surfaces in Dense Millimeter-Wave Deployment

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***Abstract*— Large intelligent surfaces (LIS) are recently gaining considerable research interest due to their simplicity and effectiveness in turning passive antennas into smart transformer of wireless channel phases. In this paper, we use LIS to increase the coverage of millimeter-wave coordinated multi-point based cellular networks operating on 28 GHz. We first derive distribution functions of equivalent LIS-assisted channel for two cases of uplink MRC reception and opportunistic selective reception under independent Nakagami-m fading channels. Then, the performance analysis is presented in terms of outage probability and ergodic capacity. Finally, the simulation results show the impact of different parameters and correctness of our analytical analysis. For instance, the impact of different parameters such as transmit power consumption, number of passive antenna elements in LIS, and number of LIS towers on the system performance are investigated.**

I. INTRODUCTION

The dense deployment of millimeter-wave (mmWave) communications is one of the main features of 5G and beyond cellular systems. The main reason for deploying many base stations near users operating over mmWave bands is the huge increase in wireless data demand. There are different enabling technologies for dense-deployment, such as use of small cells (see, e.g., [1], [2]), self-backhanding [1], cloud radio access networks (CRAN) [3], edge computing [4], coordinated-multipoint (CoMP) [5], [6], etc. Moreover, large intelligent surfaces (LIS) can further assist in improving the coverage with minimum cost in term of power consumption due to the use of passive devices. A LIS is a programmable passive planar structure made of smart metamaterials that can compensate wireless channel phases automatically. In the literature, there are different terms referring to a similar notion of LIS to help wireless communications, e.g., reconfigurable metasurface, software-defined hypersurface, intelligent reflecting surface, large intelligent antenna, reconfigurable intelligent surface, and holographic MIMO surface (see, e.g. [7]–[10]). The performance analysis of LIS systems are also recently studied in a number of works (see, e.g., [11]–[15]).

In this paper, we focus on the impact of LIS usage in the dense deployment of the mmWave-based cellular system. Moreover, our system is capable of having more than one LISs in order to improve the coverage. For this purpose, the CoMP architecture is used, in which a single centralized Anchor base station (A-BS) are connected to several adjacent LISs. We consider two types of cooperation schemes for LISs. In the first scheme, the MRC reception is used, in which signals from all LISs are employed in the uplink message detection at the A-BS. In the second scenario, an opportunistic selective reception is used, and thus, only the contribution of a LIS with the best end-to-end channels are used for the uplink signal detection at the A-BS. Furthermore, we investigate the system performance in terms of outage probability and ergodic capacity under Nakagami-m fading channels, which is suitable for modeling mmWave communication links (see, e.g., [3], [16]). More specifically, we first evaluate close-form solutions for distribution functions of LIS-enabled equivalent channels in terms of CDF and PDF. Then, these distributions are used for deriving the outage probability and ergodic capacity of uplink transmission with both MRC detection and opportunistic selective reception. Furthermore, the simulation results confirm the correctness of derived formulas. In addition, the impact of different parameters such as number of passive antenna elements in LIS, number of LIS towers, and transmit power consumption are investigated. We also consider two cases of LIS without beamforming and LIS with directional antenna capability.

II. SYSTEM MODEL

Consider an uplink large intelligent surfaces (LIS)-enabled CoMP system consisting of a centralized A-BS, several LISs, and a typical user equipment (UE). The role of LISs is to provide CoMP service to users with low coverage and at the edge of A-BS in which direct transmission is not possible due to blockage or high path-loss. By cooperation among LISs, we basically realized smart virtual massive MIMO systems. In addition, all channels are assumed to be independent and Nakagami-m distributed in order to model the effects of both LOS and NLOS components which is vital in modeling mmWave channels.

As shown in Fig. 1, the UE transmits the message s which is received by M LISs in its vicinity. Each LIS is equipped with N passive antenna elements. We call links between the UE and LISs as access links and $h_{i,j}$ denotes the channel between the UE and j-th element of LIS i. After automatic adjustment of phases at LIS elements, the signal go through

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This research was supported by the Faculty Development Competitive Research Grant (No. 240919FD3918), Nazarbayev University.

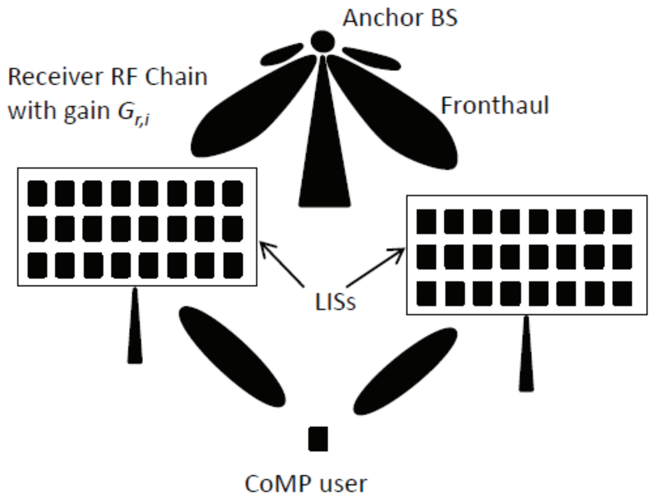

Fig. 1. The system model for an uplink LIS-enabled CoMP system served by multiple LISs over mmWave channels.

channels $f_{i,j}$ from j-th element of LIS i toward RF chain i of A-BS, which we call them fronthaul links. Since antennas elements at LIS are almost co-located, the average power gain of the access and fronthaul channels are denoted as

$$\Omega_{h,i} = \mathbb{E}\{|h_{i,j}|^2\},\ \Omega_{f,i} = \mathbb{E}\{|f_{i,j}|^2\},\ i = 1, 2, \cdots, M. \quad (1)$$

The received signal at the ith RF chain of A-BS is given by

$$y_i = \sum_{j=1}^{N} \sqrt{P_0\, G_t G_{r,i}}\, h_{i,j} e^{j\psi i,j} f_{i,j}\, s + v_i, \quad (2)$$

where P_0 denotes the average transmission power from the user, and suppose normalized message, i.e., $\mathbb{E}\{|s(n)|^2\} = 1$. In addition, v_i denotes circularly symmetric complex zero-mean white Gaussian noise with variance of σ_n^2 at RF chain i. Note that since adjustable phase interference $e^{j\psi i,j}$ looks random from interfering nodes perspective, using central limit theorem (CLT), interference is also treated as zero-mean Gaussian noise. Moreover, unlike 4G LTE-A based systems, interference is not a major challenge of 5G and beyond due to use of directional antennas at A-BS and sensitivity of mmWave bands to high path loss and blockage. Moreover, the A-BS receiver is also equipped with directional antennas with maximum main-lobe antenna gains of $G_{r,i}$, $i = 1, 2, \cdots, M$, aligned toward M LISs nearby. For LISs, we consider two scenarios. In the first one, transmit analogue beamforming with maximum antenna gain of G_t is used in the fronthaul link, since location of LISs are fixed toward A-BS. In the second scenario, no directional antennas are used for low-complex scenario. In the

In (3), ψ_i is the adjustable phase at the j-th element of LIS i for compensation of phase such that overall phase of end-to-end link becomes zero and all received signal components add up constructively. Thus, by the use of intelligence material at LIS components, we have

$$y_i = \sum_{j=1}^{N} \sqrt{P_0\, G_t G_{r,i}}\, |h_{i,j}||f_{i,j}|\, s + v_i. \quad (3)$$

III. PERFORMANCE ANALYSIS OF MRC RECEPTION

In this section, we assume MRC at the A-BS and investigate the coverage probability and capacity of the the system. From (3), the received SNR at RF chain i of the A-B can be written as

$$\gamma_i = \frac{\left(\sum_{j=1}^{N} \sqrt{P_0 G_t\, G_{r,i}}\, |h_{i,j}||f_{i,j}|\right)^2}{\sigma_n^2} = \frac{P_0\, G_t G_{r,i}}{\sigma_n^2}\, H_i^2, \quad (4)$$

where $H_i = \sum_{j=1}^{N} |h_{i,j}||f_{i,j}|$. Using maximum ratio combining (MRC) to aggregate contributions from different RF chains, the aggregated SNR can be written as [17]

$$\mathrm{SNR}_{\mathrm{MRC}} = \sum_{i=1}^{M} \rho_i H_i^2, \quad (5)$$

where $\rho_i = \frac{P_0 G_t G_{r,i}}{M\, \sigma_n^2}$.

A. Outage Probability

Assuming the desired uplink data rate of R, in this subsection, we try to find the outage probability of the system defined as $\Pr\{\mathrm{SNR}_{\mathrm{MRC}} \leq \gamma_{\mathrm{th}}\}$ where $\gamma_{\mathrm{th}} = 2^R - 1$. Before derivation of outage probability, we find closed form solution for distribution function of $\mathrm{SNR}_{\mathrm{MRC}}$.

Assuming a large number of passive reflectors with adjustable phases at each LIS, i.e., $N \gg 1$, similar to [11], we assumed H_i becomes Gaussian according to CLT. In order to find the average and variance of H_i, we remind that both $|h_{i,j}|$ and $|f_{i,j}|$ are Nakagami-m distributed and their averages becomes

$$\mu_{h,i} = \mathbb{E}\{|h_{i,j}|\} = \frac{\Gamma(m_{h,i} + 0.5)}{\Gamma(m_{h,i})\sqrt{m_{h,i}}} \sqrt{\Omega_{h,i}}, \quad (6)$$

$$\mu_{f,i} = \mathbb{E}\{|f_{i,j}|\} = \frac{\Gamma(m_{f,i} + 0.5)}{\Gamma(m_{f,i})\sqrt{m_{f,i}}} \sqrt{\Omega_{f,i}}. \quad (7)$$

Hence, due to independence of fronthaul and access channels, H_i has average of

$$\mu_{H,i} = \mathbb{E}\left\{\sum_{j=1}^{N} |h_{i,j}||f_{i,j}|\right\} = N\, \mu_{h,i}\, \mu_{f,i}, \quad (8)$$

and its power can be written as

$$\begin{aligned} P_{H,i} &= \mathbb{E}\left(\sum_{j=1}^{N} |h_{i,j}||f_{i,j}|\right)^2 \\ &= \mathbb{E}\sum_{j=1}^{N} |h_{i,j}|^2 |f_{i,j}|^2 + \mathbb{E}\sum_{j=1}^{N}\sum_{k \neq j}^{N} |h_{i,j}||f_{i,j}||h_{i,k}||f_{i,k}| \\ &= \sum_{j=1}^{N} \mathbb{E}|h_{i,j}|^2 \mathbb{E}|f_{i,j}|^2 + \mathbb{E}|h_{i,j}|\mathbb{E}|f_{i,j}| \sum_{k \neq j}^{N} \mathbb{E}|h_{i,k}|\mathbb{E}|f_{i,k}| \\ &= N\Omega_{h,i}\Omega_{f,i} + N(N-1)\, \mu_{h,i}^2\, \mu_{f,i}^2. \end{aligned} \quad (9)$$

Thus, using (8) and (9), the variance is given by

$$\sigma_{H,i}^2 = P_{H,i} - \mu_{H,i}^2 = N\mathit{\Omega}_{h,i}\mathit{\Omega}_{f,i} - N\mu_{h,i}^2\mu_{f,i}^2. \tag{10}$$

Since H_i has non-zero mean, $\mathrm{SNR}_i = \rho_i H_i^2$ would have non-central chi-squared distribution and its CDF can be written as

$$\begin{aligned} F_{\mathrm{SNR}_i}(\gamma) &= \Pr\left\{\mathrm{SNR}_i \le \gamma\right\} \\ &= 1 - Q_{1/2}\left(\frac{\mu_{H,i}}{\sigma_{H,i}}, \sqrt{\frac{\gamma}{\rho_i\,\sigma_{H,i}^2}}\right), \end{aligned} \tag{11}$$

where $Q_k(\cdot,\cdot)$ is Marcum-Q function of order k [17]. Then, aggregated SNR in (5) can be written as $\mathrm{SNR}_{\mathrm{MRC}} = \sum_{i=1}^{M} \mathrm{SNR}_i$. Thus, from (11) and [18, Eq. (2)], the outage probability can be well approximated as

$$P_{\mathrm{out}} = \Pr\left\{\mathrm{SNR}_{\mathrm{MRC}} \le \gamma_{\mathrm{th}}\right\} = 1 - Q_{M/2}\left(\frac{\mu_s}{\sigma_s}, \frac{\sqrt{\gamma_{\mathrm{th}}}}{\sigma_s}\right), \tag{12}$$

where $\mu_s = \sqrt{\sum_{i=1}^{M} \rho_i\,\mu_{H,i}^2}$ and $\sigma_s = \sqrt{\frac{1}{M}\sum_{i=1}^{M} \rho_i\,\sigma_{H,i}^2}$.

B. Ergodic Capacity

In this part, we derive ergodic capacity of the uplink LIS-assisted communication with MRC detection. The ergodic capacity is defined as average of achievable normalized data rate $\log_2(1+\mathrm{SNR}_{\mathrm{MRC}})$. Thus, the normalized bandwidth ergodic capacity is given by the system is given as

$$\begin{aligned} \bar{C}_{\mathrm{MRC}} &= \mathbb{E}\{\log_2(1+\mathrm{SNR}_{\mathrm{MRC}})\} = \mathbb{E}\left\{\log_2\left(1+\sum_{i=1}^{M}\mathrm{SNR}_i\right)\right\} \\ &= \int_{0,M-\mathrm{fold}}^{\infty} \log_2\left(1+\sum_{i=1}^{M}\alpha_i\right)\prod_{i=1}^{M} f_{\mathrm{SNR}_i}(\alpha_i)\,d\alpha_i, \end{aligned} \tag{13}$$

where $f_{\mathrm{SNR}_i}(\cdot)$ is the PDF of SNR_i and can be found using (8), (10), and [**?**, Eq. (2)] as follows

$$f_{\mathrm{SNR}_i}(\gamma) = \frac{\gamma^{-1/4}}{2\rho_i^{3/4}\mu_{H,i}^{-1/2}\sigma_{H,i}^2}\, e^{-\frac{(\gamma+\rho_i\mu_{H,i}^2)}{2\rho_i\sigma_{H,i}^2}}\, I_{-1/2}\left(\frac{\mu_{H,i}\sqrt{\gamma}}{\sqrt{\rho_i}\sigma_{H,i}^2}\right), \tag{14}$$

where $I_a(\cdot)$ is the modified Bessel function of order a.

IV. PERFORMANCE ANALYSIS OF OPPORTUNISTIC SELECTIVE RECEPTION

As another detection technique to get the spatial diversity gain, specially in low SNR scenarios, in this section, we investigate the performance of opportunistic selection scheme. In this scheme, instead of combining signals from all receiver RF chains, only the RF chain with the best SNR condition is selected.

A. Outage Probability

Using opportunistic selection scheme at the A-BS receiver, the highest SNR can be written as

$$\mathrm{SNR}_{\mathrm{sel}} = \max_i\left\{\gamma_i\right\}, i = 1, \cdots, M. \tag{15}$$

where γ_i is defined in (4). We first calculate the CDF of $\mathrm{SNR}_{\mathrm{sel}}$ as

$$\begin{aligned} F_{\mathrm{sel}}(\gamma) &= \Pr\left\{\mathrm{SNR}_{\mathrm{sel}} \le \gamma\right\} = \Pr\left\{\max_i\left\{\gamma_i\right\} \le \gamma\right\} \\ &= \Pr\left\{\gamma_1 \le \gamma, \gamma_2 \le \gamma, \cdots, \gamma_M \le \gamma\right\} \\ &= \prod_{i=1}^{M}\Pr\left\{\gamma_i \le \gamma\right\} = \prod_{i=1}^{M} F_{\mathrm{SNR}_i}\left(\frac{\gamma}{M}\right), \end{aligned} \tag{16}$$

where $F_{\mathrm{SNR}_i}(\gamma)$ is given in (11). Hence, the outage probability of opportunistic selection scheme is given by

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{sel}} &= F_{\mathrm{sel}}(\gamma_{\mathrm{th}}) = \prod_{i=1}^{M} F_{\mathrm{SNR}_i}\left(\frac{\gamma}{M}\right) \\ &= \prod_{i=1}^{M}\left[1 - Q_{1/2}\left(\frac{\mu_{H,i}}{\sigma_{H,i}}, \sqrt{\frac{\gamma}{M\rho_i\,\sigma_{H,i}^2}}\right)\right] \\ &= \prod_{i=1}^{M}\left[1 - Q_{1/2}\left(\frac{\mu_{H,i}}{\sigma_{H,i}}, \sqrt{\frac{\sigma_n^2\,\gamma}{P_0\,G_t G_{r,i}\,\sigma_{H,i}^2}}\right)\right]. \end{aligned} \tag{17}$$

B. Ergodic Capacity

In this part, we derive the ergodic capacity of the uplink LIS-assisted communication with opportunistic selective reception. The ergodic capacity is defined as average of achievable normalized data rate $\log_2(1+\mathrm{SNR}_{\mathrm{sel}})$. Thus, the normalized bandwidth ergodic capacity is given by

$$\bar{C}_{\mathrm{sel}} = \mathbb{E}\{\log_2(1+\mathrm{SNR}_{\mathrm{sel}})\} = \int_0^{\infty} \log_2(1+\gamma)\, f_{\mathrm{sel}}(\gamma)\,d\gamma. \tag{18}$$

where the PDF of $\mathrm{SNR}_{\mathrm{sel}} = \max_i\left\{\gamma_i\right\}$ is given by

$$f_{\mathrm{sel}}(\gamma) = \frac{d}{d\gamma}F_{\mathrm{sel}}(\gamma) = \sum_{i=1}^{M}\frac{1}{M}f_{\mathrm{SNR}_i}\left(\frac{\gamma}{M}\right)\prod_{k=1,k\ne i}^{M}F_{\mathrm{SNR}_k}\left(\frac{\gamma}{M}\right). \tag{19}$$

Substituting $f_{\mathrm{SNR}_i}(\cdot)$ and $F_{\mathrm{SNR}_k}(\cdot)$ from (14) and (11), respectively, into (19), we have

$$\begin{aligned} f_{\mathrm{sel}}(\gamma) = &\sum_{i=1}^{M}\frac{\gamma^{-1/4}}{2M\rho_i^{3/4}\mu_{H,i}^{-1/2}\sigma_{H,i}^2}\, I_{-1/2}\left(\frac{\mu_{H,i}\sqrt{\gamma}}{\sqrt{M\rho_k}\sigma_{H,i}^2}\right) \\ &\times e^{-\frac{\gamma+M\rho_i\mu_{H,i}^2}{2M\rho_i\sigma_{H,i}^2}}\prod_{k=1,k\ne i}^{M}\left[1 - Q_{1/2}\left(\frac{\mu_{H,k}}{\sigma_{H,k}}, \sqrt{\frac{\gamma}{M\rho_i\,\sigma_{H,k}^2}}\right)\right]. \end{aligned} \tag{20}$$

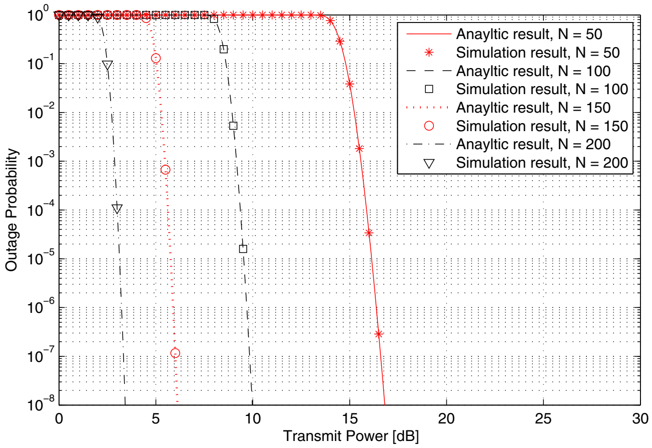

Fig. 2. The system performance in terms of outage probability curves for a MRC-detected system with $M = 2$ and $G_t = 63$ (18 dB) for different number of LIS components $N = 50, 100, 150, 200$.

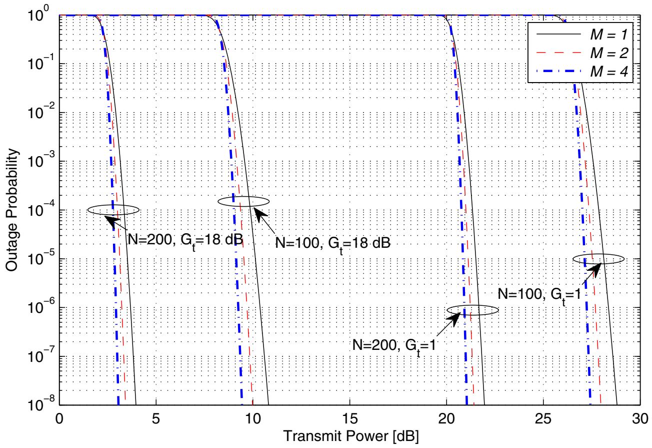

Fig. 3. The system performance in terms of outage probability curves for a MRC-detected system for different number of LISs M, LIS components N, and different values of LIS antenna gain G_t.

By replacing $\rho_i = \frac{P_0 G_t G_{r,i}}{M\,\sigma_n^2}$ in (20), the PDF can be rewritten as

$$f_{\text{sel}}(\gamma) = \sum_{i=1}^{M} \frac{\sigma_n^{3/2} e^{\frac{-\mu_{H,i}^2}{2\sigma_{H,i}^2}} \gamma^{-1/4}}{2P_0^{3/4} G_t^{3/4} G_{r,i}^{3/4} \mu_{H,i}^{-1/2} \sigma_{H,i}^2} \, e^{\frac{-\sigma_n^2 \gamma}{2P_0 G_{r,i} \sigma_{H,i}^2}} \times I_{-1/2}\left(\frac{\mu_{H,i}\sigma_n\sqrt{\gamma}}{\sigma_{H,i}^2 \sqrt{P_0 G_t G_{r,i}}} \right) \times \prod_{k=1, k\neq i}^{M} \left[1 - Q_{1/2}\left(\frac{\mu_{H,k}}{\sigma_{H,k}}, \sqrt{\frac{\sigma_n^2\,\gamma}{P_0\, G_t G_{r,k}\, \sigma_{H,k}^2}} \right) \right]. \tag{21}$$

V. SIMULATION RESULTS

The objective of this section is to evaluate the performance of LIS system under mmWave based cellular system. We assume a network operating under carrier frequency of 28 GHz and allocated bandwidth of 100 MHz. All channels are modeled as independent Nakagami-m fading which proper in modeling mmWave channels. Since LIS components are deployed in a fixed location, it is assumed that fronthaul links are line-of-sight (LoS)-connected. That is, Nakagami parameter of $m = 4$ and path-loss exponent of $\alpha = 2$ are assumed for $f_{i,j}$ links between A-BS and LIS towers. In addition, access links between the typical user and LISs are assumed to have more NLoS power, and thus, for $h_{i,j}$ links, we assume Nakagami parameter of $m = 2$ and path-loss exponent of $\alpha = 2.9$. The noise figure is also assumed to be 10 and A-Bs receiver is equipped with directional antennas with main lobe gain of 18 dB [3].

In Fig. 2, we investigate the system performance in term of outage probability for different number of LIS components N. It is assumed that the number of LISs are $M = 2$ and LISs are equipped with transmit directional antennas with gain of $G_t = 63$ (18 dB). The numerical results are derived using built-in Marcum-Q function of order k in Matlab. First, one can observe that analytical results derived in Subsection III-A are confirmed by simulations. In addition, it can be observed that error plots are sharply drops at certain point that shows the sensitivity of the system with respect to transmit power P_0. For instance, in a system with $N = 200$ LIS components, only transmit power of 3 to 4 dBm is enough to have a reliable detection. However, for a system with $N = 50$, only transmit power of around 16 dBm is required to have an outage probability of 10^{-4}.

Next, the outage probability curves are plotted versus transmit power P_0 in Fig. 3 for different number of LISs, $M = 1, 2, 3$, and passive antenna elements, $N = 100, 200$. We also consider two scenarios for LIS. In the first one, no directional antennas is used at LIS for simple implementation, i.e., omni-directional antennas are employed with gain of $G_t = 1$. In the second scenario, analogue beamforming is used to tackle adverse effect of high path-loss in mmWave frequencies. Hence, the main lobe gain of transmit beamforming in LISs are adjusted toward the A-Bs with $G_t = 63$ (18 dB). It is shown in Fig. 3 that the system with analogue beamforming at LISs significantly outperforms a system with omni-directional LIS antennas.

Fig. 4 compares the performance of MRC detection and opportunistic selective scheme discussed in Section IV for a system with $M = 4$ and $N = 100$. One can observe that opportunistic selective scheme performs slightly better than MRC detection. It is also confirm the correctness of our derivations in Subsection IV-A.

Finally, in Fig. 5, we present ergodic capacity curves for both MRC detection and opportunistic selective schemes for different parameters. Again, it is shown that opportunistic selective scheme performs slightly better than MRC detection in term of achievable data rate. Moreover, one can observe

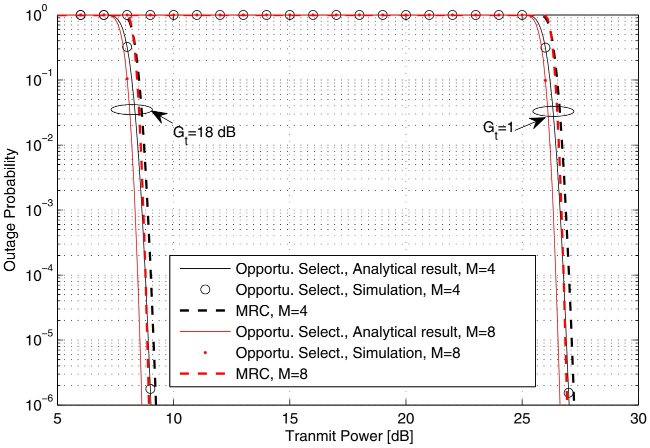

Fig. 4. The comparison between MRC detection and opportunistic selective scheme in term of outage probability versus transmit power P_0 for a system with $M = 4$ and $N = 100$.

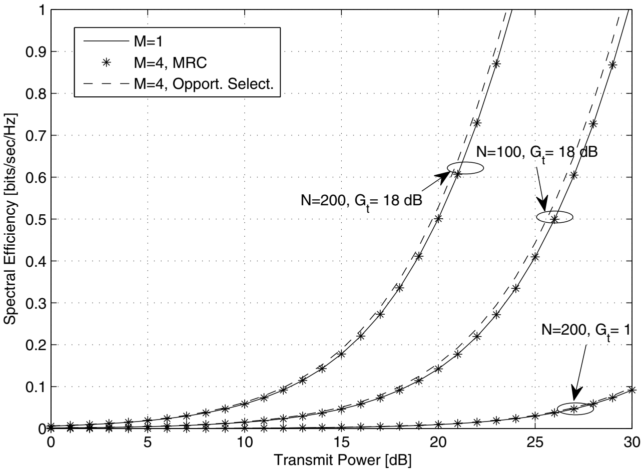

Fig. 5. The ergodic capacity of MRC detection and opportunistic selective schemes for different parameters under mmWave channels modeled by Nakagami-m fading.

that capacity is significantly improved with deployment of analogue beamfming at LISs and having more number of passive antenna components N.

VI. Conclusion

In this paper, we investigated the performance of the uplink LIS-based mmWave CoMP system under Nakagami-m links operating at 28 GHz. The performance of system has been investigated in terms of outage probability and ergodic capacity. The impact of several parameters such as transmit power, number of LIS components, number of LIS towers, and analogue beamforming gain have been studied in numerical results. Furthermore, it has been shown that opportunistic reception at anchor BS performs slightly better than MRC reception. Moreover, simulation results confirm the correctness of our derived formulas.

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