The Impact of Interference on Large-Scale Cloud Radio Access Networks

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***Abstract*—In the 5th generation cellular system, a large-scale cloud radio access network is one of the most promising structures for providing high quality-of-service to end users. This extended abstract presents the impact of interference on such a system. Based on stochastic geometry and probabilistic order notation, the scaling exponents of the guaranteed signal-to-interference-plus-noise ratio and the maximum allowed users are derived. This result is effective to understand the impact of interference on the 5G system.**

I. Introduction

Interference is one of the main bottlenecks for achieving very high throughput and qaulity of service in cellular systems. In the 5th generation cellular system, there are two key enabling techniques to reduce the interference: cloud radio-access network (C-RAN) and large-scale antenna system (LSAS). C-RAN has been widely recognized as a promising technique to enhance spectral efficiency by jointly avoiding or exploiting inter-cell interference [1], and there has been a great deal of interest for LSAS, in which a very large number of antennas are equipped in each BS and time-division duplex (TDD) mode is employed to exploit the channel reciprocity [2][3]. Compared to the conventional cellular network (equipped with several antennas), inherent merits of the LSAS are massive spatial dimensions, which can be used for 1) increasing the spectral efficiency by statistically suppressing unintended ICI [3] and 2) reducing the transmission power while guaranteeing quality of service (QoS) [4]. The natural extension is to combine C-RAN and LSAS for providing the high quality-of-service without interference and it is called large-scale C-RAN.

The fundamental question is that how much interference can be reduced in large-scale C-RAN. Our ongoing project is to define a new performance metric and to derive an asymptotic behavior of performance of such a system. We propose the guaranteed signal-to-interference-plus-noise-ratio (SINR), which is the received SINR to be achieved with probability one, and the maximum allowed users, which is the maximum number of users whom the system can support with constant quality of service. Using stochastic geometry and probabilistic order notation, we successfully derive the scaling exponent of the guaranteed SINR and the maximum allowed users.

II. System Models

The single-antenna users and the M-antenna BSs are distributed on the finite system coverage region $\mathcal{C} = b(o, R)$ according to the homogeneous Poisson point process (PPP) of densities λ_{BS} and λ_U, which are denoted as $\Phi_{BS} = \{X_1, X_2, \cdots, X_L\}$ and $\Phi_U = \{U_1, U_2, \cdots, U_K\}$, respectively. Note that $L = |\Phi_{BS}|$ and $K = |\Phi_U|$ are Poisson random variables with parameters $\pi R^2 \lambda_{BS}$ and $\pi R^2 \lambda_U$, respectively.

The $M \times 1$ flat-fading composite channel vector between BS l and user k, denoted by $\mathbf{g}_{lk}$, can be defined as $\mathbf{g}_{lk} = \sqrt{\beta_{lk}}\mathbf{h}_{lk}$, where $\mathbf{h}_{lk} \in \mathbb{C}^{M\times 1}$ is the short-term CSI whose elements are independent and identically distributed (i.i.d.) $\mathcal{CN}(0, 1)$ and $\beta_{lk}(\geq 0)$ is the long-term CSI depending on the distance-based path-loss, i.e., $\beta_{lk} = r_{lk}^{-\alpha}$, where $\alpha(> 2)$ is the path-loss exponent and $r_{lk} = |X_l - U_k|$. It is assumed that the short-term CSI of each user remains constant within a given frame but independent across different frames, while the long-term CSI does not vary during a much longer interval. Further, it is assumed that the long-term CSIs among all BSs and users are perfectly known at the CPU through an infrequent feedback with a negligible overhead.

Using the least-square (LS) channel estimator [5], the estimated short-term CSI of user k at BS l can be written as

$$\widehat{\mathbf{h}}_{lk} = \sqrt{\frac{TP_k^{\mathrm{UL}}\beta_{lk}}{TP_k^{\mathrm{UL}}\beta_{lk} + N_0}}\mathbf{h}_{lk} + \sqrt{\frac{1}{TP_k^{\mathrm{UL}}\beta_{lk} + N_0}}\tilde{\mathbf{v}}_{lk}, \quad (1)$$

where T is the length of pilot signal and P_k^{UL} is the uplink transmission power. Assume that a typical user located at the origin and indexed by U_1. Let SINR^{Υ} denote the received SINR of a typical user for a transmission scheme Υ. For given allocated powers $\{P_k^{\mathrm{DL}}\}_{k=1}^{K}$, SINR^{Υ} is given by

$$\mathsf{SINR}^{\Upsilon} = \frac{P_1^{\mathrm{DL}}\left|\sum_{l\in\mathcal{L}_1}\mathbf{g}_{l1}^H\mathbf{f}_{l1}^{\Upsilon}\right|^2}{N_0 + \sum_{j=2}^{K}P_j^{\mathrm{DL}}\left|\sum_{l\in\mathcal{L}_j}\mathbf{g}_{l1}^H\mathbf{f}_{lj}^{\Upsilon}\right|^2}, \quad (2)$$

where $\mathbf{f}_{lj}$ is the $M \times 1$ beamforming vector for user j at BS l. Note that SINR^{Υ} is a random variable depending on the realization of the short-term fadings and the long-term fadings (i.e., realization of users and BSs).

III. Performance Measure

As the main performance measure, *the guaranteed SINR* is defined as follow.

Definition 1: The guaranteed SINR for a operation Υ, Γ^{Υ}, is the highest SINR level that a typical user exceeds with high probability, given by

$$\Gamma^{\Upsilon} \triangleq \sup\{\gamma | \Pr(\mathsf{SINR}^{\Upsilon} \geq \gamma) = 1\}. \tag{3}$$

From Definition 1, all of users in the network can be served by the spectral efficiency of $\log_2(1+\Gamma^{\Upsilon})$ bps/Hz when a operation Υ is used and the total average network throughput is lower bounded by $\pi R^2 \lambda_U \log_2(1+\Gamma^{\Upsilon})$ with high probability.

The main objective in this section is to find the asymptotic behavior of Γ^{Υ} when the key network parameters such as the number of BSs L, the number of users K, the number of BS antennas M are scaled up simultaneously. To do this, an auxiliary parameter N is used to set $\lambda_{BS} = \Theta(N^{\eta_L})$, $\lambda_U = \Theta(N^{\eta_K})$, and $M = \Theta(N^{\eta_M})$, where η_L, η_K, and η_M are the scaling exponents of the number of BSs, users, and BS antennas, respectively. Then, the definition of the scaling exponent of the guaranteed SINR is given as follow:

Definition 2: The scaling exponent of the guaranteed SINR for a operation Υ, γ^{Υ}, is the order of growth of the guaranteed SINR as N increases, given by

$$\mathsf{sinr}^{\Upsilon} = \lim_{N\to\infty} \frac{\log \Gamma^{\Upsilon}}{\log N}. \tag{4}$$

Note that if $\Gamma^{\Upsilon} = \infty$, sinr^{Υ} is not well-defined so that we set $\mathsf{sinr}^{\Upsilon} = \infty$. From Definition 2, we can easily know that $\Gamma^{\Upsilon} = \Theta\left(N^{\mathsf{sinr}^{\Upsilon}}\right)$.

IV. Main Results

To quantify the impact of interference, we construct the interference-free system, in which the interference term in (2) is removed without any penalty and the beamforming vector is matched to the channel for maximizing the signal term. Note that we omit the proof due to page limit.

Lemma 1. (*IF Operation*) Suppose that $P_k^{\mathsf{DL,IF}} \overset{p}{=} \Theta\left(N^{\rho^{\mathrm{DL}}}\right)$ and $P_k^{\mathsf{UL,IF}} \overset{p}{=} \Theta\left(N^{\rho^{\mathrm{UL}}}\right)$ for $\forall k$. Then,

$$\mathsf{sinr}^{\mathsf{IF}} = \rho^{\mathrm{DL}} + \frac{\alpha}{2}\eta_L + \left(\frac{\alpha}{2}\eta_L + \eta_M + \rho^{\mathrm{UL}}\right)^+ - \left(\frac{\alpha}{2}\eta_L + \rho^{\mathrm{UL}}\right)^+ \tag{5}$$

where $(x)^+ = \max\{x, 0\}$.

Now, we move to the practical one, such as the maximum ratio transmission [6], which is the one of simple but powerful transmission scheme in LSAS.

Lemma 2. (*MRT operation*) Suppose that $P_k^{\mathsf{DL,MRT}} \overset{p}{=} \Theta\left(N^{\rho^{\mathrm{DL}}}\right)$ and $P_k^{\mathsf{UL,MRT}} = P^{\mathsf{UL,MRT}} \overset{p}{=} \Theta\left(N^{\rho^{\mathrm{UL}}}\right)$ for all k. Then,

$$\begin{aligned}\mathsf{sinr}^{\mathsf{MRT}} &= \rho^{\mathrm{DL}} + \frac{\alpha}{2}\eta_L + \left(\frac{\alpha}{2}\eta_L + \eta_M + \rho^{\mathrm{UL}}\right)^+ \\ &\quad - \left(\frac{\alpha}{2}\eta_L + \rho^{\mathrm{UL}}\right)^+ \\ &\quad - \left(\frac{\alpha}{2}\eta_K - \left(\frac{\alpha}{2} - 1\right)(\eta_K - \eta_L)^+ + \rho^{\mathrm{DL}}\right)^+.\end{aligned} \tag{6}$$

Remark: From the lemma 2, we can define the penalty of the MRT operation as the difference of $\mathsf{sinr}^{\mathsf{MRT}}$ and $\mathsf{sinr}^{\mathsf{IF}}$, given by

$$\Delta^{\mathsf{MRT}} = \mathsf{sinr}^{\mathsf{IF}} - \mathsf{sinr}^{\mathsf{MRT}} \tag{7}$$

$$= \left(\frac{\alpha}{2}\eta_K - \left(\frac{\alpha}{2} - 1\right)(\eta_K - \eta_L)^+ + \rho^{\mathrm{DL}}\right)^+. \tag{8}$$

The following corollary characterizes the penalty of operations.

Corollary 1. To approach the performance of the IF operation asymptotically, the downlink transmission power should be

$$\rho^{\mathrm{DL}} \leq -\frac{\alpha}{2}\eta_K + \left(\frac{\alpha}{2} - 1\right)(\eta_K - \eta_L)^+.$$

For a practical network, it would be of the most interest how many users can be supported with a guaranteed QoS (equivalently SINR). Also, in the future cellular system called the 5th generation, one of the most important key performance indicator is the guaranteed (edge-user) throughput by which guaranteed QoS of a network can be defined. By the following theorem, as the asymptotic behavior of operations can be answered as the network size increases.

Theorem 1. Any given non-zero finite guaranteed SINR can be achieved by consuming at most finite power as the network size N increases with $L = \Theta(N^{\eta_L})$ and $M = \Theta(N^{\eta_M}) = \Theta(N^{1-\eta_L})$, if

$$\eta_K \leq \begin{cases} \left(\frac{\alpha}{2} - \frac{1}{2}\right)\eta_L + \frac{1}{2}, & \text{if } \Upsilon = \mathsf{IF}. \\ \frac{\alpha}{4}\eta_L + \frac{1}{2}, & \text{if } \Upsilon = \mathsf{MRT}. \end{cases} \tag{9}$$

V. Conclusion

In this work, the imact of interference on the large-scale C-RAN was analyzed. As a future work, the more complicate operations will be analized and our final goal is to find the order-optimal operation in this system.

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