Achieving the Optimal Throughput Scaling in Multi-Cell Random Access Networks

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Abstract—Due to the difficulty of coordination in multi-cell random access, it is a practical challenge how to achieve the optimal throughput with decentralized transmission. In this paper, we propose a decentralized multi-cell aware opportunistic random access (MA-ORA) protocol that almost achieves the optimal throughput scaling in a multi-cell random access network with one access point (AP) and multiple users in each cell. Under our MA-ORA protocol, each user opportunistically transmits with a predefined physical layer data rate if the desired signal power to the serving AP is sufficiently large and the generating interference power is sufficiently small. As a main result, it is shown that the proposed MA-ORA protocol can achieve both the almost full multiplexing and multiuser diversity gains in a high signal-to-noise ratio regime if the number of users scales faster than a certain level. Our results are validated by computer simulations.

I. INTRODUCTION

Random access in wireless communications has received growing attention to support massive users owing to a relatively low protocol overhead with high spectral efficiency. Various random access protocols have been developed based on ALOHA and its variation with carrier sensing [1]. In random access networks, due to the explosive growth of users and their generated data packets, there is an intention to densely deploy access points (APs) to achieve higher system throughput with the unchanged limited frequency bandwidth. Thus, it is crucial to fully understand the nature of random access networks that consist of multiple cells sharing the same frequency band, so called multi-cell random access networks. In such networks, besides the intra-cell collision (simultaneous transmission from multiple users in the same cell), transmission without coordinated scheduling among APs will cause interference in other cells, which may lead to a failure of packet decoding at the receivers. Hence, inter-cell interference should be carefully managed in multi-cell random access networks.

On the one hand, there are extensive studies on handling interference issues of cellular networks with multiple base stations. While it has been elusive to find the optimal strategy with respect to the Shannon-theoretic capacity in multi-user cellular networks, interference alignment (IA) was recently proposed for fundamentally solving the interference problem when there are multiple communication pairs [2]. It was shown that IA can asymptotically achieve the optimal degrees of freedom, which are equal to \( \frac{K}{T} \), in the \( K \)-user interference channel with time-varying coefficients. Subsequent work showed that interference management schemes based on IA can be well applicable to interfering multiple access networks [3]–[5]. In addition to the multiple access scenarios in which collisions can be avoided, it is of significant importance how to manage interference in random access. For multi-cell random access networks, several studies were carried out to manage interference by performing IA [6] or successive interference cancellation (SIC) [7]. In [8], [9], decentralized power allocation approaches were introduced by means of interference mitigation for random access with capabilities of multi-packet reception and SIC at the receiver.

On the other hand, there have been extensive studies on the usefulness of fading in single-cell broadcast channels by exploiting the multi-user diversity gain as the number of users is sufficiently large [10]–[12]. Moreover, scenarios obtaining the multi-user diversity gain were studied in multi-cell environments. In particular, opportunism can be utilized in multi-cell downlink networks through a simple extension of [12]. More recently, for multi-cell uplink networks, the optimal throughput scaling was analyzed by showing that the full multiuser diversity gain can be achieved by a distributed user scheduling strategy in each cell, provided that two scheduling criteria are properly determined and the number of users in each cell is larger than a certain level [13]. Besides the aforementioned multiple access scenarios, the benefits of opportunistic transmission can also be exploited in random access networks. The idea of single-cell aware opportunistic random access (SA-ORA) (also termed channel-aware slotted ALOHA in the literature) was proposed in slotted ALOHA networks with a single AP [14]. By assuming that channel state information (CSI) can be acquired at the transmitters, the SA-ORA protocol was shown to achieve the multi-user diversity gain without any centralized scheduling. Nevertheless, the protocol in [14] deals only with the single-AP problem, and thus cannot be straightforwardly applied to multi-cell random access networks in which the inter-cell interference exists.

In this paper, we consider a \( K \)-cell random access network, consisting of one AP and \( N \) users in each cell, in the presence of quasi-static multi-path fading. Then, we introduce a decen-
centralized multi-cell aware opportunistic random access (MA-ORA) protocol that almost achieves the optimal throughput scaling in the network model. First of all, it is worthwhile addressing the fundamental differences between our MA-ORA protocol and the two aforementioned different types of opportunistic transmission protocols:

- Unlike opportunistic scheduling in [10]–[13] for cellular multiple access environments where each base station selects users via feedback information, in our MA-ORA protocol designed for random access, both the intra-cell collision and inter-cell interference are mitigated solely by users’ opportunistic transmission in a decentralized manner.
- The SA-ORA protocol in [14] was shown to achieve the multiuser diversity gain (i.e., the power gain) for single-AP random access, but its extension to multi-cell random access is not straightforward due to the existence of inter-cell interference. Moreover, in addition to the multiuser diversity gain, it remains open in the literature how to provide the $K$-fold increase in the multiplexing gain via properly mitigating the inter-cell interference.

In our multi-cell random access network, we assume that uplink channel gains to multiple APs are available at the transmitters by exploiting the uplink/downlink reciprocity in time-division duplex (TDD) mode. We utilize this local CSI at the transmitter (CSIT) to design our protocol. In the initialization phase, two thresholds and a physical layer (PHY) data rate are computed offline and broadcast over the network as system parameters. Thereafter, in each time slot, each user in a cell first estimates the uplink channel gains via the downlink channel. Then, each user determines whether both 1) the channel gain to the serving AP is higher than one threshold and 2) the inter-cell interference generated by this user to the other APs is lower than another threshold. Users opportunistically transmit with the computed PHY data rate if the above two conditions are fulfilled. It is shown that the aggregate throughput achieved by the proposed MA-ORA protocol scales as $\frac{K}{\epsilon} (1 - \epsilon) \log(\text{SNR} \log N)$ in a high signal-to-noise ratio (SNR) regime, provided that $N$ scales faster than $\text{SNR}^{-1/\epsilon}$ for an arbitrarily small constant $\epsilon > 0$ and a constant $0 < \delta < 1$. This reveals that even without any centralized scheduling from the APs, the proposed protocol is able to achieve the almost full multiplexing and multiuser diversity gains. To validate our analytical result, we perform numerical evaluation via computer simulations. Moreover, under a practical setting (i.e., in a finite SNR or $N$ regime) of our multi-cell random access, it is shown that the proposed MA-ORA protocol outperforms the conventional SA-ORA in terms of throughput.

The remainder of the paper is organized as follows. Section II presents system and channel models. Section III describes the proposed MA-ORA protocol. Section IV provides numerical results for validation. Section V concludes this paper. Detailed description and the proof of the main theorem are omitted due to page limit.

Fig. 1: The system model of a multi-cell random access network with one AP and $N$ users in each cell.

II. SYSTEM AND CHANNEL MODELS

As illustrated in Fig. 1, we consider a multi-cell random access network consisting of $K \geq 1$ APs using the same frequency band, where $N$ users are served in each cell. We assume that there is no cooperation among the APs for decoding, i.e., each AP attempts to decode the received packets from the belonging users independently. All the users and APs are equipped with a single antenna. The slotted ALOHA-type protocol is adopted and we assume the perfect slot level synchronization not only between users and the serving AP but also among the APs. We assume fully-loaded traffic such that each user has a non-empty queue of packets to transmit, similarly as in [15]. For each user, the head-of-line packet is transmitted with a probability $p$ at random, regardless of the number of retransmission, i.e., each packet is assumed to be the same for all retransmission states. We adopt a modified signal-to-interference-plus-noise ratio (SINR) capture model, where each AP can decode the received packet by treating inter-cell interference (concurrently transmitted signals from other-cell users) as noise if the received SINR of the desired packet exceeds a given decoding threshold. The concurrent intra-cell transmission such that two or more users in the same cell simultaneously transmit causes a collision, and thus the receiver (AP) fails to decode any packet. In this paper, we assume the use of single-user detection at each AP rather than any sophisticated multiuser detection, since using multiuser detection schemes cannot fundamentally increase the degrees of freedom under our random access system model.

Let $\alpha_{i \rightarrow k} h_{j \rightarrow k}$ denote the channel coefficient from the $i$-th user in the $j$-th cell to the $k$-th AP for $i \in \{1, \cdots, N\}$ and $j \in \{1, \cdots, K\}$, where $0 < \alpha_{i \rightarrow k} \leq 1$ is the large-scale path-loss component and $h_{j \rightarrow k} \in \mathbb{C}$ modeled by an independent and identically distributed (i.i.d.) complex Gaussian random variable is the small-scale fading component. In our network where the number of users is sufficiently large, it is simply assumed that $\alpha_{i \rightarrow k} = 1$. We assume the local CSIT such that the users can acquire the uplink channel gains to multiple APs.
For instance, the channel gain from the $i$-th user to the $k$-th AP, denoted by $g_{j\rightarrow k}^i = |h_{j\rightarrow k}^i|^2$, is available at the $i$-th user. We consider a quasi-static fading model, where the channel coefficients are constant during one time slot and vary independently in the next time slot. The CSIT can be acquired by exploiting the uplink/downlink reciprocity in TDD systems, by virtue of calibrations on the radio frequency chain [16]. Practical CSIT acquisition methods have also been introduced for multi-cell multi-antenna systems [17]. In the previous seminal literature on SA-ORA with one AP deployment [14], the local CSIT and the corresponding distribution information were assumed to be available. Recently, the acquisition process was described in more detail for multichannel SA-ORA [18]. Inspired by [14], [18], a channel gain acquisition process for our model deploying multiple APs (i.e., our multi-cell random access model) is described as follows. Under the slotted ALOHA protocol, each AP broadcasts $(0, 1, e)$ feedback to inform the belonging users of the reception status after each time slot by utilizing the downlink channel, where $0$ means that no packet is received (idle); $1$ means that only one packet is received (successful transmission); and $e$ indicates that two or more packets are simultaneously transmitted (collision).

In our multi-cell scenario, each AP broadcasts the feedback message in an orthogonal mini-time slot, which requires a small amount of coordination among the APs. By exploiting the channel reciprocity in TDD mode, each user is capable of estimating the channel gains to multiple APs through the received feedback messages. That is, it is possible for each user to conduct a multi-cell aware channel gain estimation. It is worth noting that since only the amplitude information of the CSI (but not the phase information) is required in our protocol, the length of this feedback stage can be greatly shortened by using quantization.

The received signal $y_k \in \mathbb{C}$ at the $k$-th AP is given by

$$
y_k = \sum_{u_k=1}^{n_k} h_{j\rightarrow k}^u \pi^{(u_k)} + \sum_{j\neq k} \sum_{u_j=1}^{n_j} h_{j\rightarrow k}^{u_j} \pi^{(u_j)} + z_k, \tag{1}
$$

where $\pi^{(u_k)}$ is the transmitted signal from the $u_k$-th user in the $k$-th cell and the binomial random integer $n_k \sim B(N, p)$ is the number of transmitting users in the $k$-th cell. The received signal is corrupted by the i.i.d. complex additive white Gaussian noise $z_k \in \mathbb{C}$ with zero-mean and variance $N_0$. For each transmission, there is an average transmit power constraint $\mathbb{E}[|x_k|^2] \leq P$.

III. Multi-Cell Aware Opportunistic Random Access (MA-ORA)

In this section, we describe the procedure of our MA-ORA protocol including the design of system parameters. As illustrated in Fig. 2, in the initialization phase, the APs broadcast two thresholds $\Phi_G$ and $\Phi_I$, and the PHY data rate $R$ for opportunistic transmission in our multi-cell random access network. During the data communication phase, it is investigated that the maximum medium access control layer (MAC) throughput is achieved at the transmission probability $p = \frac{1}{N}$ for large $N$ in the conventional slotted ALOHA protocol deploying one AP. Similarly, in our MA-ORA protocol, the transmission probability $p$ is also set to $\frac{1}{N}$ to avoid excessive intra-cell collisions or idle slots, enabling us to find a relationship between $\Phi_G$ and $\Phi_I$ (to be discussed in Section III-A).

In each time slot, each user first estimates the uplink channel gains by using the feedback messages sent from the APs. Then, the $i$-th user in the $j$-th cell for $i \in \{1, \cdots, N\}$ and $j \in \{1, \cdots, K\}$ compares the channel gains with the given two thresholds to examine whether the following two inequalities are fulfilled:

$$g_{j\rightarrow j}^i \geq \Phi_G \tag{2}$$

and

$$\sum_{k=1 \atop k \neq j}^{K} g_{j\rightarrow k}^i \leq \Phi_I, \tag{3}$$

where (2) indicates a “good” channel condition to the serving AP that leads to a large desired signal power, and (3) means that the inter-cell interference generated by this user is well confined due to a “weak” channel condition to the other APs. In each cell, users satisfying both (2) and (3) transmit with the PHY data rate $R$ (to be selected in Section III-B), while the other users keep idle in this time slot. Each AP then receives and decodes the desired packet by treating all the interference as noise. By virtue of such opportunistic transmission, when $N$ is sufficiently large, it is possible for the packets simultaneously sent from multiple users in different cells to be successfully decoded with high probability.

Note that our MA-ORA protocol operates for general $K$ values. As a special case, for $K = 1$, each user just checks
whether the condition (2) is fulfilled or not, which corresponds to the conventional SA-ORA protocol.

A. The Selection of Two Thresholds

The probability that each user accesses the channel is expressed as

\[
p = \Pr \left( g_{j \rightarrow j}^j \geq \Phi_G, \sum_{k \neq j} g_{j \rightarrow k}^j \leq \Phi_I \right)
\]

(4)

\[
= \Pr \left( g_{j \rightarrow j}^j \geq \Phi_G \right) \Pr \left( \sum_{k \neq j} g_{j \rightarrow k}^j \leq \Phi_I \right),
\]

(5)

where the second equality holds since the channel gains to different APs are independent of each other. From the fact that \( p \) is set to \( \frac{1}{N} \), we have

\[
\Pr \left( g_{j \rightarrow j}^j \geq \Phi_G \right) \Pr \left( \sum_{k \neq j} g_{j \rightarrow k}^j \leq \Phi_I \right) = \frac{1}{N},
\]

which is equivalent to

\[
F_G(\Phi_G)(1 - F_I(\Phi_I)) = \frac{1}{N},
\]

(6)

where \( F_G \) and \( F_I \) denote the cumulative distribution functions of \( g_{j \rightarrow j}^j \) and \( \sum_{k \neq j} g_{j \rightarrow k}^j \), respectively. Then, the relationship between \( \Phi_G \) and \( \Phi_I \) is given by

\[
\Phi_G = F_G^{-1} \left( 1 - (F_I(\Phi_I)N)^{-1} \right).
\]

(7)

In our MA-ORA protocol, \( \Phi_I \) is set to \( \rho^{-1} \) to achieve the almost full multiplexing and multiuser diversity gains as \( \rho \) increases, where \( \rho \) denotes the average signal-to-noise ratio (SNR). In consequence, the two thresholds are given by

\[
\begin{align*}
\Phi_I &= \rho^{-1} \\
\Phi_G &= F_G^{-1} \left( 1 - (F_I(\rho^{-1})N)^{-1} \right).
\end{align*}
\]

(8)

Note that the transmission probability \( p \) is set to \( \frac{1}{N} \) in terms of maximizing the MAC throughput in each cell, which is thus independent of \( \rho \).

B. The Selection of PHY Data Rate

At the receiver, even if an AP receives only one packet from the belonging user, this packet is still corrupted by the noise and the inter-cell interference. Thus, it is required that the received SINR of this packet exceeds a certain decoding threshold given by \( 2^R - 1 \). The successful decoding probability, \( p_s \), is given by

\[
p_s = \Pr \left( \frac{P g_{j \rightarrow j}^j}{N_0 + \sum_{k \neq j} \sum_{u=0}^{n_k} P g_{k \rightarrow j}^u} \geq 2^R - 1 \right),
\]

(9)

where the binomial random variable \( n_k \sim B(N, p) \) is the number of simultaneously transmitting users in the \( k \)-th cell and \( \pi(u) \) denotes the index of transmitting users in each cell. By using the successful decoding probability in (9), the throughput at the \( j \)-th AP is given by

\[
R_{\text{sum}}^{(j)} = Np(1 - p)^{N - 1} \cdot R \cdot p_s,
\]

(10)

where \( Np(1 - p)^{N - 1} \) is the MAC throughput and \( R \) is the target PHY data rate.\(^2\) From the fact that \( p = \frac{1}{N} \), the aggregate throughput of the \( K \)-cell random access network is given by

\[
R_{\text{sum}} = \sum_{j=1}^{K} R_{\text{sum}}^{(j)} = \sum_{j=1}^{K} \frac{\Phi_G}{\rho^j + \Phi_I^j} \geq 2^R - 1,
\]

(11)

where \( \tilde{n} \sim B((K - 1)N, p) \) is a binomial random variable, representing the total number of interfering signals from the other cells, and is given by \( \tilde{n} = \sum_{j=1}^{K} n_k \). Here, the inequality comes from (2), (3), and (9).

Now, we focus on computing a lower bound on the successful decoding probability, \( q_s \), shown below:

\[
q_s = \Pr \left( \frac{\Phi_G}{\rho^j + \Phi_I^j} \geq 2^R - 1 \right)
\]

\[
= \prod_{i=0}^{(K-1)N} \Pr \left( \frac{\Phi_G}{\rho^{-i} + \Phi_I^{-i}} \geq 2^R - 1 \right) \Pr(\tilde{n} = i).
\]

(12)

Let us consider an integer \( \nu \in \{0, 1, \ldots, (K - 1)N\} \). If \( R \) is set to a value such that \( \frac{\Phi_G}{\rho^{-\nu} + \Phi_I^{-\nu}} < 2^R - 1 \leq \frac{\Phi_G}{\rho^{-\nu-1} + \Phi_I^{-\nu-1}} \), then \( \Pr \left( \frac{\Phi_G}{\rho^{-\nu} + \Phi_I^{-\nu}} \geq 2^R - 1 \right) \) is given by 1 and 0 for \( i \in \{0, \ldots, \nu\} \) and \( i \in \{\nu + 1, \ldots, (K - 1)N\} \), respectively. Based on this observation, the entire feasible range of \( 2^R - 1 \) can be divided into the following \((K - 1)N + 1\) sub-ranges:

\[
\left\{ \frac{\Phi_G}{\rho^{-1} + (K - 1)N \Phi_I} \right\}, \ldots, \left\{ \frac{\Phi_G}{\rho^{-1} + (\nu + 1) \Phi_I} \right\}, \ldots, \left\{ \frac{\Phi_G}{\rho^{-1} + \infty \Phi_I} \right\}
\]

(13)

For \( R \in \left( \frac{\Phi_G}{\rho^{-1} + \infty \Phi_I}, \infty \right) \), we have \( q_s = 0 \), which is thus neglected in our work. By using the fact that the term \( \Pr \left( \frac{\Phi_G}{\rho^{-\nu} + \Phi_I^{-\nu}} \geq 2^R - 1 \right) \) in (12) is an indicator function of \( R \), we set \( \tilde{R} \) to the maximum under the condition that \( 2^\tilde{R} - 1 \) lies in each sub-range \( \left\{ \frac{\Phi_G}{\rho^{-1} + (\nu + 1) \Phi_I}, \frac{\Phi_G}{\rho^{-1} + \nu \Phi_I} \right\} \), which is given by

\[
\tilde{R} = \log_2 \left( 1 + \frac{\Phi_G}{\rho^{-1} + \nu \Phi_I} \right),
\]

(13)

where \( \nu \in \{0, 1, \ldots, (K - 1)N\} \). Note that we can improve \( q_s \) at the cost of a lower \( \tilde{R} \) (corresponding to a higher \( \nu \)) for each
transmitted packet. Based on this inherent trade-off between \( R \) and \( q_x \), a proper value of \( R \) (or equivalently \( \nu \)) needs to be determined in terms of maximizing the aggregate throughput.

C. The Throughput Scaling Law

In this subsection, we present our main result showing that the proposed MA-ORA protocol can achieve the optimal aggregate throughput scaling under a certain user scaling condition.

**Theorem 1.** Consider the MA-ORA protocol in the \( K \)-cell random access network. Suppose that \( \Phi R = \rho^{-1}. \) Then, the MA-ORA protocol achieves an aggregate throughput scaling of

\[
\Theta \left( \frac{K}{e} (1 - \epsilon) \log \rho (\log N) \right)
\]

with high probability in the high SNR regime if

\[
N = \Omega \left( \frac{K}{\rho^\frac{1}{1+\delta}} \right),
\]

where \( \epsilon > 0 \) is an arbitrarily small constant and \( 0 < \delta < 1 \) is a certain constant.\(^3\)

Here, the pre-log term \( \frac{1}{e} \) stems from the maximum MAC throughput obtained by the slotted ALOHA protocol for large \( N \). The term \( 1 - \epsilon \) corresponds to the successful decoding probability, where \( \epsilon \) can be interpreted as a penalty of random access without any coordination. With an arbitrarily small \( \epsilon > 0 \), our MA-ORA protocol is able to achieve the almost full \( K \)-fold multiplexing gain as well as the multiuser diversity gain in the \( K \)-cell random access network.

IV. NUMERICAL EVALUATION

In this section, we perform numerical evaluation through Monte-Carlo simulations. We validate our analytical result by evaluating the aggregate throughput [bps/Hz] of the proposed MA-ORA protocol. Suppose that we set \( \epsilon = 0.01 \) and \( \delta = 0.1 \). Then, \( \Phi R \) and \( \Phi G \) are determined according to (8) and \( R \) can be computed from (13).\(^4\)

In Fig. 3, we evaluate the aggregate throughput achieved by the MA-ORA protocol versus SNR in dB scale for \( K = 2 \). The parameter \( N \) is set to a different scalable value according to \( \rho \), i.e., \( N = \rho^{\frac{K}{K+1}} \) in (15). One can see that the slope of the simulated curve coincides with the theoretical one in the high SNR regime. This numerical results are sufficient to guarantee our achievability (i.e., the throughput scaling under the given user scaling law).

To further ascertain the efficacy of our MA-ORA protocol, performance on the aggregate throughput is evaluated in finite SNR (or \( N \)) regimes. We slightly modify the MA-ORA protocol in Section III by numerically finding the optimal parameters \( \Phi^*_G \) and \( R^* \) in terms of maximizing the resulting aggregate throughput \( R_{\text{sum}}(\Phi^*_G, R) \), which is given by

\[
(\Phi^*_G, R^*) = \arg \max_{\Phi_G, R} R_{\text{sum}}(\Phi_G, R).
\]

The optimal values of \( (\Phi^*_G, R^*) \) found via exhaustive search are summarized in Table I according to various \( K \), \( N \), and SNR. In Fig. 4, the aggregate throughput of the proposed MA-ORA protocol versus SNR in dB scale is plotted for \( K = \{2, 3, 4\} \) and \( N = 100 \). As baseline schemes, performance of the SA-ORA and slotted ALOHA protocols is also shown in the figure. Under the SA-ORA protocol, each user opportunistically transmits with the PHY data rate of \( \log_2 \left( 1 + \frac{\Phi G P}{N_0} \right) \) if its uplink channel gain exceeds \( \Phi G \) [14]. This protocol can be treated as a special case of our MA-ORA protocol with \( K = 1 \), and thus leads to worse performance as \( K \geq 2 \). For the slotted ALOHA protocol, since both details of the PHY layer and the effects of fading are neglected in the protocol design phase, we adopt the PHY data rate of \( \log_2 \left( 1 + \text{SNR} \right) \) for fair comparison. From Fig. 4, the following insightful observations can be found:

- The MA-ORA protocol outperforms the slotted ALOHA and SA-ORA protocols in the low and moderate SNR regimes, and then gets saturated to a certain value in the high SNR regime. This throughput saturation comes from
the fact that the multiplexing and multiuser diversity gains are not fully achieved due to the limited $N$ (which is less than the one required by our user scaling condition).

- When $K$ becomes large, the MA-ORA protocol achieves superior aggregate throughput in the low SNR regime, but gets saturated earlier due to a more stringent user scaling condition (note that $N$ needs to exponentially increase with $K$ for given $\rho$). The curve for $K = 2$ achieves inferior performance to the other curves for $K = \{3, 4\}$ in the low SNR regime, but tends to increase steadily with SNR and then get saturated at a relatively high SNR point.

- It is worthwhile investigating a crossover where two curves meet when the aggregate throughput of the MA-ORA and SA-ORA protocols versus SNR is plotted. The crossover SNR and the resulting aggregate throughput $R_{\text{sum}}$ (i.e., $(R_{\text{sum}}, \text{SNR})$) are summarized in Table II according to various $K$ and $N$.

V. CONCLUDING REMARKS

The MA-ORA protocol operating in a decentralized manner was proposed for the $K$-cell random access network, where no centralized coordination from the serving APs is required. As our main result, it was shown that the MA-ORA protocol asymptotically achieves the aggregate throughput scaling of $\frac{K}{\pi} (1 - \varepsilon) \log(\text{SNR} \log N)$, provided that $N$ scales faster than $\text{SNR}^{-\frac{1}{\delta}}$ for small constants $\varepsilon > 0$ and $0 < \delta < 1$. It thus turned out that the almost full multiplexing and multiuser diversity gains are obtained in our multi-cell random access network. Extensive computer simulations were also performed to validate the MA-ORA protocol and its analytical result, where the throughput scaling and user scaling laws were numerically confirmed and the superiority of our protocol over baseline schemes was shown in a practical setting. Future research directions include extensions to networks with multi-antenna configurations, carrier sense multiple access networks, and practical channel models with the path loss component.

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