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Optimal remote radio head selection for cloud radio access networks

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Abstract The cloud radio access network (C-RAN) promises significant gain to the data rate over the LTE-advanced by transferring the burdensome baseband signal processing from the remote radio heads (RRHs) to the baseband unit via the front-haul. However, scalable improvement of the overall throughput may not be maintained due to limited front-haul capacity. In this paper, we study the throughput maximization problem by selecting the active RRHs. In particular, we develop an optimum algorithm which selects a subset of active RRHs that maximize the system throughput under the front-haul constraint. In addition, the asymptotically optimum number of RRHs is derived in closed-form for low and high signal-to-noise ratio (SNR) regimes. It is demonstrated that the proposed RRH selection scheme outperforms any other existing schemes with substantial gain of achievable throughput for any given number of RRHs and any predetermined front-haul capacity constraints.

Keywords cloud radio access network (C-RAN), baseband unit (BBU), front-haul, remote radio head (RRH)

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1 Introduction

The upcoming paradigm shift from the long-term evolution (LTE)-advanced to 5G will foresee an ever-growing demand of wireless data transmission, leading to unaffordable signal processing burdens to the transmit antennas. The cloud radio access network (C-RAN) as shown in [1] provides a promising solution to this by separating the radio function unit, so-called the remote radio head (RRH), from the digital function unit, also referred to as the baseband unit (BBU) [2]. In [3], a convex optimization based approach is proposed for the C-RAN in the ultra dense networks (UDN) to tackle the new challenges of the wireless transmission design. In [4], C-RAN is examined from the soft-defined point of view by proposing a soft-defined hyper cellular architecture. In [5], C-RAN is used to decouple the cellular system into the control plane and the data plane, where a converged edge infrastructure is proposed for both the mobile terminals as well as the mobile computing services. A framework is proposed for processing the resource management in C-RAN systems with super base station. Under the C-RAN

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architecture, digital baseband signals are carried over the front-haul between the RRH and BBU, such that the BBU is devoted to the baseband signal processing, while all RRHs are responsible only for the signal transmission, thus substantially reducing the signal processing burden at each RRH [6]. In this way, C-RAN supports the implementation for the heterogeneous networks with utilizing the user social pattern in [7], the multimedia green transmissions among the cooperative base stations cellular networks in [8], the optimized transmission scheme of the massive multi-input multi-output as studied in [9], and the cooperative relaying transmission in dual-hop networks as in [10]. The structure of the C-RAN benefits to many wireless networks by gathering all or most of the signals to the BBU for central processing.

There are a number of research results over the C-RAN wireless transmissions. For example, the complexity of the C-RAN systems is theoretically analyzed by establishing a theoretical framework in [11], where the conclusion is that about ten percent of the complexity is successfully cut down in C-RAN as compared to the conventional LTE (long term evolution) systems. In [12], a interference coordination framework is proposed for mitigating the interferences between the macro base stations and the RRHs in C-RAN. To reduce the data amount from every RRH to the BBU, a joint approach of the compression at every RRH and the decompression at the BBU is developed in [13] for the uplinks in C-RAN. In [14], a novel channel estimation method is proposed for C-RAN by superimposing the training sequences for channel estimation to the data in order to reduce the training overhead. The C-RAN facilitates 5G to supply improved data rate, which has attracted a great deal of attention. For instance, the authors in [15] propose a new protocol of the compress and forward in the spatial domain at every RRH to reduce the data amount from the RRH to the BBU in C-RAN systems. A low-complexity precoding method is proposed in [16] for C-RAN with a large number of RRHs, where the alternating direction method of multiplier (ADMM) algorithm is applied. In [17], a stochastic gradient algorithm is proposed to the resource allocation in the heterogeneous C-RAN systems, where the queue theories are employed.

In spite of the benefits offered by C-RAN, an inherent problem associated with C-RAN is the limited capacity of the front-haul between every RRH and the BBU, as demonstrated in [18]. This is because the capacity of the fiber link is commercially in the order of tens of Gigabit. Yet the information traffic of single RRH is usually in the order of the Megabit. Moreover, many RRHs are employed more and more densely, especially in the ultra dense networks as described in [19]. Therefore, the capacity of the fiber link is very easy to exceed. One of the key problems in C-RAN based wireless communications is how to deal with the capacity constraint of the fiber link, which can be resorted to many methods such as the protocol design of the compress at every RRH and the proper selection scheme design over many RRH candidates. This problem distinguishes C-RAN from the distributed antenna system (DAS) in that the capacity of the front-haul in DAS is theoretically unconstrained [20]. Both of C-RAN and DAS can be used for the implementation of the massive multi-input multi-output (MIMO) technique as illustrated in [21]. Nevertheless, the studies over the DAS systems have been extensively carried out in the past ten years, most of which do not address the capacity of the fiber link. These studies assume that the fiber link has the capacity large enough to support the data rate at every RRH. In fact, the data rate at RRR ten years ago is much lower than that today. Thus, this assumption in DAS systems is not challenged in the past. Nevertheless, the amount of the data traffic grows overwhelmingly, which results in the fiber capacity very limited as compared the data requirement. In contrast, the studied over the C-RAN based transmissions emphasizes this bottleneck of the fiber capacity. To deal with the new problem, various protocols are designed to compress the data amount from every RRH to BBU. Besides, the RRH selection method is one choice among many other method candidates to reduce the data amount from RRH to BBU by balancing the diversity gain of using more RRHs and the fiber overhead cost of additional RRHs involved in transmission. From this point, it is concluded that the main difference of the C-RAN and the DAS wireless transmission comes from the bottleneck of the fiber link between the BBU and the RRHs. In this paper, we consider the realistic capacity constrained front-haul between BBU and RRHs in C-RAN networks. This constraint is widely addressed in the literature of C-RAN such as [22, 23]. The design objective of this paper is to maximize the throughput of the whole system by optimally selecting the active RRHs subject to the capacity constraint of the front-haul. Our work

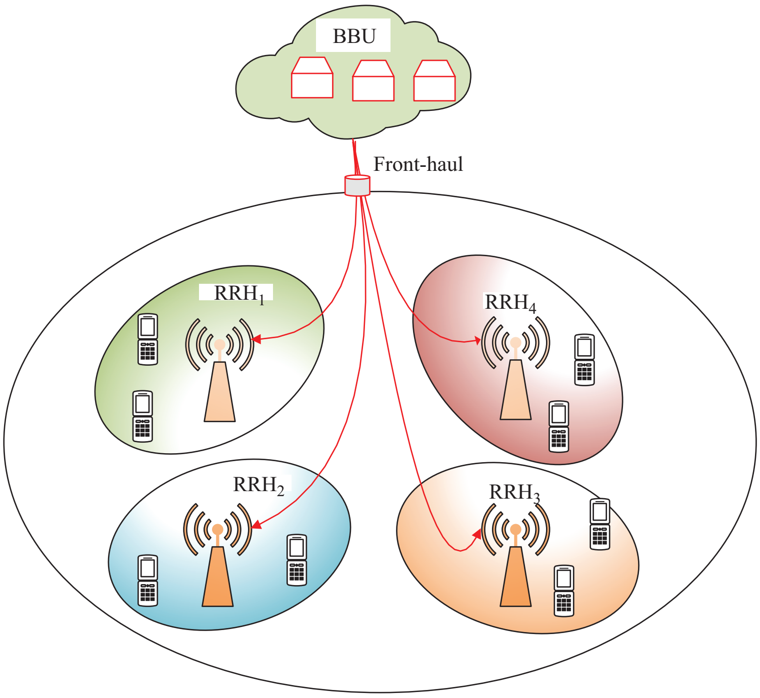

Figure 1 C-RAN with multiple RRHs connected to BBU under the limited capacity of front-haul.

is motivated by the following observations: The overall system throughput increases as the number of active RRHs increases from 0, because more and more RRHs are actively transmitting signals. However, once the number of active RRHs exceeds certain critical value where the capacity limit of the front-haul is approached, the total throughput clips. This motivates us to determine the optimum number of active RRHs which maximizes the total throughput of the C-RAN networks.

In this paper, we first derive various throughput expressions for different cases of channel conditions given the number of RRHs. By maximizing those throughput expressions, we then develop an algorithm which determines the optimum number of RRHs that corresponds to the maximum system throughput. Furthermore, we derive the asymptotically optimum number of RRHs in closed-form for both low and high signal-to-noise ratios (SNRs), which is deemed useful for practical system designs. Finally, simulations demonstrate that the proposed algorithm achieves significant throughput gain as compared to the existing methods.

Notation. We use $(\cdot)^*$, $(\cdot)^{\mathrm{T}}$, and $(\cdot)^{\mathrm{H}}$ to denote the conjugate, transpose, and conjugate transpose, respectively. For a set $\mathcal{S}$, we use $|\mathcal{S}|$ to denote its cardinality. We use $X \sim \mathcal{CN}(\mu, \sigma^2)$ to denote that X is a complex Gaussian random variable with mean μ and variance σ^2.

2 System model

As shown in Figure 1, we consider a C-RAN system where the BBU intends to communicate with the mobile terminal (MT) via a total of K active RRHs, $K \geqslant 1$. The BBU makes available the baseband signal to all the RRHs via the front-haul link, which is constrained by a limited capacity. The RRHs cooperatively send the signal to the MT through distributed beamforming. Let x denote the transmit signal with unit symbol energy, $\mathbb{E}\{|x|^2\} = 1$, and p_0 denotes the transmit power at each RRH. Suppose that the channel coefficient from the k-th RRH to the MT is modeled as $h_k \sim \mathcal{CN}(m, \sigma^2)$, $k = 1, \ldots, K$, and the additive white Gaussian noise is modeled as $n \sim \mathcal{CN}(0, 1)$. We denote the complex normal distribution by $\sim \mathcal{CN}(m, \sigma^2)$, where m denotes the mean value of this variable, and σ^2 denotes the covariance of this variable. Then the received signal at the MT is given by

$$y = \sqrt{p_0}\sum_{k=1}^{K} h_k w_k x + n = \sqrt{p_0}\boldsymbol{h}^{\mathrm{T}}\boldsymbol{w}x + n, \tag{1}$$

where $\boldsymbol{h}^{\mathrm{T}} \triangleq [h_1, \ldots, h_K]$, and $\boldsymbol{w} \triangleq [w_1, w_2, \ldots, w_K]^{\mathrm{T}}$ is the distributed beamforming vector with $\|\boldsymbol{w}\| = 1$. p_0 is the transmit power from every RRH. n is the additive white Gaussian noise with the distribution $n \sim \mathcal{CN}(0, 1)$ received at the mobile terminal. Due to the limited capacity of the front-haul, the total rate from the BBU to all of the RRHs is denoted by C. Considering the fact the every RRH is the same with all the other RRHs, the data rate R_1 between the BBU and every RRH is upper bounded as

$$R_1 = \frac{C}{K}. \tag{2}$$

Here, R_1 is the data rate between each RRH and the BBU linked for example by the fiber.

It is proved in [23] that the optimal transmit beamforming across all RRHs is $\boldsymbol{w} = \frac{\boldsymbol{h}^*}{||\boldsymbol{h}||_2}$. Thus, the achievable transmission rate over the wireless channels from all RRHs to the MT is given by

$$R_2 = \log_2\left(1 + p_0\sum_{k=1}^{K}|h_k|^2\right). \tag{3}$$

R_2 is the instantaneous data rate of the wireless channel from all the RRHs to the same mobile terminal. The value of R_2 varies according to the Shannon capacity formula with the different channel fading coefficients. Kindly note that the expression of the signal to noise ratio (SNR) involved in the above calculation is described as the ratio of the signal power to the noise power. Fortunately, the noise power is set to 1 as explained below Eq. (1). Thus, SNR= $\frac{p_0}{1} = p_0$. The effective system throughput, R, is determined by bottleneck of the front-haul (between the BBU and RRHs) and the wireless channels (from the RRHs and the MT), namely,

$$R = \min\{R_1, R_2\} = \min\left\{\frac{C}{K}, R_2\right\}. \tag{4}$$

R is the data rate from the BBU to the mobile terminal, which is jointly determined by the wireless channel from all the RRHs to the mobile terminal and the fiber link from the BBU to each RRH. It is seen from (3) that by increasing the number of RRHs, higher data rate can be achieved over the wireless channels. However, the front-haul transmission rate is degraded due to the increased K. In the next section, we will develop an algorithm which determines the optimal K to address the tradeoff between the front-haul and the wireless channels.

3 Optimal RRH selection for C-RAN

Our goal is to maximize the throughput of the whole system under the limited capacity of the front-haul between BBU and RRHs by optimizing the RRH selection. For ease of exposition, we assume, without loss of generality, that all channel coefficients are sorted in the descending order as $|h_1| \geqslant |h_2| \geqslant \cdots \geqslant |h_K|$. The considered optimization problem is formulated as

$$\max_K R = \max_K \left\{\min\left\{\frac{C}{K}, R_2\right\}\right\}, \text{ s.t. } K \geqslant 1, K \in \mathbb{Z}^+. \tag{5}$$

This problem involves the integer programming as well as the max-min optimization, which is in general difficult to solve. To tackle this problem, we first derive the achievable throughput of various RRH selection schemes under different channel conditions.

3.1 Achievable throughput

3.1.1 *Single RRH selection under strong channel condition*

For simplicity, some applications may allow only one single RRH for data transmission. In this case, the single best RRH associated with the strongest channel strength, i.e., $|h_1|$, should be selected. Suppose that the channel $|h_1|$ is so strong that the achievable rate from the selected RRH to the MT exceeds the capacity limit of the front-haul, namely,

$$\log_2\left(1+p_0|h_1|^2\right) \geqslant C. \tag{6}$$

In this case, due to the clipping effect of the front-haul, the overall data rate achieved by the single RRH selection is

$$R^* = C. \tag{7}$$

3.1.2 *Single RRH selection under weak channel condition*

When the best channel $|h_1|$ is relatively weak and its supported wireless channel capacity does not exceed the capacity limit of the front-haul, namely

$$\log_2\left(1+p_0|h_1|^2\right) < C, \tag{8}$$

the bottleneck of the throughput depends on the wireless channel capacity as

$$R^* = \log_2\left(1+p_0|h_1|^2\right). \tag{9}$$

3.1.3 *Multiple RRH selection under strong channel condition*

In this case, there are K RRHs candidates for selection. Here, $K \geqslant 2$. Moreover, the wireless channel has enough capability to support the data rate of the front-haul $\frac{C}{K}$, i.e.,

$$\log_2\left(1+p_0\sum_{k=1}^{K_o}|h_k|^2\right) \geqslant \frac{C}{K_o}, \tag{10}$$

where K_o as the number of selected RRHs in this case is the minimum integer that satisfies (10). The optimal value of K_o can be determined by the numerical searching method or the derived solution as in (18) and (25). Thus, the achievable throughput is given by

$$R^* = \frac{C}{K_o}. \tag{11}$$

It is seen from this case that the number of selected RRHs should as less as possible to maximize (11) yet this number cannot be too large constrained by the condition (10). Hence, K_o should be optimized by maximizing (11) under the constraint in (10). The solution to this optimization will be derived in the next subsection. With the obtained K_o, the RRHs corresponding to the channel coefficients $\{h_1, h_2, \ldots, h_{K_o}\}$ are selected in this case maximize (11).

3.1.4 *Multiple RRH selection under weak wireless channels*

In this case, there are $K_o \geqslant 2$ RRHs involving the transmission. Yet, the wireless channel capability of all the K_o RRHs are too weak to support the highest data rate of the front-haul, namely,

$$\log_2\left(1+p_0\sum_{k=1}^{K_o-1}|h_k|^2\right) < \frac{C}{K_o-1}. \tag{12}$$

Thus, the throughput of the whole system is given by

$$R^* = \log_2\left(1+p_0\sum_{k=1}^{K_o-1}|h_k|^2\right). \tag{13}$$

In this case, the number of selected RRHs should as more as possible to maximize (13) yet it must make the condition (12) hold on.

3.2 Optimum RRH selection

Based on the results of the four cases described as above, we proposed an algorithm to optimize the optimal RRHs selection below.

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Algorithm 1 Optimal RRH selection in C-RAN for max-rate
1. Sort all the instantaneous channel coefficients in descending order as $|h_1| \geqslant |h_2| \geqslant \cdots \geqslant |h_K|$;
2. Check whether Eq. (6) holds or not. If Eq. (6) holds, the single RRH selection with $|h_1|$ is optimal, and the maximum achievable throughput is $R^* = C$; then stop. If Eq. (6) does not hold, go to step 3.
3. Determine the number of RRHs $K_o$ by using the exhaustive searching method or the derived analytical method as in (18) and (25) to satisfy (10). If Eq. (10) does not hold at $K_o$, the number of selected RRHs shall be $K_o - 1$ that satisfies (12).
4. With $K_o$, calculate (11) as $\phi = \frac{C}{K_o}$ and (13) as $\varphi = \log_2\left(1 + p_0 \sum_{k=1}^{K_o-1} |h_k|^2\right)$. Compute
       $$R^o = \max\left\{(9),\ (11),\ (13)\right\}. \tag{14}$$
5. If $R^o = \log_2\left(1 + p_0|h_1|^2\right)$, select the first RRH $|h_1|$ for the wireless transmission. If $R^o = \phi$, select the first $K_o$ RRHs as $\{|h_1|, |h_2|, \ldots, |h_{K_o}|\}$. If $R^o = \varphi$, selected the first $K_o - 1$ RRHs as $\{|h_1|, |h_2|, \ldots, |h_{K_o-1}|\}$.
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Discussion on the optimality of Algorithm 1. The developed Algorithm 1 is optimal for the throughput maximization under any given constraint of the front-haul capacity as well as any transmit power available for RRHs.

The proof is carried out in two cases below.

Proof. Case I for $|\mathcal{S}| = 1$. There is only one RRH selected in this case. Assume that there is another algorithm denoted by Algorithm 2 which outperforms our proposed Algorithm 1. Thus, the gain, ΔR, of the achievable data rate realized by Algorithm 2 over that of Algorithm 1 must be positive.

Scenario (I-A). In this scenario, the final rate of our Algorithm 1 is $R^* = C$ as shown in (7) corresponding to single RRH selection. To enable $\Delta R > 0$, the achievable rate of Algorithm 2 must be greater than C which obviously contradicts to the constraint of the limited front-haul capacity. Thus, Algorithm 2 does not exist in this scenario.

Scenario (I-B). The other scenario of single RRH selection in our Algorithm 1 is shown in (8) and (9). The rate of Algorithm 2 is calculated according to $\log_2(1 + |h_k|^2)$, where $k \neq 1 \in \{1, 2, \ldots, K\}$. If Algorithm 2 is better than Algorithm 1, there must exist k that makes $|h_k| > |h_1|$ hold on. However, $|h_1|$ is the biggest among all the channel coefficients as described at the start of Section 3. Thus, Algorithm 2 does not exist in this scenario.

Case II for $|\mathcal{S}| \geqslant 2$. The data rate realized by Algorithm 2 is given by $\min\{\frac{C}{|\mathcal{S}|}, \sum_{m=1}^{|\mathcal{S}|} \log_2(1 + p_0|h_m|^2)\}$, where $|\mathcal{S}|$ is the number of RRH in Algorithm 2.

Scenario (II-A). If $\frac{C}{|\mathcal{S}|} = \min\{\frac{C}{|\mathcal{S}|}, \sum_{m=1}^{|\mathcal{S}|} \log_2(1 + p_0|h_m|^2)\}$, the data rate limitation comes from the front-haul since the wireless channel in this scenario is large enough to support the maximum throughput of front-haul. Our proposed Algorithm 1 achieves the data rate of C-RAN is $R^* = C$ that is always greater than the data rate of Algorithm 1, namely, $\frac{C}{|\mathcal{S}|} > R^* = C$ never holds in this scenario, indicating that Algorithm 2 does not exist.

Scenario (II-B). If $\sum_{m=1}^{|\mathcal{S}|} \log_2(1 + p_0|h_m|^2) = \min\{\frac{C}{|\mathcal{S}|}, \sum_{m=1}^{|\mathcal{S}|} \log_2(1 + p_0|h_m|^2)\}$ denoted by Scenario (II-B-1), the wireless channels as the bottleneck of C-RAN are quite poor as compared to the capacity of front-haul, namely, $\sum_{m=1}^{|\mathcal{S}|} \log_2(1 + p_0|h_m|^2) \leqslant \frac{C}{|\mathcal{S}|}$. If the data rate in our Algorithm 1 is (7) denoted by Scenario (II-B-2), it is required by the assumption of Algorithm 2 better than Algorithm 1 that $C < \sum_{m=1}^{|\mathcal{S}|} \log_2(1 + p_0|h_m|^2) \leqslant \frac{C}{|\mathcal{S}|}$, which does not hold on since $|\mathcal{S}| \geqslant 2$. If the data rate of our Algorithm 1 is (14), the assumption that Algorithm 2 outperforms our Algorithm 1 requires the following inequality hold on

$$\sum_{m=1}^{|\mathcal{S}|} \log_2(1 + p_0|h_m|^2) > \max\left\{\log_2\left(1 + p_0|h_1|^2\right),\ \frac{C}{K_o},\ \sum_{k=1}^{K_o-1} \log_2(1 + p_0|h_k|^2)\right\}. \tag{15}$$

Note that $\{|h_1|, |h_2|, \ldots, |h_{K_o-1}|\}$ are sorted in descending order as stated at the start of Section 3. From $\sum_{m=1}^{|\mathcal{S}|} \log_2(1 + p_0|h_m|^2) > \sum_{k=1}^{K_o-1} \log_2(1 + p_0|h_k|^2)$ in (15), we have $|\mathcal{S}| > K_o - 1$, i.e., $|\mathcal{S}| \geqslant K_o$. Namely, the selected RRHs in Algorithm 2 is not less than that in our Algorithm 1. From $\sum_{m=1}^{|\mathcal{S}|}\log_2(1+p_0|h_m|^2) > \frac{C}{K_o}$ in (15), we have $\sum_{m=1}^{|\mathcal{S}|}\log_2(1+p_0|h_m|^2) > \frac{C}{K_o} \geqslant \frac{C}{|\mathcal{S}|}$. This contradicts the condition in Scenario (II-B-2). Thus, Algorithm 2 does not exist in Scenario B.

It is seen from the above proof that our proposed algorithm is optimal for the RRH selection in C-RAN, which is also numerically verified in the next section.

Remark 1. In our proposed approach, only a part of RRHs is usually selected for involving the information transmission. Thus, the other RRHs that are not chosen for the mobile user association are set in sleep for power saving. In this manner, the unchosen RRHs can reduce the exchange overhead of the fiber properly yet achieve the good wireless channel capacity with the current channel fading coefficients together with the fixed capacity of the fiber link. The sleep protocol for the base station or RRH is widely employed in wireless communications such as [24,25]. After the RRH selection, the RRHs associated with the mobile terminal are chosen for the information transmission.

Remark 2. Besides, the power allocation across the chosen RRHs can be optimized, especially for the multi-user wireless communications in C-RAN networks, based on some objectives such as rate maximization and bit error rate minimization. Yet, this power allocation optimization is out of the scope in this paper, which can be studied in the future work.

Remark 3. Our proposed RRH selection approach works in the dynamic way, where the selection result is adaptive to the instantaneous channel fading coefficients as shown in Algorithm 1 and the equations involved therein. For example, when the instantaneous channel coefficients become very small in the current channel realization, more and more RRHs are chosen for information transmission until the fiber capacity is touched according to the developed Algorithm 1. In contrast, while the instantaneous channel fading coefficients are very huge in the current channel realization, less RRHs will be selected according to our Algorithm 1 since the target in this case is to reduce the fiber overhead as more as possible, where the fiber capacity is the bottleneck as compare to the instantaneous wireless capacity for this channel realization. Thus, it is concluded that our proposed approach works in the dynamic rather than the static way.

3.3 Asymptotically optimum RRH selection

The optimal number of selected RRH K_o is waiting to be derived in closed form to facilitate the RRH selection. It is seen from (10) and (11) that the optimum of K_o should enable (10) hold on at the equality. However, it is impossible to directly solve this equation for the analytical expression of K_o. Thus, we resort to the Jensen's inequality method to approximate this equation as

$$\mathop{\mathbb{E}}_{\{h_k\}_{k=1}^{K_o}}\left\{\log_2\left(1+p_0\sum_{k=1}^{K_o}|h_k|^2\right)\right\} < \log_2\left(1+K_op_0(m^2+\sigma^2)\right) \overset{(a)}{=} \frac{C}{K_o}. \tag{16}$$

Here, the goal is to get the analytical expression of K_o to the equation (a). Nevertheless, this goal is prohibitively difficult to achieve for the general regime of SNR. Fortunately, we have successfully get the asymptotic optimal solution in closed form to equation (a), respectively, in low and high SNR regime below.

In the low SNR regime, the left handside in (a) becomes

$$\lim_{p_0\to 0^+}\log_2\left(1+K_op_0(m^2+\sigma^2)\right) = K_op_0(m^2+\sigma^2), \tag{17}$$

which is substituted into (a) as $K_op_0(m^2+\sigma^2) = \frac{C}{K_o}$. Thus, we have the final solution in low SNR regime as

$$K_o = \sqrt{\frac{C}{p_0(m^2+\sigma^2)}}. \tag{18}$$

In the high SNR regime, the left handside in (a) becomes

$$\lim_{p_0\to+\infty}\log_2\left(1+K_op_0(m^2+\sigma^2)\right) = \log_2\left(K_op_0(m^2+\sigma^2)\right). \tag{19}$$

Thus, the optimum K_o in the high SNR regime should be

$$\log_2\left(K_o p_0(m^2+\sigma^2)\right) = \frac{C}{K_o}. \tag{20}$$

For descriptional convenience, let $t \triangleq \log_2\left(K_o p_0(m^2+\sigma^2)\right)$. Thus, Eq. (20) can be expressed as

$$t2^t = Cp_0(m^2+\sigma^2). \tag{21}$$

Since $2^t = \mathrm{e}^{t\ln 2}$ with e as the natural constant, Eq. (21) can be derived as

$$(t\ln 2)\mathrm{e}^{t\ln 2} = Cp_0(m^2+\sigma^2)\ln 2. \tag{22}$$

By applying the property of the Lambert function that is the inverse function of $\mathbb{W}\{f\}\mathrm{e}^{\mathbb{W}\{f\}} = f$ to (22), we obtain the final solution as

$$t\ln 2 = \mathbb{W}\{Cp_0(m^2+\sigma^2)\ln 2\}. \tag{23}$$

Thus, the number of selected RRHs in high SNR regime is obtained as

$$\frac{1}{\ln 2}\mathbb{W}\{Cp_0(m^2+\sigma^2)\ln 2\} = \log_2\left(K_o p_0(m^2+\sigma^2)\right), \tag{24}$$

namely,

$$K_o = \frac{2^{\frac{1}{\ln 2}\mathbb{W}\{Cp_0(m^2+\sigma^2)\ln 2\}}}{p_0(m^2+\sigma^2)}, \tag{25}$$

To this end, an algorithm is developed for the RRH selection in C-RAN, where every case of the fiber capacity between each RRH and BBU together with the instantaneous data rate of the wireless channel between all the RRH and the mobile terminal is jointly considered. Moreover, the proposed scheme is proved to be asymptotically optimal in the high regime of the transmit power. In the subsequent section, these theoretical results will be verified by the numerical simulations.

4 Numerical results

Monte Carlo method is used by Matlab to demonstrate our proposed scheme. All the wireless channels are randomly realized with 10000 cycles according to the distribution $\mathcal{CN}\sim(0,1)$. Kindly note that the covariance of the noise is 1, which indicates that the SNR expression can be written as $\frac{p_0}{1} = p_0$. The number of all RRH candidates for selection is set to $K = 20$. The front-haul capacity between BBU and RRH is set to $\{5, 15, 25, 35, 45\}$ $\mathrm{b\cdot s^{-1}\cdot Hz^{-1}}$. Two reference schemes, best single RRH and all participate schemes, are also plotted for comparison. For comparison, two reference schemes of the RRH selection are employed, which include the first reference scheme of all the RRH participating way and the second reference scheme of only one RRH involving for information transmission. To the authors best knowledge, there is no existing scheme of the RRH selection in C-RAN networks.

Figure 2 shows the data rate of C-RAN vs the growing transmit power p_0 for different capacities of front-haul. The four curves in Figure 2 always rise with the increasing p_0 in the regime $p_0 > -5$ dB. Yet the lowest curve corresponding to $C = 5$ $\mathrm{b\cdot s^{-1}\cdot Hz^{-1}}$ becomes horizontal after $p_0 > 10$ dB, which is because the front-haul capacity becomes the bottleneck in this region. In the low power regime, every curve is parallel to the x-axis, where the value of y-axis is determined by the data rate of front-haul, respectively, $\frac{C}{K} = \frac{1}{20}[5, 15, 25, 45]$ $\mathrm{b\cdot s^{-1}\cdot Hz^{-1}}$. In high SNR regime $p_0 > 10$ dB, the two curves of the proposed and the best single RRH selection schemes overlap with each other, which means the single RRH selection become optimal in high SNR regime. In low SNR regime $p_0 < -10$ dB, the curve of all participate RRH scheme overlaps with our curve. It is verified numerically that our proposed scheme is always better than the existing schemes. The reason is that the data rate in C-RAN is jointly determined by both of the fiber capacity and the wireless channel capacity. If the fiber capacity is very large, the bottleneck of the whole C-RAN systems mainly depends on the wireless channel capacity. In this case

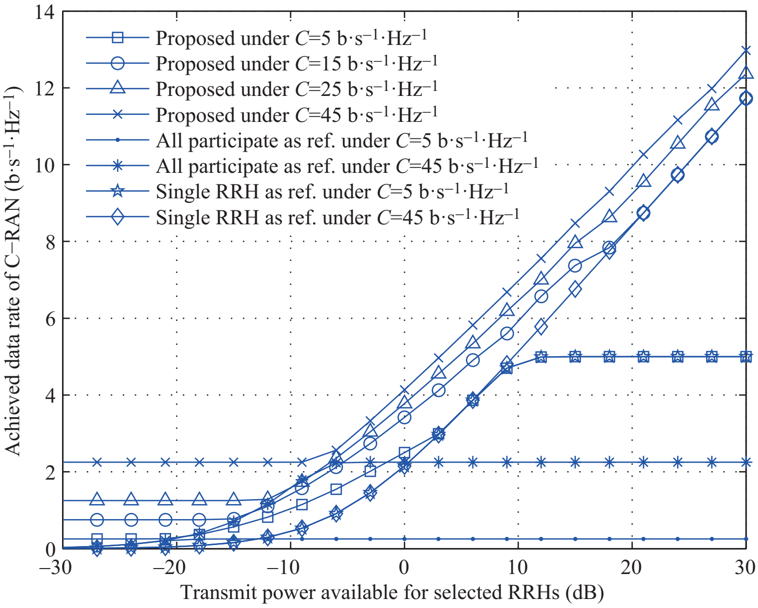

Figure 2 Throughput under limited capacity of front-haul link versus p_0.

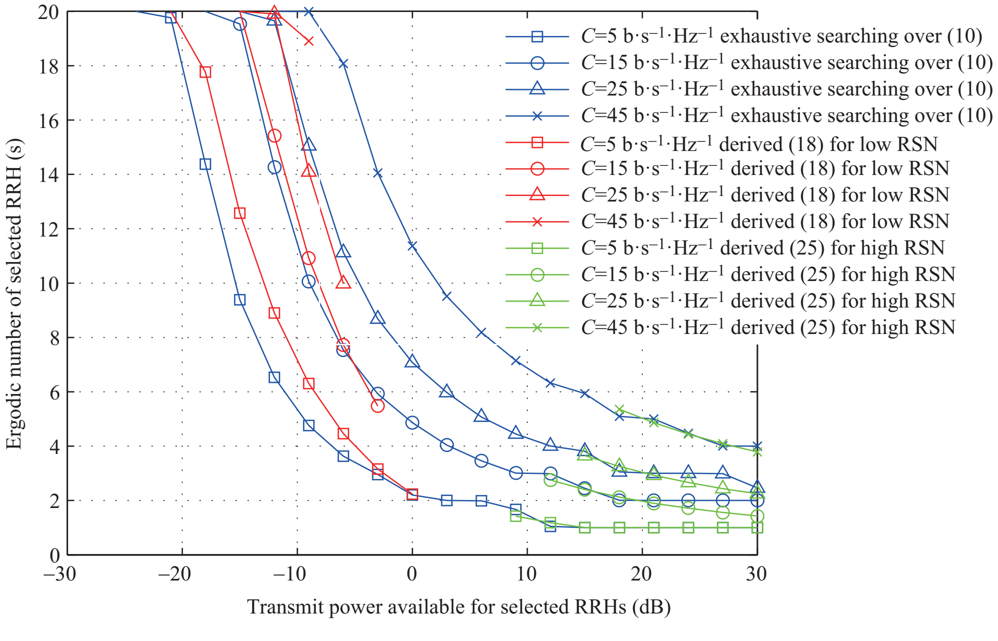

Figure 3 Ergodic number of selected RRH(s) as a function of p_0.

denoted by Case-A, more RRHs are always desirable to involving the information transmission, which can improve the wireless channel capacity increasingly. However, with the increase of the employed RRHs, the fiber capacity becomes small as compared to the wireless channel capacity with many RRHs involvement. Thus, it becomes to another case denoted by Case-B where the bottleneck of the whole C-RAN is mainly determined by the fiber capacity. In this case, the wireless channel capacity is very huge. Under this reason, our proposed scheme can always get the better performances either in the Case-A by selecting more RRHs for the information transmission or in Case-B by employing less RRHs to reduce the exchange overheard of the fiber link. Kindly note that, the discussion as above is from the instantaneous channel fading coefficients point of view. Thus, it is called the adaptive RRH selection scheme to adapt the varying wireless channel coefficients.

In Figure 3, the number of the selected RRH(s) K_o is plotted for our proposed scheme and two reference

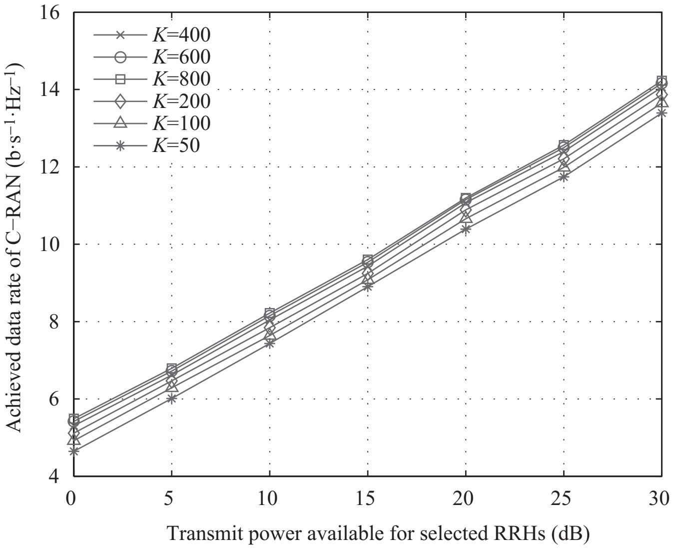

Figure 4 Throughput achieved by the proposed RRH selection approach versus p_0 under the fixed $C = 45\ \text{b}\cdot\text{s}^{-1}\cdot\text{Hz}^{-1}$ as the fiber capacity.

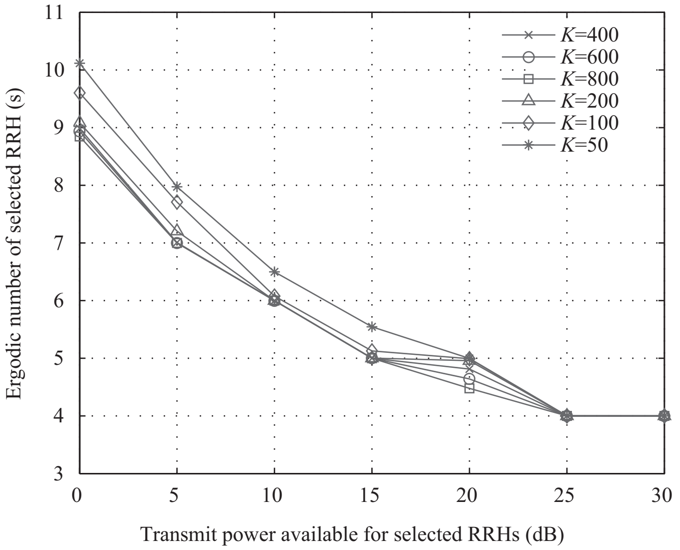

Figure 5 Throughput Ergodic number of the selected RRHs at difference values of the RRH candidates versus p_0 under the fixed $C = 45\ \text{b}\cdot\text{s}^{-1}\cdot\text{Hz}^{-1}$ as the fiber capacity.

schemes, where our numerical solution of (10) and the analytical solution in (18) for low SNR regime as well as the analytical solution in (25) for high SNR regime are verified. It is observed that the number of selected RRHs in the region $p_0 \in [-10, 10]$ dB is decreasing with the increasing p_0 that verifies by (18). Yet, the selected number of RRHs in the region $p_0 > 10$ dB becomes $1, 2, 3, 4$, respectively, which is proved as in (25) for high SNR regime.

Figures 4 and 5 demonstrate the achieved data rate and the number of the selected RRHs at different numbers of all the RRH candidates $K = [50, 100, 200, 400, 600, 800]$. It is seen from Figure 5 that the number of the selected RRHs at any given value of the transmit power increases with the decreasing number of all the RRH candidates. This is because the capacity of the wireless channel increases with the growing gain from the RRH diversity. Namely, the more RRHs that are waiting for the possible selection, the higher capacity of the wireless channel. Thus, with K increasing from 50 to 800, the number of the selected RRHs decreases to attain almost the same capacity of the wireless channel yet require less exchange overhead between BBU and the selected RRHs. With the wireless channel capacity approaching to the positive definite, the number of the selected RRHs approaches to the minimum 4 as seen from Figure 5.

5 Conclusion

We have studied the RRH selection for the emerging C-RAN systems to enhance the system throughput. Specifically, we developed an optimal RRH selection algorithm which maximizes the throughput of the C-RAN systems subject to the limited front-haul capacity constraint. Moreover, we also derived the asymptotically optimal number of the selected RRHs in closed form for both low and high SNR regimes. It is demonstrated that the proposed RRH selection algorithm outperforms the existing schemes with substantial gain of the throughput.

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Conflict of interest The authors declare that they have no conflict of interest.

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