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Fog Radio Access Network: A New Wireless Backhaul Architecture for Small Cell Networks

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ABSTRACT In this paper, we develop a novel wireless backhauling strategy for small-cell networks based on dynamic base station (BSs) cooperation, which we call the *fog-radio access network* (F-RAN) backhauling strategy. By taking advantage of fog-computing, our proposed strategy enables BSs to combine and process signals received from diverse paths, which can significantly increase the transmission efficiency of the backhaul network. We first model an F-RAN-enabled network and three existing backhauling strategies, namely, *direct transmission*, *decode and forward*, and *cloud-RAN*. We then analyze and compare the performance of these strategies. The numerical results show that our proposed strategy provides the highest throughput for cell edge users while maintaining the same performance in most of the other areas. Moreover, for dense small-cell networks with poor backhaul channels, F-RAN outperforms all other strategies.

INDEX TERMS Wireless backhaul network, fog computing, multi-BS cooperation, transmission coordination, small cell network, backhauling strategy.

I. INTRODUCTION

In the upcoming fifth generation (5G) mobile radio systems, the rapid proliferation of mobile terminals will drastically challenge the existing communication infrastructure and network topologies [1]. Meanwhile, the development of diverse mobile applications for the Internet, for instance, the Internet of Things (IoT), social networking, and real-time video communications set much higher demands for transmission rates and network capacity. Some researchers have indicated that the anticipated network traffic will increase more than 1000 times from 2015 to 2020 [2], [3]. To cope with this substantial change, small cell networks have been proposed as a promising network architecture that has the potential to significantly improve the capacity and data rate of current RANs [4], [5].

Due to the dense deployment of the BSs and interference from adjacent cells, more Low Power Nodes (LPN) like low power evolved NodeB (eNB), Micro BS, Pico BS, and Remote Radio Unit (RRU)-Baseband Unit (BBU) are considered in diverse scenarios, where most of the coverage area can be served by multiple BSs. Therefore, radio controller nodes are introduced in RANs to provide an efficient and agile resource management [6]. However, for mobile operators, the capital and operating expenditures for deploying and running a large number of LPNs can be an enormous burden. Although the cost of each small BS is relatively low, due to its lower transmit power, smaller size, and lack of cooling, the transport network such as fronthaul links and backhaul links are a major expenditure [7].

With respect to the backhaul transmission between BSs and RNC, there are two main types of backhaul links:

1) *wired backhaul*: commonly copper or optical fiber cables provide a stable and reliable data transmission with the guarantee of high capacity and low error rates. However, the cost of laying 1m of optical fiber cable is up to $100 [8]. Since cost is a key consideration for mobile operators, it will significantly limit the deployment of wired backhaul. Furthermore, some small BSs are located at inaccessible locations where a wired link is not an option. Moreover, in practice, most of the dense networks are likely built in an ad-hoc manner, while fixed backhaul networks lack the flexibility to satisfy the constant changes in UEs' requirements and network topologies.
2) *wireless backhaul*: by comparison with wired links, wireless backhaul provides a cost-effective alternative [5], [9]. In the spirit of "drop-and-play", wireless backhaul is better suited for small cell networks when mobile operators need to increase network capacity and extend the coverage in a short time. Moreover, with the benefit of cooperative management mechanisms, the network transmission topologies

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become more flexible and resilient. The main problem for the wireless backhaul is the limited availability of spectrum. As a result, there is a need for efficient cooperation strategies for small cell networks with the wireless backhaul. In this paper, we introduce such a strategy.

To coordinate the BSs and the radio resource in the network, aggregator nodes, which have fiber backhaul to the operator network are desirable for both wireless and wired connections in the backhaul network. Before the fourth generation (4G) cellular networks, the backhaul aggregation point was referred to as Base Station Controller (BSC) or Radio Network Controller (RNC) [10]. For traditional LTE architecture, the evolved NodeB is capable to assemble the backhaul links from other radio stations as a backhaul aggregation point [2]. In a Cloud Radio Access Network (C-RAN), BBU or BBU pool takes the role of the aggregator node to concentrate the fronthaul links and centrally allocate the radio resource to a cluster of RRUs [6]. In this paper, the backhaul aggregation points for all different network architectures are collectively called *RNC* as in [11].

In terms of backhauling strategies, in addition to the common *Direct Transmission* and *Decode-and-Forward Transmission*, C-RAN is first proposed in [12] and has been regarded as a centralized cost-efficient and spectrum-efficient solution [13], [14]. In C-RAN, the signals received at the BSs are first quantized and then forwarded to the BBU, which decodes the packets and also schedules the radio resources [15]. However, in the case of a wireless backhaul network, the capacity of the backhaul will limit the transmission of the quantize-and-forward (QF) data. In contrast with the centralized processing employed in C-RAN, *fog* or edge processing is first proposed by Cisco in 2014 and applied for RANs in [16] referred to as Fog-RAN or F-RAN. By exchanging the UEs' received signals between BSs through fronthaul links and between BSs and RNC through backhaul links, it is possible to receive signals from one UE through diverse paths and demodulate the combined signals at a receiving BS instead of centralized BBU or RNC [17]. In F-RAN, since the BSs are capable of signal processing [16], the topology of the backhaul network is dramatically changed.

In this paper, we focus on the uplink transmission in small cell networks consisting of one RNC and several enhanced micro BSs. All the BSs are connected to the RNC by wireless backhaul. Time-division-duplex (TDD) mode is assumed for simplicity in this network and all links share a common spectrum resource. Our purpose is to optimize the network throughput and compare the different backhaul strategies. We further study the differences of these strategies in terms of coverage and throughput. The main contributions of this paper are:

1) we propose a novel wireless backhauling strategy for small cell network called F-RAN. In this strategy, every BS connected with other BSs and RNC by wireless fronthaul and wireless backhaul respectively. In F-RAN, the signals of a UE are received by multiple adjacent BSs and then quantized-and-forwarded to the serving BS of the UE. The serving BS combines the signals from diverse paths by Maximum Ratio Combining (MRC) and then forwards the decoded data to the RNC;
2) we model our proposed strategy and three existing backhauling strategies. With the goal of maximizing network throughput, close-form expressions of the UE data rate for all these strategies are derived by taking into account their different forwarding strategies and cooperating BS selections.
3) we compare the performance of these strategies and show that F-RAN provides the best throughput for cell edge UEs, while maintaining the same performance in the rest of the area. We show that F-RAN significantly outperforms the other strategies when the backhaul link channel is poor, which is a common case in real deployments.

The rest of this paper is organized as follows: in the next section, we discuss related work. In Section III, we present our proposed uplink transmission strategy *F-RAN* and three other existing strategies: *direct transmission*, *decode-and-forward transmission* and *C-RAN*. In Section IV, we describe the system model including the quantization process and data rate analysis. Section V formulates the network throughput maximization problem for the mentioned strategies. Numerical results and analysis are shown in Section VI and conclusions are in Section VII.

II. RELATED WORK

The design of backhaul networks has attracted significant attention in recent years. The challenges in terms of new backhaul architectures and technologies in future 5G wireless networks are summarized in [2] and [9]. Biermann *et al.* [17] explain how BSs clustering and backhaul clustering have to cooperate by showing the significant performance difference between the conventional RAN and possible backhaul topologies. Other work focused on how the backhaul constraints affect network collaboration in different scenarios and proposed solutions. Ghimire and Rosenberg [18] show a backhaul-aware user scheduling under diverse backhaul limitations. Work by Zhou and Yu [19] introduce a simple scheme by using Wyner-Ziv compress-and-forward relaying and centralized successive interference cancellation in an uplink multicell joint processing model. Baracca *et al.* [11] present a rate allocation algorithm for maximizing network throughput in a cellular system, while taking into account single carrier frequency division multiple access (SC-FDMA) and quantization bits. In the area of wireless backhaul, Zhao *et al.* [20] study the problem of small cell points admission control and propose an iterative algorithm to minimize the total cost of building wireless backhaul in heterogeneous cellular networks. Wang *et al.* [21] show a joint cell association and wireless backhaul bandwidth allocation in two-tier cellular heterogeneous networks under wireless backhaul constraints.

However, changes in network architecture and topology as the result of using a wireless backhaul were not considered in [18]– [21].

As pointed in [3] and [22], C-RAN and F-RAN have been proposed as advanced mobile networking architectures relying on cloud computing and fog computing respectively. Peng *et al.* [16] show that F-RAN takes full advantage of local radio signal processing, and cooperative radio resource management at edge devices, which can decrease the heavy burden on fronthaul, and avoid massive signal processing in the BBU pool. Vaquero and Rodero-Merino [23] offer a comprehensive definition of the F-RAN and show that fog processing can dramatically change the existing information and communication technology landscape. Park *et al.* [24] study joint design of cloud and edge processing for an F-RAN architecture with the goal of maximizing the minimum delivery rate of the requested files, while satisfying the fronthaul capacity and enhanced RRH power constraints. References [7] and [15] analyze the challenging requirements on the fronthaul and backhaul networks in C-RAN. Zhou and Yu [25] present their compress-and-forward scheme for the uplink of a C-RAN network and optimize the quantization noise under a sum backhaul capacity constraint. Multihop backhaul typologies for the uplink of C-RANs have been investigated in [26]: the authors present a multiplex-and-forward and decompress-process-and-recompress backhaul schemes to maximizing the sum rate under limited backhaul. However, BS cooperation and radio resource allocation were not jointly considered, therefore, work in [26] does not optimally use the capacity of the wireless backhaul network. Work in [27] is often seen as a reference in the capacity of relay networks; however, work in [27] differs from our, in that they consider full-duplex relays (capable of receiving and transmitting at the same time in the same frequency bands), and do not consider cooperative diversity. Furthermore, Kramer *et al.* [27] consider an abstract, information theory approach, rather than focusing on a cellular network. In contrast, work in [28] considers the capacity of the network employing cooperative relays, but using decode-and-forward (DF) at each of the cooperating relays. Our work mainly focuses on cooperative QF instead, which leads to a different problem formulation and solution. In this paper, we also investigate the architecture of the backhaul network assuming that fog computing is available at each BS.

III. UPLINK TRANSMISSION STRATEGIES

In this section, we introduce our proposed F-RAN backhaul strategy and compare it with existing strategies. We consider a densely deployed network consisting of a Radio Network Controller (RNC), several micro BSs, and a single user equipment (UE). Fig.1 illustrates a basic network scenario in which one UE is surrounded by three BSs. The RNC communicates with all BSs in this network for both transmitting UE's data and scheduling the cooperation of BSs. The uplink transmission paths are classified as:

1) Uplink (UL): BSs receive the wireless signals transmitted from UEs (UE-BS);
2) Fronthaul link (FH): BSs transmit the received signals to other BSs (BS-BS);
3) Backhaul link (BH): BSs transmit the processed signal to operator network (ON), in two phases: the wireless backhaul links connect the BS with RNC, and a wired backhaul link connects RNC with the core (BS-ON).

In the example shown in Fig. 1, it is assumed that the signal from UE can be received by every BS and forwarded to RNC or other BSs according to topology and backhaul strategy. Fig.2 shows four types of wireless backhaul strategies:

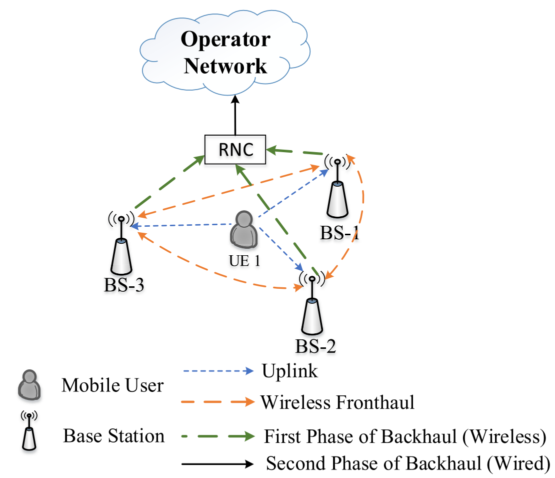

FIGURE 1. Illustration of the types of links between UE, BSs and RNC.

A. STRATEGY 1: DIRECT TRANSMISSION (DT) THROUGH ONE BS

Fig. 2(a) presents the most common backhaul transmission mode, where one BS provides direct communications for the UE in uplink. The UE is associated with only one of the BSs, which is selected by the RNC to optimize performance of the network. The receiving BS decodes the signals of the UE and then forwards the UE data to RNC via a wireless backhaul link. All BSs are assumed to share the same frequency.

B. STRATEGY 2: DECODE-AND-FORWARD (DF) RELAY NETWORK

The main advantages of a relay-enhanced network are extending the coverage of cells, and improving the data rate of UEs in remote areas. As shown in Fig. 2(b), BS-2 first decodes the received data from UE, and then forwards the re-encoded data to BS-1, which has a better channel to forwarding to RNC than BS-2 directly. BS-1 in turn, forwards the data to RNC by DF.

C. STRATEGY 3: CLOUD RADIO ACCESS NETWORK (C-RAN) WITH QUANTIZE-AND-FORWARD (QF)

To efficiently share the radio resource and processing power, C-RAN is proposed [12] to be a centralized control and

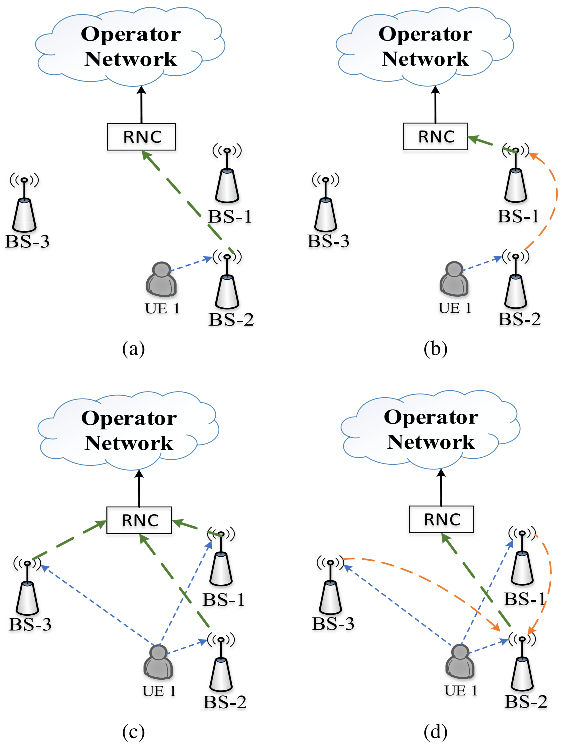

FIGURE 2. Samples of four reception strategies for the scenario shown in Fig. 1: (a) Direct Transmission; (b) Decode-and-Forward Transmission; (c) C-RAN; (d) F-RAN.

computing scheme that can flexibly adopt new coordinated resource allocation techniques (e.g., power control, scheduling, BS clustering, beamforming). In C-RAN, the UE is served collaboratively by a group of BSs that are chosen by the RNC in order to enhance interference management. However, the requirement on backhaul capacity is greatly increased. As shown in Fig. 2(c), the UE signal is received by all three surrounding BSs. The received signals at BSs are quantized and then forwarded to RNC via wireless backhaul. The RNC combines the signals from these three BSs by MRC resulting in improved the signal-to-interference-plus-noise ratio (SINR) for the UE and then transmits the decoded data to ON through the wired backhaul link.

D. STRATEGY 4: FOG RADIO ACCESS NETWORK (F-RAN)

In contrast to the C-RAN, we assume that the BSs can also demodulate signals rather than being simple RRUs that only act as relays in C-RAN. In the proposed approach, we assume the availability of communications between BSs via wireless fronthaul links. Therefore, for a UE, BSs can play one of two roles for uplink data transmission:

1) Serving-BS (S-BS): there is exactly only one S-BS for each UE. The S-BS receives copies of the wireless signal from both the UE and Forwarding-BSs (F-BSs), combines the signals (e.g., through MRC) and then decodes the UE data before forwarding it to the RNC;
2) Forwarding-BS (F-BS): there may be zero or more F-BS for each UE. An F-BS is a BS that receives the UEs' signals, quantifies it and forwards the signal to the UE's S-BS.

Of course, a BS may play neither of the two roles (S-BS or F-BS) for a given UE. To improve the SINR of the UE, the S-BS combines the signals from UE and its F-BSs by MRC as depicted in Fig. 2(d). In comparison with direct transmission, the achievable data rates of the UE are increased due to the improved SINR.

IV. SYSTEM MODEL

We consider an uplink network with wireless backhaul consisting of one UE, N micro BSs and one RNC. The RNC connects to ON with a wired link of unlimited capacity. Each BS is equipped with one transceiver, thus transmitting and receiving cannot proceed simultaneously. In this paper, we assume a time-division-duplex (TDD) scheme, which the data transmissions in uplink, fronthaul link and backhaul link occur in independent consecutive time intervals, thus avoiding interference at receivers. We assume that all transmissions are using the LTE standard.

For the wireless uplink transmission, transmitters include UEs and BSs. The receivers are BSs and RNCs. The received signal at a receiver can be expressed as:

$$y_{i,j} = h_{i,j}x_i + z_{i,j}. \tag{1}$$

where $y_{i,j}$ denotes the received signals at receiver j from transmitter i. We assume x_i represents the modulated symbols from transmitter i with average transmission power P; $h_{i,j}$ represents the channel coefficients from transmitter i to receiver j, given by $h^2_{i,j} = \frac{G_i G_j}{L_{i,j}}$, where G_i, G_j, $L_{i,j}$ are the transmitting antenna gain, receiving antenna gain and the path loss of the channel respectively; $z_{i,j}$ is the noise at receiver j, assumed to be normally distributed as $\mathcal{CN}(0, N_0)$, where N_0 denotes the noise variance. The signal-to-noise ratio (SNR) of the received signal $y_{i,j}$ is:

$$SNR_{i,j} = \frac{h^2_{i,j}P}{N_0}. \tag{2}$$

Considering the modulation and coding scheme (MCS) and link quality, the achievable data rates at receivers is [29]:

$$R_{i,j} = c_{i,j} \cdot N_{symbol} \cdot \gamma_{i,j} \cdot Code\_rate_{i,j} \cdot \frac{1}{T_{slot}}. \tag{3}$$

where $c_{i,j}$ denotes the number of subcarriers allocated on the channel between transmitter i to receiver j, N_{symbol} is the number of symbols per subcarrier per slot, $\gamma_{i,j}$ is the number of bits in one modulation symbol, which is determined by $SNR_{i,j}$, and $Code\_rate_{i,j}$ is the corresponding coding rate of each type of modulation; T_{slot} represents the slot time period in LTE.

For the fronthaul and backhaul links, the BSs are effectively relays, i.e., the outgoing data at the BSs should be equal or greater than the incoming data in order to avoid excessive buffering:

$$R_{in} \cdot t_{in} \leq R_{out} \cdot t_{out}. \tag{4}$$

where R_{in}, R_{out} are the capacities of receiving link and transmitting link at each BS, t_{in} and t_{out} are the durations of these two links time allocations respectively. For the relay with DF technology, the capacities of incoming and outgoing data can be computed by (3) according to the different SNR values of corresponding channels. Depending on QF technology, the amount of incoming data may be increased because the received signals are first sampled and then quantized according to the bandwidth of the channel and the number of quantization bits:

$$\hat{R}_{i,j} = N_{sample} \cdot s \cdot b_{i,j}. \tag{5}$$

where $\hat{R}_{i,j}$ is the transferred data rate of the quantized signal of UE i at receiver j; N_{sample} represents the sampling rate of the signals; s denotes the allocated bandwidth of sampling rate for quantization, and $b_{i,j}$ is the number of bits used for quantization for this UE. The quantization noise $w_{i,j}$ is modeled as:

$$\hat{y}_{i,j} = y_{i,j} + w_{i,j}. \tag{6}$$

where $w_{i,j}$ represents the quantization noise of UE i at receiver j with statistical power $\xi_{i,j}$. We assume an uniform distribution of the signal to be quantized and forwarded. Therefore, the power of quantization noise can be written as [30]:

$$\xi_{i,j} = \int_{\frac{-q_{i,j}}{2}}^{\frac{q_{i,j}}{2}} \frac{1}{q_{i,j}} e^2 \, de = \frac{q_{i,j}^2}{12}, \tag{7}$$

and

$$q_{i,j} = \frac{\sqrt{\mathbb{E}|y_{i,j}|^2}}{2^{b_{i,j}} - 1}. \tag{8}$$

where $q_{i,j}$ is the quantization step for UE i at receiver j. Consequently, the signal-to-quantization noise ratio (SQNR), which is used to calculate the achievable data rate of quantized signal via (3), can be obtained by:

$$\mathrm{SQNR}_{i,j} = \frac{(h_{i,j})^2 P}{N_0 + \xi_{i,j}}. \tag{9}$$

Let $\mathcal{X}_i$ be the set of BSs selected to quantize-and-forward data for the UE i (i.e., the F-BSs for the UE). The function $\mathbb{1}_{i,j}$ denotes the indicator function which is defined as:

$$\mathbb{1}_{i,j} = \begin{cases} 1, & j \in \mathcal{X}_i \\ 0, & j \notin \mathcal{X}_i \end{cases} \tag{10}$$

We assume that the S-BS and RNC use an MRC scheme to demodulate the UE transmission received from different paths. To maximize the output SQNR, the weight for each of the input signal has to be chosen such that it minimizes the impact of fading for the transmitter. With the assumption that the receiver j has the required condition knowledge of the all channels, the achievable output SQNR is given by [31]:

$$\overline{\mathrm{SQNR}_j} = \sum_{j \in \mathcal{X}_i} \mathrm{SQNR}_{i,j}. \tag{11}$$

V. PROBLEM FORMULATION AND SOLUTION

In this section, we formulate and solve the optimization problem in terms of network throughput maximization for all strategies introduced in section IV. We assume that the entire spectrum is allocated to every transmission link. The noise for each channel is assumed to be statistically independent of noise in the other channels.

A. STRATEGY 1: DIRECT TRANSMISSION (DT) THROUGH ONE BS

In this strategy, the signal of UE is delivered to RNC by only one BS with DF. The goal is to find the optimal BS for the maximum throughput. Let $\mathcal{N} = \{1, 2, \ldots, N\}$ denote the set of BSs. We indicate with $\lambda^{(UL)}$ and $\lambda_i^{(BH)}$ the fractions of time allocated to uplink and backhaul link of BS $i \in \mathcal{N}$ respectively. According to (4), the network throughput with a DF relay by BS i is equal or greater than the amount of data transmitted divided by the total time from UE to RNC:

$$\begin{aligned} T_i^{(DT)} &= \frac{R_i t_{in}}{t_{in} + t_{out}} = \lambda^{(UL)} R_i \le \frac{R_i^{(RNC)} t_{out}}{t_{in} + t_{out}} \\ &\le \frac{1}{\frac{1}{R_i} + \frac{1}{R_i^{(RNC)}}}. \end{aligned} \tag{12}$$

where R_i and $R_i^{(RNC)}$ represent the achievable data rates from UE to BS i and BS i to RNC respectively. The optimization problem of network throughput maximization can be formulated as:

$$\max_{i \in \mathcal{N}} \; T_i^{(DT)}, \tag{13}$$

subject to

$$0 \le \lambda^{(UL)}, \lambda_i^{(BH)}, \tag{14}$$

$$\lambda^{(UL)} + \lambda_i^{(BH)} \le 1, \tag{15}$$

$$\lambda^{(UL)} R_i \le \lambda_i^{(BH)} R_i^{(RNC)}. \tag{16}$$

where (14) and (15) are the constraints of the lower and upper bounds of time fractions, and (16) guarantees that there is no data loss for relaying at BS i.

Problem (13) is a non-linear integer optimization problem. Since there is only one integer search variable (namely the index of the BS), the optimal solution of this problem can be simply found by exhaustive search in N rounds. The complexity is thus $O(N)$, where N is the number of BSs in range of the UE.

B. STRATEGY 2: DECODE-AND-FORWARD (DF) RELAY NETWORK

The DF relay network, allows the addition of relay BSs, thus the received signal power and data rate at RNC can be enhanced. Let us denote with $\lambda_{i,j}^{(FH)}$ and $\lambda_j^{(BH)}$ the fractions of time allocated to fronthaul link from BS i to BS j and backhaul link from BS j to RNC respectively. The network throughput is different for pairs of different BS i-BS j due to the different achievable data rates of fronthaul and backhaul links according to their corresponding channel quality. In this strategy, the network throughput can be expressed as:

$$T_{i,j}^{(DF)} = \lambda^{(UL)} R_i \leq \frac{1}{\frac{1}{R_i} + \frac{1}{R_{i,j}} + \frac{1}{R_j^{(RNC)}}}. \quad (17)$$

Although it is theoretically possible that the best path traverses more than one relay BS, this is unlikely in a system with well-placed BSs, and therefore in our work we assume that for DF at most one relay BS is used. The best pair of BSs used for uplink transmission with DF relay should be chosen and the optimization problem of the maximum network throughput is:

$$\max_{i,j \in \mathcal{N}, i \neq j} T_{i,j}^{(DF)}, \quad (18)$$

subject to

$$0 \leq \lambda^{(UL)}, \lambda_{i,j}^{(FH)}, \lambda_j^{(BH)}, \quad (19)$$

$$\lambda^{(UL)} + \lambda_{i,j}^{(FH)} + \lambda_j^{(BH)} \leq 1, \quad (20)$$

$$\lambda^{(UL)} R_i \leq \lambda_{i,j}^{(FH)} R_{i,j} \leq \lambda_j^{(BH)} R_j^{(RNC)}. \quad (21)$$

where (19) and (20) constrain the lower and upper bounds of time fractions for uplink, fronthaul link and backhaul link, and (21) is the relaying constraint that ensures the data transferred between all BSs completely.

Problem (18) is similar to Problem (13), but unlike Problem (13), Problem (18) has two integer search variables. Since the solution of the problem given an associated BS and a forwarding BS has a closed form, even an exhaustive search $O(N^2)$ is acceptable complexity-wise. However, the complexity can be further reduced to $O(N)$ by precomputing the best path data rate for each possible receiving BS: for each BS, we consider all the other BSs as potential forwarders, and select the best one as a forwarder to that BS. This operation only needs to be done once for a given infrastructure network and does not have to be repeated for each UE. Then the UE will choose the BS with the best forwarding rate as its serving BS (as the corresponding forwarder is then also automatically selected).

C. STRATEGY 3: CLOUD RADIO ACCESS NETWORK (C-RAN)

In C-RAN, to enhance the network throughput, the RNC can centrally control the set of BSs $\mathcal{X}$ associated with a UE and allocate the time fractions for uplink and backhaul links. We assume the UE broadcasts the data to neighboring BSs, such that the transmission time of the uplink are the same for all the BSs. However, the achievable data rates at the receivers can be different due to the different channel conditions. At the RNC, the receiver will combine the signals transmitted from different BSs through MRC. Therefore, a better data rate for the UE at RNC can be obtained based on the improved SQNR and the transmission time for the uplink with the same amount of data can be significantly decreased. The network throughput in this strategy can be computed by:

$$T^{(C-RAN)} = \lambda^{(UL)} R(\overline{\text{SQNR}}) \leq \frac{R(\overline{\text{SQNR}})}{1 + \sum_{i=1}^{N} \mathbb{1}_i \frac{\hat{R}_i}{R_i^{(RNC)}}}, \quad (22)$$

where $R(\overline{\text{SQNR}})$ denotes the achievable data rate calculated by the sum of the signal-to-quantization noise ratios (SQNRs) based on all the selected channels in $\mathcal{X}$.

The optimization problem can be expressed as:

$$\max_{i \in \mathcal{X}} T^{(C-RAN)}, \quad (23)$$

subject to:

$$0 \leq \lambda^{(UL)}, \lambda_i^{(BH)}, \quad (24)$$

$$\lambda^{(UL)} + \sum_{i=1}^{N} \lambda_i^{(BH)} \leq 1, \quad (25)$$

$$\lambda^{(UL)} \hat{R}_i \leq \lambda_i^{(BH)} R_i^{(RNC)}, \quad \forall i \in \mathcal{X}. \quad (26)$$

where (26) ensures that the UE data received at a forwarding BS (F-BS) is quantized and relayed to the RNC.

Problem (23) is a non-linear integer programming problem. The complexity of this problem is $O(2^N \cdot (B_{max})^N)$. To simplify the solution, we have to iterate through two sets:

a) find the optimal set of BSs K^*, the complexity is $O(2^N)$;
b) find the optimal number of quantization bits to each BS $b_i^{(*)}$, $i \in \mathcal{N}$, the complexity is $O((B_{max})^N)$.

For the first set, it is not necessary to traverse all the BSs in the network. Denote by K_u the set of BS where the SNR of user u is greater than 1. Since the signals from receiving BS are combined by MRC, only BSs in set K_u should be considered as possible candidates. Denote by $k_u = |K_u|$ the number of BSs with SNR$>$ 1 for user u. Therefore, the available number of BSs becomes $k_u \leq N$ and the size of set a) in 2^{k_u} is $O(2^{k_u})$.

For the second set, there are two different methods to find the quantization bits of user: 1) assume the same number of quantization bits to all BSs; 2) search for a different optimal number of quantization bits for each BS. According to the results in [11], the difference of the performance between Static Bit Allocation (SBA) and Dynamic Bit Allocation (DBA) are about 1% or less, even for the cases that each subcarrier signal is quantized with different number of bits. Hence, in our paper, SBA is selected to improve the efficiency of solving the problem. We assume the maximum integer number of quantization bits is B_{max}. According to the one-dimensional space of b_i, the bisection method can be efficiently applied to obtain the maximum throughput [32], [33]. Therefore, the final complexity of solving this problem becomes $O(2^{k_u} \cdot \log_2(B_{max}))$. The proposed iterative algorithm to problem (23) is summarized in **Algorithm 1**.

D. STRATEGY 4: FOG RADIO ACCESS NETWORK (F-RAN)

The main optimization for this strategy is to improve the data rate of received signal at the RNC by selecting an optimal

Algorithm 1 Iterative Algorithm for C-RAN

1: Initialize the number of quantization bits for BS i: $b_i(1) = 1, \forall i \in \mathcal{N}$
2: Initialize all possible BSs sets K_u for the user
3: Initialize the optimal network throughput $\mathbf{T}^{(\mathbf{C-RAN})*} = 0$
4: **for** $1 \le t \le 2^{k_u}$
5: **while** $b_i(t+1) \ne b_i(t)$
6: **Compute the network throughput** $T^{(C-RAN)}(t)$ **by (22).**
7: **if** $T^{(C-RAN)}(t) > T^{(C-RAN)}(t-1)$
8: $\mathbf{T}^{(\mathbf{C-RAN})*} \leftarrow T^{(C-RAN)}(t)$
9: $\mathbf{b}_\mathbf{i}^* \leftarrow b_i(t)$
10: $K^* \leftarrow K_u(t)$
11: **end if**
12: **Compute** $b_i(t+1)$ **by the bisection method [32]**
13: **end while**
14: end for

S-BS to combine the signals from the F-BSs instead of RNC. In addition, the set of F-BSs for the UE should be selected carefully because the BSs with bad channel quality (low SQNR) will cost more time in transmission but only offer a small SNR improvement. The network throughput can be calculated by:

$$\begin{aligned} T^{(F-RAN)} &= \lambda^{(UL)} R(\overline{\text{SQNR}}) \\ &\le \frac{R(\overline{\text{SQNR}})}{1 + \sum_{i=1,i\ne j}^{N} \mathbb{1}_i \frac{\hat{R}_i}{R_{i,j}} + \frac{\hat{R}_j(\overline{\text{SQNR}})}{R_j^{(RNC)}}}, \end{aligned} \tag{27}$$

The optimization problem can be formulated:

$$\max_{i\in\mathcal{N}, j\in\mathcal{X}, i\ne j} \quad T^{(F-RAN)}, \tag{28}$$

subject to:

$$0 \le \lambda^{(UL)}, \lambda_{i,j}^{(FH)}, \lambda_j^{(BH)}, \tag{29}$$

$$\lambda^{(UL)} + \sum_{i=1}^{N} \lambda_{i,j}^{(FH)} + \lambda_i^{(BH)} \le 1, \tag{30}$$

$$\lambda^{(UL)} \hat{R}_i = \lambda_{i,j}^{(FH)} R_{i,j}, \tag{31}$$

$$\lambda_j^{(BH)} R_j^{(RNC)} \le \lambda^{(UL)} \hat{R}_j(\overline{\text{SQNR}}), \quad \forall i \in \mathcal{X}. \tag{32}$$

where (29) and (30) are the time sharing constraints of lower and upper bound for F-RAN, and constraints (31) and (32) are used to ensure no bit loss in every BS and that all the data is transferred from UE to RNC respectively.

Similar to C-RAN problem (23), the F-RAN problem (28) is also a non-linear integer programming problem with a slightly more complex BS selection; problem (28) can be decomposed into three separate subproblems: in addition to the two problems in C-RAN, there is the additional problem of finding an optimal serving-BS $\mathbf{j}$ of UE to combine the signals before RNC. Since the new subproblem is still a non-linear integer optimization problem with N possible selection solutions, the exhaustive search can be efficiently applied. Hence, the complexity is $O(2^{k_u} \cdot \log_2(B_{max}) \cdot N)$. The algorithm for solving F-RAN problem (28) is summarized in Algorithm 2.

Algorithm 2 Iterative Algorithm for F-RAN

1: Initialize the number of quantization bits between BS i to BS j: $b_{i,j}(v = 1, t = 1) = 1, i \in \mathcal{N}, j \in \mathcal{N}, i \ne j$
2: Initialize all possible BSs sets K_u for the user
3: Initialize the Serving-BS $\mathbf{j} = 1$
4: **for** $1 \le v \le N$
5: **for** $1 \le t \le 2^{k_u}$
6: **Compute the optimal network throughput** $T^{(F-RAN)}(v, t)$ **based on the same steps in Algorithm 1**
from line 4-12. Compute $T^{(F-RAN)}(v, t)$ **by (27),**
$\mathbf{T}^{(\mathbf{F-RAN})*} \leftarrow T^{(F-RAN)}(v, t)$
$\mathbf{j} \leftarrow v$
7: **end for**
8: **end for**

TABLE 1. Simulation parameters.

Parameter	Value
Number of RNCs	1
System Bandwidth	10 MHz
Thermal Noise (N_0)	-174 dBm/Hz
Micro BS Transmission Power	30 dBm
UE Transmission Power	21 dBm
Number of Antennas per BS	1
Number of Antennas per UE	1
Antenna Gain for BS	5 dBi
Antenna Gain for UE	3 dBi

VI. SIMULATION RESULTS

In this section, we evaluate the performance of wireless backhauling strategies using a simplified LTE small cell network setup with one RNC that connects to a few Micro BSs. The 3GPP specifications for pathloss of outdoor links with the noise level set to -174 dBm are used in the simulation, and the uplink transmission power for UE and BSs are set to 21 dBm and 30 dBm respectively [34]. All the uplinks, fronthaul links and backhaul links share a common bandwidth of 10 MHz. To avoid the variability of the network capacity as well as the fairness question, we evaluate the performance of the four backhaul strategies with a single UE in the simulation. The capacity of a network with multiple UEs is no different than that with a single UE with the same SNR. A detailed list of the simulation parameters are listed in Table 1.

We first show a detailed example of the transmission topologies for different backhauling strategies in the same network scenario. In Fig. 3, we assume an LTE network consisting of four Micro BSs distributed uniformly and one RNC located near BS-3 but relatively far from the others. The figure shows the best selection of BSs for all four strate-

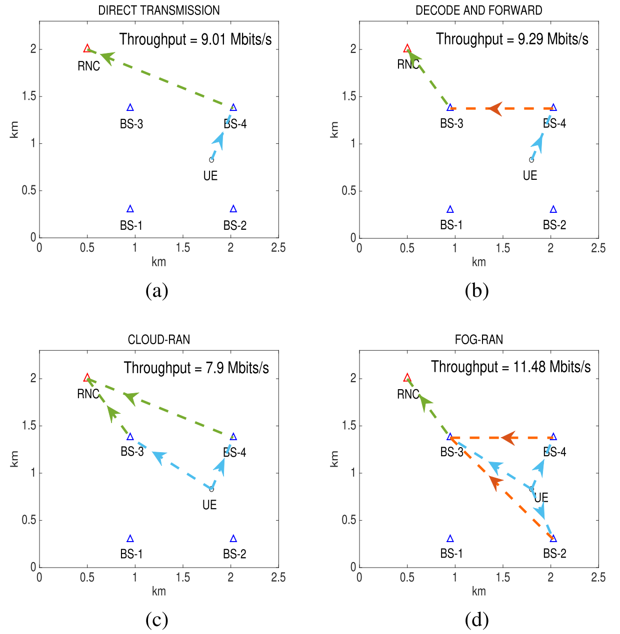

FIGURE 3. **Sample scenarios for (a) Direct Transmission; (b) Decode-and-Forward Transmission; (c) C-RAN; (d) F-RAN. Blue, orange and green dashed lines represent uplinks, fronthaul links and backhaul links respectively.**

gies considered in this paper. For Direct Transmission (DT), in Fig. 3(a), we observe that the UE selects the closest BS-4 as its serving BS even if its backhaul channel is not the best. For DT, the uplink data rate primarily affects the BS selection. For DF strategy, shown in Fig. 3(b), due to the increased backhaul data rate of BS-3 and fronthaul data rate between BS-3 with BS-4, the throughput of UE under DF strategy is 9.29Mbits/s, which is slightly higher than the 9.01Mbits/s under DT. C-RAN schedules BS-3 and BS-4 to serve the UE as shown in Fig. 3(c). By using quantize-and-forward (QF) at the relay BSs, C-RAN has to forward a larger amount of data than DF. Thus, C-RAN achieves the worst throughput when using a wireless backhaul network with limited capacity. Fig. 3(d) shows that for F-RAN, BS-3 is chosen to be S-BS, while BS-2 and BS-4 are F-BSs. By using MRC at BS-3, the quality of combined signal is significantly improved, which increases the backhaul data rate and remarkably reduces the QF overhead. As a result of taking full advantage of the surrounding BSs, F-RAN has the best performance and over 23% higher than all other strategies in this scenario.

In order to evaluate the effect of position of RNC, we explore two more examples with fixed BS location but different positions for the RNC. Figures 4(a) and 4(c) show the two scenarios with RNC located in the center and in a marginal position in the network respectively. In Fig. 4(a) and 4(c), we also show for each possible UE position the best backhaul strategy (i.e., the strategy that maximizes the UE throughput). Figures 4(b) and 4(d) present the corresponding network throughput of these two scenarios. The throughput for the best backhaul strategy is shown. When the BSs have good backhaul data rates, Direct Transmission through only one BS is the optimal strategy for most of the users. There are only a few areas better served by using C-RAN and F-RAN shown in Fig. 4(a): the preferred C-RAN area is located closer to center as C-RAN has a high requirement on the backhaul rate and C-RAN only performs better when there is more than one BS with good backhaul quality close to the UE. F-RAN has an identical performance with DT in yellow areas where only one BS is considered as the S-BS and no BS is scheduled as F-BS. Fig. 4(c) where the RNC located in a farther position that leads to longer backhaul distances for BS-1,2,4 shows that more areas prefer F-RAN than in Fig. 4(a). This result shows that F-RAN can improve the network throughput in situation where the backhaul channels of BSs are of low quality. In addition, DF strategy is preferred more often in Fig. 4(c) versus 4(a) because the UEs in DF areas in Fig. 4(c) only have poor or no available backhaul channel for their best BSs and cannot connect directly with any BSs with good backhaul links. The network throughput dramatically decreases when the UE is getting further to RNC. However, as shown in Fig. 4(d), DF and F-RAN increase the throughput significantly for the UEs at the cell edge when the RNC is far from the S-BS. In these two scenarios, we find that 100% coverage area served by F-RAN and more than 65% for C-RAN have their throughput optimized by using 1 bit for QF transmission, despite

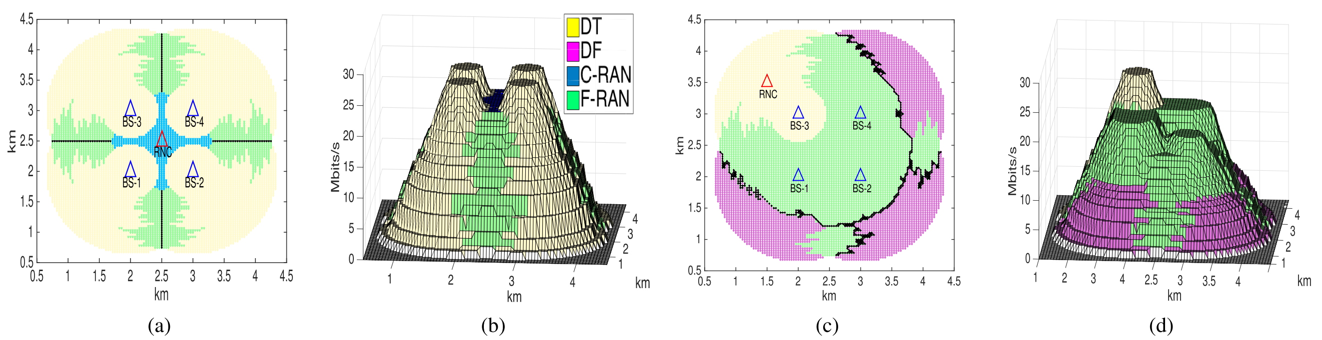

FIGURE 4. **Two scenario examples consisting of four BSs and one RNC for (a)(c) different backhauling strategies selections and (b)(d) the corresponding network throughput. The black lines mark the borders of the coverage by different BSs. The best throughput is obtained in the yellow areas by DT, in the magenta areas by DF, in the blue areas by C-RAN, and in the green areas by F-RAN.**

having the worst SQNR, and in no situation the throughput is optimized by using more than 4 bits: the higher the number of bits used in C-RAN or F-RAN, the higher the fraction of time of backhaul links is used for data transmission. Therefore, most of the locations use fewer quantization bits for QF although a higher quantization noise will be introduced. In Fig. 5, we show the best number of quantization bits for each location of the UE for F-RAN and C-RAN.

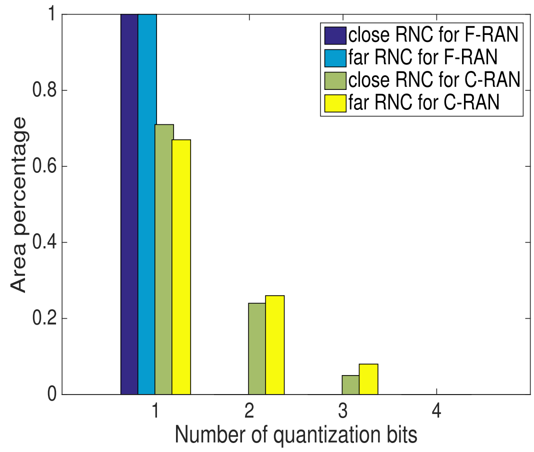

FIGURE 5. The percentage of areas in scenarios in Fig. 4(a) and 4(c) served by F-RAN and C-RAN that have their throughput optimized by using different number of quantization bits.

To evaluate the performance of each backhauling strategy, we establish a simulation area as shown in Fig. 6. We assume that the black circles represent the typical cellular cells with a coverage diameter of about 1.4km. We also assume that there are 7 BSs in the network and each BS is randomly placed inside each of the small blue circles. The red straight line is used for the RNC location for simulation of the different RNC positions. The red circle is used for simulating a variable number of RNCs, uniformly distributed on this red circle. To obtain the average network throughput value,

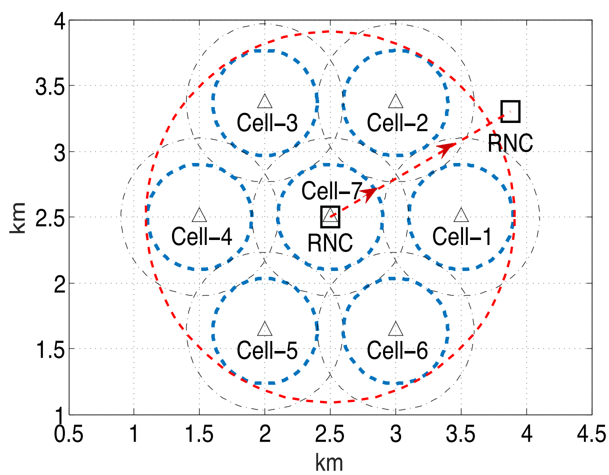

FIGURE 6. The illustration of simulation scenario for evaluating the shifting number or positions of RNCs and random positions of seven BSs.

the simulation is repeated 250 rounds for every scenario. We show the 95% confidence intervals in all the following figures.

The scenario with changing positions of RNC is simulated and shown in Fig. 7. Due to the shifting of RNC, the backhaul distances for these BSs are gradually increasing. When the RNC is in the center of network, most of the BSs have very good backhaul channels. As the RNC moves to the final position in the upper right corner along the red straight line, all BSs, except for the two closest ones, have poor backhaul conditions. Fig. 7(a) shows the average throughput of different backhauling strategies for all the areas where F-RAN can be used. For these areas, the average throughput of F-RAN outperforms the others by approximately 20% for all RNC locations. For areas served by BSs with good wireless backhaul, F-RAN provides the same throughput performance as DT, which has the highest throughput for most of the area as shown in Fig. 4(a). For area served by BSs with poor wireless backhaul, F-RAN improves the throughput by combining signals at the S-BS.

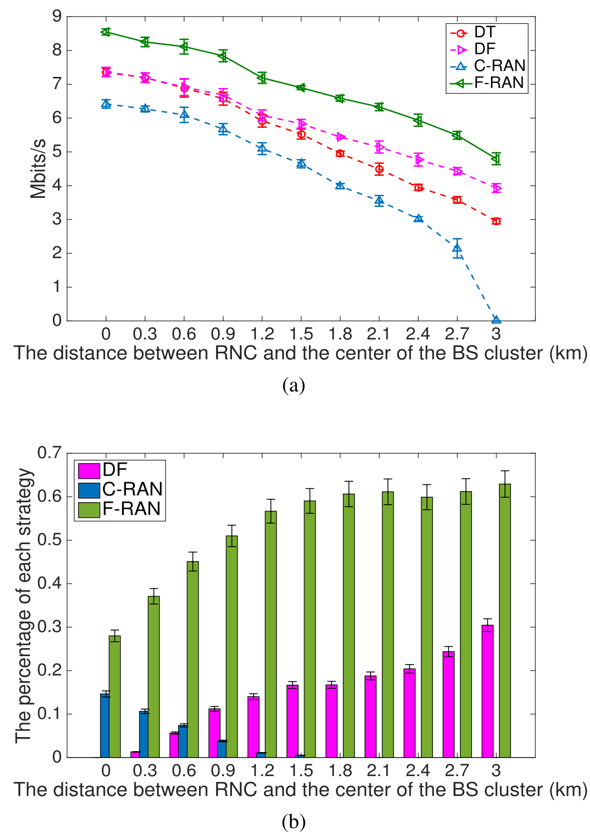

FIGURE 7. Comparison of different strategies in the scenario of varying distance between RNC and the center of the BS cluster. (a) Average throughput; (b) the percentage of coverage area best served by one strategy.

Fig. 7(b) shows the percentage of the entire coverage area best served by different backhauling strategies for the simulation scenario with shifting RNC. The figure confirms the observation in Fig. 4(a) that, where the backhaul quality

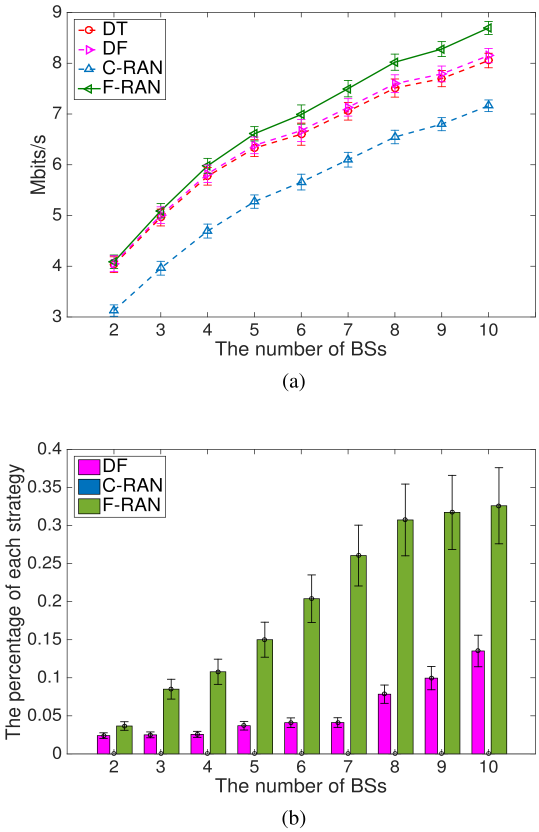

FIGURE 8. **Comparison of different strategies in the scenario of varying number of BSs. (a) Average throughput; (b) the percentage of coverage area best served by one strategy.**

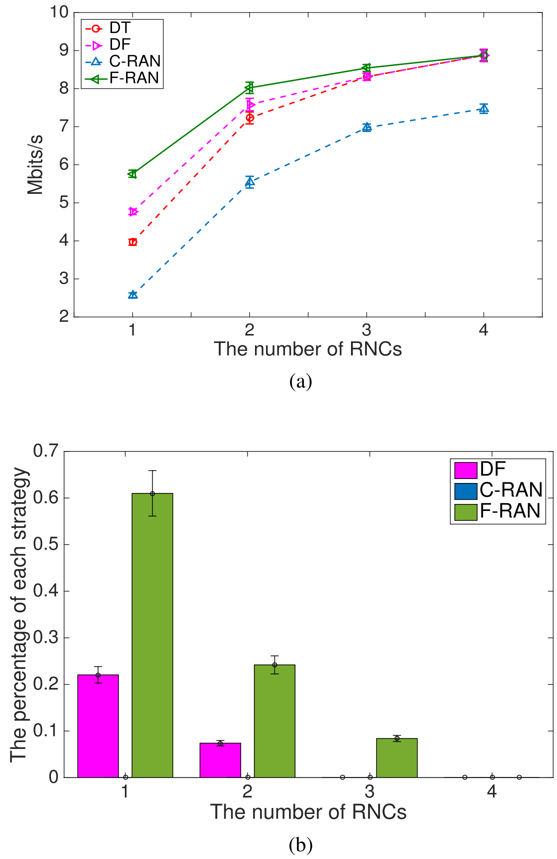

FIGURE 9. **Comparison of different strategies in the scenario of varying number of RNCs. (a) Average throughput; (b) the percentage of coverage area best served by one strategy.**

of the BSs is sufficiently high, e.g., for the RNC displacement smaller than 0.3 km, DT is the best strategy for about 50% of the area, while F-RAN only increases throughput in 25-35% of that area. When the distance of RNC to the center increases, the percentage of area increases to approximately 60%. In the scenario with poor backhaul, DF is typical for many remote areas, since it is difficult to transmit to RNC directly from BSs with a poor backhaul channel. The percentage of the area where C-RAN is optimal decreases with the distance from 15% to 0. C-RAN is rarely optimal for the positions of the RNC with poor backhaul quality. For this scenario, with poor wireless backhaul, F-RAN can obtain more than 20% improvement of network throughput, while being the optimal strategy for approximately 60% of the coverage area, and maintaining the same performance with DT in most of the remaining area.

In the next experiment, we study the impact of the density of BSs on the optimal backhaul strategy. All the BSs are randomly located in a wireless area with radius of 2.5 km and one RNC is placed in the center as shown in Fig. 6. In Fig. 8(a), we plot the average throughput as a function of the number of BSs for each strategy in the network. The throughput achieved by F-RAN increases faster than all the other strategies and performs the best when the density of BS increases. DF and DT show similar results, as when the network density is low, the number of BSs is so small that there is seldom an opportunity for two-hop DF; when the number of BSs increases, the higher network density provides better backhaul channels, therefore, two-hop DF is only utilized for some remote areas. The percentage of area optimized by each backhauling strategy in this scenario is shown in Fig. 8(b). Since the BSs are located in a larger area than in the scenario with shifting RNC, and the channel quality of the backhaul links becomes much worse, none of the area is best served by C-RAN. With the increase in the density of BSs, F-RAN and DF can better support the BS cooperation and enhance the throughput to more users. F-RAN can still optimize network performance for a large percentage of the coverage area.

Finally, we investigate the effect of the number of RNCs on the performance of the backhauling strategies. We assume that 7 BSs are randomly located in each blue circles shown in Fig. 6 and assume that the RNCs are uniformly distributed along the big red circle in Fig. 6. In Fig. 9(a), we plot the average throughput of different number of RNCs from 1 to 4. Network throughput is improved for all strategies with the increase of the number of RNCs since BSs can select the nearest RNC to obtain a better backhaul channel. When there are four RNCs in the scenario, the entire area is served by

DT because the data rate of the optimal wireless backhaul link for each BS is sufficiently high, hence, F-RAN and DF using only one BS is optimal and perform the same as DT. Fig. 9(b) shows the percentage of area optimized by different strategies under the scenario with different number of RNC. C-RAN is never optimal because of its backhaul requirement that at least two BSs must afford high backhaul channels connected with the same RNC. The percentages of area optimized by DF and F-RAN both decrease when the number of RNCs increases, as BSs can obtain higher quality backhaul channels, which significantly reduce the probability of remote backhaul transmission.

VII. CONCLUSION

In this paper, we have studied efficient cooperation transmission strategies for the wireless backhaul of radio access network with small cells. We first proposed a novel wireless backhauling strategy, *F-RAN*, in which we assume that each BS is capable of signal processing. We then illustrate our proposed strategy and compare it with other existing backhauling strategies such as *Direct Transmission*, *Decode and Forward*, and *C-RAN*. We formulated the throughput optimization problem for each strategy by taking into account their relaying protocols and cooperating BS selections. We finally provided numerical results and evaluated the performances of these strategies.

Our results show that F-RAN can achieve the highest throughput for cell edge UEs and also maintain the best performance in most the remaining area. This leads to the most effective strategy for allocating the radio resources in dense small cell network with poor backhaul channel, while shifting the burden from centralized signal processing servers to the edges of the network. In comparison with the BS cooperation in C-RAN, F-RAN provides remarkable gains for flexible fronthaul network and efficient backhaul transmission for the network under limited backhaul capacity. In contrast, C-RAN is optimal for the networks with unlimited backhaul capacity.

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