Baseband Unit Pool Planning for Cloud Radio Access Networks: An Approximation Algorithm

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***Abstract*— Cloud radio access networks (C-RANs) are proposed as promising architecture to improve the capacity and enhance the coverage of mobile communication systems. In this letter, we study the baseband unit (BBU) pools planning problem in the C-RAN, where we try to minimize the total deployment cost while satisfying the traffic demands of remote radio heads connected to the BBU pools, the processing capacity of each BBU pool, and the latency requirements of the C-RAN. Our problem formulation leads a mixed integer linear programming problem that is NP-hard. We introduce an approximation algorithm to address it efficiently. Numerical results show that our proposed algorithm performs much better than other heuristic ones that are popular to deal with such kind of optimization tasks. Moreover, our proposal also yields a performance guaranteed scheme for the BBU pools planning problem in the C-RAN.**

***Index Terms*— Approximation algorithm, BBU pool planning, C-RAN.**

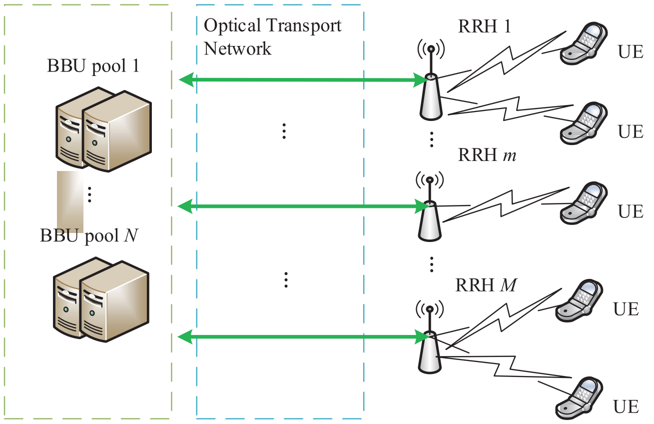

Fig. 1. Illustration of the C-RAN.

I. Introduction

GLOBAL mobile data traffic soared by 73% in 2015 and is expected to grow at a compound annual growth rate of 53% from 2015 to 2020 [1]. However, the average revenue per user is flat or even decreases slowly from the viewpoint of mobile service providers (MSPs) [2]–[4]. It is urgent to develop new mobile network architecture to reduce the capital burden of the MSPs while improving network capacity and enhancing coverage.

Cloud radio access network (C-RAN) is deemed as a promising solution to these issues [5]. The benefit of the C-RAN is multifold. Firstly, the energy consumption of air conditioner and other site support equipments can be dramatically reduced by centralizing many baseband units (BBUs) into several fixed sites, reducing a lot of capital expenditure and operating expense for the MSPs. Secondly, inter-cell interference cancellation (ICIC) and coordinated multi-point transmission (CoMP) technologies are easily implemented in the C-RAN, which can improve the system capacity significantly [6]. Lastly, the virtualized BBUs make mobile switch center more convenient to perform radio resource management and load balance. In brief, C-RAN is a high performance green network architecture for next generation mobile communication systems.

In the C-RAN, remote radio heads (RRHs) transceive signals from/to end users and send pre-processed baseband signals to the BBUs for further modulation/demodulation. Each RRH is connected to a BBU pool via a backhual with high transmission capacity. Optical transport network is a reasonable choice to provide massive capacity backhauls between the RRHs and the BBU pools. Since there is a strict latency constraint for ICIC and CoMP, the length of the optical fiber connecting the RRHs and the BBU pools should be limited [7]. As a result, multiple BBU pools are required so as to keep the distance between each RRH and its connected BBU pool below a threshold to meet the latency requirements of the C-RAN.

Deploying BBU pools is generally expensive and minimizing the deployment cost of the BBU pools is always attractive for the MSPs [8]. However, the BBU pools planning problem is not investigated extensively as far as the authors have known. In this letter, We introduce an efficient algorithm to address the cost optimization task while taking the traffic processing demand of the RRHs, the capacity of the BBU pool and the synchronization among the RRHs into consideration, which extends our preliminary results in [7]. Our proposed algorithm yields a practical deployment scheme for the C-RAN, which is verified by numerical results.

II. System Model and Problem Formulation

Consider an area $D \in R^2$ served by the C-RAN shown in Fig. 1. Denote $\mathcal{M} = \{1, 2, \ldots, M\}$ as the set of RRHs, indexed by m. Each RRH has a traffic processing demand

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TABLE I

FREQUENTLY USED TERMINOLOGIES AND NOTATIONS

$c_{m,n}$	Link cost between RRH m and BBU pool n
$l_{m,n}$	Length of optical fiber for connecting RRH m and BBU pool n
f_n	Facility cost of BBU pool n
L	Latency constraint for fronthaul
$\mathcal{M}$	Set of RRHs
M	Number of RRHs
$\mathcal{N}$	Set of candidate sites
N	Number of candidate sites
w_n	Capacity of BBU pool n
$x_{m,n}$	Binary variable indicates whether RRH m is assigned to BBU pool n or not
y_n	Binary variable indicates whether BBU pool n is selected or not
γ	Cost factor indicates the ratio of service cost and facility cost

expressed as d_m. Denote $\mathcal{N} = \{1, 2, \ldots, N\}$ as the set of candidate sites for BBU pool installing, indexed by n. Each BBU pool is equipped with capacity w_n. Facility cost for installing BBU pool n is f_n. A BBU pool only works when it is opened. Our optimization task is to decide the sites of the BBU pools and the BBU pool assignment for each RRH with the minimum deploying cost. Frequently used symbol terminologies and symbol notations are listed in Table I.

The BBU pools deploying cost consists of the RRHs connecting cost and the facilities cost, which are denoted as c_s and c_f, respectively. The former is generated from the expensive optical fiber connecting the RRHs and the BBU pools. If a BBU pool is selected for opening, the cost of connecting RRH m with BBU pool n by optical fiber is $c_{m,n}$ which is related to the distance $l_{m,n}$ between BBU pool n and RRH m. That is, $c_{m,n} = \phi(l_{m,n})$. For simplification, $c_{m,n}$ is assumed to be linear to $l_{m,n}$ in this letter and the total RRHs connecting cost is

$$c_s = \sum_{m\in\mathcal{M}} \sum_{n\in\mathcal{N}} x_{m,n} c_{m,n}, \tag{1}$$

where $x_{m,n}$ indicates whether RRH m is assigned to BBU pool n or not:

$$x_{m,n} = \begin{cases} 1, \text{ RRH } m \text{ assigned to BBU pool } n; \\ 0, \text{ otherwise.} \end{cases} \tag{2}$$

The latency between the RRH and its serving BBU pool is constrained. An RRH cannot connect with a BBU pool if the distance between them exceeds a threshold, that is:

$$x_{m,n} = 0, if\ l_{m,n} \geq L, \forall m \in \mathcal{M}, n \in \mathcal{N}. \tag{3}$$

On the other hand, the facilities cost is as follows:

$$c_f = \sum_{n\in\mathcal{N}} y_n f_n, \tag{4}$$

where y_n indicates whether BBU pool n is selected or not:

$$y_n = \begin{cases} 1, \text{ BBU pool } n \text{ is selected;} \\ 0, \text{ otherwise.} \end{cases} \tag{5}$$

Mathematically, the BBU pool planning problem can be formulated as

$$\begin{aligned} \min_{y_n, x_{m,n}} \ & \sum_{n\in\mathcal{N}} y_n f_n + \sum_{m\in\mathcal{M}} \sum_{n\in\mathcal{N}} x_{m,n} c_{m,n} \\ s.t.\ C_1 : & \sum_{m\in\mathcal{M}} x_{m,n} d_m \leq w_n y_n, \forall n \in \mathcal{N}, \\ & C_2 : x_{m,n} \leq y_n, \forall m \in \mathcal{M}, n \in \mathcal{N}, \\ & C_3 : x_{m,n} = 0, if\ l_{m,n} \geq L, \forall m \in \mathcal{M}, n \in \mathcal{N}, \\ & C_4 : \sum_{n\in\mathcal{N}} x_{m,n} = 1, \forall m \in \mathcal{M}, \\ & C_5 : y_n \in \{0, 1\}, \forall n \in \mathcal{N}, \\ & C_6 : x_{m,n} \in \{0, 1\}, \forall m \in \mathcal{M}, n \in \mathcal{N}. \end{aligned} \tag{6}$$

C_1 means that the processing capacity constraint for BBU pool n. C_2 indicates that an RRH can be connected to an active BBU pool. C_3 is the latency requirements. C_4 ensures that every RRH is served by only one BBU pool.

III. PROPOSED ALGORITHM

Eq.(6) is generally intractable because it defines a mixed integer programming task that is NP-hard. We introduce an approximation algorithm to address it. Give set $\mathcal{S}$ ($\mathcal{S} \subseteq \mathcal{N}$) as an initial solution for the BBU pool installing, the original problem can be transformed into the following form [7]:

$$\begin{aligned} \min_{x_{m,n}} \ & \sum_{n\in\mathcal{S}} f_n + \sum_{m\in\mathcal{M}} \sum_{n\in\mathcal{S}} x_{m,n} c_{m,n} \\ s.t.\ C_1 : & \sum_{m\in\mathcal{M}} x_{m,n} d_m \leq w_n, \forall n \in \mathcal{S}, \\ & C_2 : x_{m,n} = 0, if\ l_{m,n} \geq L, \forall m \in \mathcal{M}, n \in \mathcal{S}, \\ & C_3 : \sum_{n\in\mathcal{S}} x_{m,n} = 1, \forall m \in \mathcal{M}, \\ & C_4 : x_{m,n} \in \{0, 1\}, \forall m \in \mathcal{M}, n \in \mathcal{S}. \end{aligned} \tag{7}$$

The relaxed form of (7) can be written as follows:

$$\begin{aligned} \min_{x_{m,n}} & \sum_{n\in\mathcal{S}} f_n + \sum_{m\in\mathcal{M}} \sum_{n\in\mathcal{S}} x_{m,n} c_{m,n} \\ & s.t. C1 \sim C3, \\ & \quad C_4 : 0 \leq x_{m,n} \leq 1, \forall m \in \mathcal{M}, n \in \mathcal{S}. \end{aligned} \tag{8}$$

Eq.(8) is a linear programming problem which can be solved by standard algorithms or solver, such as *CVX* [9]. The solution to (7) can be obtained by rounding procedure as follows:

$$x_{m,n} = \begin{cases} 1\ n = \arg\max\limits_{m^*\in\mathcal{M}} x_{m^*,n}, \\ 0 \text{ otherwise,} \end{cases} \forall n \in \mathcal{N}, \tag{9}$$

where $x_{m^*,n}$ is the solution to (8). Then the deploying cost $c(\mathcal{S})$ for set $\mathcal{S}$ can be obtained. The BBU pool planning problem is to find the set $\mathcal{S} \subseteq \mathcal{N}$ to minimize $c(\mathcal{S})$.

We introduce a local search algorithm to update set $\mathcal{S}$ efficiently. Our proposed algorithm yields a solution with an approximation ratio of $(8+\epsilon)$ [10]. The procedure for updating set $\mathcal{S}$ is as follows: For a given set $\mathcal{S}$ that is an initial solution to (6), carry out an *operation* that can decrease the cost by at least $c(\mathcal{S})/p(n)$, where $p(n)$ is a sufficiently large polynomial

TABLE II

THE SOLVING PROCEDURE

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Procedure
Initialization: Given set $\mathcal{S}$ ($\mathcal{S} = \mathcal{N}$)
Obtain $c(\mathcal{S})$
  1: relax problem (7) and calculate $x_{m^*,n}$
  2: round $x_{m^*,n}$, obtain $x_{m,n}$ and $c(\mathcal{S})$
Update $\mathcal{S}$
  3: Repeat change the set $\mathcal{S}$
  4:     if problem (7) is solvable
  5:         if operation can save the cost
  6:             update $\mathcal{S}$
  7:         end if
  8:     else
  9:         renew $\mathcal{S}$, return to step 4
  10:    end if
  11: Until none of operation can save the cost
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TABLE III

PARAMETERS OF THE TWO ALGORITHMS

Parameters of GA		Parameters of TS	
Population size	100	Tabu size (active)	3
Crossover probability	0.7	Tabu size (candidate)	7
Mutation probability	0.3	Iterations	300

of n; continue the *operation* until the cost cannot decrease. The *operation* consists of ***Adding***, ***Dropping*** and ***Swapping***.

Initialization: Generate set $\mathcal{S} = \mathcal{N}$ as an initial solution to (6), guaranteeing that (7) is feasible.

Adding: Open a BBU pool $n \in \mathcal{N} \setminus \mathcal{S}$ and reassign all the demand of RRHs to $\mathcal{S} \cup \{n\}$ by computing $x_{m,n}$. The cost change yielded at this step is $c(\mathcal{S}) - c(\mathcal{S} \cup \{n\})$, which can be computed in polynomial time for each $n \in \mathcal{N} \setminus \mathcal{S}$. If $c(\mathcal{S}) - c(\mathcal{S} \cup \{n\}) > c(\mathcal{S})/p(n)$, add BBU pool n to $\mathcal{S}$, $\mathcal{S} \leftarrow \mathcal{S} \cup \{n\}$;

Dropping: Close a BBU pool $n \in \mathcal{S}$ and reassign all the demand of RRHs to $\mathcal{S}\setminus\{n\}$ by computing $x_{m,n}$. The cost change yielded at this step is $c(\mathcal{S}) - c(\mathcal{S}\setminus\{n\})$, which can be computed in polynomial time for each $n \in \mathcal{S}$. If $c(\mathcal{S}) - c(\mathcal{S} \setminus \{n\}) > c(\mathcal{S})/p(n)$, $\mathcal{S} \leftarrow \mathcal{S} \setminus \{n\}$);

Swapping: Swap a BBU pool between set $\mathcal{S}$ and set $\mathcal{N} \setminus \mathcal{S}$. The cost change yielded at this step is $c(\mathcal{S}) - c(\mathcal{S} \setminus \{n\} \cup \{n'\})$, where n indicates an open BBU pool in $\mathcal{S}$ and n' is a close BBU pool in $\mathcal{N} \setminus \mathcal{S}$. If this step can decrease the deploying cost by at least $c(\mathcal{S})/p(n)$, then we swap n and n' in $\mathcal{N}$, $\mathcal{S} \leftarrow \mathcal{S} \setminus \{n\} \cup \{n'\}$.

We call any *operation* that improves the solution by at least $c(\mathcal{S})/p(n)$ an admissible *operation*. The procedure terminates when no more admissible *operations* exist. The complexity of the algorithm can be counted roughly as follows. The improvement of the solution is a factor of $(1 - 1/p(n))$ at each step and the total improvement is a constant factor after $p(n)$ operations. Since the value of the solution can not be smaller than $c(\mathcal{S}^*)$, the algorithm will terminate after $O\big(p(n)log(c(\mathcal{S})/c(\mathcal{S}^*))\big)$ operations. We set $p(n) = n^2$ in numerical experiments so the complexity of the proposed algorithm is $O\big(n^2log(c(\mathcal{S})/c(\mathcal{S}^*))\big)$. The flow of the procedure is shown in Table I. It can be proved that the proposed algorithm is an approximation algorithm with approximation ratio $(8 + \epsilon)$ as shown in [10].

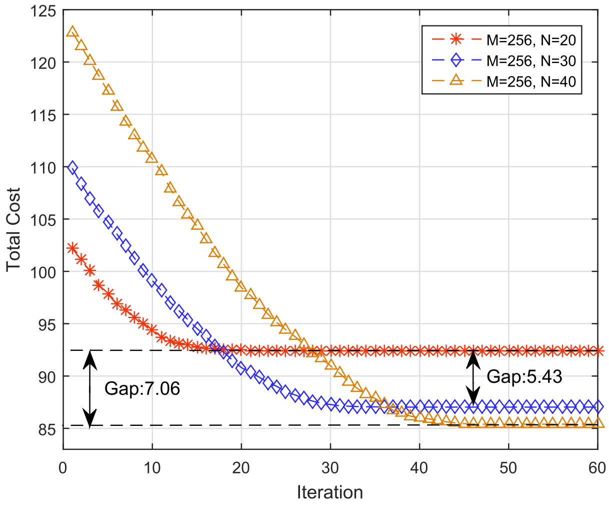

Fig. 2. Total cost during each iteration, $\gamma = 0.5$, $L = 14km$.

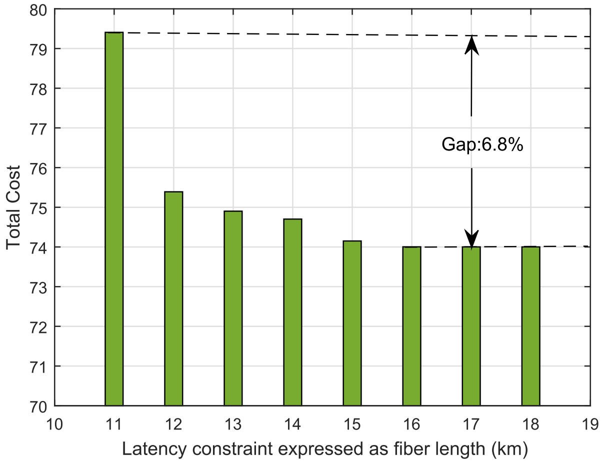

Fig. 3. Total cost with increasing L, $\gamma = 0.5$, $N = 20$, $M = 200$.

IV. NUMERICAL RESULTS

We compare the proposed algorithm with genetic algorithm (GA) [11] and tabu search (TS) [12]. The parameters of GA and TS are shown in Table II. Simulation parameters of the C-RAN are given as follows. The service region is $20 \times 20\ km^2$. The RRHs and the candidate sites for installing BBU pools are uniformly distributed. For RRH m, its traffic demand d_m is distributed uniformly within (10, 20). For BBU pool n, its processing capacity w_m is distributed uniformly within (200, 400). Without loss of generality, we assume that the facility cost of each BBU pool is the same. γ is proportional to the price of optical fiber. All results are averaged over 500 Monte Carlo simulations.

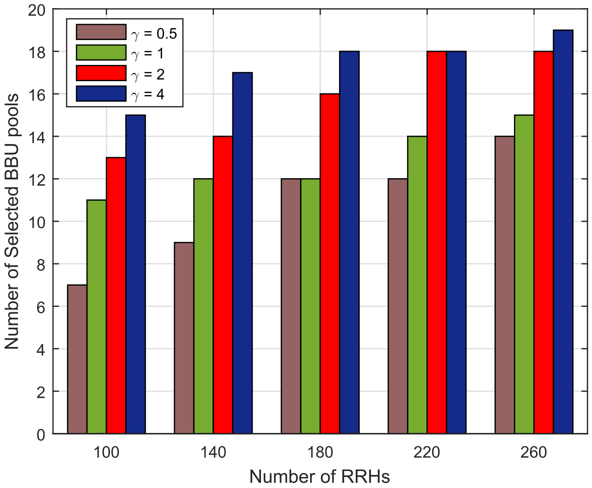

Fig. 4. Number of selected BBU pools, $\gamma = 0.5$, $N = 20$, $L = 14km$.

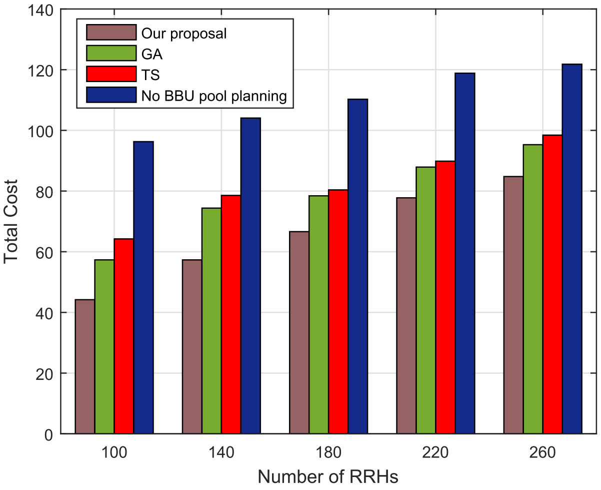

Fig. 5. Compared with GA and TS, $\gamma = 0.5$, $N = 40$, $L = 14km$.

Fig. 2 illustrates the total cost during each iteration. We can see that our proposed algorithm converges stably. It requires about 21, 35 and 46 iterations when the number of candidate sites for installing BBU pool is 20, 30 and 40, respectively. The total cost decreases as the increasing of candidate sites. It is reasonable because there are more choices for installing the BBU pools, making the reduction of the total cost possible in the sense of probability.

Fig. 3 shows a 6.8% reduction of the total cost when L increases from 11 km to 16 km. The reason is that the BBU pool can serve more RRHs when latency constraint is not stringent, which means larger L. Under this circumstance, fewer BBU pools are required to serve the RRHs in the C-RAN. However, when L is large enough, no more cost reduction can be obtained because the processing capacity limitation of each BBU pool.

Fig. 4 shows the number of the selected BBU pools for different γ. We can see that it increases as the increasing of γ for a given number of RRHs. Fig. 5 shows the total cost as a function of the number of RRHs. Our proposal is compared with GA, TS and the scheme without BBU pool planning. The last one means that we select all candidate sites and only optimize the assignments of the RRHs to the connected BBU pools. Our proposed algorithm performs better than others. The total cost of our proposal is about 16% lower than that of the GA.

V. CONCLUSION

In this letter, we investigated the minimum cost of BBU pool planning in the C-RAN. Our general formulation yields an NP-hard optimization task. We proposed an efficient approximation algorithm to obtain promising solutions quickly. Numerical results show that our proposed algorithm performs better than the representative heuristic ones. Moreover, our proposal algorithm can provide a performance-guaranteed solution for the mobile service providers to plan their networks.

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