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Infrastructure planning and topology optimization for reliable mobile big data transmission under cloud radio access networks

Xiang Hou, Bin Lin, Rongxi He* and Xudong Wang

Abstract

With the development of user-centered and environment sensing technology of 5G, large capacity and ubiquitous coverage and massive data collection and processing will bring new challenges in wireless networks. The cloud radio access network (C-RAN) has been envisioned to provide a new wireless architecture for reliable transmission of mobile big data. In this paper, we focus on network planning deployment issue based on the optical mixed diet (OMD) technology. Specifically, the ring and spur topology optimization (RSTO) problem under the C-RAN architecture is investigated. The RSTO problem is formulated as a generic integer linear program (ILP) which can optimally (i) minimize the network deploying cost; (ii) identify the locations of Remote Radio Units (RRUs) and optical add-drop multiplexers (OADMs); (iii) identify the association relations between RRUs and OADMs; and (iv) satisfy the mobile coverage requirements so as to allow the mobile big data to be transmitted through the RRUs. We propose a new heuristic algorithm based on C-RAN architecture. Numerical results validate the ILP formulation and show the performance benefits of the proposed algorithm in terms of efficiency and effectiveness against Gurobi, which is an ILP solver. In numerical studies, we also demonstrate the performance benefits of the incorporation of CoMP technology in terms of total deployment cost reduction.

Keywords: Mobile big data, C-RAN, Integer linear program (ILP), Heuristic algorithm

1 Introduction

Nowadays, the information society has stepped into a new era, in which the mobile Internet, cloud computing, big data, and Internet of Things are the leading technologies [1]. The big data has main features: volume, variety, velocity, and value [2]. Thus, future wireless networks are required to provide the ability to store and process the large data.

Wireless access network is facing new challenges, such as network deployment, resource management, mobile data security, and network consumption. To deal with these challenges, a new type the radio access network architecture named cloud radio access network (C-RAN) has been proposed in [3].

The C-RAN has four “C” characteristics, i.e., clean, centralized processing, collaborative radio, and real-time cloud radio access network. C-RAN is viewed as an architecture evolution based on distributed base stations (BSs). The C-RAN architecture breaks down the traditional BS into a base band unit (BBU) and Remote Radio Units (RRUs). The BBU is a digital unit that implements the MAC, PHY, and antenna array system functionality. The BBU is often located in a remote site such as a central office (CO) and thus the energy, real estate, and security costs are minimized. The RRU can be mounted either outdoor or indoor such as on poles, sides of buildings, or anywhere power and a broadband connection exist, making installation less costly and easier. The RRU is typically connected to the BBU using fibers. C-RAN adopts CoMP technology to reduce interference, lower power consumption, and improve spectral efficiency in [4] and [5].

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Due to the requirement of a high-volume, variety, and non-uniform distribution of the big data in time domains and space domains, wireless access networks must have high reliability. For example, many applications of online banking, mobile payment, and remote business are generated on smart phones. Thus, the networks are required to transmit data much more reliably.

Different from the tree and branch topology, the fiber can transmit the signals between the BBU and the optical add-drop multiplexers (OADMs) bidirectionally in the ring and spur topology as shown in Fig. 1. When one of the fibers is interrupted, the other fibers could continue to achieve optical signal transmission. Thus, the ring and spur topology can avoid the network paralysis caused by fiber interruption [6].

In order to increase the utilization of the optical fiber, optical mixed diet (OMD) mode is proposed. In the OMD mode, the BBU pool supplies a pair of specific wavelengths to transmit the signal to the OADM. The OMD integrates the function of WDM. The BBU and a certain RRU are using a specific wavelength module and a plurality of RRU can share a pair of optical fibers; thus, the OMD mode can increase the utilization of the optical fiber.

In this paper, we focus on the ring and spur topology optimization (RSTO) problem under the C-RAN architecture. A generic integer linear programming (ILP) model is proposed to capture the nature of the RSTO problem. In this paper, we focus on network planning deployment issue based on the OMD technology.

The RSTO problem under the C-RAN architecture is investigated. The contributions of this paper are summarized as follows. (1) The RSTO problem is formulated as a

generic ILP model which can optimally: (i) minimize the network deploying cost; (ii) identify the locations of RRUs and OADMs; (iii) identify the association relations between RRUs and OADMs; and (iv) satisfy the mobile coverage requirements so as to allow the mobile user access through the RRUs. (2) We also propose a new heuristic algorithm under C-RAN architecture. The algorithm can deploy the C-RAN architecture in small- and large-scale scenarios. (3) Compared with the result of Gurobi in different scenarios, simulation results verify that the algorithm is correct and effective.

The remainder of the paper is organized as follows. In Section 2, we review the previous related work. In Section 3, the problem formulation is given, including the network model, given inputs, variables, constraints, and objective of the RSTO problem. The heuristic algorithm is presented in Section 4. Computational results and case studies are presented in Section 5. Finally, we conclude the paper in Section 6.

2 Related work

We review the related studies on network planning and placement. In [7], three types of architectures, namely optical fiber direct-drive, optical transmission network (OTN)/wavelength division multiplexing (WDM), and unified passive optical network (Uni-PON) are proposed. These three models have been further elaborated in [8–10], respectively.

Our previous work has studied on the network planning and placement, which have direct influence on the future network deployment and long-term performance [11–15]. The problem formulated to determine the locations of communication network equipment is discussed as follows. Site planning of relay station GA-based solution in green wireless access network is proposed in [11]. An ILP

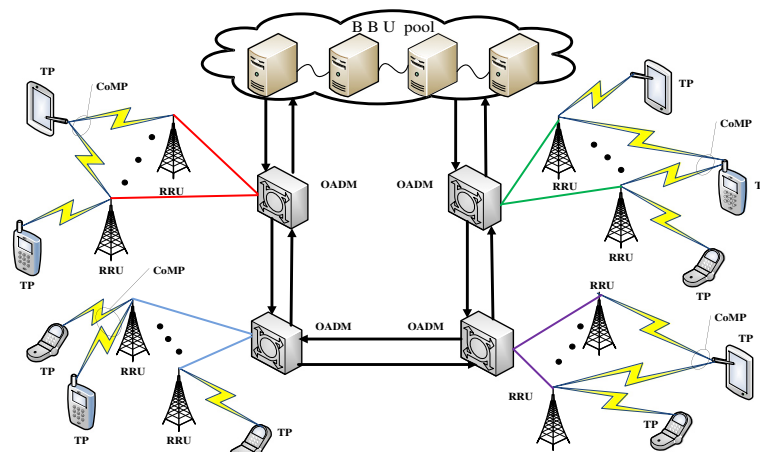


Fig. 1 The C-RAN network model based on the ring and spur topology

model is formulated to maximize the throughput of an LTE network in [12]. Cascaded splitter placement and layout in long-reach PON are discussed in [13]. A dimensioning and site-planning optimization framework was proposed for integrated PON and wireless cooperative networks in [14]. An ILP model for the cascaded LRPN topology and network equipment placement, and network dimensioning are proposed in [15].

Other related works have studied on topology and placement optimization, such as [16] and [17]. A model for combined virtual core network function placement and topology optimization is proposed in [16]. In [17], the author presents some optimization problems in WMNs and different heuristic methods such as local search, genetic algorithms, and tabu search for solving them near-optimally. Relayed-Based Heterogeneous Wireless Access Networks (RHWAN) is envisioned as the promising network architecture proposed in [18]. A hybrid wireless mesh network infrastructure which connects the smart meters of each consumer with the data aggregation points (DAP) is proposed in [19]. An optimal deployment model on Universal Data Aggregation Point (UDAP) is proposed in [20].

In this research, we choose the ring and spur topology optimization based on the OMD technology under the C-RAN architecture. The fiber can bidirectionally transmit the signal between the BBU and the OADM_s; thus, it has high network survivability. Wireless access network is demanded to provide higher reliability in the big data era. To the best of our knowledge, there are few studies on the deployment and optimization for C-RAN infrastructure under the ring and spur topology, which is just the focus of our research.

3 Network model and problem formulation

3.1 Network model

The C-RAN network model consists of four network entities: BBU, OADM, RRU, and mobile stations (MSs), as shown Fig. 1. The OADMs and the RRU_s are eligible to be deployed at certain outdoor potential sites (PSs) where uninterrupted power supply can be provided [5].

In order to construct the OADM ring, we define the concept of “flow” and related terms as shown in Fig. 2.

Term 1: Inflow: the directed path which represents the flow from BBU to OADM_k.

Term 2: Outflow: the directed path which represents the flow from OADM_k to BBU.

Term 3: Inflow path: the path starts from BBU and ends at OADM_k.

Term 4: Outflow path: the path starts from OADM_k and ends at the BBU.

Without loss of generality, we assume that the MSs are homogeneously distributed in the area of interest (AOI), which yields a uniform distribution on the traffic demand in the AOI. We define that a site is covered under the C-RAN architecture if the received radio signal strength at the site is above a given threshold level (receiver sensitivity). Small-scale fading is not explicitly included in the system model since a long-term planning and design is targeted. To test the mobile coverage, we define test points (TPs) within the AOI. The TPs are also used for testing the received power intensity for MSs from the associated RRU. In Fig. 1, the locations of TPs and PSs for both OADM and RRU are also illustrated.

3.2 Problem statement

The RSTO problem can be stated as follows. Let $G = (\Omega : E)$, where Ω is the set of the nodes and E is the set of the direct edge/links. The BBU is denoted as the node B . Ω is partitioned into four parts, i.e., the set of TP, the set of OADM, the set of RRU, and the set of BBU, which are denoted as Ω_{TP} , Ω_{OADM} , Ω_{RRU} , and Ω_B , i.e., $\Omega = \Omega_{TP} \cup \Omega_{RRU} \cup \Omega_{OADM} \cup \Omega_B$.

3.2.1 Given

- (1) The set of fixed TPs, which are the customer premises
- (2) The set of PSs for deploying RRU_s and OADM_s

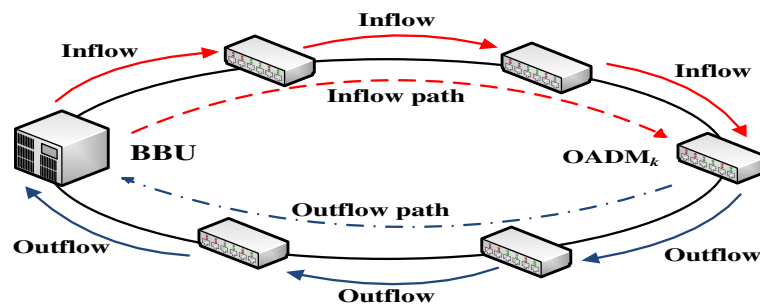


Fig. 2 Flow on the OADM ring

- (3) The location of the BBU
- (4) The cost per unit length of fiber (\$/km) C^f , including fiber purchase and deployment cost.
- (5) The Manhattan distance between node i and node j (d_{ij}).
- (6) The cost of RRU (C^R) and OADM (C^O).
- (7) The maximal transmit power of a RRU
- (8) The minimal signal-to-noise-ratio (SNR) requirement for an MS

3.3 Variable

- (1) The PS_m is selected to place a RRU if $a_m = 1$; otherwise, $a_m = 0$.
- (2) The PS_t is selected to place an OADM if $b_t = 1$; otherwise, $b_t = 0$.
- (3) The MS at TP_n is associated with the RRU if $z_{mn} = 1$; otherwise, $z_{mn} = 0$.
- (4) There is a directed link from node $i \in \Omega_B \cup \Omega_{\text{OADM}}$ to node $j \in \Omega_B \cup \Omega_{\text{RRU}} \cup \Omega_{\text{OADM}}$ if $e_{ij} = 1$; otherwise, $e_{ij} = 0$.
- (5) The TP_n is covered if $q_n = 1$; otherwise, $q_n = 0$.
- (6) e_{ij} is on the directed flow from the BBU to OADM_k if $g_{ij}^k = 1$; otherwise, $g_{ij}^k = 0$.
- (7) e_{ij} is on the directed flow from the OADM_k to BBU if $h_{ij}^k = 1$; otherwise $h_{ij}^k = 0$.

Table 1 Definitions of Symbols in the RSTO problem

Symbol	Definition
Ω_B	The set of the BBUs
Ω_{OADM}	The set of the OADMs
Ω_{RRU}	The set of the RRUs
Ω_{TP}	The set of the TPs
T	The number of OADMs in the network
M	The number of RRUs in the network
N	The number of TPs in the network
d_{ij}	The distance between node i and node j
P	The maximal transmit power of a RRU
ξ	The average normalized thermal noise in AOI
α	The path loss exponent
s_0	The minimal SNR requirement for each TP
A	The location incidence vector, $A = (a_m)_{1 \times M}$
B	The location incidence vector, $B = (b_t)_{1 \times T}$
Q	A TP coverage incidence vector, $Q = (q_n)_{1 \times N}$
Z	RRU-TP association matrix $Z = (z_{mn})_{M \times N}$
E	BBU-OADM-RRU association matrix, $E = (e_{ij})_{(T+1) \times (M+T)}$
D_{MAX}	The maximal distance of OMD-RRU that can be deployed in the network
H^K	OADM_k – BBU flow association matrix $H^K = (h_{ij}^k)_{(1+T) \times (T+M)}$
G^K	BBU – OADM_k flow association matrix $G^K = (g_{ij}^k)_{(1+T) \times (T+M)}$

3.4 Constraints

- (1) The mobile coverage requirement should be satisfied, i.e., the coverage ratio should be larger than a predefined value.
- (2) The SNR for an MS located at each TP should be larger than a SNR threshold.
- (3) Each TP is covered by at least one RRU.
- (4) The OADM ring consists the BBU and the selected OADMs.
- (5) There must be at least a RRU to connect to the selected OADM.
- (6) The RRU can cover the MS with CoMP technology.
- (7) The double-flow control is used to establish the mathematical model.
- (8) If the PS is selected to place an OADM on the OADM ring, there must be an input path and output path.

3.5 Objective

The objective is to minimize the infrastructure deployment cost of the whole C-RAN network. Table 1 lists important symbols for the problem formulation.

3.6 Problem formulation

(RSTO) objective:

$$\text{Minimize } C = C^F + C^{\text{RRU}} + C^{\text{OADM}} \quad (1.1)$$

where

$$C^F = \sum_{i \in \Omega_B} (e_{ij} + e_{ij}) \cdot d_{ij} + C^f \sum_{i \in \Omega_{\text{OADM}}} e_{ij} \cdot d_{ij} + C^f \sum_{i \in \Omega_{\text{OADM}}} \sum_{j \in \Omega_{\text{RRU}}} e_{ij} \cdot d_{ij} \quad (1.1a)$$

$$C^{\text{RRU}} = C^R \sum_{m \in \Omega_{\text{RRU}}} a_m \quad (1.1b)$$

$$C^{\text{OADM}} = C^O \sum_{t \in \Omega_{\text{OADM}}} b_t \quad (1.1c)$$

Equation (1.1) is to minimize the total deployment cost of the C-RAN network, including the cost of fibers, the cost of RRUs, and the cost of OADMs.

Subject to:

$$\sum_{m \in \Omega_{\text{RRU}}} z_{mn} \geq 1, \forall n \in \Omega_{\text{TP}} \quad (1.2)$$

$$z_{mn} \leq a_n, \forall m \in \Omega_{\text{RRU}}, \forall n \in \Omega_{\text{TP}} \quad (1.3)$$

$$e_{ij} \leq b_i, \forall i \in \Omega_{\text{OADM}}, \forall j \in \Omega_{\text{RRU}} \quad (1.4)$$

Constraint (1.2) stipulates that each TP is covered by at least one RRU, and it ensures the CoMP feature of C-RAN. Constraint (1.3) ensures that the PS is selected to place a RRU if $a_m = 1$. Constraint (1.4) ensures that the PS is selected to place an OADM if $b_i = 1$.

$$\sum_{j \in \Omega_{\text{OADM}}} e_{ij} = 1, \forall i \in \Omega_B \quad (1.5)$$

$$\sum_{i \in \Omega_{\text{OADM}}} e_{ij} = 1, \forall j \in \Omega_B \quad (1.6)$$

Constraints (1.5) and (1.6) ensure that the BBU can be connected to the OADM ring. Constraint (1.5) stipulates that the BBU has just only one OADM as BBU's output. Constraint (1.6) stipulates that the BBU has just only one OADM as BBU's input.

$$\sum_{i \in \Omega_B \cup \Omega_{\text{OADM}}} e_{ij} = a_j, \forall j \in \Omega_{\text{OADM}}, i \neq j \quad (1.7)$$

$$\sum_{j \in \Omega_B \cup \Omega_{\text{OADM}}} e_{ij} = a_i, \forall i \in \Omega_{\text{OADM}}, i \neq j \quad (1.8)$$

Constraints (1.7) and (1.8) ensure that an OADM can be connected to the OADM ring. Constraint (1.7) ensures that if the PS is selected to place an OADM on the OADM ring, then another OADM serves as an output terminal in the OADM ring. Constraint (1.8) ensures that if the PS is selected to place an OADM on the OADM ring, then another OADM serves as an input terminal in the OADM ring.

$$\sum_{i \in \Omega_{\text{OADM}}} e_{ij} = a_j, \forall j \in \Omega_{\text{RRU}} \quad (1.9)$$

$$\sum_{j \in \Omega_{\text{RRU}}} e_{ij} \geq b_i, \forall i \in \Omega_{\text{OADM}} \quad (1.10)$$

Constraint (1.9) ensures that if the PS is selected to place an OADM on the OADM ring, then at least one RRU should be connected to the selected OADM, if $a_j = 1$. Constraint (1.10) ensures that RRUs can be connected to the OADM, if $b_i = 1$.

$$e_{ij} \cdot d_{ij} \leq D_{\max}, \forall i \in \Omega_{\text{OADM}}, \forall j \in \Omega_{\text{RRU}} \quad (1.11)$$

Constraint (1.11) sets an upper bound on the fiber length between an OADM and a RRU in C-RAN network.

$$g_{ij}^k \leq e_{ij}, \forall i \in \Omega_B \cup \Omega_{\text{OADM}}, \forall j \in \Omega_{\text{OADM}}, k \in \Omega_{\text{OADM}}, i \neq k \quad (1.12)$$

$$h_{ij}^k \leq e_{ij}, \forall i \in \Omega_{\text{OADM}}, \forall j \in \Omega_B \cup \Omega_{\text{OADM}}, k \in \Omega_{\text{OADM}}, j \neq k \quad (1.13)$$

Constraint (1.12) stipulates that only when $e_{ij} = 1$, e_{ij} probably exists in the inflow path from BBU to OADM_k . Constraint (1.13) stipulates that only when $e_{ij} = 1$, e_{ij} probably exists in the outflow path from the BBU to OADM_k .

$$g_{ij}^k \leq b_k, \forall i \in \Omega_B \cup \Omega_{\text{OADM}}, \forall j \in \Omega_{\text{OADM}}, k \in \Omega_{\text{OADM}}, i \neq k \quad (1.14)$$

$$h_{ij}^k \leq b_k, \forall i \in \Omega_{\text{OADM}}, \forall j \in \Omega_B \cup \Omega_{\text{OADM}}, k \in \Omega_{\text{OADM}}, j \neq k \quad (1.15)$$

Constraints (1.14) and (1.15) ensure only when OADM_i and OADM_j exist firstly, then there probably exists the path between the BBU and OADM_k .

$$\sum_{j \in \Omega_{\text{OADM}}} g_{ij}^k = b_k, \forall k \in \Omega_{\text{OADM}}, i \in \Omega_B \quad (1.16)$$

$$\sum_{i \in \Omega_{\text{OADM}}} h_{ij}^k = b_k, \forall k \in \Omega_{\text{OADM}}, j \in \Omega_B \quad (1.17)$$

For all OADMs, constraints (1.16) and (1.17) ensure where the inflow path must start from the BBU, and the outflow path must end at the BBU.

$$\sum_{i \in \Omega_B \cup \Omega_{\text{OADM}}} g_{ik}^k = b_k, \forall k \in \Omega_{\text{OADM}}, i \neq k \quad (1.18)$$

$$\sum_{j \in \Omega_B \cup \Omega_{\text{OADM}}} h_{kj}^k = b_k, \forall k \in \Omega_{\text{OADM}}, j \neq k \quad (1.19)$$

Constraints (1.18) and (1.19) stipulate that for OADM_k , its inflow path must end at OADM_k , and its outflow must start from OADM_k .

$$\sum_{j \in \Omega_{\text{OADM}}} \sum_{k \in \Omega_{\text{OADM}}} g_{ij}^k = \sum_{k \in \Omega_{\text{OADM}}} b_k, i \in \Omega_B \quad (1.20)$$

$$\sum_{i \in \Omega_{\text{OADM}}} \sum_{k \in \Omega_{\text{OADM}}} h_{ij}^k = \sum_{k \in \Omega_{\text{OADM}}} b_k, j \in \Omega_B \quad (1.21)$$

Constraints (1.20) and (1.21) ensure that only when OADM_k is selected to place on the OADM ring, then OADM_k has an inflow path and an outflow path.

$$\sum_{i \in \Omega_B \cup \Omega_{\text{OADM}}} g_{ij}^k = \sum_{m \in \Omega_{\text{OADM}}} g_{jm}^k, \forall j, k \in \Omega_{\text{OADM}}, \\ i \neq j \neq m, i \neq j \neq k \quad (1.22)$$

$$\sum_{i \in \Omega_{\text{OADM}}} h_{ij}^k = \sum_{m \in \Omega_B \cup \Omega_{\text{OADM}}} h_{jm}^k, \forall j, k \in \Omega_{\text{OADM}}, \\ i \neq j \neq m, i \neq j \neq k \quad (1.23)$$

Constraint (1.22) stipulates that if OADM_j is on the path from BBU to OADM_k, then OADM_j has an input path and an output path. Also, there is an inflow path that belongs to the path from BBU to OADM_j. Constraint (1.23) stipulates that if OADM_j is on the path from BBU to OADM_k, then OADM_j has an input path and an output path. Also, there is an outflow path that belongs to the path from BBU to OADM_k.

$$g_{ij}^k + h_{ij}^k \leq 1, \forall i, j, k \in \Omega_{\text{OADM}}, i \neq j \neq k \quad (1.24)$$

$$e_{ij} + e_{ji} \leq 1, \forall i \in \Omega_B \cup \Omega_{\text{OADM}}, \forall j \in \Omega_{\text{OADM}}, i \neq j \quad (1.25)$$

$$\frac{1}{\xi} \sum_{m \in \Omega_{\text{RRU}}} \frac{z_{mn} \times P}{d_{mn}^\alpha} \geq s_0, \forall n \in \Omega_{\text{TP}} \quad (1.26)$$

$$q_n \geq \frac{1}{\sum_{m \in \Omega_{\text{RRU}}} \frac{P}{\xi d_{mn}^\alpha} - s_0} \left(\sum_{m \in \Omega_{\text{RRU}}} \frac{P}{\xi d_{mn}^\alpha} - s_0 \right) \quad (1.27)$$

$$1 - q_n \geq \frac{1}{\sum_{m \in \Omega_{\text{RRU}}} \frac{P}{\xi d_{mn}^\alpha} - s_0} \left(s_0 - \sum_{m \in \Omega_{\text{RRU}}} \frac{P}{\xi d_{mn}^\alpha} \right) \quad (1.28)$$

$$\frac{1}{N} \sum_{n \in \Omega_{\text{TP}}} q_n \geq \eta \times 100\% \quad (1.29)$$

For OADM_k, constraint (1.24) stipulates that the same path cannot exist in the inflow path and outflow path at the same time. Constraint (1.25) stipulates that the path is

directional, which means only one direction can be chosen. Constraint (1.26) ensures that the TP satisfies the constraint of the minimum SNR requirement. Constraints (1.27)–(1.29) stipulate the definition of Q.

$$a_m \in \{0, 1\}, \forall m \in \Omega_{\text{RRU}}, b_t \in \{0, 1\}, \forall t \in \Omega_{\text{OADM}}, \\ q_n \in \{0, 1\}, \forall n \in \Omega_{\text{TP}} \quad (1.30)$$

$$z_{mn} \in \{0, 1\}, \forall m \in \Omega_{\text{RRU}}, \forall n \in \Omega_{\text{TP}} \quad (1.31)$$

$$e_{ij} \in \{0, 1\}, \forall i \in \Omega_B \cup \Omega_{\text{OADM}}, \forall j \in \Omega_{\text{OADM}} \cup \Omega_{\text{RRU}} \quad (1.32)$$

$$g_{ij}^k \in \{0, 1\}, \forall i \in \Omega_B \cup \Omega_{\text{OADM}}, \forall j \in \Omega_{\text{OADM}}, k \in \Omega_{\text{OADM}}, i \neq k \quad (1.33)$$

$$h_{ij}^k \in \{0, 1\}, \forall i \in \Omega_{\text{OADM}}, \forall j \in \Omega_B \cup \Omega_{\text{OADM}}, k \in \Omega_{\text{OADM}}, j \neq k \quad (1.34)$$

Constraints (1.30)–(1.34) state the each entry A , B , Q , Z , E , H^k , and G^k is binary.

4 Heuristic algorithm

4.1 Algorithm description

The problem formulation is given in the previous section, including the network model, given inputs, variables, constraints, and objective of the RSTO problem. However, with the continuous expansion of network size, solving the above RSTO formulation is not an easy task especially for large-scale networks due to the exponential growing nature of ILP. To make the design more scalable for large-size networks, in this section, we propose a new heuristic algorithm.

The design and process of this new heuristic algorithm is mainly concluding some steps as follows:

- (1) Initialization of system parameters.
- (2) RRU selection. This step achieves the coverage TP through candidate RRU.
- (3) OADM selection.
- (4) Construct the C-RAN architecture based on the ring and spur topology.
- (5) C-RAN layout (including the location of selected RRUs and OADMs, the optical link between RRUs and OADMs, the optical ring of OADMs and BBU, the association between RRUs and OADMs), total deployment cost.

Now, we introduce the pseudocode of this the heuristic algorithm, and then we give an application based on this heuristic algorithm.

The pseudocode of the heuristic algorithm is outlined below.

Proposed Fast Heuristic algorithm to solve Problem (RSTO)**Input: problem parameters:** $N_{BBU}, W_{TP}, W_{RRU}, W_{OADM}, i_{threshold}, D_{max}(T, R), D_{max}(R, O), D_{max}(O, O)$ **1 BEGIN****2 //STEP 1: SET UP AND INITIALIZATION**

Input problem parameters;

3 //STEP 2: RRU SELECTION:

```

4  $W_{RRU\_select} \leftarrow \emptyset$ 
5 For each  $R_i \in W_{RRU}$  do
6   For each  $T_j \in W_{TP}$  do
7     Calculate the  $i_{SYNR-q}$  between candidates  $R_i$  and  $T_j$ 
8     If the received  $i_{SYNR-q} \geq i_{threshold}$  then
9       Add  $R_i$  into  $W_{RRU\_select}$ 
10    end if
11  end for
12 end for
13  $W_{TP\_cover\_end} \leftarrow W_{TP}$ 
14 while  $W_{TP\_cover\_end} \neq \emptyset$  do
15   for each  $R_i \in W_{RRU\_select}$  do
16     if  $R_i$  covers maximum amount number of  $W_{TP\_cover\_end}$  then
17       Select the  $R_i$ 
18        $W_{RRU\_SELECTED} \leftarrow W_{RRU\_SELECTED} \cup R_i$ 
19        $W_{TP\_cover\_end} \leftarrow W_{TP\_cover\_end} - \text{the number of } W_{TP\_cover\_end}$ 
20     end if
21   end for
22 end while

```

23 //STEP 3: OADM SELECTION:

```

24 For each  $R_i \in W_{RRU}$  do
25   For each  $O_j \in W_{OADM}$  do
26     Calculate the  $d_{ij}$  between the  $R_i$  and candidates  $O_j$ .
27     if the  $d_{ij}$  satisfies the requirement of the
28       between the  $R_i$  and candidates  $O_j$  limitations  $D_{max}(R, O)$ ;
29     Then select the candidates  $O_j$ 
30       by proximity principle;
31       Add  $O_j$  into  $W_{OADM\_SELECTED}$ 
32     end if
33   end for
34 end for

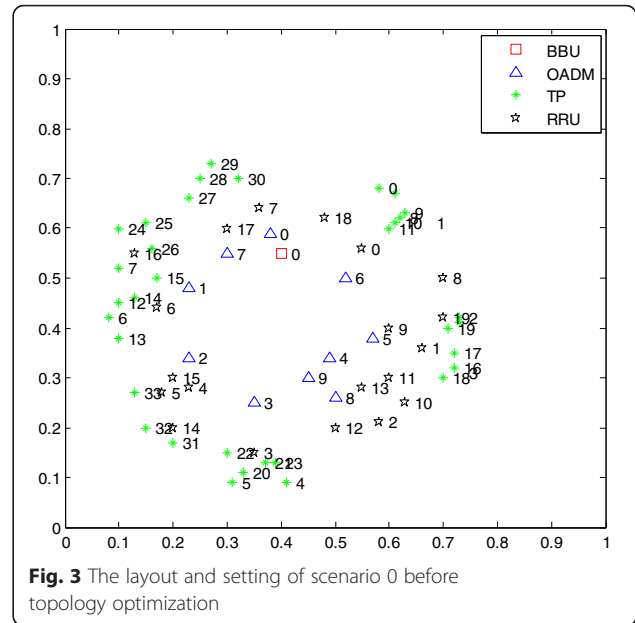
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35 //STEP 4: Construct the C-RAN architecture based on ring and spur topology:The OADM-ring will be constructed from node N_{BBU} as the start point;

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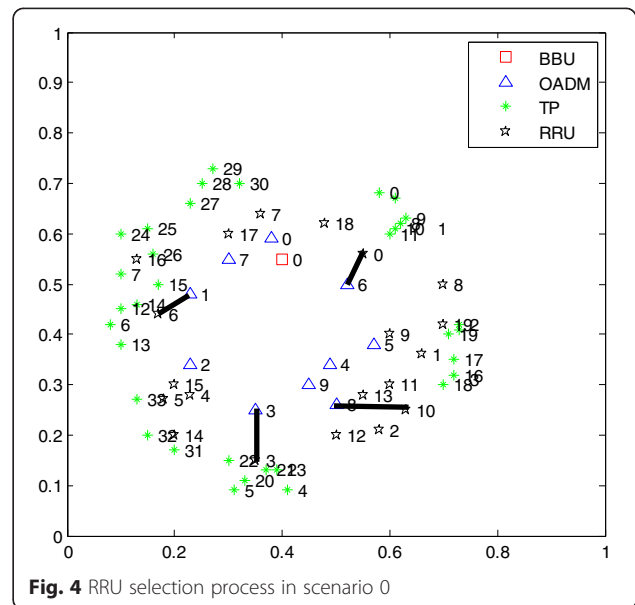
37 For each  $O_j \in W_{OADM\_SELECTED}$  do
38   Calculate  $d_{BBU-j}$  between  $N_{BBU}$  and  $O_j$ ;
39   Find the minimum  $d_{BBU-j}$ ;
40   The  $N_{BBU}$  will select the nearest  $O_j \in W_{OADM\_SELECTED}$ ;
41   Connect  $N_{BBU}$  to  $O_j$ ;
42 end
43  $W_{OADM\_SELECTED} \leftarrow W_{OADM\_SELECTED} - O_j$ 
44 while  $W_{OADM\_SELECTED} \neq \emptyset$  do
45   Calculate  $d_{ij}$  between  $O_j$  and  $O_i \in W_{OADM\_SELECTED} - O_j$ 
46   Select the  $O_i$  by proximity principle;
47   Connect  $O_j$  to  $O_i$ ;
48    $W_{OADM\_SELECTED} \leftarrow W_{OADM\_SELECTED} - O_i$ 
49 end while
50  $W_{OADM\_SELECTED}$  only has one element  $O_i$ 
51 Connect this  $O_i$  to  $N_{BBU}$ .
52 OUTPUT: C-RAN layout (including the location of selected RRUs and OADMs, the
  optical link between RRUs and OADMs, the optical ring of OADMs and and BBU, the
  association between RRUs and OADMs), total deployment cost
53 END

```

**Fig. 3** The layout and setting of scenario 0 before topology optimization

The proposed heuristic is stated in detail as follows:

Step 1 (Lines 1–2): Initialization. Firstly, a plurality of TPs, potential sites for deploying RRUs, and OADMs are set in an AOI after an actual survey. A two-dimensional coordinate graph is established on the basis of the latitude and longitude of the actual positions of TPs, and RRU candidates and OADM candidates are import into this two-dimensional coordinate graph based on their actual location of the latitude and longitude. The distances between TPs and RRU candidates (i.e., parameter d_{T-R}), RRU candidates and OADM candidates (i.e., parameter

**Fig. 4** RRU selection process in scenario 0

d_{R-O}), OADM candidates and OADM candidates (i.e., parameter d_{O-O}) are calculated and stored, respectively. The parameters of N_{BBU} , Ω_{TP} , Ω_{RRU} , Ω_{OADM} , threshold, $D_{\max}(T-R)$, $D_{\max}(R-O)$, $D_{\max}(O-O)$ are set according to the requirement of actual deployment scenarios.

Step 2 (Lines 3–22): RRU selection. The goal of this step is to make each TP covered by one candidate RRU. First, we calculate the SNR between the TPs and candidates RRUs. If the received SNR at a TP form a candidate RRU that satisfies the minimum SNR threshold, then we select the RRU which covers the maximum amount of the TPs, then add this RRU into $\Omega_{RRU-selected}$. We will delete this already selected RRU and these TPs which are covered by selected RRU. The TPs will select the RRU in turn according to the calculated TP numbers covered by the candidate RRU in descending order. The candidates can be selected until all TPs are covered by the candidate RRU.

Step 3 (Lines 23–34): OADM selection. The goal of this step is to set up the optical links between the candidate OADM and all the selected RRUs at step 2. We calculate the distances between the selected RRUs and candidate OADMs. If the distance satisfies the requirement of the selected RRU and candidate OADM limitations (i.e., parameter $D_{\max}(R-O)$), we select the candidate OADM by a proximity principle. Then, we will add this OADM into $\Omega_{OADM-selected}$. If each selected RRU could select an OADM which satisfies the requirement of the distance limitations, then these OADMs will be added into $\Omega_{OADM-selected}$. The loop will end until

Table 2 C-RAN component cost

Component	Cost (gcu)
Fiber (/km)	1
Burying fiber (/km)	50
RRU	16
OADM	50

all the selected RRU at step 2 could connect to an OADM. The optical links between the selected RRU at step 2 and OADM can be set up.

Step 4 (Lines 35–51): Construct the C-RAN architecture based on the ring and spur topology. The goal of this step is to construct the OADM ring. The ring will be constructed from the BBU as the start point. Firstly, we calculate the distance (i.e., parameter d_{BBU-O}) between the BBU and the selected OADMs (i.e., parameter $\Omega_{OADM-selected}$). Secondly, we find the minimum d_{BBU-O_j} for all O_j and connect the BBU to the corresponding O_j , then remove this O_j in $\Omega_{OADM-selected}$. Thirdly, we calculate the distance ($d_{O_j-O_i}$) between O_j and O_i ($O_i \in \Omega_{OADM-selected} - O_j$), then we also find the minimum distance and connect O_j to O_i . The loop will end until the $\Omega_{OADM-selected}$ has only one element O_i . Finally, we connect this O_i to BBU, and the OADM ring can be constructed.

Finally, in lines 52–53, the heuristic outputs the layout solution (including the location of the selected RRUs and OADMs, the optical link between RRUs and OADMs, the optical ring of OADMs and BBU, the association between RRUs and OADMs) and total deployment cost.

4.2 An example for the proposed fast heuristic algorithm

In this section, we use a small-scale scenario, denoted as scenario 0, as an example to illustrate the procedure of the proposed algorithm. The parameter setting of scenario 0 is as follows: the set of TPs denotes P_{TP} , the candidate RRUs denote P_{RRU} , and the candidate OADMs denote P_{OADM} (see Fig. 3).

We defined a generic cost unit (gcu) [21] to simplify the evaluation of deployment costs in all the case studies.

Table 3 Simulation parameter settings

Parameter	Value
a	2
P	8 W
s_0	29 dB
ξ	2 mW
D_{MAX}	10 km
Scale	20 km

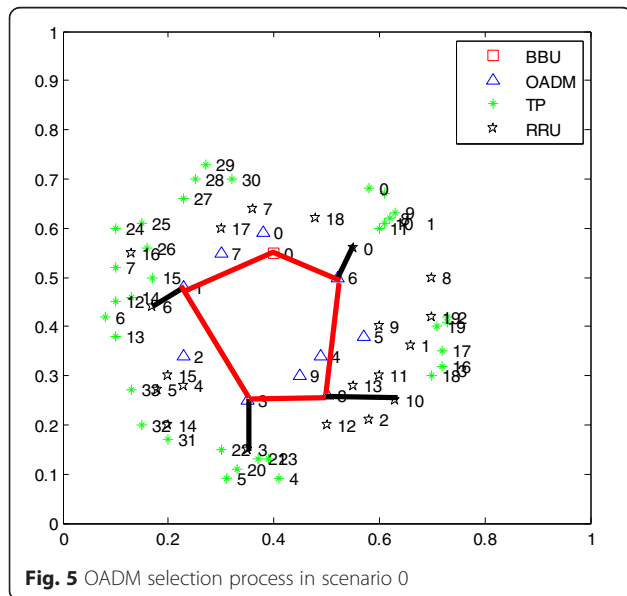


Fig. 5 OADM selection process in scenario 0

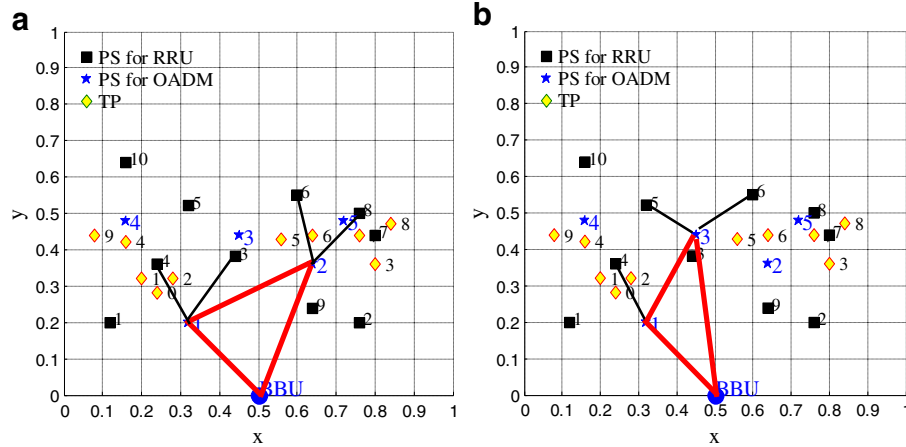


Fig. 6 Network layout results in scenario 1. **a** Without CoMP. **b** With CoMP

Step 1: Initialization.

Step 2: Achieve all of the TPs that can be covered by the candidate RRUs. In Fig. 3, the set of the candidate RRUs denotes $P_{RRU} = \{P_{RRU0}, P_{RRU1}, P_{RRU2}, \dots, P_{RRU19}\}$. The set of the candidate OADMs denotes $P_{OADM} = \{P_{OADM0}, P_{OADM1}, \dots, P_{OADM9}\}$. The set of TPs denotes $P_{TP} = \{P_{TP0}, P_{TP1}, P_{TP2}, \dots, P_{TP34}\}$. All of the TPs can be covered by the four RRUs, $P_{RRU10}, P_{RRU0}, P_{RRU3}, P_{RRU6}$. In specific, 17 TPs can be covered by P_{RRU10} ; 6 TPs can be covered by P_{RRU0} ; 6 TPs can be covered by P_{RRU3} ; and 6 TPs can be covered by P_{RRU6} .

Step 3: For all the selected RRUs, the optical link between the candidate OADMs and the selected RRUs will be connected at this step. Instead of using a proximity principle in selecting the candidate OADMs, we also conclude the distance between the RRUs and OADMs. In Fig. 4, there are four OADMs which can be connected to the RRUs, which are denoted as $P_{OADM1}, P_{OADM3}, P_{OADM6}, P_{OADM8}$. In specific, the P_{RRU6} can be connected to P_{OADM1} , the P_{RRU3} can be connected to P_{OADM3} , the P_{RRU0} can be connected to P_{OADM6} , and the P_{RRU10} can be connected to P_{OADM8} .

Step 4: Achieve the C-RAN architecture based on ring and spur. In this step, the ring topology will start form BBU, then the BBU will select the nearest OADM. We

marked this OADM as OADM-s(1). If the OADM-s(1) connects to the RRUs, then the OADM satisfies the OADM ring. In Fig. 5, the BBU connects to P_{OADM6} , then P_{OADM6} connects to P_{OADM8} , P_{OADM8} connects to P_{OADM3} , P_{OADM3} connects to P_{OADM1} , and P_{OADM1} connects to BBU. So, the ring and spur topology can be constructed at this step.

Finally, output the optical link between RRUs and OADMs, the optical link between OADM and BBU, the association between RRUs and OADMs (see Fig. 5).

Step 5: Compute the total deployment cost, computing time in this ring and spur topology.

In scenario 0, the total deployment cost is 1824.43 gcu. The topology running time is 1.308 s. The layout and total deployment cost results of the ring and spur topology under C-RAN is the same as the result obtained with Gurubi which will be introduced later in next section.

5 Numerical analysis

5.1 Parameter settings

We implement the optimization model of the previous section and solve the RSTO problem using Gurobi Optimizer [22], which is a state-of-the-art ILP solver.

Table 4 Comparison of RSTO results with and without CoMP in scenario 1

Scenario 1	Without CoMP ($s_0 = 23$ dB)	With CoMP ($s_0 = 23$ dB)
Selected number of PSs for RRU placement	4 RRUs	3 RRUs
Obj. value (gcu)	1760.8	1543.8
Compute time (s)	0.02	0.03
Optimality Gap	0 %	0 %

Table 5 Problem size of simulated scenarios

Scenario	Number of nodes			
	TP	RRU candidates	OADM candidates	
I	100	40	20	
II	500	120	50	
III	900	190	80	
	Constraints	Variables	Nonzero	Ave. memory
I	3058	2419	8423	127.59 MB
II	9371	6843	26418	736.74 MB
III	24873	18397	72629	7851.38 MB

Table 6 Comparison analysis of small-scale scenarios

Scenario	I		II		III	
	Gurobi	Heuristic	Gurobi	Heuristic	Gurobi	Heuristic
Obj. value (gcu)	3458.12	3614.47	4672.35	4928.84	6028.96	6375.14
Computing time (s)	17.24	2.07	46.39	4.15	130.12	6.34
Optimality gap	4.52 %		5.48 %		5.74 %	

Gurobi is designed to exploit modern multi-core processors and the performance is proved to be superior to CPLEX [23]. Without loss of generality, the Manhattan distance of two nodes is used to represent the corresponding edge length of the fiber deployment route, and all the fiber segment links have the same weighted deployment costs.

Tables 2 and 3 show the component cost of C-RAN and experimental parameters, respectively. We still use the generic cost unit (gcu) [21] to simplify the evaluation of deployment costs in the case studies.

In scenario 0, we have validated the solvability of (RSTO) formulation and the effectiveness of our proposed heuristic. To further investigate the effect of CoMP in the C-RAN planning strategy, we compare the resulting network layout configuration with and without CoMP technology in scenario 1 as shown in Fig. 6. We can observe the difference between Figs. 6a, b. The number of the selected RRUs in Fig. 6a is more than that in Fig. 6b. Table 4 shows the corresponding computing result of network optimal layout in scenario 1. It compares the objective value with and without CoMP. Obviously, the total cost of the network will be increased without CoMP. In other words, the incorporation of CoMP technology can lead to a significant cost reduction for C-RAN.

5.2 Numerical analysis of small-scale scenarios

Considering that the scale and configuration of a network placement may affect the performance of a network planning, we investigate a number of small-scale scenarios. Table 5 lists only three of the simulated scenarios with an increasing network scale. In the simulations, we randomly select PSs and TPs in the area. The problem size, the average computation time, the optimization gap, and the objective values in three

Table 7 Problem size of simulated large scenarios

Scenario	Number of nodes		
	TP	RRU candidates	OADM candidates
IV	1500	300	150
V	2500	450	230

Table 8 Comparison analysis for large scenarios

Scenario	IV		V	
	Gurobi	Heuristic	Gurobi	Heuristic
Obj. value (gcu)	No result	8127.67	No result	10342.14
Computing time (s)		7.15		8.63

scenarios are shown in Tables 5 and 6. The results demonstrate that our proposed heuristic algorithm can obtain the solution network layout much more effectively than Gurobi, and the optimality gap of the objective value between our heuristic and Gurobi is less than 6 %. In other words, the proposed heuristic can obtain the near-optimal solution highly efficiently.

5.3 Numerical analysis of larger-scale scenarios

To investigate the performance of proposed heuristic in larger-scale scenarios, we further simulated scenarios with thousands of nodes as listed in Table 7. The problem size, the average computation time, and the objective values in the scenarios are shown in Table 8.

From Table 8, Gurobi can hardly find the optimal result with the increase of the network scale; however, the heuristic algorithm can still obtain the solution effectively and efficiently.

Therefore, we can conclude that the RSTO-formulation-based Gurobi solution scheme are more suitable for smaller-scale C-RAN network layout planning, and our proposed heuristic algorithm could be suitable for real-world large-scale C-RAN network layout planning in practice.

5.4 Comparison of the tree and branch and ring and spur topology

Comparing Table 9 with Table 10, we can observe that:

- The deployment cost of the ring topology is relatively higher than that of the tree topology due to the deployment of bidirectional optical fiber.
- In respect to the computing time, the ring topology is shorter than the tree topology. In the tree topology, it needs to make restrictions to every path from the BBU to the RRUs, but in the ring topology, it only needs to make restrictions to the path in the OADM ring.

Table 9 The network scale of scenarios IX, X, and XI

Scenario	IX	X	XI
PS for OA/OADMs	5	5	5
PS for RRUs	20	30	50
The number of TPs	20	40	100

Table 10 Comparison of the tree and ring topology

Scenario	IX		X		XI	
	Tree	Ring	Tree	Ring	Tree	Ring
Total cost (unit, gcu)	1834.46	2208.12	2436.54	2895.03	3269.07	3890.01
Computing time	2.09	0.34	5.41	0.87	7.65	1.21

6 Conclusions

C-RAN provides a promising wireless architecture for reliable transmission of mobile big data. In this paper, we study the fundamental problem of topology optimization based on the more reliable string and spur topology. We formulate the RSTO problem to minimize the total deployment cost of the C-RAN network. We have examined the proposed RSTO problem via extensive case studies in term of its feasibility and scalability. Furthermore, we propose a new heuristic algorithm to obtain the near-optimal C-RAN network layout effectively and efficiently, especially suitable for a large-scale C-RAN network scenario in practice. In numerical studies, we also demonstrate the performance benefits of incorporation of CoMP technology in terms of total deployment cost reduction.

Competing interests

The authors declare that they have no competing interests.

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