2023 IEEE 98th Vehicular Technology Conference (VTC2023-Fall) | 979-8-3503-2928-5/23/$31.00 ©2023 IEEE | DOI: 10.1109/VTC2023-Fall60731.2023.10333785

# Cost-Effective Deployment for Fully-Decoupled Radio Access Networks: A Techno-economic Approach

Jiwei Zhao*, Jiacheng Chen†, Bo Qian†, Bo Cheng*, Yunting Xu*, Haibo Zhou*
*School of Electronic Science and Engineering, Nanjing University, Nanjing, China, 210023.
Email: jw_zhao@smail.nju.edu.cn, bocheng@smail.nju.edu.cn, yuntingxu@smail.nju.edu.cn,
haibozhou@nju.edu.cn
†Department of Mathematics and Theories, Peng Cheng Laboratory, Shenzhen 518000, China.
Email: chenjch02@pcl.ac.cn, boqian@pcl.ac.cn

***Abstract*—With the development of the Internet of Everything (IoE), future 6G networks will face the challenge of massive terminal access. However, deploying substantial high-cost, full-function base stations will undoubtedly further increase the cost of mobile network deployment, making it difficult for mobile operators to afford it. In this paper, we tackle the problem of low-cost network deployment for fully-decoupled radio access network (FD-RAN) with personalized service for large-scale terminals. We first propose a techno-economic cost model (TECM) for FD-RAN deployment based on the techno-economic approach. Then, we further formulate a cost-minimization problem for decoupled network deployment. Based on the independence brought by uplink and downlink decoupling in FD-RANs, we decompose the original problem into separate subproblems for uplink and downlink network deployment. In the following, we propose a branch and cut based network deployment (BCND) algorithm to solve two decoupled deployment subproblems, respectively. Finally, simulation results show that FD-RANs have significant cost advantages when facing differentiated service demands, and the main factors affecting network cost are power consumption and rental costs.**

***Index Terms*—FD-RAN, Network Deployment, Branch and Cut, Techno-economic**

## I. INTRODUCTION

With the explosive growth in service demand, the spectrum resources used by mobile communication are constantly moving towards higher frequencies. However, the coverage range of individual base stations is decreasing, and the network is becoming increasingly dense [1], [2]. At the same time, with the widespread use of new technologies like massive MIMO and ultra-wideband, the cost and power consumption of individual base stations are constantly rising. As a result, the overall cost of the mobile network has surged, posing a considerable challenge to operators.

With future access to trillions of terminals, uplink traffic will increase sharply, and the service model of wireless networks will undergo radical changes [3]. Deploying a large number of full-function base stations will significantly lead to wasted spectrum, energy, and economic resources. In the FD-RAN architecture, uplink base stations (UBSs) and downlink base stations (DBSs) are physically decoupled, and the network deployment based on users' differentiated service demands will be the optimal solution for solving the cost challenge. Therefore, how to deploy base stations in the FD-RAN architecture to meet differentiated service demands and minimize network deployment costs will be essential for operators to optimize network resource allocation, provide personalized service, and maintain revenue growth.

The network planning stage is one of the most critical steps to ensuring investment feasibility, and infrastructure investment efficiency can be improved by optimizing network capacity and costs [4]–[8]. Literature [9] proposes an integer linear programming approach, which optimizes the deployment of the baseband processing unit and front-haul link simultaneously to minimize capital expenditure (CAPEX). Oughton et al. developed an open-source Python simulator for the integrated modeling of 5G networks and cost evaluation in a unified framework [10]. Literature [11] proposes a method for the millimeter wave base station deployment problem based on minimum deployment cost criteria and subject to user equipment (UE) interruption constraints. Mishra et al. developed a theoretical framework using stochastic geometric tools to maximize spectral efficiency and deployment cost-effectiveness simultaneously [4]. Literature [5] studied the deployment problem of Unmanned Aerial vehicles (UAVs) for collecting data from Internet of Things (IoT) devices. Literature [6] examines a deployment strategy that maximizes roadside unit spatiotemporal coverage under a limited budget. Prasad et al. minimizes the total network operation cost required to satisfy each user's coverage constraint by jointly optimizing base station (BS) location, density, and transmit power allocation [7]. However, existing work on base station deployment optimization focuses on full-function base stations, and there is no work on the deployment of decoupled base station for differentiated uplink and downlink services.

Confronting the differentiated service scenarios in future networks and aiming to address the cost challenges faced by operators, we proposes a cost model and corresponding network decoupling deployment method for an FD-RAN network. The main contributions are summarized as follows:

- We addresses the low-cost network deployment problem for FD-RAN, which is a fully-decoupled radio access network architecture that can provide ultra-large-scale

979-8-3503-2928-5/23/$31.00 ©2023 IEEE

personalized services. We propose a techno-economic cost model (TECM) for FD-RAN deployment, and construct a cost-minimization decoupled deployment model for FD-RAN.

- Based on the decoupling characteristics of FD-RAN, we further propose a branch and cut based network deployment algorithm (BCND) to solve the uplink and downlink network deployment problems separately.
- We validate the cost for different network architectures, which shows the cost advantage in scenarios facing differentiated service demands.

The remainder of the paper is organized as follows. We describe the TECM cost model and formulate the network deployment problem In Section II. In Section III, an branch and cut based network deployment algorithm is proposed. Simulation setup and results are shown in Section IV. At last, we conclude the paper in Section V.

## II. SYSTEM MODEL

In this paper, we focuse on the massive IoT scenario that aims to address the challenge of providing differentiated service guarantees for massive access points through network deployment. Fig. 1 illustrates the FD-RAN coverage area in which considerable low-power IoT devices are uniformly distributed. The edge cloud acts as the control center for state collection, data processing, and centralized decision-making. It connects to the control base station (CBS), which handles control plane signaling interactions with all users in the coverage zone. The data base stations are physically decoupled into UBSs and DBSs. They offer on-demand service guarantees to users in the area. The FD-RAN data base stations only transmit data unidirectionally. Therefore, we can deploy the uplink and downlink networks independently based on the uplink and downlink service demands. We divide the entire FD-RAN coverage area $\mathcal{M}$ into $M$ equal-sized rectangles $m \in \mathcal{M}$. And, we assume that a base station is deployed at the center of each sub-area $m$ if one exists in $m$. We denote $x_m^i = 1, i \in \{D, U\}$ indicating deployment of either an UBS ($i = U$) or a DBS ($i = D$) at area $m$.

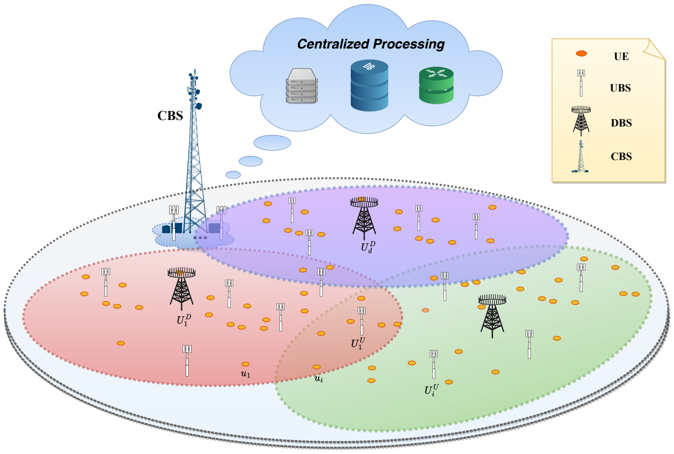

Fig. 1: FD-RAN decoupled deployment scenario.

### A. Wireless Transmission Model

The achievable rate of users is dictated by the received signal strength and interference, where the received signal strength is primarily contingent on the transmission power and channel attenuation. We constructs a large-scale channel attenuation model $g_{m,k} = f(l_m, l_k)$ based on the 3GPP wireless channel model [12], tailored for the Urban Macro (UMa) scenario. Here, $l_m \in \mathbb{R}^3$ and $l_k \in \mathbb{R}^3$ represent the spatial coordinates of base station $m$ and user $k$, respectively. Consequently, the receiving power of the terminal can be derived as

$$\rho^i\left(d_{m,k}, P_{\max}^i\right) = P_{\max}^i \cdot g_{m,k}^i\left(d_{m,k}\right). \tag{1}$$

We assumed that the base station and user both operate at maximum power $P_{\max}^i$. Considering the different uplink and downlink service modes of users, it is assumed that the user is served by an independent DBS on the downlink transmission, while being served cooperatively by multiple UBSs on the uplink transmission. Maximum ratio combining is assumed for signal combining from the cooperating base stations at the edge cloud. Therefore, the receiving power of user $k$ is

$$p_k^i = \sum_{m=1}^{M} a_{m,k}^i \cdot \rho^i\left(d_{m,k}, P_{\max}^i\right). \tag{2}$$

In this paper, the virtual uplink cooperative serving set for user $k$ is determined by the binary variable $a_{m,k}^i$. Let $N_k^i$ denote the noise power for either the user ($i = D$) or UBS ($i = U$). Then, the achievable throughput of the user is

$$R_k^i = B^i * \mathbb{E}\left\{\log_2\left(1 + p_k^i / N_k^i\right)\right\}. \tag{3}$$

where $B^i$ denotes the bandwidth. Since the primary concern for FD-RAN deployment is the service guarantee, we employ the temporal mean of the noise puls interference when acquring throughput of users. Therefore, $N^i$ is assumed to be a constant

$$N_k^i = \mathbb{E}\left[\sum_{m \in \mathcal{M}-m} x_m^i \cdot \rho^i\left(d_{m,k}, P_{\max}^i\right)\right] + \mathrm{N}_0, \tag{4}$$

where $\mathrm{N}_0$ represents the thermal noise power. For simplification, the expected interference is assumed identical for all users, i.e., $N^i = N_k^i, k \in \mathcal{K}$. It is posited that a user can only satisfy the coverage condition when its achievable rate surpasses the threshold $T_k^i$

$$B^i \cdot \log_2\left(1 + p_k^i / N^i\right) \geq T_k^i. \tag{5}$$

Assuming the capacity per base station is $M_K$, i.e., each base station can serve up to $M_k$ users, there are the ensuing constraints

$$\sum_{k=1}^{K^i} a_{m,k}^i \leq M_K. \tag{6}$$

Additionally, there is a consistency constraint between the base station deployment decision variable $x_m^i$ and user access decision variable $a_{m,k}^U$

$$\sum_{k=1}^{K^i} a_{m,k}^U \geq x_m^U, a_{m,k}^i \leq x_m^i. \tag{7}$$

For the downlink FD-RAN, we assume that the user is served by a single base station,which satisfies

$$\sum_{k=1}^{K^i} a_{m,k}^D = x_m^D. \tag{8}$$

Here, $a_{m,k}^i$ denotes whether the hypothetically deployed base station in sub-area $m$ serves user $k$.

### *B. Network Cost Model*

In this paper, we construct a FD-RAN deployment cost model called TECM, which systematically categorizes the total cost of ownership (TCO) over the entire network life cycle from building to withdrawal into two classes capital expenditure (CAPEX) and operating expenditure (OPEX).

*1) Deployment Cost:* The network CAPEX constitutes the capital costs from network building to providing wireless communication services to users. It primarily encompasses four elements radio access network $C_{RAN}^i$, fronthaul links $C_{FH}^i$, and device installation $C_{IT}^i$

$$C_{CAPEX} = C_{RAN} + C_{FH} + C_{IT}. \tag{9}$$

Wherein, the cost of the radio access network chiefly consists of active antenna processing unit (AAU) , remote radio unit (RRU), and baseband processing unit (BBU). And, corresponding costs are denoted as $C_{AAU}^i$, $C_{R,RRU}^i$, $C_{R,BBU}^i$

$$C_{RAN} = \sum_{m=1}^{M} x_m^D \cdot C_{AAU}^D + \sum_{m=1}^{M} x_m^D \cdot C_{R,RRU}^D + \sum_{m=1}^{M} x_m^U \cdot C_{RU}^U + C_{R,BBU}. \tag{10}$$

The access network also entails fronthaul link costs such as fiber fronthaul $C_{B,FB}^i$, router $C_{B,RT}$, etc.

$$C_{BH} = \sum_{i\in D,U} \sum_{m=1}^{M} x_m^i \cdot C_{B,FB}^i + C_{B,RT}. \tag{11}$$

Additionally, considering equipment deployment, the access network includes associated manpower costs like installation, deployment, and commissioning of base stations and fibers

$$C_{IT} = \sum_{i\in D,U} \left( \sum_{m=1}^{M} x_m^i \cdot C_{I,TW}^i + \sum_{m=1}^{M} x_m^i \cdot C_{I,FB}^i \right). \tag{12}$$

Notably, given that base station towers and network operators may not be the same entity, we assumes operators lease base station sites from a third party, and only account for the rental cost of site resources instead of base station construction costs.

*2) Operating Cost:* The OPEX refers to the routine operating, management and maintenance costs of the system. It chiefly incorporates three components power consumption $C_{PW}$, rental $C_{RT}$, operation and maintenance $C_{OM}$

$$C_{OPEX} = C_{PW} + C_{RT} + C_{OM} \tag{13}$$

The power cost of the system primarily considers the aggregated energy consumption of the BBU, RRH/AAU, room equipment, air conditioning, etc. For simplification, the power usage of all equipment in the central server room such as cooling and centralized remote radio unit (C-BBU) resource pool is abstracted as a unified power consumption term $C_{P,Fix}^i$.

Since different network architectures use varied terminologies for base stations, their costs are uniformly denoted as $C_{P,RF}^i$. The fiber fronthaul/backhaul power consumption corresponding to each base station is assumed to be $C_{P,FB}^i$. Let $T$ represent the total operating time from system running to final withdrawal. Then, the total power cost over the network life cycle is

$$C_{PW} = T \cdot \sum_{i\in D,U} \left\{ C_{P,FIX}^i + \sum_{m=1}^{M} x_m^i \cdot C_{P,RF}^i + \sum_{m=1}^{M} x_m^i \cdot C_{P,FB}^i \right\}. \tag{14}$$

The rental costs chiefly entail two elements infrastructure rental cost $C_{R,TW}^i$ required for base station deployment, and rental cost for central server room $C_{R,RM}$

$$C_{RT} = T \cdot \left( \sum_{i\in D,U} C_{R,TW}^i + C_{R,RM} \right). \tag{15}$$

For micro base stations or UBSs, owing to their compact size and ease of deployment, it is assumed they can be directly installed on buildings such as indoors and apartment rooftops. In this case, the rental cost of micro base stations will be far lower than the tower rental cost $C_{RT}$.

The maintenance cost $C_{OM}$ involves many factors like random repairs, system inspections, routine maintenance, etc., making it difficult to accurately quantify. Hence, we takes a systemic view of the operating and maintenance costs, and quantifies the average maintenance cost across the system.

### *C. Problem Formulation*

The ultimate optimization goal is to minimize the TCO while satisfying users' differentiated service requirements in both uplink and downlink FD-RAN. Next, the network deployment cost optimization problem will be formulated based on the deployment constraints and TECM cost model. According to the expressions for CAPEX (9) and OPEX (13), the objective function can be expressed as (16).

According to the previous derivations, the deployment constraints can be obtained as (5), (6), (7), (8). Based on the TECM formulation, the original deployment problem can be modeled as a minimum network cost coverage problem

$$\min_{\mathcal{X},\mathcal{A}} \quad \phi(\mathcal{X},\mathcal{A}) \tag{17}$$

$$\text{s.t.} B^i \cdot \log_2\left(1 + p_k^i / N^i\right) \geq T_k^i, \tag{17a}$$

$$a_{m,k}^i \leq x_m^i, \tag{17b}$$

$$\sum_{m=1}^{M} a_{m,k}^U \geq 1, \tag{17c}$$

$$\sum_{m=1}^{M} a_{m,k}^D = 1, \tag{17d}$$

$$\sum_{k=1}^{K^i} a_{m,k}^i \leq M_K, \tag{17e}$$

$$\forall m \in \mathcal{M}, k \in \mathcal{K}^i, i \in \{D, U\}. \tag{17f}$$

$$\begin{aligned}\phi\left(\mathcal{X},\mathcal{A}\right)=&\sum_{m=1}^{M}x_m^D\cdot\left(C_{AAU}^D+C_{R,RRU}^D+C_{B,FB}^D+C_{I,TW}^D+C_{I,FB}^D+T\cdot\left(C_{P,RF}^D+C_{P,FB}^D\right)\right)\\&+\sum_{m=1}^{M}x_m^D\cdot\left(C_{RU}^U+C_{B,FB}^U+C_{I,TW}^U+C_{I,FB}^U+T\cdot\left(C_{P,RF}^U+C_{P,FB}^U\right)\right)\\&+\sum_{i\in\{D,U\}}T\cdot\left(C_{RT,TW}^i+C_{OM}^i\right)+T\cdot C_{P,FIX}+C_{B,RT}+C_{R,BBU}\end{aligned}\tag{16}$$

## III. Low-Cost Network Deployment Based on Mixed Integer Programming

### A. Problem Transformation

The optimization problem specified by equation (17) becomes a nonlinear programming problem due to the nonlinear constraint (17a). To address this, the variables in (17a) are shifted out of the logarithm through exponential operations, thereby transforming it into an equivalent linear constraint

$$-\sum_{m=1}^{M}a_{m,k}^i\cdot P_{\max}^i\cdot g_{m,k}^i\left(d_{m,k}\right)N^i\cdot 2^{T_k^i/B^i}\leq N^i\tag{18}$$

Thus, the nonlinear constraint (17a) in the original problem is converted into the linear constraint (18). This yields a new optimization problem

$$\begin{aligned}\min_{\mathcal{X},\mathcal{A}}\quad&\phi\left(\mathcal{X},\mathcal{A}\right)\\\text{s.t.}\quad&(18),(17\text{b})\sim(17\text{f})\end{aligned}\tag{19}$$

In existing networks, the uplink and downlink of each user must be served by the same base station. In FD-RAN, the uplink and downlink are enabled through two independent uplink and downlink networks. Observing problem (19), the two networks can be deployed independently. Hence, problem 2 can be decomposed into two separate subproblems with one subproblem for downlink deployment, and another for uplink deployment. The downlink deployment subproblem is

$$\begin{aligned}P_1:\min_{\mathcal{X}^U}\quad&\sum_{m=1}^{M}x_m^D\\\text{s.t.}\quad&(18),(17\text{b}),(17\text{d}),(17\text{e})\\&i=D,x_m^D\in\{0,1\},a_{m,k}^D\in\{0,1\}\\&\forall m\in\mathcal{M},\forall k\in\mathcal{K}^D.\end{aligned}\tag{20}$$

The uplink deployment subproblem can be expressed as

$$\begin{aligned}P_2:\min_{\mathcal{X}^U}\quad&\sum_{m=1}^{M}x_m^U&(21\text{a})\\\text{s.t.}\quad&(18),(17\text{b}),(17\text{c}),(17\text{e})&(21\text{b})\\&i=U,x_m^U\in\{0,1\},a_{m,k}^U\in\{0,1\}&(21\text{c})\\&\forall m\in\mathcal{M},\forall k\in\mathcal{K}^U.&(21\text{d})\end{aligned}$$

The objectives and constraints of subproblems (20) and (21) are linear, making them mixed integer linear programming (MILP) problems.

### B. Network Deployment Based on Branch and Cut

The Branch and Cut (B&C) concept comprises two known optimization methods branch and bound and cutting plane. Using these tools, B&C algorithms can generate upper bounds by relaxing the problem to find optimal solutions. Relaxing the problem simplifies complex problems for easier solving. Cutting planes are additional linear constraints that violate relaxed linear programming (LP) solutions but do not eliminate integer feasible solutions. Specifically, the cutting plane (sometimes called valid inequalities) method iteratively adds cuts (constraints) to the LP problem, excluding parts of the feasible region so that the LP relaxation can be tightened, ensuring the current relaxed solution lies in the cut space while the integer optimal remains in the cut-after space. Relying solely on cutting planes for MILP solving is infeasible, so they are always combined with B&B. Next, the B&C algorithm for base station deployment is briefly introduced.

Algorithm 1 delineates the network deployment algorithm BCND using B&C adopted in this paper. First, a subproblem $\mathcal{P}$ is selected from the queue in Step 3. When solving $\mathcal{P}$ in Step 4, the LP relaxation without integer constraints is solved using the simplex method. If the optimal solution $\bar{x}(\mathcal{P})$ has non-integer values, cutting plane algorithms can be leveraged to find additional linear constraints satisfying all feasible integer points but violating the current LP relaxation. In Step 16, these inequalities are added to the linear program for re-solving, yielding a different solution. In the branch and bound part of Step 18, problem $\mathcal{P}$ is partitioned into two subproblems $\mathcal{P}_1$ and $\mathcal{P}_2$, which are then added to the queue $Q$. In the branch and bound process, non-integer LP relaxation solutions serve as upper bounds while integer solutions provide lower bounds. Nodes can be pruned if the upper bound is less than the current lower bound. Finally in Step 20, the algorithm returns the optimal $x^*$ and minimum cost $y^*$. It starts by solving a single subproblem the LP relaxation of the original problem. In the algorithm execution, new subproblems are created via branching, with subproblem solutions potentially generating two or more child subproblems. This process can be represented as a tree, where different nodes correspond to the associated subproblems and edges denote parent-child relationships between subproblems.

## IV. Simulation Results

We considers network deployment for a random area to meet the personalized service guarantees of massive access points. To study the relationship between network cost and number of users, it is assumed there are 1000 ~ 15000 users in the area.

**Algorithm 1** Base Station Deployment Based on B&C Algorithm

```
Require: Original problem $\mathcal{P}0$
Ensure: Optimal solution $x^* \in X_{\mathrm{MILP}}$, objective value $y^*$; or $X_{\mathrm{MILP}} = \emptyset$, $y^* = +\infty$
 1: Define subproblem queue $Q \triangleq \{\mathcal{P}_0\}, y^* = +\infty, x^* = \text{null}$
 2: while $Q \neq \emptyset$ do
 3:     Select a subproblem $\mathcal{P}$ from queue $Q$ and remove $Q = Q \backslash \{\mathcal{P}\}$
 4:     Solve LP $y(\mathcal{P}) = \min\left\{c^T x x \in \mathcal{P}\right\}$, obtain optimal $\bar{x}(\mathcal{P})$
 5:     if $\bar{x}(\mathcal{P})$ is infeasible then
 6:         Return to Step 2
 7:     end if
 8:     if $y(\mathcal{P}) \geq y^*$ then
 9:         Return to Step 2
10:     end if
11:     if $\bar{x}(\mathcal{P})$ is integer then
12:         $y^{=}y(\mathcal{P})$, $x^* = \bar{x}(\mathcal{P})$
13:     end if
14:     Cut Use heuristic algorithm to obtain cutting planes $Dx \geq e$, where $D \in \mathbb{R}^{k \times n}$, $e \in \mathbb{R}^k$
15:     if Cutting planes exist then
16:         Add constraints to $\mathcal{P} = \mathcal{P} \cup \{Dx \geq e\}$, return to Step 4
17:     end if
18:     Branch Partition $\mathcal{P}$ into two subproblems $\mathcal{P}_1$ and $\mathcal{P}_2$, add them to queue $Q$. Return to Step 3.
19: end while
20: return Optimal $x^*$ and $y^*$
```

But in other scenarios, 10000 UEs are fixed as the baseline. The guaranteed rate of users is assumed to follow a normal distribution with a mean of 1 Mb/s and variance of 0.1. The default uplink-to-downlink (U/D) ratio is 5 in the simulation. Additionally, the transmit power is assumed to be 23 dBm for users, 46 dBm for macro base stations or DBSs, and 39 dBm for micro base stations or access points (APs).

In this paper, the basic prices of all equipment costs are based on real data of domestic operators and related public data [13]. However, assumptions are made for FD-RAN costs based on functional simplification and cost reduction principles, since real network data for FD-RAN does not yet exist. The total deployment cost of an UBS is around 1300, with transmit power set as 500 W. It is based on the assumption that the functionality of FD-RAN UBSs will be greatly simplified (removing transmitter function). Considering the calculation period of total power consumption, 20 years is chosen as the baseline network service life, since 2G networks have been operating for over 20 years. Since APs and UBSs are similar in size to wireless WiFi nodes that can be deployed indoors, their rental costs are much lower than tower rental costs. Moreover, considering that various network operation and maintenance costs have no quantified benchmark, and networks like FD-RAN and Cell-free have no real deployments, this paper uses a typical value of 1000 per month for the operating cost of all networks. This helps offset the impact of this parameter on the TCO analysis.

Fig. 2 shows the variation of network TCO with number of users under different network architectures. It can be observed that mMIMO requires much higher costs than other networks when meeting user service requirements, due to its high device prices and power consumption. The cost of FD-RAN is far lower than all other networks, mainly because the uplink network devices are lower than other networks, and the UBS power consumption is much lower than that of the full-function base station. Additionally, Small Cell and Cell-free have similar costs, since they both employ full-function base stations with similar power consumption and rental costs, leading to similar network costs. It is worth noting that for any network, when the number of users increases to over 10000, the cost growth curve approximates a linear ascent. It is related to the proposed cost modeling, and also reflects that deployment decisions need to meet the service requirements of all users in the wide area when network demand is low. At this moment, the network is coverage-constrained. As service demands gradually increase, more resources need to be deployed to meet higher service demands, and the network becomes service-constrained.

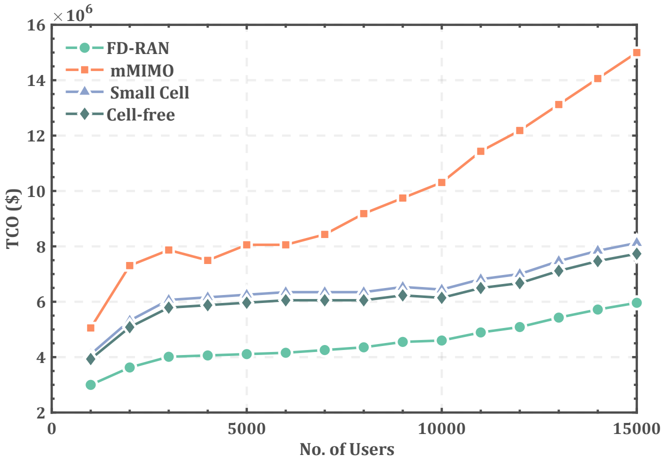

Fig. 2: The TCO variation with the number of users under different network architectures.

Fig. 3 illustrates the cost of FD-RAN at varying U/D traffic ratios. In this paper, we maintain a constant uplink traffic volume while altering the U/D ratio, effectively reducing the downlink transmission volume. As depicted in Fig. 3, network cost decreases as the U/D traffic ratio increases, with network power consumption and tower rental being the primary factors affecting network cost. When the U/D ratio changes from 1 to 5, the total cost decreases by 44.6%, with RAN, total power consumption, and rental costs decreasing by 59.9%, 44.7%, and 46.2%, respectively. However, when the U/D ratio increases from 5 to 10, the total cost only decreases by 14.0%. It indicates that as the U/D ratio continues to increase, the rate of cost reduction decelerates, which is attributed to the coverage requirements that limit the further reduction of UBSs/DBSs.

Fig. 4 shows the system cost required when the uplink traffic volume is fixed and the ratio of U/D traffic changes.

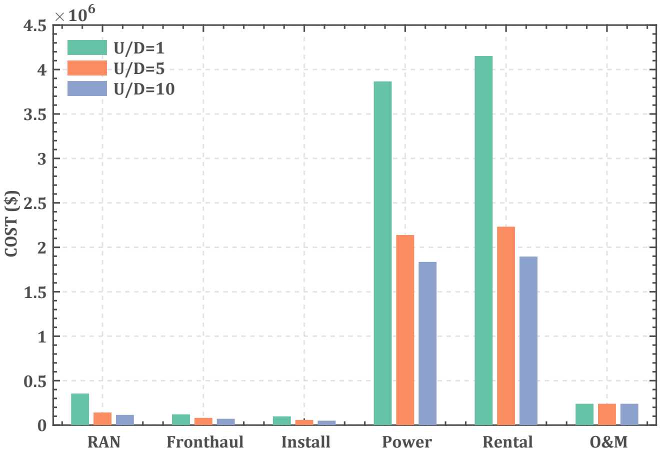

Fig. 3: The cost variation of different factors under different U/D ratios.

We observe that as the ratio of U/D traffic increases, the cost of the FD-RAN network gradually decreases until the ratio reaches a certain threshold and then stabilizes, while the other three network architectures are almost insensitive to the change of U/D traffic ratio. The simulation scenario in this paper has a stable ratio of U/D traffic of about 8, but this does not imply that other scenarios have the same threshold. However, at a U/D ratio of 18, all networks have a slight increase in cost, which is due to simulation randomness. In our simulation, FD-RAN can save 59%, 36%, and 33% of the cost compared to mMIMO, Small Cell, and Cell-free architectures respectively in the optimal case. Therefore, Fig. 4 illustrates that FD-RAN will have substantial cost advantages in business scenarios where uplink traffic predominates.

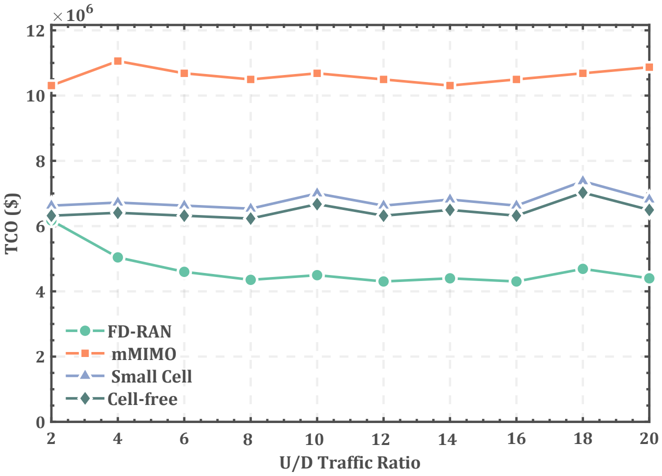

Fig. 4: The TCO variation with different U/D ratios under different network architectures.

## V. Conclusion

In this paper, we propose the TECM model for FD-RAN deployment based on the techno-economic method, and further formulate a cost-minimization problem for decoupled network deployment. Based on the independence brought by the uplink and downlink decoupling in FD-RANs, we decompose the original problem into separate subproblems for uplink and downlink network deployment. For the decoupled deployment subproblems, we propose a BCND algorithm to solve the uplink and downlink network deployment problems, respectively. Finally, simulation results show that FD-RANs have significant cost advantages when facing differentiated service demands, and the main factors affecting network cost are system power consumption and rental costs. For future work, we will investigate the network deployment issue considering the time-varying traffic.

## VI. ACKNOWLEDGEMENT

This work was supported in part by the National Natural Science Foundation Original Exploration Project of China under Grant 62250004, the National Natural Science Foundation of China under Grant 62271244, the Natural Science Fund for Distinguished Young Scholars of Jiangsu Province under Grant BK20220067, and the Natural Sciences and Engineering Research Council of Canada (NSERC).

## References

[1] Q. Yu, H. Zhou, J. Chen, Y. Li, J. Jing, J. J. Zhao, B. Qian, and J. Wang, "A Fully-Decoupled RAN Architecture for 6G Inspired by Neurotransmission," *Journal of Communications and Information Networks*, vol. 4, no. 4, pp. 15–23, Dec. 2019.

[2] H. Zhou, W. Xu, J. Chen, and W. Wang, "Evolutionary v2x technologies toward the internet of vehicles: Challenges and opportunities," *Proceedings of the IEEE*, vol. 108, no. 2, pp. 308–323, 2020.

[3] J. Zhao, Q. Yu, B. Qian, K. Yu, Y. Xu, H. Zhou, and X. Shen, "Fully-Decoupled Radio Access Networks: A Resilient Uplink Base Stations Cooperative Reception Framework," *IEEE Transactions on Wireless Communications*, pp. 1–1, 2023.

[4] M. K. Mishra and A. Trivedi, "Spectral Efficiency and Deployment Cost Efficiency Analysis of mmW/UHF-Based Cellular Network," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 7, pp. 6565–6577, Jul. 2019.

[5] W. Xu, T. Xiao, J. Zhang, W. Liang, Z. Xu, X. Liu, X. Jia, and S. K. Das, "Minimizing the Deployment Cost of UAVs for Delay-Sensitive Data Collection in IoT Networks," *IEEE/ACM Transactions on Networking*, vol. 39, no. 2, pp. 812–825, Apr. 2022.

[6] D. Kim, Y. Velasco, W. Wang, R. Uma, R. Hussain, and S. Lee, "A New Comprehensive RSU Installation Strategy for Cost-Efficient VANET Deployment," *IEEE Transactions on Vehicular Technology*, pp. 1–1, 2016.

[7] G. Prasad, D. Mishra, and A. Hossain, "Joint Optimization Framework for Operational Cost Minimization in Green Coverage-Constrained Wireless Networks," *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 3, pp. 693–706, Sep. 2018.

[8] X. Yu, D. Xu, D. W. K. Ng, and R. Schober, "Irs-assisted green communication systems: Provable convergence and robust optimization," *IEEE Transactions on Communications*, vol. 69, no. 9, pp. 6313–6329, 2021.

[9] F. Yaghoubi, M. Mahloo, L. Wosinska, P. Monti, F. D. S. Farias, J. C. W. A. Costa, and J. Chen, "A Techno-Economic Framework for 5G Transport Networks," *IEEE Wireless Communications*, vol. 25, no. 5, pp. 56–63, Oct. 2018.

[10] E. J. Oughton, K. Katsaros, F. Entezami, D. Kaleshi, and J. Crowcroft, "An Open-Source Techno-Economic Assessment Framework for 5G Deployment," *IEEE Access*, vol. 7, pp. 155 930–155 940, 2019.

[11] M. Dong, M. Cho, K. Lee, S. Yoon, and T. Kim, "Cost-Optimal Deployment of Millimeter-Wave Base Stations Under Outage Requirement," *IEEE Transactions on Wireless Communications*, vol. 21, no. 12, pp. 10 544–10 559, Dec. 2022.

[12] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.901, 3 2022, version 17.0.0.

[13] Canbang, Liu, "China mobile's 5g base station centralized procurement project is completed, and many manufacturers benefit from it," http://www.news.cn/fortune/2023-06/12/c_1212198069.htm, 2021.