Adaptive Network Architecture with Moving Nodes Towards Beyond 5G Era

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***Abstract*—In metropolitan areas, spatio-temporal patterns of human mobility result in significant fluctuations of mobile traffic. Such fluctuations drastically deteriorate the efficiency and financial viability of conventional mobile networks. This is because mobile networks have been designed to cope with the peak traffic, and thus their capacities are underutilized for most of time. To make matters worse, this trend will be intensified with the increase in mobile traffic. To address this issue, this paper proposes a concept of adaptive mobile network architecture with moving nodes towards beyond 5G era. It consists of densely deployed radio units (RUs) and moving distributed units (DUs) in the centralized radio access network (C-RAN) architecture. The mobile traffic is forwarded through optical midhaul links and wireless relay fronthaul links satisfying the latency requirement. This paper also proposes an algorithm for optimizing the activation states of RUs, the relocation schedule of DUs, and forwarding paths of fronthaul streams according to the demand distribution. It was confirmed with computer simulations that the proposed architecture can efficiently activate RUs and DUs by optimizing the location of DUs and forwarding paths of fronthaul streams.**

***Index Terms*—C-RAN, midhaul, fronthaul, wireless relay, network design**

I. Introduction

Centralized radio access network (C-RAN) architecture has been developed to efficiently forward the ever increasing mobile traffic [1]. Network capacity is enhanced by densely deploying many small cells, because cell size reduction results in the increase in spectrum efficiency [2]. For the C-RAN architecture, the redefinition of functional split points for a mobile base station (BS) is under consideration [3]. A mobile base station is split into three components; a central unit (CU), a distributed unit (DU), and a radio unit (RU) [4]. The link between a CU and a DU is called midhaul, and that between a DU and an RU is called fronthaul. A CU pool is installed in a central office. Many RUs are densely deployed in urban area. DUs are placed near RUs because the latency requirement of fronthaul is very strict, e.g. $\leq 100\mu$s [3]. The increase in the number of RUs and DUs results in the growing concern about the optimization of DU/RU deployment and fronthaul/midhaul connection [5].

There is a significant fluctuation in the demands of mobile traffic in metropolitan areas [6] [7]. The number of mobile phone users is higher during the daytime than at night, and during weekdays than on weekends, because of daily commuter movement between cities and residential areas. It has also attracted considerable attentions to support moving hot spots, which are generated by the increasing data traffic of mobile users [8]. The fluctuations in the traffic demands caused by such patterns of human mobility drastically deteriorate the financial viability and efficiency of mobile networks. This is because mobile networks have been deployed for dealing with the peak rate, so that their capacities are underutilized for most of time. Furthermore, the fluctuations in the mobile traffic will be intensified in accordance with the increase in mobile traffic in the future.

To address this problem, the autonomous base stations with optical reflex backhaul (ABSORB) architecture [9] was proposed to adapt to fluctuations in mobile traffic. In the ABSORB architecture, mobile traffic is forwarded with a moving BS which follows the demand movement and optical reflex backhaul consisting of fiber optic networks. The moving BSs follow the demand movement, and consequently the mobile network is flexibly reconstructed according to the demand distribution. As a deployment scenario of the ABSORB architecture, the concept of optically backhauled moving network for

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local trains was proposed for dealing with moving hot spots [10], [11]. However, it has not been investigated to apply the proposed ABSORB to the C-RAN architecture towards beyond 5G era. Therefore, this paper proposes a concept of adaptive mobile network architecture with moving nodes as a deployment scenario of the ABSORB architecture. With the proposed architecture, the activation states of RUs and locations of moving DUs are flexibly optimized according to the demand distribution. The mobile traffic is forwarded through optical midhaul links and wireless relay fronthaul links satisfying the latency requirement.

The rest of the paper is organized as follows. Section II describes related work. Section III introduces the proposed network architecture and the problem definition. In section IV, we explain the scheduling and routing algorithm for the proposed architecture. Then, section V describes the performance evaluation through computer simulations. The conclusion is provided in section VI.

II. Related work

A. C-RAN architecture

The C-RAN architecture assumed in this paper is depicted in Fig. 1. The functions of a mobile BS are divided into a CU, a DU, and an RU [4]. A CU provides the functions for radio link control (RLC) and packet data convergence protocol (PDCP), and it is placed as a CU pool in a central office of a telecommunications carrier. An RU is equipped with an antenna element and a part of physical (PHY) layer functions. An ultra high-density distributed antenna system (UHD-DAS) is composed by densely deploying many RUs [12]. It is proposed to improve the energy efficiency by switching ON/OFF of RUs depending on the amount of mobile traffic [13]. Note that how to optimize the states of each RU is not mentioned in [13]. A DU is equipped with other PHY and media access control (MAC) layer functions. In this architecture, there are different requirements for the midhaul and fronthaul. The midhaul links require high bandwidth because of its high data rate. The fronthaul traffic requires strict latency requirements, e.g. 100μs [14] [3]. Thus, the distance between a DU and an RU is limited and technologies for low-latency are needed to satisfy the latency requirements.

B. Fronthaul network

Although the mobile fronthaul has conventionally been composed of point-to-point optical links, fronthaul networking has been a hot research topic in recent years considering that the data rate becomes variable and is proportional to the wireless link data rate [14]. A valuable option is passive optical network (PON) based architecture [15], [16]. This architecture is investigated to improve optical link utilization by sharing fibers with multiple RUs. Upstream wavelength and bandwidth allocation techniques for reducing queuing delay was proposed [17], [18]. Another approach for fronthaul networking is time-sensitive networks for fronthaul which is standardized in IEEE 802.1CM [19]. Fronthaul streams are transported via a fronthaul bridged network, which consists of inexpensive layer-2 switches using time-sensitive networking (TSN) features to meet the strict service requirements [20], [21]. Moreover, a wireless relay system has been studied to construct inexpensive fronthaul by reducing optical fiber deployment [22]. A deployment design of DU site incorporating wireless connection was proposed [5]. This paper focuses on fronthaul networking with wireless relay in view of reducing optical fiber deployment cost.

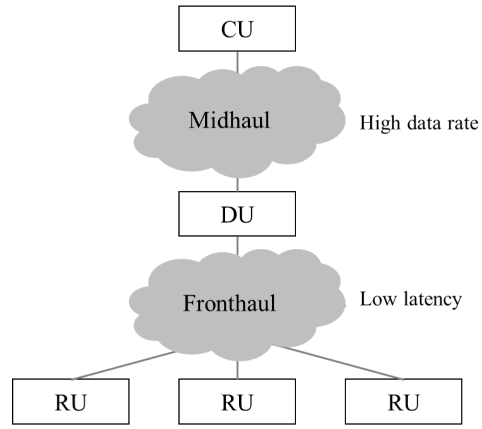


Fig. 1: C-RAN architecture model.

C. UAV cell

A mobile network composed of unmanned aerial vehicles (UAVs) such as drones has been a hot research topic in recent years [23]–[26]. The functions of mobile BSs are installed on UAVs and they are deployed on-demand for establishing cost-effective wireless connectivity without infrastructure coverage. The advantages of the UAV cell are flexibility for timely reconfiguration and better communication channels because of the presence of short-range line-of-sight (LoS) links. However, this concept is still under investigation and there has been no concrete idea of utilizing UAV cells in the C-RAN architecture. In this paper we propose the utilization of UAVs in an adaptive C-RAN architecture towards beyond 5G.

III. Proposed network architecture

A. Network architecture

The proposed architecture is based on the C-RAN shown in Fig. 1. Fig. 2 depicts the conceptual architecture of the proposed network. RUs are equipped with the minimum functions required, i.e. an antenna element and analog-to-digital/digital-to-analog converter (ADC/DAC). They are densely deployed on structures such as traffic signals and telegraph poles in a city area.

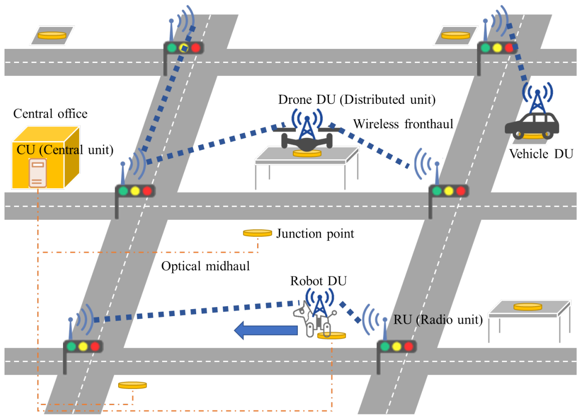


Fig. 2: Conceptual architecture of proposed network.

The activation states of RUs switch between active and sleep according to the spatio-temporal distribution of traffic demands.

The DU functions are implemented on movable machine such as UAVs, robots, and vehicles. Movable DUs move around a city area to adapt to fluctuating demand. This is because it is inefficient and costly to densely deploy a large number of DUs all over the area, and there are limitations on hop counts and propagation distance for fronthaul links because of the strict latency requirement. The DUs establish communication with the CU pool by connecting optical midhaul links at junction points (JPs). A junction point is linked to the CU pool in a central office via fiber optic networks and provides optical fiber connector for a movable DU to connect. The topology of optical midhaul can be point-to-point and PON. When a DU is connected to optical midhaul, it establishes wireless relay fronthaul links with neighboring RUs. The cost of fiber optic networks for fronthaul is reduced by employing wireless relay [5].

The activation states of RUs, the relocation schedule of DUs, and forwarding paths of fronthaul streams are optimized following the demand distribution. They are computed by a controller installed in a remote computer. The proposed algorithm is described in the next section.

B. Variables and graph representation

The variables used in the problem definition are summarized in Table. I. The details of each variable are introduced in the following explanation.

Let $\mathcal{R}$ and $\mathcal{J}$ denote the set of RUs and JPs in the target area, respectively. When t is defined as the time period, $\mathcal{R}_t^{on} \subset \mathcal{R}$ represents the set of active RUs at tth period. The activation probability of RUs at t is denoted as P_t. An active RU in $\mathcal{R}_t^{on}$ is identified with an identifier r_t. We define an undirected graph $G_t = (\mathcal{R}_t, \mathcal{E}_t)$, where $\mathcal{R}_t$ compose the vertices and the set of edges $\mathcal{E}_t$ comprises the connectable wireless links between active RUs. The weight of each edge

TABLE I: Variables

Variable	Definition
t	Time period
$\mathcal{R}$	Set of all RUs in the target area
$\mathcal{J}$	Set of JPs in the target area
P_t	Activation probability of RUs at t
$\mathcal{R}_t^{on}$	Set of active RUs at t
r_t	Active RU identifier at t, $r \in \mathcal{R}_t^{on}$
$\mathcal{E}_t$	Set of edges between active RUs at t
$\mathcal{J}_t^{DU}$	Set of JPs connected to DUs at t
j_t	Active JP identifier at t, $j_t \in \mathcal{J}_t^{DU}$
$\mathcal{C}_t$	Set of candidate edges at t
$\mathcal{C}_t^{on}$	Set of activated edges in $\mathcal{C}_t$
c	Activated edge identifier, $c \in \mathcal{C}_t^{on}$
$\mathcal{F}$	Set of fronthaul flows in fronthaul network
f	Fronthaul stream identifier, $f \in \mathcal{F}$
d_f	end-to-end delay of fth flow
d_n^{prc}	Processing delay of nth node
d_l^{prp}	Propagation delay of lth link
d_l^q	Queuing delay of lth link
τ	Threshold for worst case delay of fronthaul
M_1, M_2	Number of iterations for Monte Carlo simulations

is determined as the physical distance between RUs. The JPs in $\mathcal{J}$ establish virtual candidate edges with neighboring active RUs, and the set of candidate edges is denoted as $\mathcal{C}_t$. Fig. 3a shows an example distribution of RUs and JPs in a downtown city-block model. The graph representation of this situation is depicted in Fig. 3b, where the edges shown in solid lines mean the probability for wireless connections $\mathcal{E}_t$ and the dotted lines represents the virtual candidate edges $\mathcal{C}_t$.

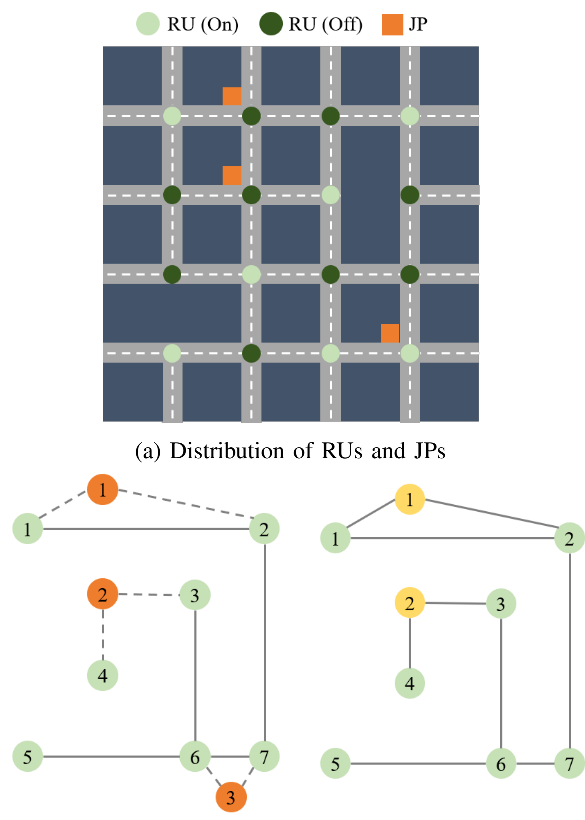
The set of JPs which are connected to DUs at tth period is described as $\mathcal{J}_t^{DU} \subset \mathcal{J}$. The JPs in $\mathcal{J}_t^{DU}$ are identified with an identifier j_t. When a DU is connected to a JP, the JP is activated as a vertex in the graph and corresponding candidate edges are activated as shown in Fig. 3c. The set of activated candidate edges is denoted as $\mathcal{C}_t^{on} \subset \mathcal{C}_t$, and c denotes the identifier for them. The updated graph G_t' can be described as $G_t' = (\mathcal{R}_t^{on} + \mathcal{J}_t^{DU}, \mathcal{E}_t + \mathcal{C}_t^{on})$.

IV. Scheduling and Routing Algorithm

This section describes the proposed algorithm. The goal of the proposed algorithm is to optimize the activation states of RUs, the relocation schedule of DUs, and forwarding paths of fronthaul streams in accordance with the demand distribution. It is computed by a controller installed in a remote computer.

A. Fronthaul delay formulation

First, the latency of fronthaul is formulated to explain the proposed algorithm. This formulation is based on [20] and the end-to-end delay in fronthaul is defined as the required time between a DU and an RU. Let $\mathcal{F}$ denote the set of fronthaul streams and f denote



(a) Distribution of RUs and JPs

(b) Graph representation (W/O DUs)

(c) Graph representation (W/ DUs)

Fig. 3: Graph representation of node distribution.

the identifier for them. A fronthaul stream corresponds to an RU. When the forwarding path of fth flow is determined, the end-to-end delay d_f is calculated as:

$$d_f = \sum_n d_n^{prc} + \sum_l d_l^{prp} + \sum_l d_l^q, \tag{1}$$

where d_n^{prc} denotes the processing delay at nth RU on the forwarding path which depends on the processing speed. d_l^{prp} is the propagation delay at lth link, which is decided by the physical distance of it. d_l^q denotes the queuing delay at lth link which represents the waiting time for transmission at an RU. This is determined by the number of aggregated streams and the slot size for wireless transmission. To satisfy the latency requirement of fronthaul, $d_f \leq \tau$ is required where τ denotes the threshold.

B. DU relocation

1) Definition of Markov state: Let x_{jt} denote a binary variable that represents the state of DU connection for jth JP at tth period; $x_{jt} = 1$ is satisfied if a DU is connected to optical midhaul at jth JP, and $x_{jt} = 0$ otherwise. We define $X(t) = \{x_{1t}, x_{2t}, \dots\}$, which denotes the state of DU connection for JPs at tth period, as a state in a Markov chain model. The relocation of DUs is described as a transition between the states using $X(t)$ in the same way as [9].

2) State transition: When the location of DUs at $t+1$th period is calculated, we assume that the activation probability of RUs P_{t+1} is decided in advance using a forecast of the demand distribution generated from statistical data. That is, $X(t+1)$ is computed with a Markov chain Monte Carlo (MCMC) method using $X(t)$ and P_{t+1} as input data.

The proposed algorithm is summarized in Algorithm 1. First, the combination of active RUs $\mathcal{R}_{t+1}^{on}$ is generated from $\mathcal{R}$ and P_{t+1}. To avoid the deviation of active RU distribution, neighboring RUs are grouped and they are activated so that P_t is satisfied for each group. The graph of active RUs and candidate edges $G_{t+1} = (\mathcal{R}_{t+1}^{on}, \mathcal{E}_{t+1})$ is generated. Then, $X(t+1)$ is generated with the random transition from $X(t)$. It is assumed that the transition probabilities between states are equally allocated. The updated graph with RUs, DUs, and active edges $G'_{t+1} = (\mathcal{R}_{t+1}^{on} + \mathcal{J}_{t+1}^{DU}, \mathcal{E}_{t+1} + \mathcal{C}_{t+1}^{on})$ is computed. The forwarding paths of fronthaul streams are set with Dijkstra's algorithm on G'_{t+1}. The end-to-end delay d_f is calculated with 1 for each flow, and if $d_f \leq \tau$ is satisfied for all streams, G'_{t+1} is a candidate solution. If it is a candidate solution, G'_{t+1} is compared with the stored best solution G_{best} in view of the number of active DUs $N_{DU} = \sum_j x_{jt+1}$ and the Hamming distance between $X(t)$ and $X(t+1)$, which is equivalent to the relocation of DUs and defined as H. Let N_{best} and H_{best} denote the objective values of G_{best}. If $N_{DU} \leq N_{best}$ and $H \leq H_{best}$ are satisfied, G'_{t+1} is stored as the best solution and N_{best} and H_{best} are updated. This calculation is iterated for M_2 times with different $X(t+1)$. The above procedure is repeated for M_1 times with different $\mathcal{R}_{t+1}^{on}$, and the optimum solution which consists of $\mathcal{R}_{t+1}^{on}$ and $X(t+1)$ is computed from stored G'_{t+1}.

V. Evaluation

The effectiveness of the proposed network architecture and proposed algorithm was evaluated with computer simulations.

A. Simulation condition

The simulation scenario was a downtown city-block model (9×9 St.) with grid-pattern roads as shown in Fig. 4. RUs were deployed on traffic signals or signs at each intersection. 6 JPs were randomly deployed for each street. The latency requirement of fronthaul τ was set as 100μs. The processing delay and time slot length at each hop were both 20μs. The time period $t = 1$ is a daytime model where 100% RUs are active. Then, $t = 2$, $t = 3$, and $t = 4$ are nighttime models with 60, 40, and 20% activation of RUs, respectively. Neighboring RUs were grouped as depicted with the blue box in Fig. 4.

Algorithm 1 DU relocation algorithm

Input: $X(t)$, P_{t+1}
Output: $\mathcal{R}^{on}_{t+1}$, $X(t+1)$
$count_1 \leftarrow 0$
while $count_1 < M_1$ **do**
  $\mathcal{R}^{on}_{t+1} \leftarrow$ GetRandomRuStates(P_{t+1})
  $G_{t+1} \leftarrow$ GenerateGraph($\mathcal{R}^{on}_{t+1}$, $\mathcal{E}_{t+1}$))
  $count_2 \leftarrow 0$
  while $count_2 < M_2$ **do**
    $X(t+1) \leftarrow$ GetRandomTransition($X(t)$)
    $G'_{t+1} \leftarrow$ GenerateGraph($\mathcal{R}^{on}_{t+1} + \mathcal{J}^{DU}_{t+1}$, $\mathcal{E}_{t+1} + \mathcal{C}^{on}_{t+1}$))
    for all $f \in \mathcal{F}$ **do**
      GetForwardingPath(f)
    end for
    for all $f \in \mathcal{F}$ **do**
      $d_f \leftarrow$ CalculateDelay()
    end for
    if $d_f \leq \tau \quad \forall f \in \mathcal{F}$ **then**
      if $N_{DU} \leq N_{best}$ and $H \leq H_{best}$ **then**
        $G'_{t+1} \rightarrow G_{best}$
        $N_{best} \leftarrow N_{DU}$
        $H_{best} \leftarrow H$
      end if
    end if
    $count_2 \leftarrow count_2 + 1$
  end while
  $count_1 \leftarrow count_1 + 1$
end while
$\mathcal{R}^{on}_{t+1}$, $X(t+1) \leftarrow$ RestoreFrom(G_{best})

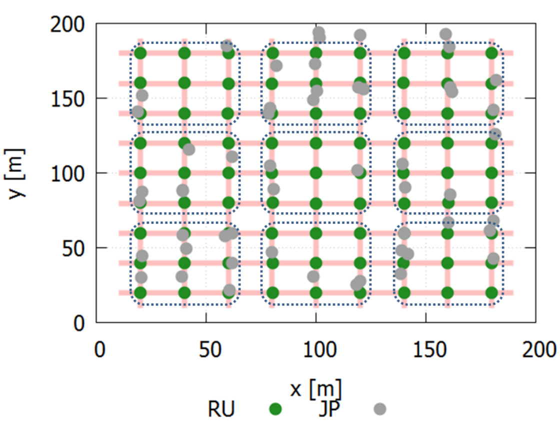


Fig. 4: Simulation condition.

RUs were activated so that the activation probability P_t was satisfied for each group.

The effectiveness of the proposed network architecture under this condition was evaluated by computing the optimum states of RUs and locations of DUs for each time period. The proposed architecture was compared with the conventional static architecture, where the states and locations of RUs and DUs do not change.

B. Simulation results

The computed optimum solution for the proposed architecture is depicted in in Fig. 5. Figs. 5a–5c show the distribution of active RUs, JPs, and candidate edges at each time period. Figs. 5d–5f depict the location of active DUs and the forwarding paths of fronthaul streams. The active DUs are efficiently relocated according to the changes in the distribution of active RUs, and fronthaul streams are forwarded to DUs via wireless relay between RUs.

Fig. 6 shows the number of active RUs and DUs at each time period. The number of active nodes are drastically reduced with the proposed architecture. It was confirmed through the computer simulations that the proposed architecture can efficiently deactivate DUs and RUs by optimizing the location of DUs and wireless links.

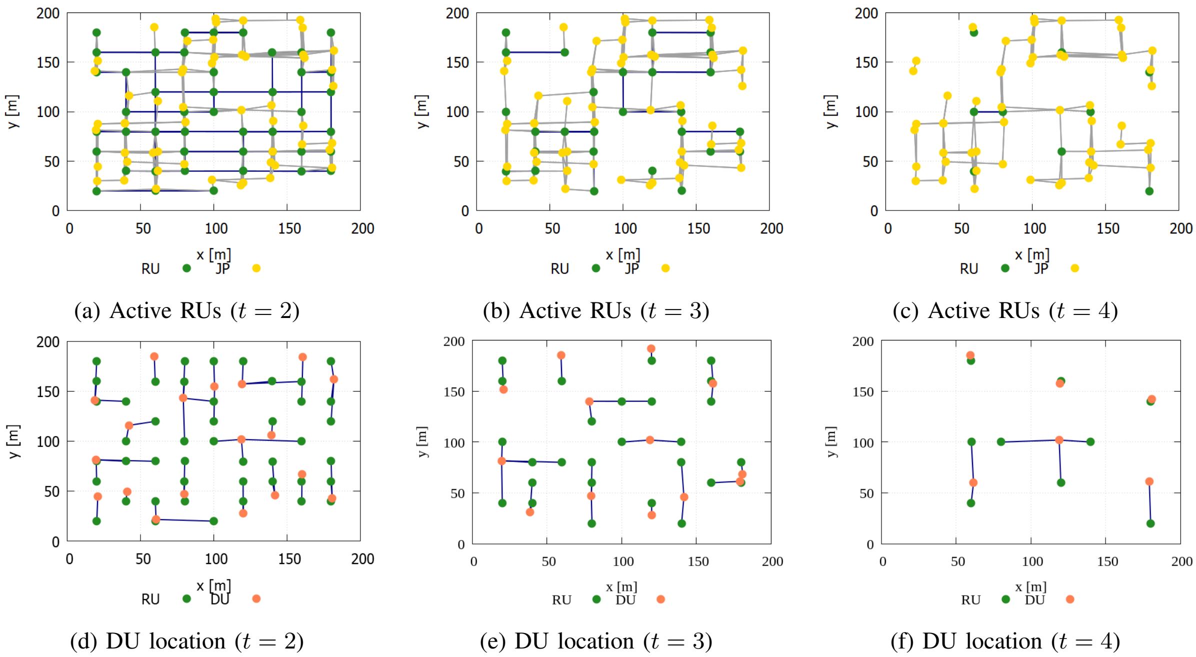
C. Discussion

The proposal in this paper is a concept of adaptive mobile network architecture with moving nodes, which is a deployment scenario of the ABSORB architecture [9]. This is because the idea proposed in [9] was general and not optimized for the C-RAN architecture. Thus, we described the detailed functions and deployment strategy of nodes to efficiently forward mobile traffic in beyond 5G era. The proposal in this paper also includes the activation algorithm of RUs which was not considered in the previous paper.

Although the efficiency of the proposed architecture was confirmed in the simulation, there are remaining challenges. Additional computer simulation needs to be done in other scenarios such as a region that includes workplaces and homes and covers more larger scale. The computational complexity of the proposed algorithm should be evaluated in such a larger scale of problems. In addition, cost evaluation is required to show the financial viability of the proposed architecture considering the infrastructure cost of laying down midhaul optical connections and power consumption of DUs and RUs. The performance of wireless relay fronthaul should also be evaluated as regards the latency and effect of signal interference.

VI. Conclusions

There are significant fluctuations of mobile traffic due to spatio-temporal patterns of human mobility in metropolitan areas. The efficiency and financial viability of mobile networks are drastically deteriorated by such fluctuations. This is because conventional networks are designed to deal with the peak traffic rate, and their capacities are underutilized for most of time at each site. This trend is expected to be intensified in accordance



(a) Active RUs ($t = 2$) (b) Active RUs ($t = 3$) (c) Active RUs ($t = 4$)

(d) DU location ($t = 2$) (e) DU location ($t = 3$) (f) DU location ($t = 4$)

Fig. 5: Distribution of active RUs and DUs in simulation.

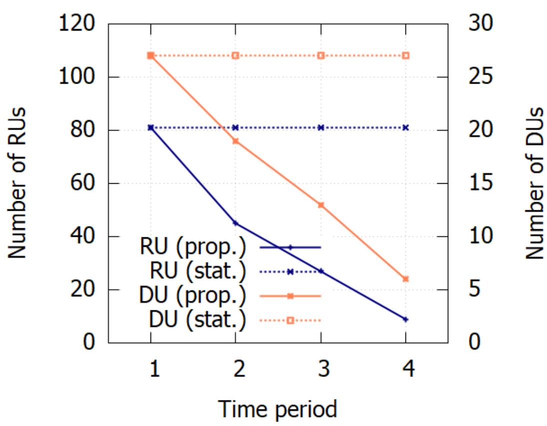


Fig. 6: Number of active nodes.

with the increase in mobile traffic. To address this problem, this paper proposed the concept of adaptive mobile network architecture with moving nodes towards beyond 5G era. With the proposed architecture, the activation states of RUs and locations of moving DUs are flexibly optimized according to the demand distribution. The mobile traffic is forwarded through wireless multihop fronthaul links and optical midhaul links satisfying the latency requirement. We also proposed the scheduling and routing algorithm for optimizing the activation states of RUs, the relocation schedule of DUs, and forwarding paths of fronthaul streams in accordance with the demand distribution. It was confirmed through computer simulations that the proposed architecture can efficiently activate/deactivate RUs and DUs by optimizing the location of DUs and wireless links. The implementation and experiment of moving DUs constitute future work.

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