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A Novel Network Design and Operation for Reducing Transmission Power in Cloud Radio Access Network with Power over Fiber

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***Abstract*—As the number of mobile users and the variety of contents increase, future access networks need to improve their capacity and latency. The concept of Cloud Radio Access Network (C-RAN), which densely deploys a large number of Remote Radio Heads (RRHs), presents a solution to guarantee such communication quality. However, the network still suffers cost issues related to power line supply to a large number of RRHs. Therefore, in this paper, we describe our envisioned C-RAN based on Passive Optical Network (PON) exploiting Power over Fiber (PoF), which is able to provide communication services without external power supply for RRHs. We also describe the conventional network design and operation schemes. Then, power-effective network design and operation approaches to equalize the transmission power of all Optical Line Terminals (OLTs) in the assumed network are presented. Our proposed power-effective network design demonstrates how to deploy the RRHs. Also, based on the proposed design approach, we present a joint control algorithm of the sleep schedule of RRHs and the transmission power of OLTs by considering the distribution of users. Furthermore, the effectiveness of our proposed approach is evaluated through numerical calculation.**

I. Introduction

Recently, the number of mobile users and the variety of contents have increased and this trend is expected to continue in the future. As a result, future access networks need to improve their capacity and latency [1]. Therefore, Cloud Radio Access Network (C-RAN) has been attracting much attention because of its high capacity and low latency [2]. C-RAN deploys and controls a large number of Remote Radio Heads (RRHs) which are antennas that cover small or femto cell, in order to provide high capacity and low latency.

Although C-RAN is expected to be a promising architecture for 5G realization, some issues remain for making it practical. Firstly, while the provision of high-bandwidth link between Central Office (CO) and RRHs is required because the traffic amount of the link is much larger than traditional radio access network (RAN), it is necessary to reduce the installation cost related to the physical link between CO and RRHs. Secondly, C-RAN needs a large number of RRHs to be deployed, so some RRHs must be deployed where there is no external power supply e.g. rural areas. Consequently, in this paper, we introduce Passive Optical Network (PON) exploiting Power over Fiber (PoF), which is able to solve the aforementioned issues [3], as a fronthaul network in our envisioned C-RAN. Our envisioned C-RAN based on PON exploiting PoF, it is possible to deploy with low installation cost because the COs and RRHs are connected by one shared high capacity optical fiber. In addition, external power supplies are unnecessary because electric power is transmitted from the Optical Line Terminals (OLTs) to the RRHs through optical fiber that is used for communication.

However, there is a limitation to supply power through optical-fiber cable. If high optical power is transmitted through an optical fiber, the fiber fuse effect can occur in the optical fiber. This can lead to the destruction of the optical fibers along several kilometers, and can also destroy the network passive components [4]. In addition, if the distribution of users is concentrated in specific area, the transmission power will increase because there are many RRHs which are communicating the users. To avoid this problem, it is necessary to reduce not only the transmission power but also the consumption power of RRHs. For these reasons, we must consider designing power-effective network design and operation approaches.

In this work, we propose a method to deploy the RRHs based on our proposed power-effective network design. In this design, by scattering the RRHs connected to different OLTs, the electric power transmitted from the OLTs does not need to be increased even if users are concentrated. Also, based on the proposed operation approach, we propose a joint control algorithm of the sleep schedule of RRHs and the transmission power of OLTs by considering the information of user distribution. By the proposed scheme, the number of RRHs in active state can be reduced, and as a result, the transmission power of OLTs can also be reduced.

The remainder of this paper is organized as follows. Section II describes our considered C-RAN architecture and the roles of each network component. Section III explains the network system models. Section IV introduces the conventional network design and operation approaches. Section V presents our proposed network design and operation schemes. In section VI, we evaluate the transmission power of OLT through numerical calculation. Finally, the paper is concluded in Section VII.

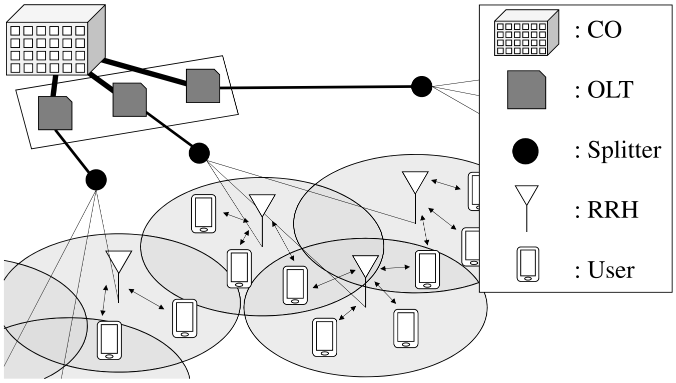

Fig. 1. Our considered cloud radio access network.

II. Considered Network Architecture

In this paper, Cloud Radio Access Network (C-RAN) based on PON exploiting the PoF technology is considered as Fig. 1. As shown in Fig. 1, our considered network is divided into three components, namely CO, OLTs, and RRHs. We suppose that the CO controls the overall operation of the network, i.e., the CO centrally controls all the OLTs and RRHs. The PON transmits data from the CO to each RRH through the OLT and splitter. Additionally, the OLT sends optical power to the RRHs by exploiting the broadcast communication of the PON [5]. Because the OLT broadcasts the data to all RRHs, some RRHs receive unnecessary data, and then, the RRHs convert such data into electric power by PoF [6]. Also, the OLT changes its transmission power by controlling the optical signal power.

In the considered network, an RRH has three parts, namely ONU module, battery module, and antenna module. The optical fiber is connected between the OLT and the ONU module for the communication between them. The OLT receives data from the CO, and then sends the data to the RRH over the optical fiber. If the ONU module of the RRH receives unnecessary data, the Receiver (Rx) component of the ONU module converts the optical signal into electric power. Then, the Rx component sends the electric power to the battery module. The battery module is charged by the electric power and the charged energy is used to operate the Transmitter (Tx) of the ONU module and the antenna. In addition, the RRH has a sleep mode which can reduce the energy consumption of the RRH by turning down specific modules. However, the Rx component of the ONU module connected to the OLT and the battery module are always in active state to receive power from the OLT.

III. System Model

In this section, we demonstrate the system model of our envisioned network.

Firstly, let $L = \{l_1, l_2, \cdots, l_{|L|}\}$ be a set of OLTs and $R_{l_k} = \{r_{l_k,1}, r_{l_k,2}, \cdots, r_{l_k,|R_{l_k}|}\}$ be a set of RRHs which are connected to the OLT l_k. Let R be the set of all RRHs in the network and R can be presented as $R = R_{l_1} \cup R_{l_2} \cup \cdots \cup R_{l_{|L|}}$. The considered area, A, is divided into n_{local} spaces of the same area and let a_p be each divided area. In each area a_p, the RRHs are deployed uniformly as a square grid pattern. Let U_{l_k} be the set of users that are covered by RRHs R_{l_k}. Let U be the set of all users in the network and U can be presented as $U = U_{l_1} \cup U_{l_2} \cup \cdots U_{l_{|L|}}$. In addition, let $U_{r_{l_k,i}}$ be a set of users that are covered by RRH $r_{l_k,i}$. Also we assume that s is the maximum number of users that each RRH can cover. Additionally, each RRH can cover its adjacent RRHs.

With PoF, RRH $r_{l_k,i}$ receives optical power from OLT l_k. Let $P_{l_k}^{r_{l_k,i}}$ be receiving power of RRH $r_{l_k,i}$ and P_{l_k} be transmission power of OLT l_k. We assume that there is no power loss in power conversion and power transmission over optical fiber. In addition, we assume that the splitters do not have any power loss and distribute optical power equally. In this assumption, the receiving power of RRH $P_{l_k}^{r_{l_k,i}}$ can be calculated as

$$P_{l_k}^{r_{l_k,i}} = P_{l_k} / |R_{l_k}|. \tag{1}$$

We assume that the power consumption of RRH does not change regardless of the number of users that connect to the RRH. Let P_{a} and P_{s} be the power consumption of RRHs in active state and sleep state, respectively. Assuming that time is divided into multiple time-slots, the elapsed time at the mth time-slot, t_m, is expressed, as $m \cdot \tau$ with length of time-slot, τ. Additionally, we define $e_{r_{l_k,i}}^{t_m}$, which denotes the amount of battery energy of RRH $r_{l_k,i}$ at instant t_m. The value of $e_{r_{l_k,i}}^{t_m}$ can be expressed as equation (2) and (3),

$$e_{r_{l_k,i}}^{t_m} = e_{r_{l_k,i}}^{t_{m-1}} + (P_{l_k}^{r_{l_k,i}} - P_{\text{a}}) \cdot \tau, \tag{2}$$

$$e_{r_{l_k,i}}^{t_m} = e_{r_{l_k,i}}^{t_{m-1}} + (P_{l_k}^{r_{l_k,i}} - P_{\text{s}}) \cdot \tau. \tag{3}$$

Equation (2) and (3) are the battery energy at t_m when the RRH $r_{l_k,i}$ was in active state and sleep state during the mth time-slot, respectively. Because we assume that the receiving power of RRH is smaller than the power consumption of RRHs in active state but larger than in sleep state, the battery is consumed in active state but charged in sleep state in each time-slot. Note that if $e_{r_{l_k,i}}^{t_{m-1}} + (P_{l_k}^{r_{l_k,i}} - P_{\text{a}}) \cdot \tau < 0$, the RRH should enter the sleep state during the mth time-slot.

IV. Conventional Network Design and Operation Approaches

In this section, we present the conventional network design and operation approaches. First, a conventional RRH deployment scheme is presented. Then, we demonstrate the RRH sleep mechanism and transmission power of OLT in the considered RRH deployment.

A. RRH deployment

As shown in Fig. 2, we divide A into nine equal spaces. Therefore, in this case, $n_{\text{local}} = 9$ and the divided areas are presented as a_k. Also, we deploy the RRHs R_{l_k} which are connected to the same OLT in the same area a_k. In each area, we deploy the RRHs uniformly as a square grid pattern. In addition, the pattern of deployment of RRHs is the same in all areas. This conventional network design is called Gathered

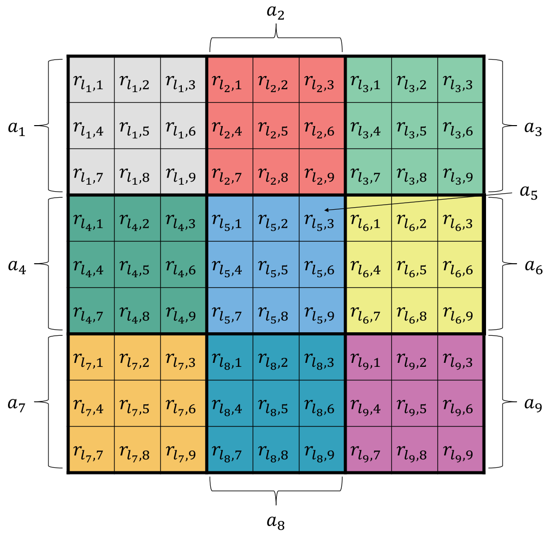

Fig. 2. Gathered Distribution of RRHs.

Procedure 1 Conventional transmission power control

$R^{\text{act}}_{l_k} \leftarrow \{r_{l_k,i} \in R_{l_k} \mid e^{t_{m-1}}_{r_{l_k,i}} + (P^{r_{l_k,i}}_{l_k} - P_{\text{a}}) \cdot \tau \geq 0\}$
$D^{\text{act}}_{l_k} \leftarrow \emptyset$
/* Start RRH allocation phase */
while $R^{\text{act}}_{l_k} \neq \emptyset$ and $U_{l_k} \neq \emptyset$ **do**
  Choose $r_{l_k,i} \in R^{\text{act}}_{l_k}$ which has maximum $e^{t_{m-1}}_{r_{l_k,i}}$
  $W_{r_{l_k,i}} \leftarrow \{r_{l_k,i'} \in R_{l_k} \mid \text{RRHs adjacent to } r_{l_k,i}\}$
  $(U_{l_k}, D^{\text{act}}_{l_k}) \leftarrow \text{RSC}(r_{l_k,i}, U_{r_{l_k,i}}, U_{l_k}, D^{\text{act}}_{l_k}, W_{r_{l_k,i}}, s)$
  $R^{\text{act}}_{l_k} \leftarrow R^{\text{act}}_{l_k} \setminus \{r_{l_k,i}\}$
end while
$D^{\text{slp}}_{l_k} \leftarrow R_{l_k} \setminus D^{\text{act}}_{l_k}$
Decide P_{l_k} according to equation (4)

Distribution of RRHs (GDR). In the GDR, the RRHs that are connected to the same OLT are concentrated at one area. By the GDR, it is possible to reduce the cost to install fiber cable because the distance between splitter and RRHs can be short due to the concentration of RRHs in one area. As a result, most networks are currently designed based on GDR as in Fig. 2.

B. Joint control of RRH sleep and transmission power of OLT

Here, we demonstrate a network operation procedure for the conventional RRH deployment, GDR. In this procedure, the CO lets some RRHs enter sleep state and controls the coverage area of RRHs in active state to make those RRHs cover the users that were formerly connected to the RRHs in sleep state. Additionally, the CO controls the transmission power of OLTs according to the number of RRHs in sleep state and that in active state.

Procedure 1 and 2 are executed separately for each OLT. Firstly, among the RRHs which are connected to the OLT l_k, the CO checks the RRHs that can be in active state during the mth time-slot. Then, the CO adds the RRHs that are able to be in active state during the mth time-slot to the set $R^{\text{act}}_{l_k}$. Let $D^{\text{act}}_{l_k}$ be the set of RRHs which are decided to be in active state by the CO and, initially, $D^{\text{act}}_{l_k}$ is an empty set. Next, while $R^{\text{act}}_{l_k}$ and U_{l_k} are not empty sets, the CO executes the RRH allocation phase. In the RRH allocation phase, firstly, the CO chooses the RRH that has the highest battery energy. Let $W_{r_{l_k,i}}$ be the set of RRHs that are adjacent to RRH $r_{l_k,i}$. Here, adjacent RRHs are defined as the RRHs connected to OLT l_k, and adhere to RRH $r_{l_k,i}$. In the next step, the CO executes RSC. After the process of the RSC, the CO excludes RRH $r_{l_k,i}$ from the set $R^{\text{act}}_{l_k}$.

Procedure 2 RSC(r, U, U', D, W, s)

$s' \leftarrow |U|$, $U' \leftarrow U' \setminus U$
/* Start user allocation phase */
while $W \neq \emptyset$ and $s' < s$ **do**
  Choose $w_j \in W$ which has minimum $e^{t_{m-1}}_{w_j}$
  if $s' + |U_{w_j}| \leq s$ **then**
    $s' \leftarrow s' + |U_{w_j}|$, $U' \leftarrow U' \setminus U_{w_j}$
    $U_{w_j} \leftarrow \emptyset$
  end if
  $W \leftarrow W \setminus \{w_j\}$
end while
if $s' > 0$ **then**
  $D \leftarrow D \cup \{r\}$
end if
return U', D

In RSC, shown as Procedure 2, s' represents the number of users that RRH r has accepted. First, the CO adds the number of users connected to RRH r to s' and then, the CO excludes those users from the set U'. While W is not an empty set and s' is smaller than s, the CO executes the user allocation phase. In the user allocation phase, the CO chooses an RRH w_j which has the least battery energy. If the RRH r can still accept the users that RRH w_j can cover, RRH r covers those users and then, that number of users is added to s'. Also, the CO excludes the users that RRH w_j can cover from the set U' and then empties the set U_{w_j}. After these processes for RRH w_j are finished, the CO excludes the RRH w_j from the set W. After all process of the user allocation phase is ended, the CO adds RRH r to the set D if s' is larger than 0. When s' is larger than 0, it means that RRH r is connected to at least one user. Finally, the RSC returns U' and D.

After process of the RRH allocation phase in Procedure 1, the CO determines the set of RRHs which are in sleep state during the mth time-slot by excluding the RRHs which are in active state from the set of RRHs R_{l_k}. Finally, the CO determines the transmission power of OLT l_k, P_{l_k} as

$$P_{l_k} = |D^{\text{act}}_{l_k}| \cdot P_{\text{a}} + |D^{\text{slp}}_{l_k}| \cdot P_{\text{s}}. \tag{4}$$

C. Impact of user distribution on transmission power of OLT

If the distribution of users is concentrated, for example when users are concentrated in one area a_k, $|U_{l_k}|$ is drastically high. Therefore, the number of RRHs in active state connected to OLT l_k, $|D^{\text{act}}_{l_k}|$, will be high. Also, the RRHs are in active state for a longer period of time because there are many users

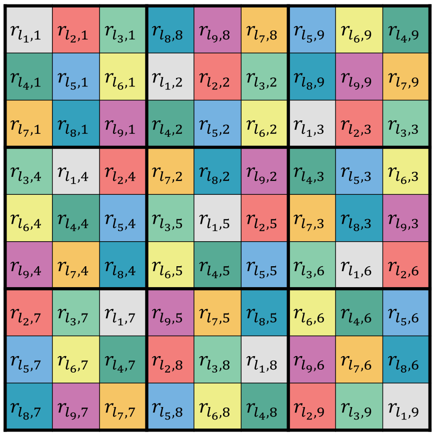

Fig. 3. An example of Scattered Distribution of RRHs.

Procedure 3 Proposed transmission power control

$R^{\text{act}} \leftarrow \{r_{l_k,i} \in R \mid e^{t_{m-1}}_{r_{l_k,i}} + (P^{r_{l_k,i}}_{l_k} - P_{\text{a}}) \cdot \tau \geq 0\}$
$D^{\text{act}} \leftarrow \emptyset$
/* Start RRH allocation phase */
while $R^{\text{act}} \neq \emptyset$ and $U \neq \emptyset$ **do**
  Choose $r_{l_k,i} \in R^{\text{act}}$ which has maximum $e^{t_{m-1}}_{r_{l_k,i}}$
  $W_{r_{l_k,i}} \leftarrow \{r_{l_{k'},i'} \in R \mid$ RRHs adjacent to $r_{l_k,i}\}$
  $(U, D^{\text{act}}) \leftarrow \text{RSC}(r_{l_k,i}, U_{r_{l_k,i}}, U, D^{\text{act}}, W_{r_{l_k,i}}, s)$
  $R^{\text{act}} \leftarrow R^{\text{act}} \setminus \{r_{l_k,i}\}$
end while
for $k = 1$ to $k = n_{\text{local}}$ **do**
  $D^{\text{act}}_{l_k} \leftarrow D^{\text{act}} \cap R_{l_k}$
  $D^{\text{slp}}_{l_k} \leftarrow R_{l_k} \setminus D^{\text{act}}_{l_k}$
end for
Decide P_{l_k} according to equation (4)

who are communicating through the RRHs. As a result, the transmission power of OLT P_{l_k} greatly increases. Additionally, the fiber fuse effect may occur, which can destroy the optical fiber and the network passive components.

V. Proposed Network Design and Operation Schemes

In this section, we describe our proposed scheme. First, we show our proposed RRH deployment strategy to reduce the transmission power of OLT in the environment where user distribution is concentrated. Next, we present a joint control scheme of the sleep period of RRH and transmission power of OLT, which is adequate to the proposed RRH deployment.

A. Scattered Distribution of RRHs

To solve the problem where the transmission power of OLT increases and the fiber fuse effect may occur when the distribution of users is concentrated, we propose the RRH deployment called Scattered Distribution of RRHs (SDR). In the SDR, we deploy the RRHs as uniformly as possible in the network. Fig. 3 shows one example of such a distribution. Note that in the GDR demonstrated in Fig. 2, the RRHs connected to the same OLT are marked with the same color and gathered in the same area. On the contrary, in Fig. 3, the same color marked RRHs are scattered to different areas so that in each small area (3x3 size), we have exactly 9 different colors. In this case, if an OLT connected to the same RRHs is placed in the middle among those RRHs, all OLTs will be close to each other and also close to the center of the network connecting them. In addition, among the RRHs connected to the same OLT, the Euclidean distances between an RRH and another RRH close to it are almost equal for all OLTs. In this figure, we can see that the RRHs deployed in an area are all connected to different OLTs. In the conventional scheme, if the distribution of users is not balanced over the network, for example when users are concentrated in area a_1, the number of users connected to OLT l_1, $|U_{l_1}|$, increases drastically. However in our proposed scheme, the RRHs in a_1 are connected to different OLTs, so $|U_{l_1}|$ does not increase as much as in the conventional scheme.

B. Proposed network operation algorithm

In the conventional network design, the algorithm only considers RRHs which are connected to the same OLT because RRHs that are connected to different OLTs do not cooperate with each other in the scheme. In the proposed network design, however, the algorithm also considers RRHs which are connected to different OLTs because there are no adjacent RRHs that are connected to the same OLT. By cooperating the RRHs connected to different OLTs, the battery energy is used more effectively, i.e., the RRHs which have higher battery energy can cover for other RRHs which have lower battery energy.

As shown in Procedure 3, firstly, among the RRHs, the CO checks the RRHs that can be in active state during the mth time-slot. Then, the CO adds the RRHs that are able to be in active state during the mth time-slot to the set R^{act}. Let D^{act} be the set of RRHs which are decided to be in active state by the CO and, initially, D^{act} is an empty set. Next, while R^{act} and U are not empty sets, the CO executes the RRH allocation phase. In the RRH allocation phase, firstly, the CO chooses the RRH that has the highest battery energy. In the proposed procedure, $W_{r_{l_k,i}}$ can include not only the RRHs connected to OLT l_k but also the RRHs connected to other OLTs. In the next step, the CO executes RSC according to Procedure 2. After process of the RSC, the CO excludes RRH $r_{l_k,i}$ from the set R^{act}.

After processes of the RRH allocation phase, the CO counts the RRHs $D^{\text{act}}_{l_k}$ which are connected to each OLT l_k and in active state. And then, the CO determines the set of RRHs in sleep state $D^{\text{slp}}_{l_k}$. Finally, the CO determines the transmission power of OLT l_k, P_{l_k} according to equation (4).

VI. Perfomance Evaluation

In this section, we evaluate the transmission power of the OLT in the conventional and proposed schemes through numerical analysis.

TABLE I
THE DISTRIBUTION OF USERS

The Area	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
The Number of Users	22	72	44	42	168	78	14	36	24

TABLE II
NUMERICAL ANALYSIS RESULTS

The OLTs		l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8	l_9
The Number of RRHs in Active State	Gathered Distribution of RRHs	2	5	3	3	9	5	1	3	2
	Scattered Distribution of RRHs	3	4	3	4	4	4	3	4	3
Transmission Power of OLTs [W]	Gathered Distribution of RRHs	7.9	10.3	8.7	8.7	13.5	10.3	7.1	8.7	7.9
	Scattered Distribution of RRHs	8.7	9.5	8.7	9.5	9.5	9.5	8.7	9.5	8.7

A. Evaluation Environment

In this evaluation, we evaluate the transmission power of OLTs in the GDR and SDR, and compare the transmission power in those two cases. To assume the environment where the distribution of users is concentrated in a specific area, we set the distribution of users as Table I. Based on Table I and Procedure 1, 2 and 3, we derive the number of RRHs in active state as Table II. For example, in area a_5, there are 168 users in the area. In the GDR, there are only RRHs which are connected to OLT l_5 in area a_5 so all RRHs in area a_5 should be in active state. In comparison with, in the SDR, we considered users in all areas and allocated the RRHs as balanced as possible by Procedure 3. As a result, the number of RRHs in active state in the SDR is roughly alike.

We set the number of OLTs as 9, the number of RRHs connected to each OLT as 9, the number of divided area as 9, and the interval of time-slot as 10 second. The energy consumption of RRH in the sleep state and that in active state are set to 0.7W [7] and 1.5W [8], respectively. Also, the maximum users that an RRH is able to connect is set to 20.

B. Transmission power of OLT in the two cases of distribution

Table II and Fig. 4 shows the transmission power of OLTs in each case, GDR and SDR. From the result, the transmission power of OLT l_5, P_{l_5}, is greatly higher than the others in the GDR. On the other hand, in the SDR, the transmission power of all OLTs are approximately the same and they are lower than P_{l_5}. This result demonstrates that if the users are gathered in specific area and there are RRHs which are connected to the same OLT as in the GDR, the number of RRHs connected to the same OLT in active state increases, so the transmission power of OLT also increases. In the SDR, even if the users are gathered in specific area, the users are connected to RRHs that are connected to different OLTs. Therefore, because the RRHs in active state are connected to different OLTs, the transmission power of OLTs are almost equal. As a result, our proposed scheme decreases the maximum transmission power of OLT even in cases where the distribution of users is concentrated in the network.

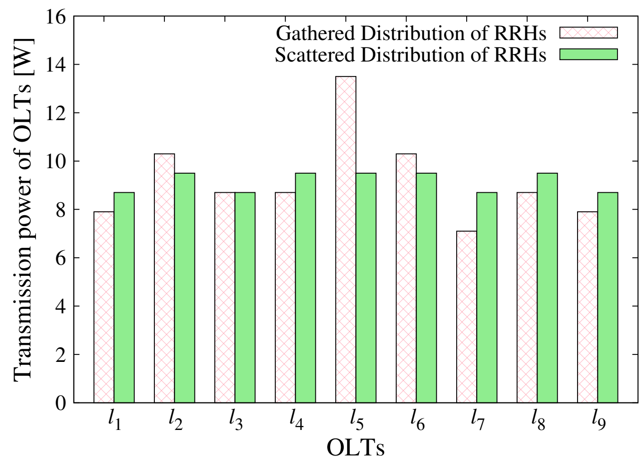

Fig. 4. The transmission power of OLTs in the GDR and SDR.

VII. CONCLUSION

As the number of mobile users and the variety of contents increase, future access networks need to improve their capacity and latency. In this paper, we focused on C-RAN based on PON exploiting PoF. The assumed network can supply power to RRHs without external power. In the conventional network design and operation schemes, however, the transmission power of OLT greatly increases if the users are gathered in specific area. We proposed power-effective network design and operation approaches to equalize the transmission power of all OLTs. Then we evaluated the transmission power of OLTs in case of conventional and proposed network design and operation approaches. The numerical result demonstrated the effectiveness of our proposed scheme.

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