A Cloud Radio Access Network with Power over Fiber toward 5G Network: QoE-Guaranteed Design and Operation

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***Abstract*—While the concept of Cloud Radio Access Networks (C-RANs) presents a promising solution to provide required Quality of Service (QoS) for the future network environment, i.e., more than 10Gbps capacity, less than 1ms latency, and connectivity for numerous devices, it is still susceptible to Quality of Experience (QoE). Until now, only a few researchers considered the design and operation of C-RANs based on QoE. In this article, we describe our envisioned C-RAN based on Passive Optical Network (PON) exploiting Power over Fiber (PoF), which can be installed with low installation cost and is capable of providing communication services without external power supply for Remote Radio Head (RRH), and describe QoE requirement on the envisioned network. For all users in the envisioned network to satisfy their QoE, effective network design and operation approaches are then presented. Our proposed design and operation approaches demonstrate how to construct the envisioned network, i.e., numbers of RRHs and Optical Line Terminals (OLTs), and a sleep scheduling of RRHs for an energy-efficient optical power transmission.**

***Index Terms*—Cloud Radio Access Network (C-RAN), Passive Optical Network (PON), Power over Fiber (PoF), Quality of Experience (QoE), network design and operation.**

I. Introduction

Fifth-Generation (5G) mobile networks need to support new emerging services with a high network capacity, as well as deliver reduction in both delay and energy consumption, e.g., three-dimensional video streaming, Augmented Reality (AR), data collection and real-time control from/to a massive number of devices for realizing the Internet of Things (IoT), and so forth. The use of super-dense small cell deployments and centralized resource management, i.e., cloud computing, is becoming a popular concept for achieving the aforementioned 5G requirements [1]. While small cells are capable of providing good quality communication between Remote Radio Head (RRH) and users, the users are vulnerable to interference from inter-cells that results in the decrease of network capacity. Therefore, Cloud Radio Access Networks (C-RANs), wherein a central office (CO) connects with RRHs via front-haul links and controls traffic for mitigating inter-cell interference, has been attracting much attention [2].

Although C-RAN is expected as an effective solution, a few issues remain in its architecture. First, since the amount of traffic between the CO and RRHs is much higher in contrast with the traditional RAN, high-speed links are required. However, setting up private optical-fiber cables to each RRH indicates a high installation cost. Second, some RRHs should be deployed in places lacking external power supply in order to fulfill the desired coverage. To this end, Passive Optical Network (PON) exploiting Power over Fiber (PoF) is recognized as the key enabling technology [3]. In PON with PoF, an optical splitter is used to enable a single optical-fiber cable to serve multiple RRHs, and an Optical Line Terminal (OLT) that aggregates multiple RRHs supplies power to RRHs through the optical-fiber cable.

Moreover, the emergence of various species of services indicates the need to improve the overall performance from a user's perspective. Indeed, telecom-operators and service providers are now switching their focus from network Quality of Service (QoS) to user Quality of Experience (QoE). According to many investigations accomplished by [4], [5], the QoE value has slightly different measurement from QoS value since QoE is determined by the user satisfaction. On the other hand, the QoE model on C-RAN including our considered network has not yet been established while QoS on Long Term Evolution (LTE) networks has been already defined by 3GPP TS 23.203. For these reasons, QoE assurance model, and QoE-guaranteed network design and operation for our considered C-RAN is absolutely imperative.

In contrast with the existing works in [6], [7] that employ resource management approaches, e.g., spectrum management for RRHs [6] and End-to-End (E2E) network management with Software Defined Networking (SDN) and Network Function Virtualization (NFV) [7], in this article, we aim to demonstrate design and operation methodologies for guaranteeing certain QoE levels in our considered C-RAN. First, we present a QoE assurance model based on QoS on our considered C-RAN. This model is used to guarantee QoE of users. Additionally, we demonstrate the QoE-guaranteed network design methodology, which decides the number of required RRHs and OLTs in a given area, based on the QoE assurance model. Furthermore, we present a joint control method of RRH sleep and transmission power of OLTs to reduce the

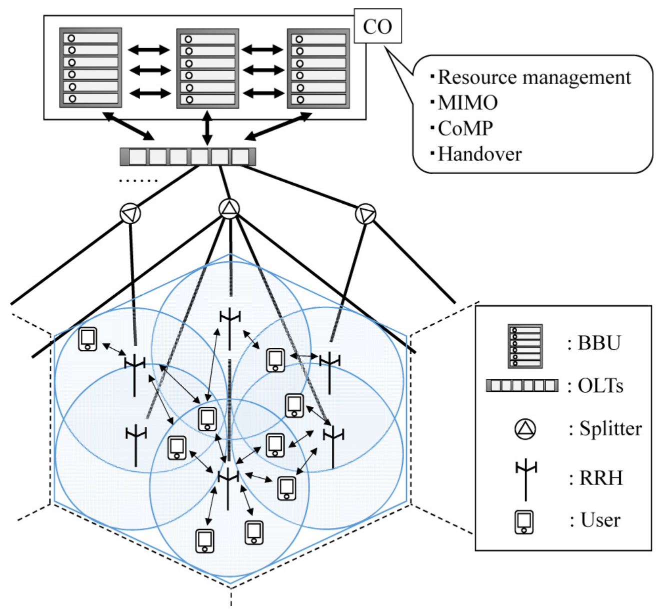

Fig. 1. Our considered cloud radio access network.

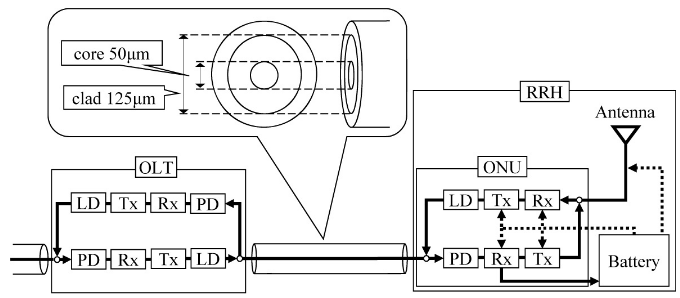

Fig. 2. Power over fiber (PoF) in our considered network.

transmission power while satisfying the individual QoE.

The remainder of this article is organized as follows. Section II describes our considered C-RAN architecture and the roles of each network component. QoE assurance models to establish QoE-guaranteed network design and operation methodologies are elucidated in Section III. Section IV presents the QoE-guaranteed network design and operation methodologies. Finally, the article is concluded in Section V.

II. Considered Network Architecture

C-RAN is a prominent area where QoE assurance model is quite important. However, researchers have not considered any effective QoE assurance model for C-RAN, particularly using PON. So, before discussing our envisioned QoE assurance model, it is necessary to describe which network model we consider to provide QoE guarantee to the users.

Our supposed C-RAN is based on PON exploiting the PoF technology as shown in Fig. 1. As illustrated in the figure, our assumed network can be roughly divided into three parts, namely the CO, the OLT, and the RRH. The overall operation of the network is controlled by the CO. In other words, we assume that the CO is able to centrally control the RRHs. The PON broadcasts the data from the CO to each RRH through splitter from the OLT. The OLT uses PoF to send electric power to the RRHs. As mentioned earlier in Section I, the key feature of this network is its ability to operate with the RRHs using PoF, which exploits the broadcast nature of the PON whereby unnecessary data are transmitted by the PON to some of the RRHs. In the remainder of the section, the roles of CO, OLT, and RRH are described.

A. Central Office - CO

C-RAN offers a whole-new RAN architecture concept whereby the Base-Band Units (BBUs) of different base-stations are co-located in the same CO [8]. This is referred to as the BBU hostelling or centralization at the CO. In BBU hostelling, there exists a BBU which handles all the RRHs located at the remote site, and the BBUs are able to communicate with each other within the BBU hostel through the BBUs. The CO is assumed to control both the wireless and optical parts in the considered C-RAN. In the wireless part, the CO intensively controls the RRHs. Additionally, the CO is responsible for resource management and other tasks involving Multiple Input Multiple Output (MIMO), Coordinated MultiPoint (CoMP), and handover. On the other hand, in the optical part, the CO performs bandwidth control between the OLT and the RRHs. Furthermore, the amount of electric power, which is sent from the OLT to the RRHs, is also decided by the CO.

B. Optical Line Terminal - OLT

In our work, we consider the OLT to integrate the RRHs without controlling them and we assume centralized control of the RRHs by the CO. Basically, the OLT forwards the data, that it receives from the CO, to the RRHs. In addition, the OLT sends electric power to the RRHs. This is done by exploiting the broadcast communication feature employed by the PON [9]. Because the OLT broadcasts the data received from the CO to all the RRHs, some RRHs receive the data which were not meant for those RRHs. This means that some RRHs receive "unnecessary data" which are converted to electric power by the PoF technology. The OLT is, therefore, used by the CO to supply the electric power to the RRHs by using the unnecessary data.

C. Remote Radio Head - RRH

In the considered C-RAN, a large number of distributed RRHs are assumed. As shown in Fig. 2, each RRH has three parts, namely the ONU module, battery module, and antenna module. Furthermore, Fig. 2 illustrates how the ONU module of a RRH communicates with the OLT. As shown in the figure, the optical fiber used for communication between the OLT and the ONU module of the RRH is assumed to be a multi-mode fiber having core diameter of 50μm and clad diameter of 125μm [10]. In case of downlink communication, the OLT receives the data from the CO at its Rx component [11], then sends the data to its Tx component, then sends it to its Laser Diode (LD). The LD of the OLT converts the data into optical signal, which is transmitted over the fiber to the RRH. In case of receiving unnecessary data, the Photo Diode (PD) of the RRH's ONU module converts the optical signal into electric power, which the Rx component of the ONU sends to the battery module. The battery module stores the received power from the OLT over the fiber (i.e., PoF). The battery module provides the electric power for ONU and antenna modules to function. In addition to this, each RRH has a sleep mode via which it can reduce energy consumption by turning down specific modules. However, the Rx part of the ONU module and the battery module of the RRH remain active all the time to get electric power from the OLT.

III. QoE Assurance Model

In this section, we demonstrate the QoE assurance model, which is used to guarantee the QoE level. First, we discuss an important factor to measure the QoE value from the network and users' perspective. Then, we describe our considered QoE assurance models. Finally, key challenges pertaining to the use of the QoE assurance model are discussed.

A. What is the important factor to measure QoE?

The subjective and objective measurement approaches are considered as basic QoE measurement framework [12]. Subjective measurement is carried out by evaluating experienced service based on the user's subjective perception. Since the user's subjective perception is directly reflected to QoE in real-time, this approach achieves higher accurate performance. However, in order for the user to achieve QoE, detailed diagnosis is required to reveal causal factors of QoE degradation. Therefore, the approach may control user QoE by using the causal factors provided from the users. In contrast with the aforementioned approach, the objective measurement aims at modeling the subjective and user QoE based on theoretical methodology (i.e., learning algorithms and mathematical formulas) using objective factors of networks, applications, devices, and user context. Since the major factor that affects the subjective user QoE is the network QoS, QoE measurement based on QoS is recognized as a key approach.

For an accurate QoE/QoS measurement and management, end-to-end (E2E) communication should be considered. The future 5G network can be classified into the front-haul, back-haul, and core networks. The back-haul and core networks, which consist of wireline technologies, i.e., Asynchronous Transfer Mode (ATM), Ethernet, and Multi Protocol Label Switching (MPLS), are capable of providing accurate QoS services with IntServ and DiffServ defined by IETF RFC 1633 and 2474. On the other hand, since the various wireless and wireline technologies are accommodated in the front-haul network, the QoS control mechanism has not yet been established. This implies that the QoS of the front-haul network has a greater impact on the user's QoE. This article, therefore, focuses on QoE modeling on the front-haul network.

In addition to QoS, the energy consumption of user devices should be considered as a main factor to model subjective QoE [13]. This is because users often exhibit dissatisfaction at the decline in their own QoE due to the dead battery of devices. Besides, current advancement of miniaturized computer escalates the significance of this issue. On the other hand, the user's QoE from the energy perspective changes depending on the experienced services. For instance, most of the users might allow higher energy consumption in case of video streaming services compared with voice calling services.

Consequently, it is obvious that the QoS on the front-haul network and energy consumption of user devices are the main factors to measure QoE.

B. How to construct QoE assurance model

Here, we demonstrate QoE assurance models that indicate QoS and energy consumption required to satisfy QoE, where the packet loss ratio and amount of assigned resources are considered as the QoS factors. The packet loss and amount of assigned resources are the factors on the network side, and QoE is affected by the network factors. To construct the QoE assurance models, the qualitative relationship between each factor and QoE value (e.g., a Mean Opinion Score (MOS)) is demonstrated. MOS is a subjective quality rating method, which evaluates a quality with 5 stages. Therefore, we evaluate QoE with 5 stages. Then, three QoE assurance models based on the aforementioned relationship are presented.

In Fig. 3, each blue box demonstrates the general shape of the mapping curve between QoE and each factor, i.e., the packet loss ratio, amount of assigned resources, and energy consumption. On the x axis, a factor is denoted, while the y axis indicates a QoE value. In general, as shown in Fig. 3, the lower the packet loss ratio and energy consumption (or the larger the assigned resource), the higher the QoE value. Additionally, the shape of the curve changes depending on the factors. Besides, as mentioned in [12], each curve is split in the following areas, separated by thresholds (e.g., in case of the packet loss ratio, a_{ST} and a_{RT} denote the strict threshold and the relaxed threshold, respectively).

Constant Optimal QoE Area: For users, lower packet loss ratio and energy consumption (or larger amount of assigned resources) are desirable. On the other hand, a slight worsening of these factors may not affect the QoE at all. For instance, small packets loss can be recovered with certain communication technologies (e.g., retransmission control, erasure coding, and so forth), without the user noticing the QoE degradation. Since the service quality might not be improved even if more resources than required are assigned, there exist specific thresholds on the amount of assigned resources. In case of the lower energy consumption in communication, users cannot notice the slight exhaustion of the remaining battery. Therefore, all users absolutely satisfy their QoE if each factor is lower (or larger) than each strict threshold, a_{ST}, b_{ST}, and c_{ST}.

Sinking QoE Area: When the factor exceeds the strict threshold, the QoE level cannot be further maintained. While some users may still maintain their satisfaction when factors are approximate to the strict thresholds, most users drastically decrease their own satisfaction as soon as the debasement of factors grow (i.e., when factors reach the relaxed thresholds, a_{RT}, b_{RT}, and c_{RT}).

Unacceptable QoE Area: As soon as each factor outreaches each relaxed threshold, the subjective perception of users becomes unacceptably negative. Additionally, providing service becomes difficult with the much further increase of packet loss ratio or the much further decrease of assigned resources.

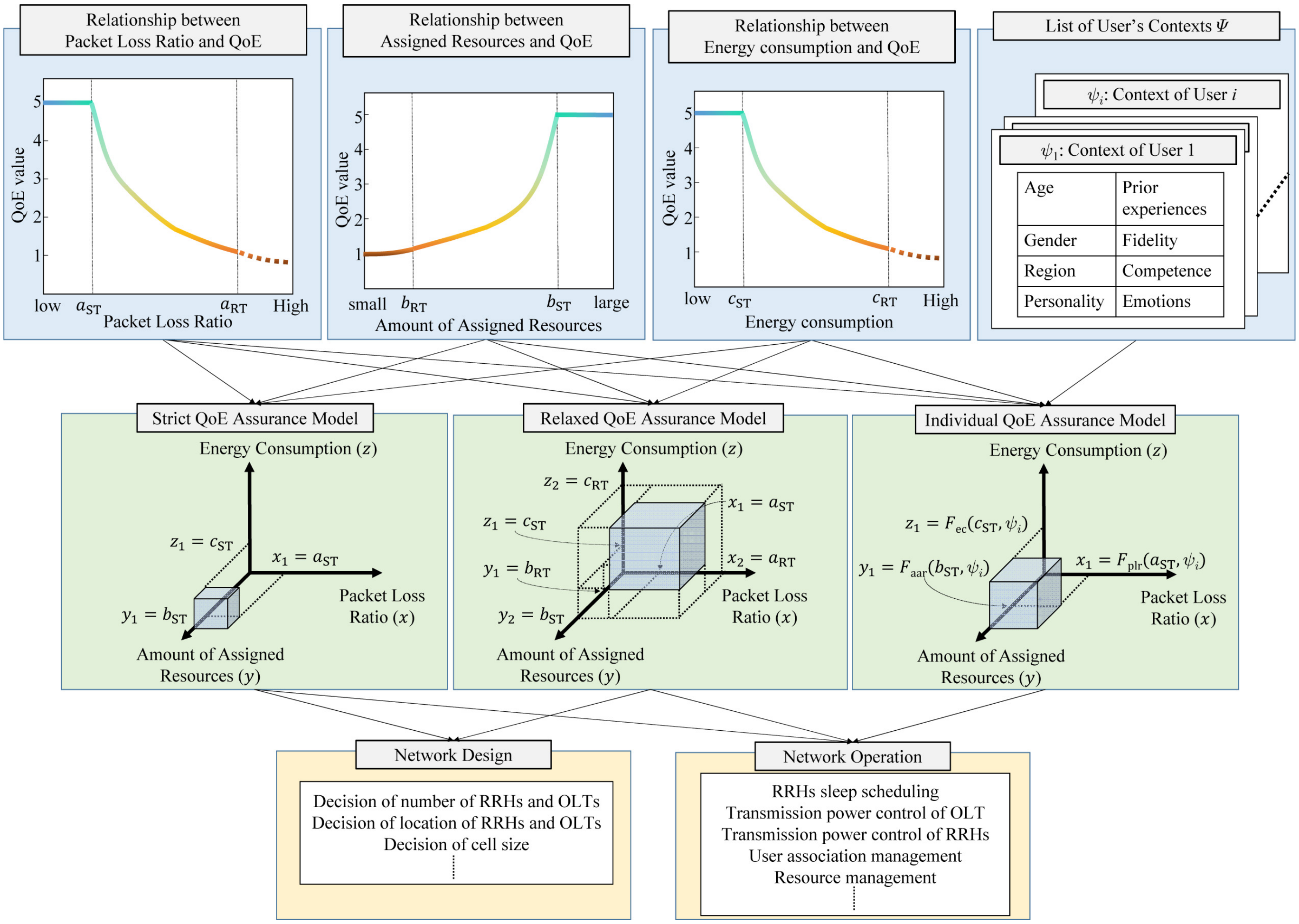

Fig. 3. Our envisioned QoE assurance models based on the packet loss ratio, amount of assigned resources, energy consumption of devices, and user context, which are able to guarantee QoE.

In the remainder of this section, we demonstrate our envisioned QoE assurance model, which is used for facilitating development of QoE-oriented network design and operation strategy. The green boxes in Fig. 3 depict our envisioned QoE assurance model. In our envisioned QoE assurance model, x, y, and z axes denote the packet loss ratio, the amount of assigned resources, and the energy consumption, respectively, while the blue cube indicates the range of each factor, which is required to satisfy the QoE level. Moreover, the QoE assurance model can be classified into three models, which are described further below.

Strict QoE Assurance Model: This model is used to guarantee all user's QoE. To this end, this model sets the range of acceptable value of each factor to the constant optimal QoE area. In other words, for guaranteeing QoE strictly, the actual packet loss ratio and energy consumption should be lower than a_{ST} and c_{ST}, respectively, while the actual amount of assigned resources should be larger than b_{ST}.

Relaxed QoE Assurance Model: Since the strict QoE assurance model requires high quality of each factor, the relaxed QoE assurance model, which eases the restrictions on the required quality, is introduced. Since this model sets the range of acceptable value of each factor to the sinking QoE area, QoE of some users can be guaranteed with lower quality of each factor.

Individual QoE Assurance Model: Since the aforementioned models do not deal with the individual user context, an individual QoE assurance model from the micro view should be constructed to guarantee the QoE of individual users. In Fig. 3, the top-right box depicts a list of user contexts. In order to construct thresholds for user i, the specific context of user i, ψ_i, is used. For instance, when we construct an individual QoE assurance model based on the strict model, the strict thresholds, a_{ST}, b_{ST}, and c_{ST}, are redefined as functions $F_{\mathrm{plr}}(a_{\mathrm{ST}}, \psi_i)$, $F_{\mathrm{aar}}(b_{\mathrm{ST}}, \psi_i)$, and $F_{\mathrm{ec}}(c_{\mathrm{ST}}, \psi_i)$, respectively.

How these models are used for the appropriate network design and operation, respectively, are described in the remainder of the section.

C. Challenging issue: how to use QoE assurance model

Our envisioned QoE assurance models are used to decide how our envisioned network is deployed and operated. In Fig. 3, the yellow boxes summarize research issues on QoE-guaranteed network design and operation. While the network design aims to construct a cornerstone to guarantee the entire QoE from the macro view, the network operation makes it possible to guarantee the QoE of individual users from micro view. Therefore, QoE level can be guaranteed exactly by using both technologies.

QoE-guaranteed network design is capable of providing communication service with a certain QoE level. For development of QoE-guaranteed network, the number of RRHs and OLTs, location of RRHs and OLTs, and cell size of RRHs are determined based on the strict QoE assurance model or relaxed QoE assurance model. However, since these QoE assurance models do not take into account individual subjective perception, some users might become unhappy.

QoE-guaranteed network operation is able to dynamically control QoE of individual users even if a network environment changes such as the change of user density with different times in a day or user mobility. Therefore, the users that are dissatisfied at QoE improve their own QoE with the network operation. For the adequate network operation, the RRHs sleep scheduling, user association management, transmission power control of OLTs and RRHs, and resource management should be considered. In contrast with the network design, for the development of network operation technologies, the individual QoE assurance model is also used.

IV. Envisioned QoE-Guaranteed Network Design and Operation

In this section, we demonstrate the network design and operation approaches based on the QoE assurance model. First, we derive the relationship between the number of RRHs and QoE value. Then, we demonstrate the QoE-guaranteed network design based on the derived relationship. The network operation method is also presented to reduce the transmission power of OLTs while satisfying the QoE value. Furthermore, we confirm the effectiveness of our proposed operation method through numerical calculation.

A. The relationship between the number of RRHs and QoE

Here, we demonstrate the relationship between the number of RRHs and QoE. In this article, we focus on the QoE value related to the packet loss ratio. In our assumed network, each RRH is deployed in a grid pattern. Assuming that the user distribution is uniform, the average communication distance between RRHs and users, x, is decided with the number of RRHs, N_{rrh}. Additionally, the average communication distance affects the average packet loss ratio, as indicated by (19) in [14], where we model the m factor in (19) with the continuous value of x, as $m = 1.5^{150/x} - 0.5$. Furthermore, since the QoE value is determined with the packet loss ratio as indicated by (5) in [12], we can derive the QoE value from the number of RRHs.

Fig. 4 shows the QoE value in different numbers of RRHs. To derive this result, the field size and the maximum communication range of each RRH are set to 500m and 400m, respectively. It is clear from this graph that the QoE value can be improved with the increase of the number of RRHs.

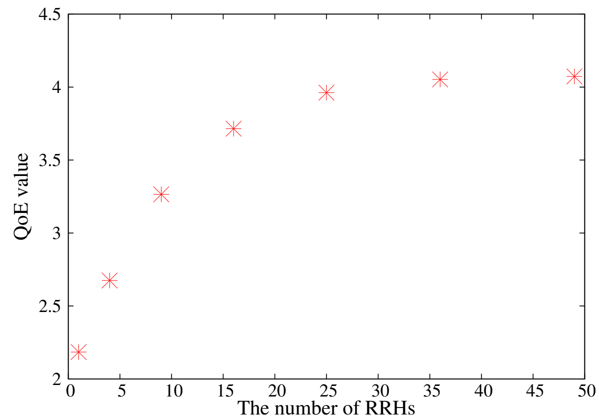

Fig. 4. The relationship between the number of RRHs and QoE value.

B. Network design approach

To design and install network infrastructure, it is required to decide the number of RRHs and OLTs. Therefore, we envision a network design approach to satisfy an allowable QoE level, which could be decided by network operators.

The number of RRHs can be decided by using the relationship between the number of RRHs and the QoE value shown in Fig. 4. For instance, when the network operators set the allowable QoE level to 4, they need to deploy 36 RRHs. On the other hand, the number of RRHs per OLT is restricted. This happens because the amount of the received electrical power decreases with the increase of the number of RRHs due to the optical signal branch, while the maximum transmission power is limited due to the optical fiber fuse. Therefore, the number of required OLTs is determined with the number of RRHs required for the entire QoE assurance.

C. Joint control method of RRH sleep and transmission power

Here, we present a joint control method of RRH sleep and transmission power of the OLT. While the network design approach decides the number of RRHs and OLTs to satisfy the static QoE value, this method can deal with the dynamic QoE value, which is controlled by the network operators. In other words, the method can reduce the transmission power of OLTs by allowing some RRHs to enter the sleep state if the set value is lower than the static QoE value. The method consists of two phases: (i) the battery-charging phase, which aims to charge the power for the initial operation of RRHs, and (ii) the battery-powered phase, which is consistently executed after the battery-charging phase in order to permit some RRHs to enter the sleep state.

Battery-charging phase: When the QoE level is changed, this phase is executed. First, the adequate number of RRHs in the sleep state, $N_{\mathrm{rrh}}^{\mathrm{sleep}}$, is decided based on our derived relationship shown in Fig. 4. Once the value of $N_{\mathrm{rrh}}^{\mathrm{sleep}}$ is determined, multiple groups consisting of multiple RRHs are constructed. We make the groups so that each divided area comprises all kinds of groups. The RRHs in a group can be either in sleep state or active state. Here, even if all the member RRHs of a group enter sleep state during a time-slot, the active group's RRHs temporarily increase their coverage area only during that time-slot in order to service the users belonging to the sleeping RRHs. Suppose that $N_{\rm rrh}$ is the total number of the deployed RRHs. Then, the number of groups, $N_{\rm group}$, is expressed as $N_{\rm rrh}/N_{\rm rrh}^{\rm sleep}$. If $N_{\rm rrh}^{\rm sleep}$ is larger than the number of RRHs in active state $N_{\rm rrh}^{\rm active}$, $N_{\rm group}$ is expressed as $N_{\rm rrh}/N_{\rm rrh}^{\rm active}$. Additionally, the set of group, $S_{\rm group}$, is defined as $\{s_1, s_2, \ldots, s_{N_{\rm group}}\}$. In order to charge the power, the RRHs that belong to the group s_i are made to enter the sleep state during time-slot i. The RRHs in the group s_i store the power in their own battery between $(N_{\rm group} - 1)$ time-slots.

Battery-powered phase: Following the battery-charging phase, the battery-powered phase is repeatedly executed. In this phase, the RRHs in the active state operate with the help of the charged power in order to reduce the transmission power of the OLTs. At time-slot i, the RRHs that belong to the groups except the group s_i enter the active state, where the power supplied from battery, E, is controlled to be empty after completing $(N_{\rm group} - 1)$ time-slots. Therefore, the OLTs control the transmission power according to the value of E. As a result, the transmission power of the OLTs can be reduced.

D. Evaluating the improvement in average transmission power

To confirm the effectiveness of our proposed joint control approach, we present the evaluation of our proposal through numerical calculation. In the assumed network, 72 RRHs and 15 OLTs are deployed. When this network guarantees QoE level 4, from Fig. 4, the required number of RRHs is 36. In other words, the numbers of RRHs that can enter the sleep state is 36. The energy consumptions of RRHs in the sleep and active states are set to $0.7W$ [15] and $1.5W$ [10], respectively. Furthermore, we suppose the anticipated PoF requirement in the future 5G C-RAN by setting the maximum transmission power of each OLT to send optical signal to RRHs and the efficiency of Optic-Electric (O/E) conversion to $20W$ and 0.5, respectively.

Fig. 5 demonstrates the average transmission power between the OLTs with and without our proposal. From the result, it is clearly evident that our joint control method reduces the average transmission power of the OLTs. The reason behind the result is that our proposed method effectively schedules the sleep of RRHs. In addition, our proposed method controls the adequate transmission power according to the amount of charged power.

V. Concluding Remarks

In this article, we addressed the challenges of QoE-guaranteed design and operation for C-RAN based on PON exploiting PoF. To address these challenges, we proposed QoE assurance models based on network QoS. Based on the QoE assurance models, we proposed an adequate network design and operation approach to reduce the transmission power of OLT while satisfying the QoE level. Numerical result demonstrated the effectiveness of our proposed joint control method of RRH sleep and transmission power.

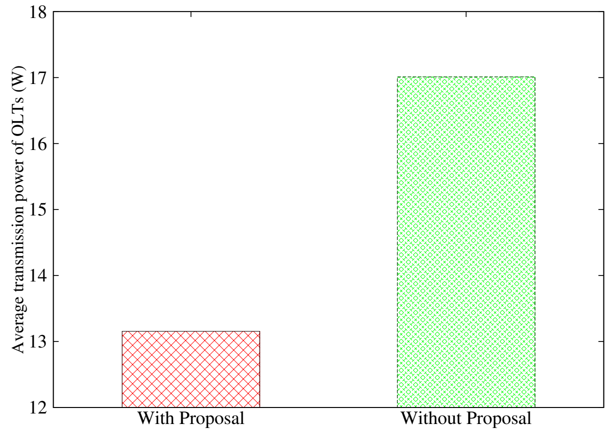

Fig. 5. Performance comparison between the average transmission power of OLTs with and without our proposal.

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BIOGRAPHIES

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Katsuya Suto [S'11] is pursuing the Ph.D. degree in the GSIS at Tohoku University. His research interests are in the areas of cloud computing, big data mining, and robust network architecture. He was a recipient of the prestigious Deans Award from Tohoku University in March 2013. He received the Best Paper Award at the IEEE 77th Vehicular Technology Conference (VTC'2013-spring).

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