Resource Management and Admission Control for Tactile Internet in Next Generation of RAN

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Abstract

In this paper, a new queuing model for the Tactile Internet (TI) is proposed for the cloud radio access network (C-RAN) architecture of the next generation wireless networks, e.g., 5G, assisted via orthogonal frequency division multiple access (OFDMA) technology. This model includes both the radio remote head (RRH) and baseband processing unit (BBU) queuing delays and reliability for each end to end (E2E) connection between each pair of tactile users. For this setup, with the aim to minimize the transmit power of users subject to guaranteeing tolerable delay of users, and fronthaul and access limitations, we formulate a resource allocation problem. Since the proposed optimization problem is highly non-convex, to solve it in an efficient manner, we utilize diverse transformation techniques such as successive convex approximation (SCA) and difference of two convex functions (DC). In addition, we propose an admission control (AC) algorithm to make problem feasible. In our proposed system model, we dynamically adjust the fronthaul and access links to minimize the transmit power. Simulation results reveal that by dynamic adjustment of the access and fronthaul delays, transmit power can be saved compared to the case of fixed approach per each transmission session. Moreover, the number of rejected users in the network is significantly reduced and more users are accepted.
Index Terms
Cloud Radio Access Network (C-RAN), Tactile Internet (TI), Admission Control (AC).

I. INTRODUCTION
The Tactile Internet (TI) is a new service portfolio of the next generation of wireless networks, e.g., the fifth-generation (5G) wireless networks, where a novel communication paradigm is introduced. For instance, via the TI, touch sensation can be remotely transmitted. One of the most important requirements of TI service is ultra low end-to-end (E2E) delay, e.g., E2E delay should be less than one millisecond [1]–[4]. These requirements cannot be guaranteed via existing wireless networks such as fourth-generation (4G) wireless networks [4]. However, 5G platform via its own soft, virtualized, and cloud-based architecture can be leveraged to implement the TI services [1], [2].

For instance, via the concept of cloud radio access network (C-RAN) in 5G, spectral efficiency (SE) and energy efficiency (EE) along with cost can be efficiently optimized, where the baseband processing is performed by the baseband units (BBUs) which are connected to remote radio heads (RRHs) via the fronthaul links [5], [6]. Specifically, C-RAN reduces energy consumption and cost, and improves throughput in dense environment [7], [8]. Therefore, this RAN architecture is a proper environment for the implementation of the TI services in dense areas.

In 5G, due to the introduction of various services, each to be provided with a high quality of service (QoS) via the virtualization techniques, the concept of slice has been defined for each service in which each slice is a bundle of users with a specific set of QoS requirements [9], [10]. The slice concept adds flexibility to utilize resources which leads to higher SE and EE. However, in this concept, the isolation between slices should be preserved such that the activities of users of one slice do not have harmful effects on QoS of the users of other slices. One of the major issues in the slicing is how to translate the isolation concept to the proper notation for the networks procedures. There exists a large body of work for this translation, such as dynamic and static methods [9]–[11]. In this paper, we consider the minimum required data rate of each slice as a
means of preserving the isolation between slices [11], [12]. Obviously, for this setup due to the complexity of system architecture, diverse transmission parameters such as power, and different QoS requirements, the problem of resource allocation is highly essential which has drawn a lot of attention recently [3], [13]–[16]. For instance, in [13], a resource allocation problem for the TI in the Long-Term Evolution-Advanced (LTE-A) is investigated where the average queuing delay and queuing delay violation in one base station (BS) are optimized. Orthogonal frequency division multiple access (OFDMA) and single carrier frequency division multiple access (SC-FDMA) are considered for downlink (DL) and uplink (UL), respectively. A cross-layer resource allocation problem for the TI is proposed in [3] for single BS where the packet error probability, maximum allowable queuing delay violation probability, and packet dropping probability are jointly optimized with the objective to minimize the total transmit power subject to maximum allowable queuing delays. In [13], queuing delay, packet loss induced by queuing delay violation, packet error, and packet drop caused by channel fading are considered for analyzing the E2E delay of RAN. In [14], the effect of frequency diversity and spatial diversity on the transmission reliability in UL is studied in the TI service where the number of subcarriers, the bandwidth of each subcarrier, and the threshold for each user are optimized for minimizing the total bandwidth to ensure the transmission reliability. In [15], a multi-cell network based on frequency division multiple access (FDMA) with a fixed delay for backhaul is studied in the TI service. Moreover, queuing delay, delay violation probability, and decoding error probability are considered for analyzing the E2E delay of the TI service [15].

In the above-mentioned works, a network is considered in which for each user one queue at the BS is assumed. Therefore, by increasing the number of users, a lot of queues are needed at the BS for both UL and DL. However, given that the TI is assumed to be implemented in the 5G framework, it is necessary to consider C-RAN architecture. There exists a set of RRHs in the highly dense network which are connected to BBU center via fronthaul links. Furthermore, the results in the above works generally ignore the fronthaul delay. However, due to the importance
of delay in the TI, it is crucial to consider queuing delay in fronthaul as well, otherwise, the resulting allocation of the resources may not practically fulfill the requirement of the TI.

To address the mentioned issues, we consider a C-RAN architecture serving a set of tactile users. The contributions of this paper are as follows, many of which have been considered for the first time in the TI:

- We propose a C-RAN scenario in ultra dense environment in 5G platform. This will impose new constraints to the system as far as the number of queues is concerned. For the considered C-RAN architecture, we propose a practical queuing model for sequential queues in the TI that can be implemented in realistic networks. Moreover, we consider slicing for the TI service in our work.

- Given that TI services are extremely delay sensitive, there is a possibility that due to high channel fading, the delay requirements is not met for some tactile users, i.e., the resource allocation problem is not feasible. To tackle this issue and reach an efficient solution, we propose an admission control (AC) where a set of users who has the worst condition to reach a feasible solution is not admitted.

- In contrast to [3], [13], [14] where the fronthaul delay is ignored, we take this delay into consideration. Moreover, we consider dynamic adjustment of the access and fronthaul delays based on channel state information (CSI) for each pair of users instead of fixed maximum delay values per each transmission part of our setup and show that it can significantly reduce the required total transmit power.

The rest of this paper is as follows. In Section II, the system model is described. In Section III, we formulate the optimization problem. Numerical results and simulation are presented in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL

We consider a C-RAN network where all RRHs are connected to the BBU via fronthaul links. In this region, there exist several pairs of tactile users where each user aims to send
Fig. 1: The illustration of the considered network in which three slices with two RRHs are considered. Here as an example, a pair of tactile users is shown by the dotted circles.

its information to its paired tactile user via the closest RRH through the UL transmission link. Then, RRH sends the received data to the BBU via the fronthaul link. The BBU processes all the received data and then sends the data to the corresponding RRH of its paired tactile user. Finally, this RRH transmits the relevant message to the paired tactile user via the DL transmission link.

Assume each RRH has only one queue for UL transmission and all the data of tactile users is stored in this queue. In addition, we consider only one queue in the BBU to store all received data from RRHs. In DL, we assume that each RRH has a queue for each user for sending data to the paired users.

As shown in Fig. 1, in the considered system model, we have $\mathcal{J} = \{1, \ldots, J\}$ RRHs, $\mathcal{S} = \{1, \ldots, S\}$ slices, and $\mathcal{I} = \{1, \ldots, I\}$ pairs of tactile users. Slice $s$ contains $\mathcal{I}_s = \{1, \ldots, I_s\}$ tactile users and the total number of tactile users in our system model is equal to $\mathcal{I} = \bigcup_{s \in \mathcal{S}} \mathcal{I}_s$ pairs of users. The terms of access link and fronthaul link often are used to express the RRH-user connection and RRH-BBU connection, respectively. In order to reduce the cost of cabling, wireless fronthaul is used instead of fiber fronthaul [5], [17]. We assume that the fronthaul links
are provided via wireless channels in an ultra-dense environment and that there exist two sets of subcarriers $\mathcal{K}_1 = \{1, \ldots, K_1\}$ and $\mathcal{K}_2 = \{1, \ldots, K_2\}$ for access and fronthaul links, respectively. Moreover, we define $\mathcal{Q} = \{\text{UL}, \text{DL}\}$ for simplicity. We consider a two-phase transmission; in the first phase, all tactile users send their data to the corresponding RRH and simultaneously all RRHs send their buffered data to the BBU via fronthaul links. In the second phase, all RRHs send data to the corresponding tactile users, and simultaneously, BBU sends the buffered data to all RRHs via fronthaul links. These two phases do not perform at the same frequency. Therefore, the proposed system model is based on the frequency division duplex (FDD) transmission mode in which each RRH can transmit and receive simultaneously in different frequencies. In order to isolate slices, a minimum required data rate for each slice $s$ must be reserved [11], [18], [19].

By considering the above definitions, we can now proceed to review the system parameters.

**Remark 1.** To estimate the CSI for DL transmission, pilot signals are transmitted via RRHs to all users. Then, each user sends the channel estimation to RRHs via feedback channels. To estimate the CSI for UL, pilot signals are transmitted via users to RRHs, and then, the channel estimations are sent to the users. For the CSI estimation, one of the proposed approaches in [20]–[22] can be applied.

### A. Access Links Parameters

We introduce a binary variable $\tau_{i,k_1}^{s,q,j}$ which is set to 1 if subcarrier $k_1$ is assigned to user $i$ in slice $s$ at RRH $j$, i.e.,

$$
\tau_{i,k_1}^{s,q,j} = \begin{cases} 
1, & \text{if subcarrier } k_1 \text{ is assigned to user } i \text{ in slice } s \text{ at RRH } j \text{ and } q \in \mathcal{Q}, \\
0, & \text{otherwise}.
\end{cases}
$$

Since we deploy OFDMA in this setup, each subcarrier can be allocated to at most one user. Therefore, we have the following constraint:

$$
\text{C1: } \sum_{s \in S} \sum_{i \in I_s} \tau_{i,k_1}^{s,q,j} \leq 1, \forall j \in J, k_1 \in \mathcal{K}_1, q \in \mathcal{Q}.
$$
Here, for all \( j \in \mathcal{J}, k_1 \in \mathcal{K}_1, s \in \mathcal{S}, i \in \mathcal{I}_s, \) and \( q \in \mathcal{Q}, \) the achievable rate for user \( i \) on subcarrier \( k_1 \) at RRH \( j \) can be calculated as [15], [23]

\[
r_{i,k_1}^{s,j,q} = \frac{w_{k_1}}{\ln 2} \left[ \ln(1 + \gamma_{i,k_1}^{s,j,q}) - \frac{\sqrt{V_{i,k_1}^{s,j,q}}}{\phi w_{k_1}} f_Q^{-1}(\varepsilon_{i,k_1}^{s,j,q}) \right],
\]

where \( \gamma_{i,k_1}^{s,j,q} = \frac{p_{i,k_1}^{s,j,q} h_{i,k_1}^{s,j,q}}{\sigma_{i,k_1}^{s,j,q}} \) in which \( p_{i,k_1}^{s,j,q}, h_{i,k_1}^{s,j,q}, \) and \( \sigma_{i,k_1}^{s,j,q} \) represent the transmit power, channel power gain from RRH \( i \), subcarrier \( k \), and noise power, respectively. Also, \( I_{i,k_1}^{s,j,q} \) is the inter-cell interference which is equal to \( I_{i,k_1}^{s,j,q} = \sum_{f \in \mathcal{J}/j} \sum_{v \in \mathcal{S}} \sum_{u \in \mathcal{I}_v} \tau_u^{v,f,q} p_u^{v,f,q} h_u^{v,f,q} \) Also \( \phi, w_{k_1}, \) and \( f_Q^{-1}(\cdot) \) represent time unit, the bandwidth of subcarrier \( k_1 \), and the inverse of Gaussian-Q function, respectively. Moreover, \( V_{i,k_1}^{s,j,q} \) is defined as \( V_{i,k_1}^{s,j,q} = 1 - \frac{1}{(1 + \gamma_{i,k_1}^{s,j,q})^2} \). Moreover, in each time unit (short blocklength regime), the total number of transmitted bits of user \( i \) at RRH \( j \) in slice \( s \) over subcarrier \( k_1 \) is \( \Omega = r_{i,k_1}^{s,j,q} \phi \). From (1), the error probability \( \left( \varepsilon_{i,k_1}^{s,j,q} \right) \) can be calculated as follows:

\[
\varepsilon_{i,k_1}^{s,j,q} = f_Q \left( \frac{w_{k_1}}{\sqrt{V_{i,k_1}^{s,j,q}}} \left[ \ln(1 + \gamma_{i,k_1}^{s,j,q}) - \frac{\ln 2 \phi}{w_{k_1}} \right] \right), \forall j \in \mathcal{J}, k_1 \in \mathcal{K}_1, s \in \mathcal{S}, i \in \mathcal{I}_s, q \in \mathcal{Q}. \tag{2}
\]

Since the reliability is important for the TI services, we consider the following constraint:

**C2:** \( \varepsilon_{i,k_1}^{s,j,q} \leq \xi, \forall j \in \mathcal{J}, k_1 \in \mathcal{K}_1, s \in \mathcal{S}, i \in \mathcal{I}_s, q \in \mathcal{Q}, \)

where \( \xi \) is error probability threshold. Given that the Q-function does not have a closed-form, we deploy approximation \( \Xi(\gamma_{i,k_1}^{s,j,q}) \approx f_Q\left( \frac{\ln(1 + \gamma_{i,k_1}^{s,j,q}) - \Omega/(w_{k_1} \phi)}{\sqrt{V_{i,k_1}^{s,j,q} (\ln 2)^2/(w_{k_1} \phi)}} \right) \) as follows [15], [23]:

\[
\Xi(\gamma_{i,k_1}^{s,j,q}) = \begin{cases} 
1, & \gamma_{i,k_1}^{s,j,q} \leq B_{k_1} - \frac{1}{2\Lambda_{k_1} \sqrt{w_{k_1} \phi}}, \\
1/2 - A_{k_1} \sqrt{w_{k_1} \phi} (\gamma_{i,k_1}^{s,j,q} - B_{k_1}), & B_{k_1} - \frac{1}{2\Lambda_{k_1} \sqrt{w_{k_1} \phi}} \leq \gamma_{i,k_1}^{s,j,q} \leq B_{k_1} + \frac{1}{2\Lambda_{k_1} \sqrt{w_{k_1} \phi}}, \\
0, & B_{k_1} + \frac{1}{2\Lambda_{k_1} \sqrt{w_{k_1} \phi}} \leq \gamma_{i,k_1}^{s,j,q}, \end{cases}
\]

where \( A_{k_1} = \frac{1}{2\pi \sqrt{2^{2\Omega/(w_{k_1} \phi)}} - 1} \) and \( B_{k_1} = 2^{\Omega/(w_{k_1} \phi)} - 1. \)
The total achievable rate in the access links at RRH $j$ is as follows:

$$R_{RRH_j}^{q} = \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} \tau_{u,k_1}^{s,j,q} r_{u,k_1}^{s,j,q}, \forall j \in J, q \in Q. \quad (4)$$

Due to the power limitation of each RRH in DL transmission, we have the following constraint:

$$C3: \sum_{i \in I} \sum_{s \in S} \sum_{k_1 \in K_1} \tau_{i,k_1}^{s,j,DL} p_{i,k_1}^{s,j,DL} \leq P_{DL}^{RRH_j}, \forall j \in J.$$  

Moreover, due to the power limitation of each user, we have

$$C4: \sum_{j \in J} \sum_{s \in S} \sum_{k_1 \in K_1} \tau_{i,k_1}^{s,j,UL} p_{i,k_1}^{s,j,UL} \leq P_{UL}^{USER_i}, \forall i \in I.$$  

B. Fronthaul Links Parameters

We introduce a binary variable $x_{k_2}^{j,q}$ denoting that subcarrier $k_2$ is assigned to RRH $j$ which is defined by

$$x_{k_2}^{j,q} = \begin{cases} 1, & \text{if subcarrier } k_2 \text{ is assigned to RRH } j \text{ and } q \in Q, \\ 0, & \text{Otherwise.} \end{cases}$$

Assuming that OFDMA is also deployed for the fronthaul links, again each subcarrier can be allocated to at most one RRH, and hence, we have the following constraint:

$$C5: \sum_{j \in J} x_{k_2}^{j,q} \leq 1, \forall k_2 \in K_2, q \in Q.$$  

The achievable rate for each RRH on subcarrier $k_2$ is calculated as follows [15], [23]:

$$r_{k_2}^{j,q} = \frac{w_{k_2}}{\ln 2} \left[ \ln(1 + \gamma_{k_2}^{j,q}) - \sqrt{\frac{V_{k_2}}{\phi w_{k_2}}} f_Q^{-1}(\varepsilon_{k_2}^{j,q}) \right], \forall j \in J, k_2 \in K_2, q \in Q, \quad (5)$$

where $\gamma_{k_2}^{j,q}$ is defined as $\gamma_{k_2}^{j,q} = \frac{p_{k_2}^{j,q} h_{k_2}^{j,q}}{\sigma_{k_2}^{j,q}}, \forall j \in J, k_2 \in K_2, q \in Q$. $w_{k_2}$ is the bandwidth of subcarrier $k_2$ and $V_{k_2}^{j,q}$ is defined as $V_{k_2}^{j,q} = 1 - \frac{1}{(1+\gamma_{k_2}^{j,q})^2}$. In addition, in each time unit, the total number of transmitted bits is $\tilde{\Omega} = r_{k_2}^{j,q} \phi$. Similar to the previous subsection (II-A) and based on (5), the error probability $\varepsilon_{k_2}^{j,q}$ can be calculated as follows:

$$C6: \varepsilon_{k_2}^{j,q} \leq \xi, \forall j \in J, k_2 \in K_2, q \in Q. \quad (6)$$
Given that the Q-function does not have a closed-form, we deploy approximation
\[
\tilde{F}(\gamma_{k_2}) \approx \frac{f_Q(\ln(1+\gamma_{k_2})) - \Omega/(w_{k_2} \phi)}{\sqrt{\frac{\ln 2}{(w_{k_2} \phi)}}}
\]
similar to the previous subsection (II-A).

The total achievable rate in the BBU is obtained as follows:
\[
R_{BBU}^q = \sum_{j \in J} \sum_{k_2 \in K_2} x_{j,q,k_2}^{\text{DL}} r_{j,q,k_2}^{\text{DL}}, \forall q \in Q.
\tag{7}
\]

Due to the power limitation of each RRH in UL transmission, we have
\[
C_7: \sum_{k_2 \in K_2} x_{j,k_2}^{\text{UL}} p_{k_2}^{\text{UL}} \leq P_{\text{UL,RRH}}^{\text{UL}}, \forall j \in J.
\]

Moreover, due to the power limitation of the BBU, we have
\[
C_8: \sum_{j \in J} \sum_{k_2 \in K_2} x_{j,k_2}^{\text{DL}} p_{k_2}^{\text{DL}} \leq P_{\text{BBU}}^{\text{DL}}.
\]

C. Queuing Delay Model

The total delay of this architecture consists of three components: delay resulting from UL queues at RRHs, BBU queue, and DL queues at RRHs, as shown in Fig. 2. Due to delay constraint in the TI service, we have
\[
C_9: D_{\text{max}}^{i,j} + D_{\text{max}}^{i,j} + D_{\text{BBU}}^{i,j} \leq D_{\text{max}}^{i,j,s}, \forall i \in \mathcal{I}, j \in J, s \in \mathcal{S},
\]
where \( D_{\text{max}}^j \), \( D_{\text{max}}^{i,j} \), \( D_{\text{max}}^{BBU} \), and \( D_{\text{max}}^{i,j,s} \) are the delays of UL queues at RRHs, BBU queue, DL queues at RRH, and the total delay, respectively.

1) UL Queuing Delay: The aggregation of receiving bits from several nodes can be modeled as a Poisson process [3], [24]. The effective bandwidth for a Poisson arrival process in RRH \( j \) is defined as [3], [24], [25]

\[
E_{B}^j(\theta_j) = \frac{\lambda_j(e^{\theta_j} - 1)}{\theta_j}, \forall j \in J,
\]

where \( \theta_j \) is the statistical QoS exponent of the \( j \)-th RRH. A larger \( \theta_j \) indicates a more stringent QoS and a smaller \( \theta_j \) implies a looser QoS requirement. \( \lambda_j \) is the number of bits arrived at RRH \( j \) queue defined as

\[
\lambda_j = \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} r_{u,k_1}^{s,j,UL}, \forall j \in J.
\]

The probability of queuing delay violation for RRH \( j \) can be approximated as

\[
\epsilon_j^1 = \Pr\{D_j > D_{\text{max}}^j\} = \eta_1 \exp(-\theta_j E_{B}^j(\theta_j) D_{\text{max}}^j),
\]

for all \( j \in J \) where \( D_j \) is the \( j \)-th RRH delay, \( D_{\text{max}}^j \) is the maximum delay, and \( \eta_1 \) is the non-empty buffer probability. Equation (8) can be simplified to

\[
\exp(-\theta_j E_{B}^j(\theta_j) D_{\text{max}}^j) = \exp(-\theta_j \lambda_j \frac{(e^{\theta_j} - 1)}{\theta_j} D_{\text{max}}^j) = \exp(-\lambda_j (e^{\theta_j} - 1) D_{\text{max}}^j) \leq \delta_1.
\]

Therefore, we have

\[
C10: \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} r_{u,k_1}^{s,j,UL} \geq \frac{\ln(1/\delta_1)}{(e^{\theta_j} - 1) D_{\text{max}}^j}, \forall j \in J.
\]

2) BBU Queuing Delay: We consider a queue for all RRHs at the BBU for processing data. Therefore, the formulas in the previous section can also be used for this section. The effective bandwidth for each queue in BBU is

\[
E_{B}^{BBU}(\theta_{BBU}) = \Lambda_{BBU}^j \frac{(e^{\theta_{BBU}} - 1)}{\theta_{BBU}}, \text{ where } \theta_{BBU} \text{ is the statistical QoS exponent in the BBU and } \Lambda_{BBU}^j \text{ is the number of bits arrived at the queue in the BBU which is defined as } \Lambda_{BBU}^j = \sum_{j \in J} \sum_{k_2 \in K_2} r_{k_2}^{j,UL}. \text{ The probability of queuing delay violation at the BBU can be approximated as}
\]
\[ \epsilon_{\text{BBU}} = \Pr\{D_{\text{BBU}} > D_{\text{BBU}}^{\text{max}}\} = \eta_2 \exp(-\theta_{\text{BBU}}^* E_B^{\text{BBU}}(\theta_{\text{BBU}}) D_{\text{BBU}}^{\text{max}}), \]  

(9)

where \( \eta_2 \) is the non-empty buffer probability. Equation (9) can be simplified to

\[ \exp(-\theta_{\text{BBU}}^* E_B^{\text{BBU}}(\theta_{\text{BBU}}) D_{\text{BBU}}^{\text{max}}) = \exp(-\theta_{\text{BBU}}^* \frac{(e^{\theta_{\text{BBU}}} - 1) D_{\text{BBU}}^{\text{max}}}{\theta_{\text{BBU}}}) \leq \delta_2. \]

Therefore, we have

\[ \text{C11: } \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} r_{j,k_2} \geq \frac{\ln(1/\delta_2)}{(e^{\theta_{\text{BBU}}} - 1) D_{\text{BBU}}^{\text{max}}}. \]

3) DL Queuing Delay: The effective bandwidth for each user in RRH \( j \) is defined as \( E_{B}^{i,j}(\theta_i^j) = \lambda_i^j \frac{(e^{\theta_i^j} - 1)}{\theta_i^j}, \forall i \in \mathcal{I}, j \in \mathcal{J} \), where \( \theta_i^j \) is the statistical QoS exponent of the \( i \)th user in RRH \( j \) and \( \lambda_i^j \) is the number of bits arrived at user \( i \) queue in RRH \( j \) which is defined as

\[ \lambda_i^j = \sum_{s \in \mathcal{S}} \sum_{u \in \mathcal{I}_s} \sum_{k_1 \in \mathcal{K}_1} r_{u,k_1}^{s,j,DL}, \forall i \in \mathcal{I}, j \in \mathcal{J}. \]

The probability of queuing delay violation for user \( i \) can be approximated as

\[ e_i^{j,i} = \Pr\{D_i^j > D_i^{j,\text{max}}\} = \eta_3 \exp(-\theta_i^j E_B^{i,j}(\theta_i^j) D_{\text{max}}) \leq \delta_3. \]

(10)

where \( D_i^j \) is the \( i \)th user delay in RRH \( j \) and \( \eta_3 \) is the non-empty buffer probability. Equation (10) can simplified to

\[ \exp(-\theta_i^j E_B^{i,j}(\theta_i^j) D_{\text{max}}) = \exp(-\lambda_i^j \frac{(e^{\theta_i^j} - 1)}{\theta_i^j} D_{\text{max}}) = \exp(-\lambda_i^j (e^{\theta_i^j} - 1) D_{\text{max}}) \leq \delta_3. \]

Therefore, we have

\[ \text{C12: } \sum_{k_1 \in \mathcal{K}_1} r_{j,k_1}^{s,j,DL} \geq \frac{\ln(1/\delta_3)}{(e^{\theta_i^j} - 1) D_{\text{max}}}, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}. \]

In order to avoid bit dropping, the output rate of queues must be greater than the input rate of queues. Therefore, we have two following constraints:

\[ \text{C13: } \sum_{s \in \mathcal{S}} \sum_{u \in \mathcal{I}_s} \sum_{j \in \mathcal{J}} \sum_{k_1 \in \mathcal{K}_1} \tau_{u,k_1}^{s,j,UL} r_{u,k_1}^{s,j,UL} \leq \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} x_{j,k_2}^{UL} r_{j,k_2}^{UL}, \]

\[ \text{C14: } \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} x_{j,k_2}^{DL} r_{j,k_2}^{DL} \leq \sum_{s \in \mathcal{S}} \sum_{u \in \mathcal{I}_s} \sum_{j \in \mathcal{J}} \sum_{k_1 \in \mathcal{K}_1} \tau_{u,k_1}^{s,j,DL} r_{u,k_1}^{s,j,DL}. \]
III. Optimization Problem Formulation

In this section, our aim is to allocate resources to minimize the overall power consumption in our setup by considering a bounded delay constraint to satisfy the E2E delay requirements. Based on the mentioned constraints C1-C14, the optimization problem can be written as

\[
\begin{align*}
\min_{P, T, X, D} \quad & \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} \sum_{s \in \mathcal{S}} \sum_{u \in \mathcal{I}_s} \sum_{k_1 \in \mathcal{K}_1} x_{j, k_2}^{UL} P_{k_2}^{j, UL} + x_{j, k_2}^{DL} P_{k_2}^{j, DL} + \tau_{s,j,q,u,k_1}^{s,j,UL} p_{u,k_1}^{s,j,UL} + \tau_{s,j,q,u,k_1}^{s,j,DL} p_{u,k_1}^{s,j,DL} \\
\text{s.t.} : & (C1)-(C14), \\
& C15: \sum_{k_1 \in \mathcal{K}_1} \sum_{u \in \mathcal{I}_s} \sum_{j \in \mathcal{J}} \tau_{s,j,q,u,k_1}^{s,j,UL} p_{u,k_1}^{s,j,UL} \geq R_{s,q}^{s,j,UL}, \forall s \in \mathcal{S}, q \in \mathcal{Q}.
\end{align*}
\]

The optimization variables in (11) are subcarrier allocation, power allocation, and delay adjustment for different users in the access and fronthaul as well as in both UL and DL where \( P, T, X, \) and \( D \) are the transmit power, the access subcarrier allocation, fronthaul subcarrier allocation, and delay vector for users, respectively. The rate constraint C15 is used to isolate the network slices.

In problem (11), the rate is a non-convex function, which leads to the non-convexity of the problem. In addition, this problem contains both discrete and continuous variables, which makes the problem more challenging. Therefore, we resort to an alternate method to propose an efficient iterative algorithm [26], [27] with three subproblems, namely, subcarrier allocation subproblem, power allocation subproblem, and delay adjustment subproblem which will be explained in the followings.

IV. An Efficient Iterative Algorithm

Due to the complex nature of (11), and specially having C9-C15, obtaining feasible initial values for problem (11) is not trivial. Therefore, to find a feasible point for Problem (11), we
propose to solve the following optimization problem instead of Problem (11):

\[
\min_{P, T, X, D, \alpha} \sum_{j \in J} \sum_{k_2 \in K_2} \sum_{s \in S} \sum_{u \in I} \sum_{k_1 \in K_1} x_{k_2}^{j,UL} p_{k_2}^{j,UL} + x_{k_2}^{j,UL} p_{k_2}^{j,UL} + r_{u,k_1}^{s,j,DL} p_{u,k_1}^{s,j,DL} + r_{u,k_1}^{s,j,UL} p_{u,k_1}^{s,j,UL} + M\alpha_{u,k_1}^{s,j}
\]

s.t.: (C1), (C3-C9), (C11),

\[\sum_{s \in S} x_{k_2}^{j,UL} + \alpha_{u,k_1}^{s,j} \geq \frac{\ln(1/\delta_j)}{(e^{\theta_j} - 1)D_{\text{max}}^{j}}, \forall j \in J,\]

\[\sum_{k_1 \in K_1} r_{u,k_1}^{s,j,DL} + \alpha_{u,k_1}^{s,j} \geq \frac{\ln(1/\delta_i)}{(e^{\theta_i} - 1)D_{\text{max}}^{i,j}}, \forall i \in I, \forall j \in J,\]

\[\sum_{s \in S} \sum_{u \in I} \sum_{k_1 \in K_1} r_{u,k_1}^{s,j,UL} - \alpha_{u,k_1}^{s,j} \leq \sum_{j \in J} \sum_{k_2 \in K_2} x_{k_2}^{j,UL} r_{k_2}^{j,UL},\]

\[\sum_{j \in J} \sum_{k_2 \in K_2} x_{k_2}^{j,DL} r_{k_2}^{j,DL} \leq \sum_{s \in S} \sum_{u \in I} \sum_{j \in J} \sum_{k_1 \in K_1} r_{u,k_1}^{s,j,DL} - \alpha_{u,k_1}^{s,j},\]

\[\sum_{k_1 \in K_1} \sum_{u \in I} \sum_{j \in J} r_{u,k_1}^{s,j,q} p_{u,k_1}^{s,j,q} + \alpha_{u,k_1}^{s,j} \geq R_{\text{res}}, \forall s \in S, q \in Q\]

where \(\alpha \geq 0\) is an elastic variable and if the original problem (11) is feasible, the optimal value is \(\alpha^* = 0\). Moreover, \(M\) is a large coefficient, i.e., \(M >> 1\). By using this variable, in this section, we propose an AC method to reject users who make the problem infeasible based on a defined criterion and guarantee the QoS of other users. (12) is also non-convex and we utilize an iterative algorithm based on the difference of two convex (DC) approximation. To solve (12), we set all the initial values except \(\alpha\) to zero and set \(\alpha\) to a large value which is a feasible point of (12). After deriving the solution of (12), we check out if the constraints hold or not. If these constraints hold and \(\alpha^* = 0\), the derived solution of (12) is an initial value of (11); otherwise, we run the admission control to remove a user and then repeat this procedure.

As mentioned earlier, to solve (12), we deploy an iterative algorithm that divides the problem into four subproblems and solve them alternately [26], [27]. This procedure is presented in Algorithm.1. Let \(z\) be the iteration number and \(P^{(0)}, X^{(0)}, \) and \(T^{(0)}\) be the initial values. In
**Algorithm 1 Seven-Step Iterative Algorithm**

**Step 1: Initialization**

\[ \mathcal{J} = \{1, \ldots, J\}, \mathcal{K}_1 = \{1, \ldots, K_1\}, \mathcal{K}_2 = \{1, \ldots, K_2\}, \mathcal{I}_s = \{1, \ldots, I_j\}, \mathcal{S} = \{1, \ldots, S\}, \]
\[ \epsilon_{TH} = 10^{-4}, Z_{TH} = 100 \text{ and } z = 0. \]

Set initial value \( p^{(z)} = p^0 = 0, \tau^{(z)} = \tau^0 = 0 \) and \( x^{(z)} = x^0 = 0, \alpha^{(z)} > 0 \).

**Step 2: Subcarrier Allocation**

Allocate subcarrier by minimizing the transmit power and satisfying the problem constraints i.e., (13).

**Step 3: Power Allocation**

Allocate power to each user according to problem (15) and subcarrier allocated in Step 2.

**Step 4: Delay Adjustment**

Adjust delay of each user according to problem (17).

**Step 5: Finding the Value of \( \alpha \)**

Solving problem (18).

**Step 6: Admission Control**

If \( \alpha^* \neq 0 \), reject user \( u^* \) based on criterion (19), then return to Step 1.

If \( \alpha^* = 0 \), go to Step 7.

**Step 7: Iteration**

\[ z = z + 1, \text{ Repeat Step 2 to 6 until } ||P^{(z)} - P^{(z-1)}|| \leq \epsilon_{TH} \text{ or } Z_{TH} < z. \]

Each iteration, we solve each subproblem by considering the optimization parameters of other subproblems as fixed values derived in the previous steps. The iteration stops when the error in Step 6 is less than a predetermined threshold, i.e., \( \epsilon_{TH} \), or the number of iterations exceeds a predetermined value, i.e., \( Z_{TH} \). The solution of the last iteration is then declared as the solution.
of (12). The flowchart of Algorithm 1 is shown in Fig. 3, which is explained following in more detail.

**Proposition 1:** The presented iterative algorithm which is described in Algorithm 1 converges.

**Proof:** See Appendix A.

A. Subcarrier Allocation Sub-Problem

With assuming fixed value $P$, $\alpha$ and $D$, the subcarrier allocation subproblem is written as follows:

$$
\min_{T, X} \sum_{j \in J} \sum_{k_2 \in K_2} \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} x_{j,k_2}^{UL} P_{k_2} + x_{j,k_2}^{UL} P_{k_2} + \tau_{s,j,DL}^s P_{u,k_1} + \tau_{u,k_1}^{s,j,UL} P_{u,k_1} + M \alpha_{u,k_1}
$$

s.t. (C1), (C2), (C3-C8), (C10), (C11), (C12-C15).

While (13) has less computational complexity than (12), it suffers from non-convexity due to the interference in the rate functions. In addition, this problem contains discrete variables. We apply time sharing method and relax discrete variables as $x_{j,k_2}^{UL} \in [0, 1], \forall k_2 \in K_2, \forall j \in J, \forall q \in Q$ and $\tau_{u,k_1}^{s,j,UL} \in [0, 1], \forall u \in I_s, \forall k_1 \in K_1, \forall j \in J, \forall q \in Q$. To solve this problem, we use DC approximation to transform the problem into a convex form. The subcarrier allocation subproblem
is transformed into the following form (See Appendix C):

$$\begin{align*}
\min_{T, X} & \sum_{j \in J} \sum_{k_2 \in K_2} \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} x_{j, k_1}^{UL} p_{k_2}^{UL} + x_{j, k_1}^{UL} p_{k_2}^{DL} + \tau_{u, k_1}^{s, j} p_{u, k_1}^{UL} + \tau_{u, k_1}^{s, j} p_{u, k_1}^{DL} + \alpha_{u, k_1}^{s, j} \\
\text{s.t.} & : (C1), (\tilde{C}2), (C3-C8), (C11), (\tilde{C}10), (\tilde{C}12-\tilde{C}15), \quad (14) \end{align*}$$

The above problem is a convex problem and can be solved with the CVX toolbox in Matlab [28], [29]. **Proposition 3**: The proposed iterative algorithm based on the SCA method for subcarrier allocation subproblem converges.

*Proof*: See Appendix B by considering fixed value for power (P).

### B. Power Allocation Sub-Problem

For the fixed value of $T, X, \alpha$ and $D$ the power allocation subproblem is obtained as follows

$$\begin{align*}
\min_{p} & \sum_{j \in J} \sum_{k_2 \in K_2} \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} x_{j, k_1}^{UL} p_{k_2}^{UL} + x_{j, k_1}^{UL} p_{k_2}^{DL} + \tau_{u, k_1}^{s, j} p_{u, k_1}^{UL} + \tau_{u, k_1}^{s, j} p_{u, k_1}^{DL} + \alpha_{u, k_1}^{s, j} \\
\text{s.t.} & : (\tilde{C}2), (C3-C4), (C6-C8) (\tilde{C}10), (C11), (\tilde{C}12-\tilde{C}15), \quad (15) \end{align*}$$

Similar to the subcarrier allocation subproblem, in problem (15), the rate is a non-convex function, which leads to the non-convexity of the problem. Therefore, it is necessary to approximate (15) with a convex problem. To solve this problem, we use the DC approximation to transform
the problem into a convex form. Therefore, the power allocation subproblem is transformed as follows (See Appendix C):

$$\min_{P} \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} \sum_{s \in S} \sum_{u \in \mathcal{T}_s} \sum_{k_1 \in \mathcal{K}_1} x_{k_2}^{j,j,UL} p_{k_2}^{j,UL} + x_{k_2}^{j,UL} p_{k_2}^{j,UL} + \tau_{u,k_1}^{s,j,DL} p_{u,k_1}^{s,j,DL} + \tau_{u,k_1}^{s,j,UL} p_{u,k_1}^{s,j,UL} + \alpha_{u,k_1}^{s,j}$$

s.t. : \((\tilde{C}2)\), \((C3-C4)\), \((C6-C8)\), \((C11)\),

\[
\tilde{C}10: \sum_{s \in S} \sum_{u \in \mathcal{I}_s} \sum_{k_1 \in \mathcal{K}_1} f_{AC}^{UL}(p_{u,k_1}^{s,j,UL}) - g_{AC}(p_{u,k_1}^{s,j,UL}) + \alpha_{u,k_1}^{s,j} \geq \frac{\ln(1/\delta_1)}{(e^{\theta_1} - 1)D_{max}}, \forall j \in \mathcal{J},
\]

\[
\tilde{C}12: \sum_{k_1 \in \mathcal{K}_1} f_{DL}^{UL}(p_{u,k_1}^{s,j,DL}) - g_{AC}(p_{u,k_1}^{s,j,DL}) + \alpha_{u,k_1}^{s,j} \geq \frac{\ln(1/\delta_2)}{(e^{\theta_2} - 1)D_{max}}, \forall i \in \mathcal{I}, \forall j \in \mathcal{J},
\]

\[
\tilde{C}13: \sum_{s \in S} \sum_{u \in \mathcal{I}_s} \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} f_{AC}^{UL}(p_{u,k_1}^{s,j,q}) - g_{AC}(p_{u,k_1}^{s,j,q}) + \alpha_{u,k_1}^{s,j} + \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} \log_2(1 + \frac{x_{k_2}^{j,UL} p_{k_2}^{j,UL} \tilde{h}_{k_2}^{j,UL}}{\alpha_{k_2}^{s,j}}) \geq 0,
\]

\[
\tilde{C}14: \sum_{s \in S} \sum_{u \in \mathcal{I}_s} \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} f_{DL}^{UL}(p_{u,k_1}^{s,j,DL}) - g_{AC}(p_{u,k_1}^{s,j,DL}) + \alpha_{u,k_1}^{s,j} - \sum_{j \in \mathcal{J}} \sum_{k_2 \in \mathcal{K}_2} g_{FH}(p_{k_2}^{j,DL}) \geq 0,
\]

\[
\tilde{C}15: \sum_{s \in S} \sum_{u \in \mathcal{I}_s} \sum_{k_1 \in \mathcal{K}_1} f_{AC}^{q}(p_{u,k_1}^{s,j,q}) - g_{AC}(p_{u,k_1}^{s,j,q}) + \alpha_{u,k_1}^{s,j} \geq R_{\text{res}}, \forall s \in S, q \in Q.
\]

Similar to the subcarrier allocation subproblem, the above problem is a convex problem and can be solved with the CVX toolbox in Matlab [28], [29].

**Proposition 3:** The proposed iterative algorithm based on the SCA method for power allocation subproblem converges.

**Proof:** See Appendix B by considering fixed values for subcarrier allocation parameters i.e, (T) and (X).

**C. Delay Adjustment Sub-Problem**

With assuming fixed values of \(P, T, \alpha\) and \(X\), the delay adjustment subproblem is obtained as

find \(D\)

s.t. : \((C9)\), \((\tilde{C}10)\), \((C11)\), \((\tilde{C}12)\).

The delay adjustment subproblem can be solved by the linear programming (LP) of any optimization toolbox.
D. Finding the Value of $\alpha$

The finding the value of $\alpha$ subproblem is as follows

$$\min_{\alpha} \sum_{j \in J} \sum_{s \in S} \sum_{u \in I} \sum_{k_1 \in K_1} \alpha_{s,j}^{u,k_1}$$

s.t. : ($\tilde{C}10$), ($\tilde{C}12$-$\tilde{C}15$).

Similar to the delay adjustment problem, this problem can be solved by the linear programming (LP) of any optimization toolbox.

E. Admission Control (AC)

In this paper, we deploy an AC method to make the problem feasible. As shown in Fig.3, in this method, when the problem is infeasible, the user that has the most impact on infeasibility is recognized based on a newly defined criterion and then, this user will be rejected. Then the problem is resolved for other remaining users. This process continues until the problem becomes feasible. It’s worth noting that if $\alpha^* = 0$ (step 5 of Fig.3), it means that all the constraints are satisfied and there is no need to reject any user. However, for $\alpha^* \neq 0$, all constraints of problem (11) are not satisfied. Therefore, the algorithm rejects user $u^*$ which force the most infeasibility to the problem based on the following criterion (returns to Step 1 of Fig.3):

$$u^* = \arg \max_{u \in I} \alpha_{s,j}^{u,k_1}$$

F. Computational Complexity

The number of required iterations for the DC approximation is $\frac{\log C}{\xi} t_0 \rho$, where $0 \leq \rho \leq \infty$ is the stopping criterion for the interior point method (IPM), $\xi$ is used to update accuracy of the IPM, $t_0$ is initial point for approximating the accuracy of IPM, and $C$ is the total number of constraints. For the subcarrier allocation subproblem, the total number of constraints is shown
by $C_{\text{Sub}}$ which is $C_{\text{Sub}} = 2JK_1 + 2JK_1 I + 2K_2 + 2JK_2 + 3J + I + JI + 2S + 4$ [27]. Similarly, for the power allocation subproblem, the total number of constraints is $C_{\text{Pow}} = 2JK_1 I + 3J + I + JI + 2JK_2 + 2S + 4$. For the delay adjustment subproblem, the total number of constraints is $C_{\text{Delay}} = J + 2JI + 1$. In AC subproblem, the total number of constraints is $C_{\text{AC}} = J + JI + 2S + 3$.

For instance, in subcarrier allocation subproblem and power allocation subproblem, the number of RRHs and the number of users have significant impact on the complexity. Moreover, the subcarrier allocation subproblem has more complexity than other subproblems. In contrast, the AC subproblem has lower complexity than the others.

V. Simulation and Results

In this section, the simulation results are presented to evaluate the performance of the proposed system model. To simulate dense urban area, we consider a BBU is at the center of the coverage area whose distance is 1 Km from a set of RRHs. The coverage area is considered 10 square Kilometers. Moreover, we consider a Rayleigh fading wireless channel in which the subcarrier gains are independent. Channel power gains for the access links are set as $h_{i,k_1}^{s,j,q} = \Omega_{i,k_1}^{s,j,q} d_i^{j,q}^{-\alpha}$ where $d_i^{j,q}$ is the distance between user $i$ and RRH $j$, $\Omega_{i,k_1}^{s,j,q}$ is a random variable which is generated by Rayleigh distribution, and $\alpha = 3$ is the path-loss exponent. Channel power gains for fronthaul links are set to $h_{k_2}^{j,q} = \Omega_{k_2}^{j,q} d_j^{q}^{-\beta}$ where similar to access links, $d_j^{q}$ is the distance between RRH $j$ and BBU, $\Omega_{k_2}^{j,q}$ is a random variable generated according to the Rayleigh distribution, and $\beta = 3$ is the path-loss exponent. The power spectral density (PSD) of the received Gaussian noise is set to $-174$ dBm/Hz. At each RRH, we set $P_{\text{DL}_{\text{RRH}} j} = 43$ dBm and $P_{\text{UL}_{\text{RRH}} j} = 43$ dBm $\forall j \in \mathcal{J}$. For the BBU, we set $P_{\text{DL}_{\text{BBU}}} = 46$ dBm, and for each user, we set $P_{\text{UL}_{\text{USER_i}}} = 23$ dBm [15], [23]. The frequency bandwidth of wireless access and fronthaul links are $W_{\text{AC}} = 100$ MHz and $W_{\text{FH}} = 100$ MHz, respectively. Moreover, the bandwidth of each subcarrier is $W_{S} = 2$ MHz [15], [23]. The QoS exponent is $\theta = 10$ [27]. Moreover, we assume packet size is equal to 20 bytes.

In this section, we use Monte-Carlo method for simulation where the optimization problem is
solved for 1000 channel realizations and the total transmit power is the average value over all derived solutions.

A. Effects of Network Parameters

Here, we study the effects of network parameters on the performance of the proposed algorithm based on OFDMA assisted C-RAN. In this regard, we introduce the percentage of service acceptance ratio (SAR) criterion to evaluate the performance of the proposed system model. If the number of users who request the service is \( I \), and the number of admitted users is \( \tilde{I} \), the percentage of service acceptance ratio criterion is equal to \( 100 \times \frac{\tilde{I}}{I} \)%.

In this section, we also evaluate this criterion for the network performance analysis in addition to the total transmit power.

Unless otherwise stated, we consider 3 RRHs, 2 slices, 1 ms E2E delay and packet error rate (PER) of about \( 10^{-7} \). Fig. 4(a) shows the total transmit power versus the total number of users per cell for different reservation rates \( R_{\text{rsv}} \). As expected, the total transmit power increases by increasing the number of users per cell. It stems from the fact that each user has its own QoS determined by the corresponding delay requirement. Moreover, the total transmit power increases by increasing the value of the reservation rate \( R_{\text{rsv}} \). Fig. 4(b) shows the service acceptance ratio.
versus the total number of users per cell for different reservation rates $R_{\text{rs}}$. As expected, when the number of users is increased, the amount of service acceptance ratio reduces. On the other hand, increasing the reservation rate leads to degradation in the service acceptance ratio. For low reservation rates, e.g., $R_{\text{rs}} \in \{0, 1\}$ bps/Hz, when a few number of users exist in the network, all the users’ requested services are accepted. In contrast, for the high reservation rates, e.g., $R_{\text{rs}} \in \{2, 2.5\}$ bps/Hz, the reason for not accepting all requested services is the lack of satisfying the reservation rate constraint. Therefore, by increasing the reservation rate $R_{\text{rs}}$ the service acceptance ratio is decreased.

Here, we investigate the impact of the delay and reliability on the system performance. As can be seen from Figures 5 and 6, for low PER (values close to $10^{-10}$), i.e., high reliability requirement and low E2E delay requirements (values close to 1 ms), the total transmit power is high and the service acceptance ratio is low. By decreasing the reliability requirement (PER close to $10^{-1}$) or delay requirement (E2E delay close to 10 ms), the total transmit power decreases and also the service acceptance ratio increases. Therefore, for high reliability (low PER) or low E2E delay services, it is necessary to increase the amount of the network resources such as transmit power to reduce the number of rejected users. Moreover, it can be seen that compared to the
E2E delay, the reliability has more impact on the total transmit power and service acceptance ratio.

B. Admission Control Performance

Here, we investigate the AC effect and compare the problem with the case without AC. In this regard, we remove the power budget constraints from problem (11) and solve the following problem:

$$\begin{align*}
\min_{P,T,X,D} & \sum_{j \in J} \sum_{k_2 \in K_2} \sum_{s \in S} \sum_{u \in I} \sum_{k_1 \in K_1} x_{k_2}^{j,UL} p_{k_2}^{j,UL} + x_{k_2}^{j,UL} p_{k_2}^{j,UL} + \tau_{s,j,DL} s_{j,DL} p_{u,k_1}^{s,j,UL} + \tau_{u,k_1}^{s,j,UL} p_{u,k_1}^{s,j,UL} \\
\text{s.t.} & \quad (C1)-(C3), (C6), (C9)-(C14),
\end{align*}$$

The new problem can be solved with the iterative algorithm and DC approximation. In problem (11) the power budget constraints, i.e., (C4)-(C5) and (C7)-(C8), limit the amount of total transmit power, and if the power is not enough, the problem becomes infeasible. Therefore, with AC method some users are rejected and the problem becomes feasible. By removing power constraints, the total transmit power increases to meet all constraints. Therefore, as shown in Fig. 7, for $R_{res} = 2$, the amount of the total transmit power without utilizing AC is increased by about 7 dBm.
C. Dynamic Approach versus Fixed approach

To evaluate the performance of the proposed system model, we consider a different scenario which is called fixed approach. In our proposed system model, we adjust the delay dynamically to minimize the transmit power which is called dynamic approach. In the traditional scenario, i.e., fixed approach, we assume the delay constraints are fixed and cannot be adjusted for the access and fronthaul links. In this case, we have a new optimization problem, referred to as, the relaxed problem, in which we remove the delay variables from problem (12) and ignore constraint C9. Moreover, we set access and fronthaul delays manually in constraints \( \tilde{C}_{10}, \tilde{C}_{11}, \) and \( \tilde{C}_{12} \) as \( D_{\text{max}}^j = D_{\text{BPU}}^\text{max} = D_{\text{max}}^{i,j,s} = D_{\text{max}}^{i,j,s}/3. \) The new problem can be solved with the DC approximation.

In Fig. 8a, we investigate the effect of the actual value of the delay \( D_{\text{max}}^{i,j,s} = 1, 2 \) ms on the total transmit power. It is evident that for 1 ms E2E delay and 10 users, in the fixed approach compared to the dynamic approach, the total transmit power increases by 2 dB. However, for a large number of users, the total transmit power is not enough and the acceptance ratio significantly decreases especially in the fixed approach. Moreover, from Fig. 8, the proposed system model has a considerably better performance than the system model corresponding to the relaxed problem.
(fixed approach). As can be seen from 8(a), when we have enough power, by the dynamic adjustment of the delay, we can save around 2 dBm in transmit power. Moreover, when the power is not enough e.g., for 30 users, we can seen from Fig. 8(b), in the fixed approach the service acceptance ratio is below 50% while 85% of users are accepted in our proposed algorithm (dynamic approach).

D. Convergence Study of Algorithm.1

In this subsection, we investigate the proof of the proposed system model convergence in Propositions 1-3. In Fig. 9, the convergence of the alternate method for the proposed system model is demonstrated. It can be seen that the solution of the proposed algorithm converges to a fixed value after 15 iterations. For this simulation, we set $R_{sv} = 0$ bps/Hz and the total number of users per cell is equal to 50.

VI. Conclusion

In this paper, we proposed a novel queuing model for the TI services in OFDMA-based C-RANs serving several pairs of tactile users. For each pair of tactile users within C-RAN coverage area, our setup includes RRH and BBU queuing delays in one E2E connection which
is a more practical scenario in this context compared to previous works. We proposed a resource allocation problem to minimize the transmit power by considering E2E delay and reliability of joint access and fronthaul links for each pair of tactile users where the delays of fronthaul and access links are dynamically adjusted. We also propose how admission control can be applied to convert infeasible situations of the system into feasible ones. To solve the highly non-convex proposed resource allocation problem, we applied SCA method. Simulation results revealed that by dynamic adjustment of the access and fronthaul delays and admission control process, transmit power can be considerably saved and the service acceptance ratio can be significantly increased compared to the case of fixed approach per each transmission.

**APPENDIX A**

In this algorithm, the convergence can be guaranteed if we can show that the objective function is a decreasing function with respect to the number of iterations. For the algorithm in Table.1, in the first step of iteration $i + 1$, with a given power allocation at iteration $i$, $\mathbf{x} = \mathbf{x}^{(i+1)}$ and $\tau = \tau^{(i+1)}$ are derived. Based on DC approximation, we will have $f(\mathbf{x}^{(i)}, \mathbf{p}^{(i)}) \leq f(\mathbf{x}^{(i+1)}, \mathbf{p}^{(i)})$ and $f(\tau^{(i)}, \mathbf{p}^{(i)}) \leq f(\tau^{(i+1)}, \mathbf{p}^{(i)})$ [27]. In the second step, with a given subcarrier allocation at iteration $i + 1$, the power allocation at iteration $(i+1)$ is obtained. Based on DC approximation, we will have $f(\mathbf{x}^{(i+1)}, \mathbf{p}^{(i)}) \leq f(\mathbf{x}^{(i+1)}, \mathbf{p}^{(i+1)})$ and $f(\tau^{(i+1)}, \mathbf{p}^{(i)}) \leq f(\tau^{(i+1)}, \mathbf{p}^{(i+1)})$. Finally,
we have $\cdots \leq f(x^{(i)}, p^{(i)}) \leq f(x^{(i+1)}, p^{(i)}) \leq f(x^{(i+1)}, p^{(i+1)}) \leq \cdots \leq f(x^*, p^*)$, and 
$\cdots \leq f(\tau^{(i)}, p^{(i)}) \leq f(\tau^{(i+1)}, p^{(i)}) \leq f(\tau^{(i+1)}, p^{(i+1)}) \leq \cdots \leq f(\tau^*, p^*)$, where $x^*$, $\tau^*$ and $p^*$ are optimal solutions which are obtained in the previous iteration. After each iteration, we have $f(\tau^{(i+1)}, p^{(i+1)}) - f(\tau^{(i)}, p^{(i)})$ and $f(x^{(i+1)}, p^{(i+1)}) - f(x^{(i)}, p^{(i)})$ which is a decreasing function and consequently the proposed algorithm converges.

APPENDIX B

We approximate the rate function with the DC approximation as explained in Appendix C. In each iteration for each subproblem, the objective function and all constraints are single variable functions. With DC method which is described in Appendix C, the non-convex problem can be converted into a convex problem [30]. Given the fact that the functions in each iteration for each subproblem are single-variable, we show the functions $f_{AC}^q(P, \tau)$, $g_{AC}^q(P, \tau)$, $y_{AC}^q(P, \tau)$, $f_{FH}^q(P, x)$, and $g_{FH}^q(P, x)$ as a function $\nu(\rho)$, where according to the subproblem $\rho$ can be $P$, $x$ or $\tau$ for simplicity. Therefore, we have $\nu(\rho^{(i)}) \leq \nu(\rho^{(i-1)}) + \nabla \nu(\rho^{(i-1)})(\rho^{(i)} - \rho^{(i-1)})$. Consequently, from [27], for iteration $i$, we have $f(\rho^{(i)}) - \{g(\rho^{(i-1)}) + \nabla g(\rho^{(i-1)})(\rho^{(i)} - \rho^{(i-1)})\} \geq R_0$. Moreover, we have $f(\rho^{(i+1)}) - g(\rho^{(i+1)}) \geq f(\rho^{(i)}) - g(\rho^{(i)}) - \nabla g(\rho^{(i)})(\rho^{(i+1)} - \rho^{(i)}) \geq f(\rho^{(i)}) - g(\rho^{(i)})$ [30]. In other words, after each iteration, a distance of new solution to the optimum solution is always smaller than that of the previous iteration [30]. Therefore, SCA with the DC approximation converges to a suboptimal solution [30], [31].
First, we transform the access rate into a convex function by using the DC approximation as

\[
\sum_{s \in S} \sum_{u \in I_s} \sum_{j \in J} \sum_{k_1 \in K_1} x_{s, j, q, u, k_1} = \sum_{j \in J} \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} \tau_{u, k_1} \left[ \ln (1 + \gamma_{s, j, q, u, k_1}) - \sqrt{\frac{V_{s, j, q, u, k_1}}{\tilde{\phi} w_{k_1}}} f^{-1}_Q (\varepsilon_{s, j, q, u, k_1}) \right]
\]

\[
\sum_{j \in J} \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} \tau_{u, k_1} \frac{w_{k_1}}{2} \ln 2 + 2 \sum_{j \in J} \ln 2 \left( \tau_{u, k_1} \left[ \ln (1 + \gamma_{s, j, q, u, k_1}) - \sqrt{\frac{V_{s, j, q, u, k_1}}{\tilde{\phi} w_{k_1}}} f^{-1}_Q (\varepsilon_{s, j, q, u, k_1}) \right] \right)
\]

\[
- \tau_{u, k_1} \frac{w_{k_1}}{2} \ln 2 \sqrt{\tilde{\phi}} \left[ 1 - \frac{1}{1 + \gamma_{s, j, q, u, k_1}^2} f^{-1}_Q (\varepsilon_{s, j, q, u, k_1}) \right]
\]

\[
\sum_{j \in J} \sum_{s \in S} \sum_{u \in I_s} \sum_{k_1 \in K_1} f_{AC}^q (P_{s, j, q, u, k_1}, \tau_{s, j, q, u, k_1}) - g_{AC}^q (P_{s, j, q, u, k_1}, \tau_{s, j, q, u, k_1}) - y_{AC}^q (P_{s, j, q, u, k_1}, \tau_{s, j, q, u, k_1}),
\]

where \( f_{AC}^q (P_{s, j, q, u, k_1}, \tau_{s, j, q, u, k_1}) \) and \( g_{AC}^q (P_{s, j, q, u, k_1}, \tau_{s, j, q, u, k_1}) \) are concave functions as follows

\[
f_{AC}^q (P_{s, j, q, u, k_1}, \tau_{s, j, q, u, k_1}) = \frac{w_{k_1}}{2} \ln 2 \left( \tau_{s, j, q, u, k_1} \left[ \ln (1 + \gamma_{s, j, q, u, k_1}) - \sqrt{\frac{V_{s, j, q, u, k_1}}{\tilde{\phi} w_{k_1}}} f^{-1}_Q (\varepsilon_{s, j, q, u, k_1}) \right] \right)
\]

\[
g_{AC}^q (P_{s, j, q, u, k_1}, \tau_{s, j, q, u, k_1}) = \frac{w_{k_1}}{2} \ln 2 \left( \tau_{s, j, q, u, k_1} \left[ \ln (1 + \gamma_{s, j, q, u, k_1}) - \sqrt{\frac{V_{s, j, q, u, k_1}}{\tilde{\phi} w_{k_1}}} f^{-1}_Q (\varepsilon_{s, j, q, u, k_1}) \right] \right)
\]

Then, to transform \( \sum_{s \in S} \sum_{u \in I_s} \sum_{j \in J} \sum_{k_1 \in K_1} \tau_{s, j, q, u, k_1} \) to a convex function, we use

\[
g_{AC}^q (P, \tau) \approx g_{AC}^q (P, \tau)^{(t-1)} + \nabla g_{AC}^q (P, \tau)^{(t-1)} ((P, \tau)^{(t)}) - (P, \tau)^{(t-1)}),
\]

where \( \nabla g_{AC}^q (P, \tau) \) for subcarrier allocation subproblem is as follows

\[
\nabla g_{AC}^q (\tau) = \begin{cases} 0, & \text{if } m = j, \\ \frac{h_{s, m, q, s, j, q} g_{s, j, q, u, k_1}}{\sigma_{s, j, q, u, k_1} + I_{s, j, q, u, k_1}}, & \text{if } m \neq j, \end{cases}
\]

and for power allocation subproblem, we have

\[
\nabla g_{AC}^q (P) = \begin{cases} 0, & \text{if } m = j, \\ \frac{h_{s, m, q, s, j, q} g_{s, j, q, u, k_1}}{\sigma_{s, j, q, u, k_1} + I_{s, j, q, u, k_1}}, & \text{if } m \neq j. \end{cases}
\]
Similarity, for $y_{AC}^q(P_{u,k_1}, u,k_1) = \frac{s^{j,q}_{u,k_1} \sqrt{w_{k_1}}}{\ln 2 \sqrt{\phi}} \sqrt{1 - \frac{1}{(1+\gamma^{j,q}_{u,k_1})^2}} f^{-1}_Q(\epsilon^{s,j,q}_{u,k_1})$, we have

$$y_{AC}^q(P, \tau) \approx y_{AC}^q(P, \tau)^{(t-1)} + \nabla y_{AC}^q T(P, \tau)^{(t-1)}((P, \tau)^{(t)} - (P, \tau)^{(t-1)}).$$

Notice that, in power allocation subproblem, the values of subcarrier allocation subproblem are fixed, and in subcarrier allocation subproblem, the variables of transmit power allocations are fixed. Therefore, in power allocation subproblem, we have

$$\nabla y_{AC}^q(P) = \begin{cases} 
0.5(2r^{s,j,q}_{u,k_1} + 2e^{s,j,q}_{u,k_1} h^{s,j,q}_{u,k_1} + 2r^{s,j,q}_{u,k_1} + 2e^{s,j,q}_{u,k_1}) & \text{if } m = j, \\
0.5(2r^{s,m,q}_{u,k_1} h^{s,m,q}_{u,k_1} + 2e^{s,m,q}_{u,k_1}) & \text{if } m \neq j,
\end{cases}$$

where $\psi^{s,j,q}_{u,k_1} = \sqrt{p^{s,j,q}_{u,k_1} h^{s,j,q}_{u,k_1} + 2e^{s,j,q}_{u,k_1}}$ and $\Gamma^{s,j,q}_{u,k_1} = \sigma^{s,j,q}_{u,k_1} + I^{s,j,q}_{u,k_1}$. Similarly, in subcarrier allocation subproblem, we have

$$\nabla y_{AC}^q(\tau) = \begin{cases} 
0.5(2r^{s,j,q}_{u,k_1} + 2e^{s,j,q}_{u,k_1} h^{s,j,q}_{u,k_1} + 2r^{s,j,q}_{u,k_1} + 2e^{s,j,q}_{u,k_1}) & \text{if } m = j, \\
0.5(2r^{s,m,q}_{u,k_1} h^{s,m,q}_{u,k_1} + 2e^{s,m,q}_{u,k_1}) & \text{if } m \neq j,
\end{cases}$$

For fronthaul links, we have

$$\sum_{j \in J} \sum_{k_2 \in K_2} x^{j,q}_{k_2} f^{j,q}_{k_2} = \sum_{j \in J} \sum_{k_2 \in K_2} x^{j,q}_{k_2} w_{k_2} \ln 2 \left[ \ln \left(1 + \frac{p^{j,q}_{k_2} h^{j,q}_{k_2}}{\sigma^{j,q}_{k_2}} \right) - \frac{\sqrt{V^{j,q}_{k_2}}}{\phi w_{k_2}} \right] f^{-1}_Q(\epsilon^{j,q}_{k_2})$$

$$\sum_{j \in J} \sum_{k_2 \in K_2} \frac{x^{j,q}_{k_2} w_{k_2}}{\ln 2} \ln \left(1 + \frac{p^{j,q}_{k_2} h^{j,q}_{k_2}}{\sigma^{j,q}_{k_2}} \right) - \frac{x^{j,q}_{k_2} w_{k_2}}{\ln 2 \sqrt{\phi}} \sqrt{1 - \frac{1}{(1+\gamma^{j,q}_{k_2})^2}} f^{-1}_Q(\epsilon^{j,q}_{k_2}) =$$

$$\sum_{j \in J} \sum_{k_2 \in K_2} f^{j,q}_{k_2}(p^{j,q}_{k_2}, x^{j,q}_{k_2}) - g^{j,q}_{k_2}(p^{j,q}_{k_2}, x^{j,q}_{k_2}),$$

where $f^{j,q}_{k_2}(p^{j,q}_{k_2}, x^{j,q}_{k_2}) = \frac{x^{j,q}_{k_2} w_{k_2}}{\ln 2} \ln \left(1 + \frac{p^{j,q}_{k_2} h^{j,q}_{k_2}}{\sigma^{j,q}_{k_2}} \right)$ and $g^{j,q}_{k_2}(p^{j,q}_{k_2}, x^{j,q}_{k_2}) = \frac{x^{j,q}_{k_2} w_{k_2}}{\ln 2 \sqrt{\phi}} \sqrt{1 - \frac{1}{(1+\gamma^{j,q}_{k_2})^2}} f^{-1}_Q(\epsilon^{j,q}_{k_2}).$

Then, we deploy

$$g^{j,q}_{k_2}(P, X) \approx g^{j,q}_{k_2}(P, X)^{(t-1)} + \nabla g^{j,q}_{k_2} T(P, X)^{(t-1)}((P, X)^{(t)} - (P, X)^{(t-1)}),$$
in which for power subcarrier problem, we have

\[
\nabla g_{\text{FH}}^q(P) = \frac{0.5(2x_{k_2}^j p_{k_2}^j |h_{k_2}^j| + 2\sigma_{k_2}^j x_{k_2}^j p_{k_2}^j h_{k_2}^j)(\Phi_{u,k_1}^{s,j,q} - (\Pi_{u,k_1}^{s,j,q} - x_{k_2}^j p_{k_2}^j (\Phi_{u,k_1}^{s,j,q})}{(\Pi_{u,k_1}^{s,j,q})^2})
\]

where \(\Phi_{u,k_1}^{s,j,q} = \sqrt{2x_{k_2}^j p_{k_2}^j |h_{k_2}^j| + 2\sigma_{k_2}^j x_{k_2}^j p_{k_2}^j h_{k_2}^j}\) and \(\Pi_{u,k_1}^{s,j,q} = \sigma_{k_2}^j + x_{k_2}^j p_{k_2}^j h_{k_2}^j\). For subcarrier allocation subproblem, we have

\[
\nabla g_{\text{FH}}^q(X) = \frac{0.5(2x_{k_2}^j p_{k_2}^j |h_{k_2}^j| + 2\sigma_{k_2}^j x_{k_2}^j p_{k_2}^j h_{k_2}^j)(\Phi_{u,k_1}^{s,j,q} - (\Pi_{u,k_1}^{s,j,q} - x_{k_2}^j p_{k_2}^j (\Phi_{u,k_1}^{s,j,q})}{(\Pi_{u,k_1}^{s,j,q})^2})
\]

C13 and C14 are functions of the rates, i.e., (1) and (5). Therefore, by the DC approximation, C13 is transformed into a convex function as

\[
- \sum_{s \in S} \sum_{u \in U} \sum_{j \in J} \sum_{k_1 \in K_1} r_{u,k_1} s_{j,U}^{s,UL} + \sum_{j \in J} \sum_{k_2 \in K_2} x_{k_2}^j r_{k_2}^j
\]

\[
\sum_{j \in J} \sum_{s \in S} \sum_{u \in U} \sum_{k_1 \in K_1} \left( - \frac{\gamma_{s,j} u_{k_1}}{\ln 2} \ln 2\sigma_{u,k_1}^{s,j,q} + \frac{\gamma_{s,j} u_{k_1}}{\ln 2} p_{u,k_1}^{s,j,q} h_{k_2}^j q_{s,j,q} + \frac{\gamma_{s,j} u_{k_1}}{\ln 2} \ln 2(1 + \sigma_{s,j} h_{k_2}^j q_{s,j,q}) - \sum_{j \in J} \sum_{k_2 \in K_2} \left( - f_{\text{UL}}(P_{u,k_1}^{s,j,q}, \tau_{u,k_1}^{s,j,q}) + g_{\text{AC}}(P_{u,k_1}^{s,j,q}, \tau_{u,k_1}^{s,j,q}) + f_{\text{FH}}^q(p_{k_2}^j, x_{k_2}^j) - g_{\text{FH}}^q(p_{k_2}^j, x_{k_2}^j),\right)
\]

where \(- f_{\text{UL}}(P_{u,k_1}^{s,j,q}, \tau_{u,k_1}^{s,j,q})\) is non-convex and based on DC approximation, we convert it to a convex function as follows:

\[
f_{\text{AC}}^{UL}(P, \tau) \approx f_{\text{AC}}^{UL}(P, \tau)^{(t-1)} + f_{\text{AC}}^{UL}(P, \tau)^{(t-1)}((P, \tau)^{(t-1)} - (P, \tau)^{(t-1)}),
\]

in which for subcarrier allocation subproblem, we have

\[
\nabla f_{\text{AC}}^{UL}(\tau) = \begin{cases} 
\frac{\sum_{s \in S} \sum_{u \in U} \sum_{j \in J} \sum_{k_1 \in K_1} \gamma_{s,j} u_{k_1}}{\sum_{s \in S} \sum_{u \in U} \sum_{j \in J} \sum_{k_1 \in K_1} \gamma_{s,j} u_{k_1}} & \text{if } m = j, \\
\frac{\sum_{s \in S} \sum_{u \in U} \sum_{j \in J} \sum_{k_1 \in K_1} \gamma_{s,j} u_{k_1}}{\sum_{s \in S} \sum_{u \in U} \sum_{j \in J} \sum_{k_1 \in K_1} \gamma_{s,j} u_{k_1}} & \text{if } m \neq j,
\end{cases}
\]

(23)
Hence, \( C_{13} \) becomes a convex constraint via the DC approximation. Similarly, for \( C_{14} \), we have

\[
\nabla f_{\text{AC}}(P) = \begin{cases} 
\frac{m_{j,m} P_{s,j,q}^* + p_{s,j,q}^*\ln 2}{\sigma_{u,k_1} + \tau_{u,k_1}} & \text{if } m = j, \\
\frac{m_{j,m} P_{s,j,q}^* + p_{s,j,q}^*\ln 2}{\sigma_{u,k_1} + \tau_{u,k_1}} & \text{if } m \neq j.
\end{cases}
\tag{24}
\]

Hence, \( C_{13} \) becomes a convex constraint via the DC approximation. Similarly, for \( C_{14} \), we have

\[
\sum_{s \in S} \sum_{u \in I_s} \sum_{j \in J} \sum_{k_1 \in K_1} \sum_{s,j,q} x_{s,j,q}^* \ln 2 \left( \frac{\sigma_{u,k_1}^* + r_{u,k_1}^* P_{s,j,q}^* + p_{s,j,q}^* h_{s,j,q}^*}{\sigma_{u,k_1}^* + \tau_{u,k_1}^*} \right) - \sum_{j \in J} \sum_{k_2 \in K_2} \sum_{s,j,q} x_{s,j,q}^* \ln 2 \left( \frac{\sigma_{u,k_1}^* + r_{u,k_1}^* P_{s,j,q}^* + p_{s,j,q}^* h_{s,j,q}^*}{\sigma_{u,k_1}^* + \tau_{u,k_1}^*} \right)
\]

\[
- \frac{\tau_{s,j,q}^*}{\ln 2} \sqrt{w_{k_1}} \left( \frac{1}{1 + \gamma_{s,j,q}^*} \right)^2 f_Q(\varepsilon_{s,j,q}^* ) - \frac{\tau_{s,j,q}^*}{\ln 2} \sqrt{w_{k_2}} \left( \frac{1}{1 + \gamma_{s,j,q}^*} \right)^2 f_Q(\varepsilon_{s,j,q}^* )
\]

where \( f_{\text{DL}}(P, X) \) can be transformed to a convex function by DC approximation as follows

\[
f_{\text{DL}}(P, X) \approx f_{\text{DL}}(P, X)^{(t-1)} + \nabla f_{\text{DL}}(P, X)^{(t-1)}((P, X)^{(t-1)} - (P, X)^{(t-1)}),
\]

in which for subcarrier allocation subproblem, we have

\[
\nabla f_{\text{DL}}(X) = \begin{cases} 
0, & \text{if } m = j, \\
\frac{p_{s,j,q}^* + p_{s,j,q}^* h_{s,j,q}^*}{\sigma_{s,j,q}^* + \tau_{s,j,q}^*} & \text{if } m \neq j,
\end{cases}
\tag{25}
\]

and for power allocation subproblem, we have

\[
\nabla f_{\text{DL}}(P) = \begin{cases} 
0, & \text{if } m = j, \\
\frac{x_{s,j,q}^*}{\sigma_{s,j,q}^* + \tau_{s,j,q}^*} & \text{if } m \neq j.
\end{cases}
\tag{26}
\]

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