Joint Uplink/Downlink Resource Allocation and Data Offloading in OFDMA-Based Wireless Powered HetNets

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Abstract

This paper considers joint uplink/downlink of an orthogonal frequency division multiple access (OFDMA)-based heterogeneous network (HetNet) consisting of a single macro base station (MBS), multiple femto base stations (FBSs) and access points (APs) where base stations (BSs) can offload data to APs and each mobile user (MU) is able to harvest the received energy using the simultaneous wireless information and power transfer (SWIPT) technique. We also suppose that the harvested energy of MUs are used for their uplink information transmission. We devise a radio resource allocation (RRA) algorithm to maximize the uplink sum data rate of MUs subject to a minimum required downlink data rate of each MU and maximum allowable transmit power of each BS, AP, and MU. More specifically, both the frequency division duplex (FDD) and time division duplex (TDD) schemes are investigated. The proposed non-convex optimization problems are solved using an iterative algorithm. It is also proved that the proposed algorithm converges to a near-optimal solution. Simulation results illustrate that the TDD scheme improves the performance compared to the FDD scheme. In addition, it is shown that utilizing the data offloading technique improves the uplink sum data rate of MUs compared to the scenario without any AP.

Index Terms– OFDMA, energy harvesting, resource allocation, joint uplink/downlink, SWIPT, data offloading.

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I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is a useful modulation technique which is used in many wireless communication systems such as long term evolution (LTE) cellular networks. The main challenge in multi-user OFDM or orthogonal frequency division multiple access (OFDMA) technique is radio resource allocation (RRA), i.e., transmit power and subcarrier allocation [1].

The emergence of mobile services with different quality of service (QoS) for users in both uplink and downlink leads us to couple both uplink and downlink in the design of RRA algorithms. In other words, the radio resources in downlink and uplink should be allocated jointly [2]. Generally, uplink and downlink are separated by a duplex scheme. There exist two duplex schemes in LTE systems, namely, frequency division duplex (FDD) and time division duplex (TDD).

The emerging simultaneous wireless information and power transfer (SWIPT) technique provides an energy source for wireless networks. SWIPT-based systems realize both of the two main utilizations of radio signals: transferring energy and information [3]–[6]. In [3], the authors investigate two practical schemes for SWIPT called time switching (TS) and power splitting (PS) in downlink of OFDMA-based system where receivers can harvest energy and decode information using the same signals received from an access point (AP). In TS, the received signal is either considered for energy harvesting (EH) by an energy receiver or information decoding (ID) by an information receiver at each time slot. In PS, the received signal is split into two signal streams with an arbitrary PS ratio at each user where a portion of the received power is used at the energy receiver and the other is used at the information receiver.

In order to reduce the data traffic of BS, mobile data offloading techniques are developed [7]. The principle of mobile data offloading is reducing the data traffic load at a BS by using small BSs (SBSs) or APs [7], [8]. Note that integration of the aforementioned technologies significantly improve heterogeneous networks (HetNets) from energy consumption and spectrum efficiency perspective which motivates us to consider them in this paper.

A. Related Works

Many RRA algorithms are proposed for the downlink of cellular networks [9]–[12]. The authors in [9] design an optimization problem for the downlink of a heterogeneous cellular network in order to maximize the downlink sum data rate of femto-cell users subject to minimum
required downlink sum data rate of macro-cell users and maximum allowable transmit power of each base station (BS). They also design iterative RRA algorithms to obtain near-optimal solutions where the transmit power and subcarriers are iteratively optimized. Same iterative algorithm is also proposed in [12]. Moreover, the authors in [13]–[16] study various uplink RRA algorithms. Specifically, in [13], the authors devise a joint subcarrier and transmit power allocation algorithm where the transmit powers are allocated using the Lagrange dual method and the subcarrier assignment is based on the maximum marginal data rate among users. On the other hand, some existing works, in uplink, consider the best-effort services [15].

There are many works investigating joint uplink/downlink resource allocation optimization problems [2], [17]. In [2], the authors propose a joint uplink/downlink resource allocation problem for both the best-effort and real time classes of service. Furthermore, the authors in [17] study the joint uplink and downlink resource allocation optimization problem considering both the FDD and TDD schemes. They also consider user-level satisfaction to the communication service which couples the uplink and downlink.

With the aspect of EH, many RRA algorithms are devised for the downlink of wireless powered networks (WPNs). The authors in [3] consider two types of transmission techniques called time division multiple access (TDMA) and OFDMA. At the receivers, they utilize both the TS and PS techniques to coordinate EH and ID separately. Specifically, for the TDMA-based system, they consider the TS technique while for the OFDMA-based system, the PS technique is utilized. In addition, they design RRA algorithms to maximize the weighted sum data rate of all users by considering different time/frequency transmit power allocation and both the TS and PS techniques subject to minimum harvested power of each user and maximum allowable transmit power of the transmitter. The authors in [4] design downlink RRA algorithms to maximize the energy efficiency of OFDMA-based systems utilizing SWIPT. They also investigate two scenarios. In the first scenario, the receiver splits the received transmit signal into a continuous set of power streams with arbitrary PS ratios in the same way as in [3]. In the second scenario, at each user, the received transmit signal is only split into a discrete set of power streams with fixed power splitting ratio for the user. In [5], the authors propose a RRA algorithm for downlink of an OFDMA-based system with exploiting SWIPT. The proposed algorithm is based on maximizing energy efficiency of data transmission subject to minimum required data rate of each user, minimum harvested power of each user, and maximum allowable circuit power consumption of the system.

While most of the existing works on SWIPT concentrate on capacity-energy characterization and
do not consider cooperative transmission for SWIPT, the authors in [6] propose two protocols called PS relaying and transmission mode adaptation protocols in downlink of SWIPT OFDM-based relaying system consisting of three nodes: one as the source node, one as the relay node, and the other as the destination. In PS relaying, they assume that the data transmission occurs in two hops: one from the source node to the relay node and the other from the relay node to the destination. The relay node splits the received signal into two separated parts: one for ID and the other for EH. The harvested power is used for the data transmission from the relay to the destination. They also assume that the relay receiver has ideal bandpass filters which is able to tap into different subcarriers.

There are a few works with the aim of devising RRA algorithms for joint uplink and downlink of WPNs [18]–[20]. The authors in [18] propose a RRA algorithm for uplink and downlink of a WPN in which a single hybrid access point (H-AP) with a constant power supply communicates with multiple users. Specifically, they design a novel protocol, called harvest-then-transmit, in which users at first harvest the received energy broadcasted by the H-AP in downlink and use it for transmitting their independent information to the H-AP while assuming TDMA for uplink. In [19], the authors study RRA algorithm design for uplink and downlink of an OFDMA-based network consisting of a single AP and multiple users. More specifically, they assume the TDD scheme and utilize the PS technique for EH, and subsequently propose an optimization problem with the aim of maximizing both the uplink and downlink energy efficiencies subject to exclusive subchannel assignment, maximum allowable transmit power of AP and each user, and minimum harvested power of each user. They also consider a specific circuit power consumption at each receiver in both uplink and downlink. Moreover, they assume that each user has a battery with a fixed maximum power which can be utilized for uplink transmission and circuit power consumption at users. The authors in [20] design a RRA algorithm for uplink and downlink of a WPN composed of a single BS and multiple users where users can harvest the received power from BS and use it for transferring their information to BS. They also propose an optimization problem with the aim of maximizing joint uplink/downlink users’ data rates. They consider both TDMA and non orthogonal multiple access (NOMA) communication protocols for the downlink, and NOMA with time-sharing in the uplink. The SWIPT scheme with the PS technique is also considered for EH. They also assume that the transmit power of each user is only supplied from the harvested power of the user. Hence, they do not consider the battery power, circuit power consumption, and PS power consumption at users.
B. Our Contributions

Since both the data offloading and EH concepts are necessary for HetNets, we consider these techniques together in this paper. To the best of our knowledge, no RRA algorithm has been designed yet for the following topics:

- Joint uplink/downlink RRA of OFDMA-based HetNets in which BSs are able to offload data to APs.
- Joint uplink/downlink RRA of OFDMA-based wireless powered HetNets with the inter-cell interference management and user association.
- Joint EH and data offloading for OFDMA-based HetNets in which BSs can offload data to APs.

Therefore, in contrast to previous works, in this paper, we aim to design two RRA algorithms for joint uplink/downlink of both the FDD and TDD schemes in an OFDMA-based wireless powered HetNet consisting of a single macro base station (MBS) and multiple femto base stations (FBSs) and APs where BSs are able to offload data to APs. Furthermore, mobile users (MU) can harvest the received energy by using the PS technique. Specifically, we assume that each MU can use a fraction of the received signal power on each subcarrier for ID and the remaining for EH\(^1\). Hence, unlike the previous works, we optimize the PS ratios on all subcarriers for all MUs. We also consider the best-effort services for uplink while minimum required downlink data rate of each MU is satisfied. We assume that the uplink transmission power of MUs are supplied from the harvested power. Hence, we set the harvested power at each MU as the maximum allowable transmit power of that MU for its uplink information transmission \[19\], \[20\]. This can be a practical assumption for the best-effort services in uplink where minimum uplink data rate of MUs are not guaranteed. Accordingly, we propose two optimization problems for both the FDD and TDD schemes to maximize the uplink sum data rate of MUs subject to minimum required downlink data rate of each MU and maximum allowable transmit power of each BS, AP, and MU. The resulting non-convex optimization problems are solved by the proposed iterative algorithms. We also obtain the computational complexity of the proposed iterative algorithms in each subproblem and show that the considered FDD scheme has lower computational complexity in contrast to the TDD scheme. Simulation results illustrate that the considered mobile data offloading technique improves both the uplink sum data rate of MUs

\(^1\)This assumption can be easily applied by using bandpass filters in MUs \[6\].
and average harvested power of each MU. Moreover, we show that the considered schemes can be implemented practically for the best-effort services in uplink as well as the guaranteed QoS services in downlink.

C. Paper Organization

The rest of this paper is organized as follows: The system model and problem formulations are presented in Section II. Section III designs RRA solutions for both the FDD and TDD schemes. Section IV studies the computational complexity of the proposed iterative algorithms in each subproblem for both the FDD and TDD schemes. In addition, the simulation results and numerical examples are presented in Section V. Finally, the conclusion of this paper is presented in Section VI.

II. SYSTEM MODEL AND PROBLEM FORMULATIONS

Consider both uplink and downlink of a three-tier HetNet in which there is a single MBS, $F$ FBSs, $L$ APs, and $U$ MUs. The set of all BSs is denoted by $\mathcal{B} = \{0, 1, \ldots, B\}$ where 0 denotes the MBS and $\{1, \ldots, B\}$ is the set of FBSs. Furthermore, the set of APs and MUs are denoted by $\mathcal{L} = \{1, \ldots, L\}$ and $\mathcal{U} = \{1, \ldots, U\}$, respectively. Fig. 1 shows the considered system model. Let $W_{\text{BS}}$ be the available licensed bandwidth of channels for BSs and $W_{\text{AP}}$ be the available unlicensed bandwidth of channels for APs. We assume that the OFDMA technique is applied in
both uplink and downlink of BSs and APs. The frequency band of each subcarrier is assumed to be $W_S$. Therefore, the number of subcarriers of BSs and APs are given by $N_{BS} = W_{BS}/W_S$ and $N_{AP} = W_{AP}/W_S$, respectively. The set of subcarriers for BSs and APs are also denoted by $N_{BS} = \{1, \ldots, n_{BS}, \ldots, N_{BS}\}$ and $N_{AP} = \{1, \ldots, n_{AP}, \ldots, N_{AP}\}$, respectively [3].

### A. FDD Scheme with Power Splitting

In this scheme, the frequency band $W_{BS}$ is divided into two non-overlapping bands where one frequency band is considered for uplink and is denoted by $W^U_{BS}$ and the other is indicated by $W^D_{BS}$ for downlink [17]. Similar to $W_{BS}$, let $W^U_{AP}$ and $W^D_{AP}$ be the frequency band of uplink and downlink of APs, respectively. Accordingly, the number of subcarriers for uplink of BSs and APs are indicated by $N^U_{BS} = W^U_{BS}/W_S$ and $N^U_{AP} = W^U_{AP}/W_S$, respectively, and the number of subcarriers for downlink of BSs and APs are indicated by $N^D_{BS} = W^D_{BS}/W_S$ and $N^D_{AP} = W^D_{AP}/W_S$, respectively. Expressed by $N^U_{BS} = \{1, \ldots, n^D_{BS}, \ldots, N^D_{BS}\}$ and $N^D_{BS} = \{1, \ldots, n^U_{BS}, \ldots, N^U_{BS}\}$ the set of subcarriers of downlink for BSs and APs, respectively, and $N^U_{AP} = \{1, \ldots, n^U_{AP}, \ldots, N^U_{AP}\}$ the set of subcarriers of uplink for BSs and APs, respectively. Let $h^D_{t,u,BS}$ and $h^D_{t,u,AP}$ be the channel power gain from BS $b \in B$ to MU $u$ on subcarrier $n^D_{BS}$ and the channel power gain from AP $l$ to MU $u$ on subcarrier $n^D_{AP}$, respectively. We also define $h^U_{b,u,BS}$ and $h^U_{l,u,AP}$ as the channel power gain from MU $u$ to BS $b$ on subcarrier $n^U_{BS}$ and the channel power gain from MU $u$ to AP $l$ on subcarrier $n^U_{AP}$, respectively. Moreover, denoted by $p^D_{b,u,BS}$ the transmit power of BS $b$ to MU $u$ on subcarrier $n^D_{BS}$, $p^D_{l,u,AP}$ the transmit power of AP $l$ to MU $u$ on subcarrier $n^D_{AP}$, $p^U_{b,u,BS}$ the transmit power of MU $u$ to BS $b$ on subcarrier $n^U_{BS}$, and $p^U_{l,u,AP}$ the transmit power of MU $u$ to AP $l$ on subcarrier $n^U_{AP}$, respectively. For notational convenience, let us denote $\mathbf{p} = [p_{BS}, p_{AP}]$, $\mathbf{p}_{BS} = [p^D_{BS}, p^U_{BS}]$, $\mathbf{p}_{AP} = [p^D_{AP}, p^U_{AP}]$, $\mathbf{p}^D_{BS} = [p_{D,BS}, p^{D,AP}]$, $\mathbf{p}^U_{BS} = [p_{U,BS}, p^{U,AP}]$, $\mathbf{p}^D_{AP} = [p^{D,BS}, p^{D,AP}]$, and $\mathbf{p}^U_{AP} = [p^{U,BS}, p^{U,AP}]$. The subcarrier assignment is indicated by binary variables $\rho^D_{b,u,BS}$, $\rho^D_{l,u,AP}$, $\rho^U_{b,u,BS}$, and $\rho^U_{l,u,AP}$ where $\rho^D_{b,u,BS} = 1$ if subcarrier $n^D_{BS}$ is assigned to the channel from BS $b$ to MU $u$ and $\rho^D_{l,u,AP} = 1$ if subcarrier $n^D_{AP}$ is assigned to the channel from AP $l$ to MU $u$ and $\rho^U_{b,u,BS} = 0$ otherwise, $\rho^U_{l,u,AP} = 1$ if subcarrier $n^U_{BS}$ is assigned to the channel from MU $u$ to BS $b$ and $\rho^U_{b,u,BS} = 0$ otherwise, and $\rho^U_{l,u,AP} = 1$ if subcarrier $n^U_{AP}$ is assigned to the channel from MU $u$ to AP $l$ and $\rho^U_{l,u,AP} = 0$ otherwise. For the sake of simplicity, we also indicate $\mathbf{\rho} = [\mathbf{\rho}_{BS}, \mathbf{\rho}_{AP}]$, $\mathbf{\rho}_{BS} = [\rho^D_{BS}, \rho^U_{BS}]$, $\mathbf{\rho}_{AP} = [\rho^D_{AP}, \rho^U_{AP}]$, $\mathbf{\rho}^D_{BS} = [\rho^D_{b,u,BS}, \rho^D_{l,u,AP}]$, $\mathbf{\rho}^U_{BS} = [\rho^U_{b,u,BS}, \rho^U_{l,u,AP}]$, and $\mathbf{\rho}^U_{AP} = [\rho^U_{b,u,BS}, \rho^U_{l,u,AP}]$. 


We assume that each MU is able to be associated with at most one BS or one AP in the network. Furthermore, joint uplink and downlink consideration enforces us to have same decision for assigning MUs in uplink and downlink. For example, if MU $u$ is connected to AP $l$ in downlink, it should be assigned to AP $l$ in uplink. According to the above, we have the following subcarrier assignment constraints for each MU as:

\[
\begin{align*}
\rho_{b,u}^{D,n_{BS}} + \rho_{l,u}^{D,n_{AP}} &\leq 1, \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D} \in \mathcal{N}_{AP}^{D}, & (1) \\
\rho_{b,u}^{U,n_{BS}} + \rho_{l,u}^{U,n_{AP}} &\leq 1, \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{U} \in \mathcal{N}_{BS}^{U}, n_{AP}^{U} \in \mathcal{N}_{AP}^{U}, & (2) \\
\rho_{b,u}^{D,n_{BS}} + \rho_{l,u}^{U,n_{AP}} &\leq 1, \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D} \in \mathcal{N}_{BS}^{D}, n_{AP}^{U} \in \mathcal{N}_{AP}^{U}, & (3) \\
\rho_{b,u}^{U,n_{BS}} + \rho_{l,u}^{D,n_{AP}} &\leq 1, \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{U} \in \mathcal{N}_{BS}^{U}, n_{AP}^{D} \in \mathcal{N}_{AP}^{D}, & (4)
\end{align*}
\]

where (1) and (2) are the MU association constraints in downlink and uplink, respectively, and constraints (3) and (4) ensure MUs to have same decisions for both uplink and downlink. On the other hand, the following sets of constraints guarantee the OFDMA assumption in downlink and uplink of each BS, respectively, as [3], [9], [19]:

\[
\begin{align*}
\sum_{u \in \mathcal{U}} \rho_{b,u}^{D,n_{BS}} &\leq 1, \forall b \in \mathcal{B}, n_{BS}^{D} \in \mathcal{N}_{BS}^{D}, & (5) \\
\rho_{b,u}^{D,n_{BS}} &\in \{0, 1\}, \forall u \in \mathcal{U}, b \in \mathcal{B}, n_{BS}^{D} \in \mathcal{N}_{BS}^{D}, & (6)
\end{align*}
\]

and

\[
\begin{align*}
\sum_{u \in \mathcal{U}} \rho_{b,u}^{U,n_{BS}} &\leq 1, \forall b \in \mathcal{B}, n_{BS}^{U} \in \mathcal{N}_{BS}^{U}, & (7) \\
\rho_{b,u}^{U,n_{BS}} &\in \{0, 1\}, \forall u \in \mathcal{U}, b \in \mathcal{B}, n_{BS}^{U} \in \mathcal{N}_{BS}^{U}. & (8)
\end{align*}
\]

In order to guarantee the OFDMA technique in downlink and uplink for unlicensed frequency bands of each AP, we formulate the following constraints, respectively, as [19]:

\[
\begin{align*}
\sum_{u \in \mathcal{U}} \rho_{l,u}^{D,n_{AP}} &\leq 1, \forall l \in \mathcal{L}, n_{AP}^{D} \in \mathcal{N}_{AP}^{D}, & (9) \\
\rho_{l,u}^{D,n_{AP}} &\in \{0, 1\}, \forall l \in \mathcal{L}, u \in \mathcal{U}, n_{AP}^{D} \in \mathcal{N}_{AP}^{D}, & (10)
\end{align*}
\]

and

\[
\begin{align*}
\sum_{u \in \mathcal{U}} \rho_{l,u}^{U,n_{AP}} &\leq 1, \forall l \in \mathcal{L}, n_{AP}^{U} \in \mathcal{N}_{AP}^{U}, & (11)
\end{align*}
\]
\[ \rho^U_{l,u} \in \{0, 1\}, \forall l \in \mathcal{L}, u \in \mathcal{U}, n^U_{AP} \in \mathcal{N}^U_{AP}. \] (12)

In downlink, each MU performs both EH and ID on the received signal by using the PS technique [3], [4]. We assume that the received signal at MU \( u \) over subcarrier \( n^D_{BS} \) is split into two signals by a power splitter with ratio \( \zeta^D_{BS} \in [0, 1] \) called PS ratio [3], [6]. The received signal at MU \( u \) on subcarrier \( n^D_{AP} \) is also split into two signals by a power splitter with ratio \( \zeta^D_{AP} \in [0, 1] \). In other words, \( \zeta^D_{BS} \) portion of the received power at MU \( u \) which is associated to a BS on subcarrier \( n^D_{BS} \) is sent to its energy receiver and the remaining ratio \( (1 - \zeta^D_{BS}) \) is sent to its information receiver. We also assume that each MU has ideal bandpass filters and is able to tap them into different subcarriers for ID [6]. We note that all the received power from APs at each MU, which is associated to a BS, is considered for EH, and all the received power from BSs at each MU, which is associated to an AP, is considered for EH. Denoted by \( \zeta^{BS} = [\zeta^D_{BS}] \), \( \zeta^{AP} = [\zeta^D_{AP}] \), and \( \zeta = [\zeta^{BS}, \zeta^{AP}] \). The received SINR at MU \( u \) from BS \( b \) on subcarrier \( n^D_{BS} \) can be obtained by [3]

\[
\gamma^D_{b,u} = \frac{(1 - \zeta^D_{BS}) p^D_{b,u} n^D_{BS} h^D_{b,u} (1 - \rho^D_{n^D_{BS} \neq b} \rho^D_{n^D_{BS} \neq u} \sigma^D_{n^D_{BS}} \rho^D_{n^D_{BS} \neq i,j} h^D_{n^D_{BS} \neq i,u})}{\sum_{i=0}^{B} \sum_{i \neq b}^{D} \sum_{j \neq u}^{D} (1 - \zeta^D_{BS}) p^D_{i,j} n^D_{BS} h^D_{i,u} (1 - \rho^D_{n^D_{BS} \neq i,j} \rho^D_{n^D_{BS} \neq u} \sigma^D_{n^D_{BS}} \rho^D_{n^D_{BS} \neq i,j} h^D_{n^D_{BS} \neq i,u}) + \sigma^D_{n^D_{BS}}},
\] (13)

where \( \sigma^D_{n^D_{BS}} \) is the additive white Gaussian noise (AWGN) power at MU \( u \) on subcarrier \( n^D_{BS} \). Accordingly, the achievable downlink data rate at MU \( u \) from BS \( b \) on subcarrier \( n^D_{BS} \) can be expressed by

\[
r^D_{b,u} = \log_2(1 + \gamma^D_{b,u}).
\] (14)

The received SINR at MU \( u \) from AP \( l \) on subcarrier \( n^D_{AP} \) is also given by [19]

\[
\gamma^D_{l,u} = \frac{(1 - \zeta^D_{AP}) p^D_{l,u} n^D_{AP} h^D_{l,u} (1 - \rho^D_{n^D_{AP} \neq l} \rho^D_{n^D_{AP} \neq u} \sigma^D_{n^D_{AP}} \rho^D_{n^D_{AP} \neq i,j} h^D_{n^D_{AP} \neq i,u})}{\sum_{i=1}^{L} \sum_{i \neq l}^{L} \sum_{j \neq u}^{L} (1 - \zeta^D_{AP}) p^D_{i,j} n^D_{AP} h^D_{i,u} (1 - \rho^D_{n^D_{AP} \neq i,j} \rho^D_{n^D_{AP} \neq u} \sigma^D_{n^D_{AP}} \rho^D_{n^D_{AP} \neq i,j} h^D_{n^D_{AP} \neq i,u}) + \sigma^D_{n^D_{AP}}},
\] (15)

where \( \sigma^D_{n^D_{AP}} \) is the AWGN noise power at MU \( u \) on subcarrier \( n^D_{AP} \). Hence, the achievable downlink data rate at MU \( u \) from AP \( l \) on subcarrier \( n^D_{AP} \) can be formulated as:

\[
r^D_{l,u} = \log_2(1 + \gamma^D_{l,u}).
\] (16)
In order to guarantee the QoS of each MU in downlink, we define $R_u^{\min}$ as minimum required data rate of MU $u \in \mathcal{U}$. Therefore, the downlink data rate of MU $u \in \mathcal{U}$ should not be less than $R_u^{\min}$. Hence, we formulate the following QoS constraint as:

$$
\sum_{b \in B} \sum_{n_{BS}^b=1}^{N_{BS}^b} \rho_{b,u}^{D} n_{BS}^b D_{n_{BS}^b} + \sum_{l \in L} \sum_{n_{AP}^l=1}^{N_{AP}^l} \rho_{l,u}^{D} n_{AP}^l D_{n_{AP}^l} \geq R_u^{\min}, \forall u.
$$

(17)

Let $0 < \eta < 1$ be the conversion efficiency [3], [4]. Accordingly, the harvested energy at the energy receiver of MU $u$ is given by [3], [19], [20]

$$
P_{Hv}^u = \sum_{i \in B} \sum_{j \in U} \sum_{n_{BS}^i=1}^{N_{BS}^i} \eta \zeta_{i,j}^{D} n_{BS}^i D_{n_{BS}^i} + \sum_{i=1}^{L} \sum_{j \in U} \sum_{n_{AP}^i=1}^{N_{AP}^i} \eta \zeta_{i,j}^{D} n_{AP}^i D_{n_{AP}^i} D_{n_{AP}^i},
$$

(18)

where the first and second terms are the harvested energy of MU $u$ from the downlink transmission of BSs and APs, respectively. An example of the energy utilization for the PS scheme in an OFDMA-based SWIPT system consisting of a single MBS and two MUs is illustrated in Fig. 2. As shown, we assume that subcarrier $n_{BS}^1$ is assigned to MU 2, i.e., $\rho_{0,1}^{D} n_{BS}^1 = 0$ and $\rho_{0,2}^{D} n_{BS}^1 = 1$. Therefore, the total received power of MBS at MU 1 on subcarrier $n_{BS}^1$ is considered for EH (i.e., $\zeta_{1}^{D} = 1$) whereas a fraction $\zeta_{2}^{D} \in [0, 1]$ of the received power of MBS at MU 2 on subcarrier $n_{BS}^1$ is considered for EH and the remaining part of it for ID. Furthermore, just $\eta$ portion of the considered power for EH can be harvested at each MU, and the remaining part of it, is the wasted energy harvesting (WEH). We also assume that the maximum allowable transmit
power of BS $b$ and AP $l$ are denoted by $P_{b,\text{max}}^{\text{BS}}$ and $P_{l,\text{max}}^{\text{AP}}$, respectively. Hence, the maximum allowable transmit power constraints for BS $b$ and AP $l$ are given, respectively, by

$$\sum_{u \in U} \sum_{n_{BS}^U = 1}^{N_{BS}^U} \rho_{b,u}^U P_{b,u}^{U,\text{BS}} \leq P_{b,\text{max}}^{\text{BS}}, \forall b \in B,$$

$$\sum_{u \in U} \sum_{n_{AP}^U = 1}^{N_{AP}^U} \rho_{l,u}^U P_{l,u}^{U,\text{AP}} \leq P_{l,\text{max}}^{\text{AP}}, \forall l \in L. \quad (19)$$

In uplink, MUs use the harvested energy for transmitting their information. Unlike downlink, we consider the best-effort services in uplink. Accordingly, we suppose that the uplink transmission power of each MU is supplied only from the harvested energy of it \cite{18}, \cite{20}. The maximum allowable transmit power constraint for MU $u$ is given by

$$\sum_{b \in B} \sum_{n_{BS}^U = 1}^{N_{BS}^U} U_{b,u}^{U,\text{BS}} P_{b,u}^{U,\text{BS}} h_{b,u}^{U} + \sum_{l \in L} \sum_{n_{AP}^U = 1}^{N_{AP}^U} U_{l,u}^{U,\text{AP}} P_{l,u}^{U,\text{AP}} h_{l,u}^{U} \leq p_{Hv}^{U}. \quad (21)$$

The achievable data rate at BS $b$ from MU $u$ on subcarrier $n_{BS}^U$ is expressed as follows:

$$r_{b,u}^{U,\text{BS}} = \log_2 \left( 1 + \frac{U_{b,u}^{U,\text{BS}} P_{b,u}^{U,\text{BS}} h_{b,u}^{U}}{\sum_{i=0}^{B} \sum_{j \in U} \rho_{i,j}^{U,\text{BS}} U_{i,j}^{U,\text{BS}} U_{i,j}^{U,\text{BS}} + \sigma_{b,\text{BS}}^{U}} \right), \quad (22)$$

where $\sigma_{b,\text{BS}}^{U}$ is the received AWGN noise at BS $b$ on subcarrier $n_{BS}^U$. Similarly, the data rate at AP $l$ from MU $u$ on subcarrier $n_{AP}^U$ can be written as:

$$r_{l,u}^{U,\text{AP}} = \log_2 \left( 1 + \frac{U_{l,u}^{U,\text{AP}} P_{l,u}^{U,\text{AP}} h_{l,u}^{U}}{\sum_{i=1}^{L} \sum_{j \in U} \rho_{i,j}^{U,\text{AP}} U_{i,j}^{U,\text{AP}} U_{i,j}^{U,\text{AP}} + \sigma_{l,\text{AP}}^{U}} \right), \quad (23)$$

where $\sigma_{l,\text{AP}}^{U}$ is the received AWGN noise at AP $l$ on subcarrier $n_{AP}^U$.

This paper aims to design joint transmit power and subcarrier allocation algorithms for uplink and downlink of the FDD and TDD schemes. Specifically, in this subsection, with considering FDD as our duplex scheme, we propose an optimization problem to maximize the total uplink throughput of MUs subject to minimum required data rate of each MU and maximum allowable
transmit power of BSs, APs and MUs. The total uplink throughput of MUs can be obtained as follows:

\[ R^U = \sum_{u \in U} \left( \sum_{b \in \mathcal{B}} \sum_{n_{BS}^{U,b}=1}^{N_{BS}^{U,b}} \rho_{b,u}^{U,n_{BS}^{U,b}} r_{b,u}^{U,n_{BS}^{U,b}} + \sum_{l \in \mathcal{L}} \sum_{n_{AP}^{U,l}=1}^{N_{AP}^{U,l}} \rho_{l,u}^{U,n_{AP}^{U,l}} r_{l,u}^{U,n_{AP}^{U,l}} \right). \]  

(24)

Hence, the proposed RRA optimization problem is formulated as follows:

\[
\begin{align*}
\max_{p, \rho, \zeta} & \quad R^U \\
\text{s.t.} & \quad (1)-(12), (17), (19)-(21), \\
& \quad \rho_{D,n_{BS}^{D,b,u}}, \rho_{U,n_{BS}^{U,b,u}}, \rho_{D,n_{AP}^{D,l,u}}, \rho_{U,n_{AP}^{U,l,u}} \geq 0, \\
& \quad 0 \leq \zeta_{n_{BS}^{D,b,u}}^{D} \leq 1, \ \forall u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, \\
& \quad 0 \leq \zeta_{n_{AP}^{D,l,u}}^{D} \leq 1, \ \forall u \in \mathcal{U}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}.
\end{align*}
\]  

(25a)

\[
\begin{align*}
\text{s.t.} & \quad \frac{\rho_{D,n_{BS}^{D,b,u}}^{D} + \rho_{U,n_{BS}^{U,b,u}}^{D}}{\rho_{U,n_{BS}^{U,b,u}}^{D}} \leq 1, \ \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}, \\
& \quad \frac{\rho_{D,n_{BS}^{D,b,u}}^{U} + \rho_{U,n_{BS}^{U,b,u}}^{U}}{\rho_{U,n_{BS}^{U,b,u}}^{U}} \leq 1, \ \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}, \\
& \quad \frac{\rho_{D,n_{BS}^{D,b,u}}^{U} + \rho_{U,n_{BS}^{U,b,u}}^{D}}{\rho_{U,n_{BS}^{U,b,u}}^{D}} \leq 1, \ \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}, \\
& \quad \frac{\rho_{D,n_{BS}^{D,b,u}}^{U} + \rho_{U,n_{BS}^{U,b,u}}^{U}}{\rho_{U,n_{BS}^{U,b,u}}^{U}} \leq 1, \ \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}.
\end{align*}
\]  

(25b)

B. TDD Scheme with Power Splitting

In this scheme, uplink and downlink operates on the same frequency band based on time sharing [17], [21]. In the LTE TDD frame structure, each TDD frame consists of downlink, uplink, and special sub frames. There are seven configurations for LTE TDD frame as shown in Table 1 in [21]. In a TDD scheme, a portion of transmission time is defined for each uplink and downlink. Let \( 0 < \tau_D < 1 \) and \( 0 < \tau_U < 1 \) be the predefined portion of transmission times for downlink and uplink transmissions, respectively [17], [19], [21]. Regardless of the special sub frame, we have \( \tau_D = 1 - \tau_U \) [17], [20]. To avoid replications, we just note that in the TDD scheme, both the downlink frequency bands of BSs and APs are \( W_{BS} \) and \( W_{AP} \), respectively, and are also used in uplink of them. In addition, both the uplink and downlink data rates are multiplied to their portion of transmission times \( \tau_U \) and \( \tau_D \), respectively. The RRA optimization problem for the TDD scheme can thus be formulated as follows:

\[
\begin{align*}
\max_{p, \rho, \zeta} & \quad \sum_{u \in \mathcal{U}} \left( \sum_{b \in \mathcal{B}} \sum_{n_{BS}^{U,b,u}=1}^{N_{BS}^{U,b,u}} \tau_U \rho_{b,u}^{U,n_{BS}^{U,b,u}} r_{b,u}^{U,n_{BS}^{U,b,u}} + \sum_{l \in \mathcal{L}} \sum_{n_{AP}^{U,l,u}=1}^{N_{AP}^{U,l,u}} \tau_U \rho_{l,u}^{U,n_{AP}^{U,l,u}} r_{l,u}^{U,n_{AP}^{U,l,u}} \right) \\
\text{s.t.} & \quad \frac{\rho_{D,n_{BS}^{D,b,u}}^{U} + \rho_{U,n_{BS}^{U,b,u}}^{U}}{\rho_{U,n_{BS}^{U,b,u}}^{U}} \leq 1, \ \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}, \\
& \quad \frac{\rho_{D,n_{BS}^{D,b,u}}^{U} + \rho_{U,n_{BS}^{U,b,u}}^{U}}{\rho_{U,n_{BS}^{U,b,u}}^{U}} \leq 1, \ \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}, \\
& \quad \frac{\rho_{D,n_{BS}^{D,b,u}}^{U} + \rho_{U,n_{BS}^{U,b,u}}^{U}}{\rho_{U,n_{BS}^{U,b,u}}^{U}} \leq 1, \ \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}, \\
& \quad \frac{\rho_{D,n_{BS}^{D,b,u}}^{U} + \rho_{U,n_{BS}^{U,b,u}}^{U}}{\rho_{U,n_{BS}^{U,b,u}}^{U}} \leq 1, \ \forall l \in \mathcal{L}, b \in \mathcal{B}, u \in \mathcal{U}, n_{BS}^{D,b,u} \in \mathcal{N}_{BS}^{D}, n_{AP}^{D,l,u} \in \mathcal{N}_{AP}^{D}.
\end{align*}
\]  

(26a)

(26b)

(26c)

(26d)

(26e)
\[
\sum_{u \in U} \rho_{D,b,u}^{n_{BS}} \leq 1, \forall b \in B, n_{BS} \in N_{BS},
\]
(26f)
\[
\rho_{D,b,u}^{n_{BS}} \in \{0, 1\}, \forall b \in B, u \in U, n_{BS} \in N_{BS},
\]
(26g)
\[
\sum_{u \in U} \rho_{D,b,u}^{n_{BS}} \leq 1, \forall b \in B, n_{BS} \in N_{BS},
\]
(26h)
\[
\rho_{D,b,u}^{n_{BS}} \in \{0, 1\}, \forall b \in B, u \in U, n_{BS} \in N_{BS},
\]
(26i)
\[
\sum_{u \in U} \rho_{U,b,u}^{n_{BS}} \leq 1, \forall b \in B, n_{BS} \in N_{BS},
\]
(26j)
\[
\rho_{U,b,u}^{n_{BS}} \in \{0, 1\}, \forall b \in B, u \in U, n_{BS} \in N_{BS},
\]
(26k)
\[
\sum_{u \in U} \rho_{U,b,u}^{n_{BS}} \leq 1, \forall b \in B, n_{BS} \in N_{BS},
\]
(26l)
\[
\sum_{b \in B} N_{BS} \sum_{n_{BS}=1}^{N_{BS}} \tau_{U}^{U} \rho_{U,b,u}^{n_{BS}} \leq P_{BS,max}^{AP}, \forall b \in B,
\]
(26m)
\[
\sum_{u \in U} N_{BS} \sum_{n_{BS}=1}^{N_{BS}} \rho_{D,b,u}^{n_{BS}} \leq P_{BS,max}^{D}, \forall b \in B,
\]
(26n)
\[
\sum_{u \in U} N_{BS} \sum_{n_{BS}=1}^{N_{BS}} \rho_{D,b,u}^{n_{BS}} \rho_{D,b,u}^{n_{BS}} \leq P_{BS,max}^{AP}, \forall b \in B,
\]
(26o)
\[
\tau_{U}(\sum_{b \in B} N_{BS} \sum_{n_{BS}=1}^{N_{BS}} \rho_{U,b,u}^{n_{BS}} h_{D,b,u}^{n_{BS}} + \sum_{l \in L} N_{AP} \sum_{n_{AP}=1}^{N_{AP}} \rho_{U,l,u}^{n_{AP}} h_{U,l,u}^{n_{AP}}) \leq \tau_{D}^{H}, \forall u \in U,
\]
(26p)

where,
\[
P_{Hv}^{u} = \sum_{i \in B} \sum_{j \in L} N_{BS} \sum_{n_{BS}=1}^{N_{BS}} \eta_{i,j}^{u} h_{U,l,u}^{n_{BS}} h_{D,b,u}^{n_{BS}} + L \sum_{i \in L} \sum_{j \in L} N_{AP} \sum_{n_{AP}=1}^{N_{AP}} \eta_{i,j}^{u} h_{U,l,u}^{n_{AP}} h_{D,b,u}^{n_{AP}}.
\]
(27)

Besides, constraint (26q) represents that the energy transmission of MU \( u \) in uplink is equal or less than the harvested energy in downlink which is \( \tau_{D}^{H} \) in each time unit \[19\], \[20\]. Since the FDD and TDD schemes have the same optimization problem structure for the objective function and the constraints, the solution of (25) is similar to (26).

III. Solution

The non-convex optimization problem (25) is a mixed-integer nonlinear programming (MINLP) problem which is intractable and NP-hard. In general, there is no standard approach to find a global solution for MINLP problems. In order to make (25) tractable, we propose an iterative
Algorithm 1 The proposed iterative algorithm.

1: Initialize $\zeta_0$, $\rho_0$ and $p_0$ according to Subsection III-A.

repeat

2: for $t_1 = 1$ to $T_1$ do

3: For a fixed $\zeta_{t_1}$, find joint $p_{t_1}$ and $\rho_{t_1}$ by solving (32).

4: For fixed $(p_{D,BS,t_1}, p_{D,AP,t_1}, \rho_{D,BS,t_1}, \rho_{D,AP,t_1})$, find $\zeta_{t_1}, p_{U,BS,t_1}, p_{U,AP,t_1}, \rho_{U,BS,t_1}, \rho_{U,AP,t_1}$ by solving (60).

5: Until $R_{t_1}^U - R_{t_1-1}^U \leq \omega_1$ or $t_1 = T_1$.

6: Set $t_1 = t_1 + 1$.

end for

8: $\zeta_{t_1}$, $p_{t_1}$ and $\rho_{t_1}$ are adapted for the network.

algorithm in which the main optimization problem (25) is divided into two subproblems where the first subproblem is the joint transmit power and subcarrier allocation problem for a fixed $\zeta$ and the second subproblem is the joint uplink transmit power and subcarrier assignment with the PS ratio optimization problem for fixed $(p_{D,BS}, p_{D,AP}, \rho_{D,BS}, \rho_{D,AP})$ [9], [12]. The pseudo code of the proposed iterative algorithm is presented in Alg. 1. Specifically, we first initialize $(\zeta_0, p_0, \rho_0)$ to feasible values. At each iteration $t_1$, we first find $(p_{t_1}, \rho_{t_1})$ for a given $\zeta_{t_1-1}$ from previous iteration $(t_1 - 1)$. Then, for fixed $(p_{BS,t_1}, p_{AP,t_1}, \rho_{BS,t_1}, \rho_{AP,t_1})$, we find $(\zeta_{t_1}, p_{BS,t_1}, p_{AP,t_1}, \rho_{BS,t_1}, \rho_{AP,t_1})$. We repeat these iterations until $|R_{t_1}^U - R_{t_1-1}^U| \leq \omega_1$ or the number of iterations exceeds a predefined threshold $T_1$ which is large enough.

**Proposition 1**: The proposed iterative Alg. 1 improves the objective function (25a) and converges to a near-optimal value, in each iteration.

**Proof.** Please refer to Appendix A.

A. Initialization Method

In order to find a feasible solution $(\rho_0, p_0)$, the difficulty is how to satisfy (17). Therefore, we first obtain feasible $(p_{BS}^{D}, \rho_{BS}^{D}, p_{AP}^{D}, \rho_{AP}^{D})$. A feasible solution can be obtained by assuming that all FBSs and APs do not transmit and are turned off. Moreover, we assume that all received downlink transmit powers are used for ID to achieve maximum downlink data rate for each MU with respect to $\zeta$. Therefore, we set $\zeta_{n}^{D,BS} = 0, \forall u, n_{BS}^{D}$, and $\zeta_{n}^{D,AP} = 0, \forall u, n_{AP}^{D}$. We also note
that the objective function (25a) is not function of \((p_{\text{BS}}^D, \rho_{\text{BS}}^D)\). Accordingly, we propose a RRA problem to maximize the downlink sum data rate of MUs as follows:

\[
\max_{D, n_{\text{BS}}^D, u, 0, u} \sum_{u \in U} \sum_{n_{\text{BS}}^D = 1}^{N_{\text{BS}}^D} \rho_{0, u}^D r_{0, u}^D n_{\text{BS}}^D
\]

subject to:

\[
\sum_{n_{\text{BS}}^D = 1}^{N_{\text{BS}}^D} \rho_{0, u}^D r_{0, u}^D n_{\text{BS}}^D \geq R_{\min}^u, \forall u \in U,
\]

\[
\sum_{u \in U} \sum_{n_{\text{BS}}^D = 1}^{N_{\text{BS}}^D} \rho_{0, u}^D r_{0, u}^D n_{\text{BS}}^D \leq P_{\text{BS,max}}^0,
\]

\[
\sum_{u \in U} \rho_{0, u}^D n_{\text{BS}}^D \leq 1, \forall n_{\text{BS}}^D \in N_{\text{BS}}^D,
\]

\[
\rho_{0, u}^D \in \{0, 1\}, \forall u \in U, n_{\text{BS}}^D \in N_{\text{BS}}^D.
\]

The optimization problem (28) is still non-convex. We can solve (28) by utilizing the Lagrange dual decomposition algorithm and the subgradient method [4]. By using the Karush-Kuhn-Tucker (KKT) conditions, \(p_{0, u}^D n_{\text{BS}}^D\) can be obtained by

\[
p_{0, u}^D n_{\text{BS}}^D = \left[ \frac{1 + \overline{\lambda}_u}{\kappa \ln 2} - \frac{\sigma_{u} n_{\text{BS}}^D}{p_{0, u}^D} \right]^+,
\]

where \(\overline{\lambda} = [\overline{\lambda}_u]\) and \(\kappa = [\kappa]\) are the Lagrangian multipliers and can be updated using the subgradient method, corresponding to (28b) and (28c), respectively. The optimal MU \(\tilde{u} \in U\) for assigning subcarrier \(n_{\text{BS}}^D\) can be obtained by

\[
\tilde{u} = \arg \max_{u \in U} (1 + \overline{\lambda}_u) r_{0, u}^D n_{\text{BS}}^D - \kappa p_{0, u}^D n_{\text{BS}}^D,
\]

subject to:

\[
\begin{cases}
\rho_{0, u}^D n_{\text{BS}}^D = 1, & \text{if } u = \tilde{u}, \\
\rho_{0, u}^D n_{\text{BS}}^D = 0, & \text{if } u \neq \tilde{u}.
\end{cases}
\]

B. Joint Transmit Power and Subcarrier Allocation

In this subsection, for a determined \(\zeta\), we solve the following joint transmit power and subcarrier allocation optimization problem which is given by

\[
\max_{p, \rho} R^U
\]

subject to:

\[
(1)-(12), (17), (19)-(21), (25b).
\]
The above optimization problem is a MINLP problem which is intractable and NP-hard. Accordingly, we propose an iterative algorithm to solve it. Specifically, in each iteration, we first find \( \rho \) for a predefined \( p \) and then, for a determined \( \rho \), we find \( p \). We repeat these iterations until convergence to a sub-optimal solution.

**Proposition 2**: The proposed iterative algorithm for solving the optimization problem (32) converges to a sub-optimal solution.

**Proof.** Please refer to Appendix B.

1) **Subcarrier Assignment**: For a given \( p \) from previous iteration, we aim to find a near-optimal subcarrier assignment \( \rho \). The corresponding optimization problem can thus be formulated as follows:

\[
\max_{\rho} R^U \tag{33a}
\]

s.t. (1)-(12), (17), (19)-(21).

Two mesh adaptive direct search (MADS) and time sharing methods can be adopted to solve (33). The optimization problem (33) is an integer non-linear programming (INLP) problem which can be solved by applying the MADS algorithm using available optimization softwares such as NOMAD solver which is a good choice for INLP problems [22], [23].

2) **Transmit Power Allocation**: The transmit power allocation optimization problem for a determined \( \rho \) is formulated as follows:

\[
\max_{p} R^U \tag{34a}
\]

s.t. (17), (19)-(21), (25b).

The optimization problem (34) is non-convex because of non-concavity of the data rate functions (14), (16), (22) and (23). Hence, we apply the SCA approach to approximate the data rate functions in concave form based on the difference-of-two-concave-functions (D.C.) approximation [9], [24]. The main structure of the SCA approach is also described in the following. At first, we initialize \( p_0 \) and approximation parameters. Then, for a given \( p_{t_2-1} \) from previous iteration \( t_2-1 \), we approximate the non-concave data rates with concave functions using the D.C. approximation method. Subsequently, we solve the convex approximated problem and find \( p_{t_2} \) and then, we update the approximation parameters for the next iteration. We repeat these iterations until \( \| p_{t_2} - p_{t_2-1} \| \leq \omega_2 \) or the number of iterations exceeds a predefined threshold \( T_2 \). In order to
overcome the non-concavity of the data rates (14), (16), (22) and (23), we first formulate the non-concave downlink data rate (14) in a D.C. form as [9], [24], [25]:

\[ r_{b,u}^{D,n_{BS}} = f_{b,u}^{D,n_{BS}} - g_{b,u}^{D,n_{BS}}, \]  

(35)

where the concave functions \( f_{b,u}^{D,n_{BS}} \) and \( g_{b,u}^{D,n_{BS}} \) for each \( b \in B, \ u \in U \), \( n_{BS}^{D} \in \Lambda_{BS}^{D} \) are given, respectively, by

\[ f_{b,u}^{D,n_{BS}} = \log_2 \left( \sum_{i=0}^{B} \sum_{j \in U} (1 - \zeta_{u}^{n_{BS}}) \rho_{i,j}^{n_{BS}} p_{i,j}^{n_{BS}} h_{i,u}^{n_{BS}} + \sigma_{u}^{n_{BS}} + (1 - \zeta_{u}^{n_{BS}}) p_{b,u}^{n_{BS}} h_{b,u}^{n_{BS}} \right), \]  

(36)

\[ g_{b,u}^{D,n_{BS}} = \log_2 \left( \sum_{i=0}^{B} \sum_{j \in U} (1 - \zeta_{u}^{n_{BS}}) \rho_{i,j}^{n_{BS}} p_{i,j}^{n_{BS}} h_{i,u}^{n_{BS}} + \sigma_{u}^{n_{BS}} \right), \]  

(37)

and then, we express the non-concave downlink data rate (16) in a D.C. form as:

\[ r_{l,u}^{D,n_{AP}} = f_{l,u}^{D,n_{AP}} - g_{l,u}^{D,n_{AP}}, \]  

(38)

where the concave functions \( f_{l,u}^{D,n_{AP}} \) and \( g_{l,u}^{D,n_{AP}} \) are obtained, respectively, by

\[ f_{l,u}^{D,n_{AP}} = \log_2 \left( \sum_{i=1}^{L} \sum_{j \in U} (1 - \zeta_{u}^{n_{AP}}) \rho_{i,j}^{n_{AP}} p_{i,j}^{n_{AP}} h_{i,u}^{n_{AP}} + \sigma_{u}^{n_{AP}} + (1 - \zeta_{u}^{n_{AP}}) p_{b,u}^{n_{AP}} h_{b,u}^{n_{AP}} \right), \]  

(39)

\[ g_{l,u}^{D,n_{AP}} = \log_2 \left( \sum_{i=1}^{L} \sum_{j \in U} (1 - \zeta_{u}^{n_{AP}}) \rho_{i,j}^{n_{AP}} p_{i,j}^{n_{AP}} h_{i,u}^{n_{AP}} + \sigma_{u}^{n_{AP}} \right), \]  

(40)

and subsequently, we formulate the uplink non-concave data rate (22) in a D.C. form as follows:

\[ r_{b,u}^{U,n_{BS}} = f_{b,u}^{U,n_{BS}} - g_{b,u}^{U,n_{BS}}, \]  

(41)

where

\[ f_{b,u}^{U,n_{BS}} = \log_2 \left( \sum_{i=0}^{B} \sum_{j \in U} \rho_{i,j}^{n_{BS}} p_{i,j}^{n_{BS}} h_{b,j}^{n_{BS}} + \sigma_{b}^{n_{BS}} + p_{b,u}^{n_{BS}} h_{b,u}^{n_{BS}} \right), \]  

(42)

\[ g_{b,u}^{U,n_{BS}} = \log_2 \left( \sum_{i=0}^{B} \sum_{j \in U} \rho_{i,j}^{n_{BS}} p_{i,j}^{n_{BS}} h_{b,j}^{n_{BS}} + \sigma_{b}^{n_{BS}} \right), \]  

(43)

and the uplink non-concave data rate (23) in a D.C. form can thus be obtained by

\[ r_{l,u}^{U,n_{AP}} = f_{l,u}^{U,n_{AP}} - g_{l,u}^{U,n_{AP}}, \]  

(44)
where

\[
    f_{i,u}^{U,n_{AP}^U} = \log_2 \left( \sum_{i=1}^{L} \sum_{j \neq i}^{L} \rho_{i,j}^{U,n_{AP}^U} p_{i,j}^{U,n_{AP}^U} r_{i,j}^{U,n_{AP}^U} + \sigma_{i}^{n_{AP}^U} + p_{i,u}^{U,n_{AP}^U} h_{i,u}^{U,n_{AP}^U} \right),
\]

\[
    g_{i,u}^{U,n_{AP}^U} = \log_2 \left( \sum_{i=1}^{L} \sum_{j \neq i}^{L} \rho_{i,j}^{U,n_{AP}^U} p_{i,j}^{U,n_{AP}^U} r_{i,j}^{U,n_{AP}^U} + \sigma_{i}^{n_{AP}^U} \right),
\]

Then, we use the following linear approximation for concave functions \(g_{b,u}^{D,n_{BS}^U}(P_{BS}^{D,t_2})\) and \(g_{l,u}^{D,n_{AP}^U}(P_{AP}^{D,t_2})\) at iteration \(t_2\) \([9], [24], [25]\):

\[
    g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2}) \approx g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2-1}) + \nabla g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2-1})(P_{BS}^{D,t_2} - P_{BS}^{D,t_2-1}),
\]

for a fixed \(P_{BS}^{D,t_2-1}\) from previous iteration \(t_2 - 1 \geq 0\), and \(\nabla g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D})\) is a vector of length \(UN_{BS}^D\) and its entry is defined as:

\[
    \nabla g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D}) = \begin{cases} 
    0, & \forall i = b, \\
    \frac{(1-\zeta_{u}^{D,n_{BS}^D})\rho_{i,b}^{U,n_{BS}^U} h_{i,b}^{U,n_{AP}^U}}{(\ln 2) \sum_{v=0}^{L} \sum_{k \neq u}^{L} (1-\zeta_{u}^{D,n_{BS}^D})\rho_{v,k}^{U,n_{BS}^U} h_{v,k}^{U,n_{AP}^U} + \sigma_{u}^{n_{BS}^D}} , & \forall i \neq b, j \in U - \{u\}, 
\end{cases}
\]

and

\[
    g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2}) \approx g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2-1}) + \nabla g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2-1})(P_{AP}^{D,t_2} - P_{AP}^{D,t_2-1}),
\]

for a fixed \(P_{AP}^{D,t_2-1}\) from previous iteration \(t_2 - 1 \geq 0\), and \(\nabla g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D})\) is a vector of length \(UN_{AP}^D\), whose entries are defined as:

\[
    \nabla g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D}) = \begin{cases} 
    0, & \forall i = l, \\
    \frac{(1-\zeta_{u}^{D,n_{AP}^D})\rho_{i,l}^{U,n_{AP}^U} h_{i,l}^{U,n_{AP}^U}}{(\ln 2) \sum_{v=0}^{L} \sum_{k \neq u}^{L} (1-\zeta_{u}^{D,n_{AP}^D})\rho_{v,k}^{U,n_{AP}^U} h_{v,k}^{U,n_{AP}^U} + \sigma_{u}^{n_{AP}^D}} , & \forall i \neq l, j \in U - \{u\}. 
\end{cases}
\]

We also approximate the concave functions \(g_{b,u}^{U,n_{BS}^U}(P_{BS}^{U,t_2})\) and \(g_{l,u}^{U,n_{AP}^U}(P_{AP}^{U,t_2})\) at iteration \(t_2\) as follows:

\[
    g_{b,u}^{U,n_{BS}^U}(P_{BS}^{U,t_2}) \approx g_{b,u}^{U,n_{BS}^U}(P_{BS}^{U,t_2-1}) + \nabla g_{b,u}^{U,n_{BS}^U}(P_{BS}^{U,t_2-1})(P_{BS}^{U,t_2} - P_{BS}^{U,t_2-1}),
\]

for a fixed \(P_{BS}^{U,t_2-1}\) from previous iteration \(t_2 - 1 \geq 0\), and \(\nabla g_{b,u}^{U,n_{BS}^U}(P_{BS}^{U})\) is a vector of length \(UN_{BS}^U\) whose entries are obtained by

\[
    \nabla g_{b,u}^{U,n_{BS}^U}(P_{BS}^{U}) = \begin{cases} 
    0, & \forall i = b, \\
    \frac{\rho_{i,b}^{U,n_{BS}^U} h_{i,b}^{U,n_{BS}^U}}{(\ln 2) \sum_{v=0}^{L} \sum_{k \neq u}^{L} \rho_{v,k}^{U,n_{BS}^U} h_{v,k}^{U,n_{BS}^U} + \sigma_{b}^{n_{BS}^U}} , & \forall i \neq b, j \in U - \{u\}, 
\end{cases}
\]
and
\[
g_{l,u}^{U,n_{AP}^U}(p_{AP}^U) \approx g_{l,u}^{U,n_{AP}^U}(p_{AP}^{t_2-1}) + \nabla g_{l,u}^{U,n_{AP}^U}(p_{AP}^{t_2-1})(p_{AP}^U - p_{AP}^{t_2-1}),
\]
(53)
for a fixed \(p_{AP}^{t_2-1}\) from previous iteration \(t_2 - 1 \geq 0\), and \(\nabla g_{l,u}^{U,n_{AP}^U}(p_{AP}^U)\) is a vector of length \(U N_{AP}^U\) whose entries are given by
\[
\nabla g_{l,u}^{U,n_{AP}^U}(p_{AP}^U) = \begin{cases} 
0, & \forall i = l, \\
\frac{\rho_{l,j}^{U,n_{AP}^U} D_{l,u}^{D,n_{AP}^U} \ln 2}{(\ln 2)(\sum_{v=1\atop v \neq l}^L \sum_{k=1\atop k \neq u}^U n_{AP}^U s_{l,k} + \sigma_l)}, & \forall i \neq l, j \in \mathcal{U} - \{u\}.
\end{cases}
\]
(54)
According to the above, we have
\[
r_{b,u}^{D,n_{BS}^D} \approx f_{b,u}^{D,n_{BS}^D}(p_{BS}^{t_2}) - g_{b,u}^{D,n_{BS}^D}(p_{BS}^{t_2-1}) - \nabla g_{b,u}^{D,n_{BS}^D}(p_{BS}^{t_2-1})(p_{BS}^U - p_{BS}^{t_2-1}),
\]
(55)
\[
r_{l,u}^{D,n_{AP}^D} \approx f_{l,u}^{D,n_{AP}^D}(p_{AP}^{t_2}) - g_{l,u}^{D,n_{AP}^D}(p_{AP}^{t_2-1}) - \nabla g_{l,u}^{D,n_{AP}^D}(p_{AP}^{t_2-1})(p_{AP}^U - p_{AP}^{t_2-1}),
\]
(56)
\[
r_{b,u}^{U,n_{BS}^U} \approx f_{b,u}^{U,n_{BS}^U}(p_{BS}^{t_2}) - g_{b,u}^{U,n_{BS}^U}(p_{BS}^{t_2-1}) - \nabla g_{b,u}^{U,n_{BS}^U}(p_{BS}^{t_2-1})(p_{BS}^U - p_{BS}^{t_2-1}),
\]
(57)
\[
r_{l,u}^{U,n_{AP}^U} \approx f_{l,u}^{U,n_{AP}^U}(p_{AP}^{t_2}) - g_{l,u}^{U,n_{AP}^U}(p_{AP}^{t_2-1}) - \nabla g_{l,u}^{U,n_{AP}^U}(p_{AP}^{t_2-1})(p_{AP}^U - p_{AP}^{t_2-1}),
\]
(58)
where the right-hand side of (55)-(58) are concave functions of \(p_{BS}^{t_2}, p_{AP}^{t_2}, p_{BS}^U, p_{AP}^U\), respectively. Therefore, by substituting \(r_{b,u}^{D,n_{BS}^D}, r_{l,u}^{D,n_{AP}^D}, r_{b,u}^{U,n_{BS}^U}\) and \(r_{l,u}^{U,n_{AP}^U}\) with respect to \(p_{BS}^{t_2-1}, p_{AP}^{t_2-1}, p_{BS}^U\) and \(p_{AP}^U\) from previous iteration \(t_2 - 1\), respectively, the optimization problem (34) is transformed into the following convex optimization problem in each iteration \(t_2\) as:
\[
\max_p \sum_{u \in \mathcal{U}} \left( \sum_{b \in \mathcal{B}} \sum_{n_{BS}^D=1}^{N_{BS}^D} r_{b,u}^{D,n_{BS}^D} + \sum_{t \in \mathcal{L}} \sum_{n_{AP}^U=1}^{N_{AP}^U} r_{l,u}^{U,n_{AP}^U} \right)
\]
(59a)
s.t. (19)-(21), (25b),
\[
\sum_{b \in \mathcal{B}} \sum_{n_{BS}^D=1}^{N_{BS}^D} r_{b,u}^{D,n_{BS}^D} r_{b,u}^{D,n_{BS}^D} + \sum_{t \in \mathcal{L}} \sum_{n_{AP}^U=1}^{N_{AP}^U} r_{l,u}^{U,n_{AP}^U} r_{l,u}^{U,n_{AP}^U} \geq T_{iu}^\min, \forall u.
\]
(59b)
Since the approximated transmission power allocation problem (59) is convex, we can solve it using the existing optimization softwares such as CVX. The obtained \(p\) in each iteration \(t_2\) is used as initial value for the next iteration \(t_2 + 1\). We repeat these iterations until more improvement is not made. The proposed SCA approach with D.C. approximation is summarized in Algorithm 2.
Algorithm 2 The proposed SCA algorithm with D.C. approximation

1: Initialize $p^{(0)}$.
2: for $t_2 = 1$ to $T_2$ do
3: Obtain $r_{b_u}^{D,n^D_BS}$, $r_{l_u}^{D,n^D_AP}$, $r_{b_u}^{U,n^U_BS}$ and $r_{l_u}^{U,n^U_AP}$ using (55), (56), (57) and (58), respectively.
4: Solve (59) and find $p^{(t_2)}$.
5: Until $||p^{(t_2)} - p^{(t_2-1)}|| \leq \omega_2$ or $t_2 = T_2$.
6: Set $t_2 = t_2 + 1$
7: end for
8: $p^{(t_2)}$ is the output of the algorithm.

Proposition 3: The SCA approach, with D.C. approximation, generates a sequence of improved solutions and converges to a sub-optimal solution $p$ of the optimization problem (34).

Proof. Please refer to Appendix C.

C. PS Ratio Allocation

After finding joint $\rho$ and $p$, we propose an optimization problem to find $\zeta$. We note that by optimizing $\zeta$, the feasible region of (21) is changed. Therefore, we jointly find $\zeta$ and the uplink transmit power and subcarrier assignment of MUs in this step. Hence, the optimization problem can be formulated as:

$$\max_{\zeta, p^{U_BS}, p^{U_AP}, \rho^{U_BS}, \rho^{U_AP}} R^U$$

s.t. (2), (4), (7), (8), (11), (12), (17), (21), (25b)-(25d).

In order to solve (60), we use an iterative algorithm similar to Algorithm 1 in which at first, we find uplink subcarriers ($\rho^{U_BS}, \rho^{U_AP}$) and then give it to the joint uplink transmit power and PS ratio allocation to find ($\zeta, p^{U_BS}, p^{U_AP}$). We repeat these iterations until convergence to a near-optimal solution.

Proposition 4: The proposed iterative algorithm to solve (60) improves the objective function (60a) or remains constant in each iteration.

Proof. Please refer to Appendix D.
At the beginning of each iteration, we first solve the following uplink subcarrier assignment problem for fixed \((\zeta, p)\) as:

\[
\max_{\rho_{\text{BS}}, \rho_{\text{AP}}} R^U \quad \text{(61a)}
\]

subject to \((2)-(4), (7), (8), (11), (12), (21)\).  

The INLP problem \((61)\) can be easily solved using available optimization softwares such as NOMAD.

After finding \((\rho_{\text{BS}}^U, \rho_{\text{AP}}^U)\), we assume fixed uplink subcarrier assignment indicators and apply change of variables \(\zeta_{\text{up}}^{D_{\text{BS}}} = 1 - \zeta_{\text{up}}^{D_{\text{BS}}}^{n_u} \) and \(\zeta_{\text{up}}^{D_{\text{AP}}} = 1 - \zeta_{\text{up}}^{D_{\text{AP}}}^{n_u}\). Similar to \((34)\), we use the SCA algorithm with D.C. approximation method which is presented in Algorithm 2 to solve the following joint PS ratio and uplink transmit power allocation optimization problem:

\[
\max_{\xi} R^U \quad \text{(62a)}
\]

subject to \((17), (21), (25b)-(25d)\),

where \(\xi = [\xi_{\text{BS}}, \xi_{\text{AP}}], \xi_{\text{BS}} = [\zeta_{\text{up}}^{D_{\text{BS}}}^{n_u}], \) and \(\xi_{\text{AP}} = [\zeta_{\text{up}}^{D_{\text{AP}}}^{n_u}]\). In the proposed algorithm, we first approximate the non-concave data rate functions into concave functions and then solve the convex approximated problem by using CVX. The approximated concave data rate functions can thus be obtained by

\[
\tilde{f}_{b,u}^{D_{\text{BS}}} \approx f_{b,u}^{D_{\text{BS}}}((\tilde{\xi}_{\text{BS}}^{D_{\text{BS}}})), \quad \nabla g_{b,u}^{D_{\text{BS}}}((\tilde{\xi}_{\text{BS}}^{D_{\text{BS}}})), \quad \text{and} \quad \nabla^2 g_{b,u}^{D_{\text{BS}}}((\tilde{\xi}_{\text{BS}}^{D_{\text{BS}}})),
\]

where

\[
f_{b,u}^{D_{\text{BS}}} = \log_2 \left( \sum_{i=0}^{B} \sum_{j \in U} \zeta_{i,u}^{D_{\text{BS}}} \rho_{i,j}^{D_{\text{BS}}} h_{i,u}^{D_{\text{BS}}} + \sigma_{u}^{D_{\text{BS}}} \right),
\]

\[
g_{b,u}^{D_{\text{BS}}} = \log_2 \left( \sum_{i=0}^{B} \sum_{j \in U} \zeta_{i,u}^{D_{\text{BS}}} \rho_{i,j}^{D_{\text{BS}}} h_{i,u}^{D_{\text{BS}}} + \sigma_{u}^{D_{\text{BS}}} \right),
\]

\[
\nabla g_{b,u}^{D_{\text{BS}}}((\xi_{\text{BS}}^{D_{\text{BS}}})) = \left\{ \begin{array}{ll}
0, & \forall i = b, \\
\frac{\sum_{v=0}^{B} \sum_{k \in U} \zeta_{i,k}^{D_{\text{BS}}} \rho_{i,k}^{D_{\text{BS}}} h_{i,u}^{D_{\text{BS}}}}{(\ln 2)(\sum_{v=0}^{B} \sum_{k \in U} \zeta_{i,k}^{D_{\text{BS}}} \rho_{i,k}^{D_{\text{BS}}} h_{i,u}^{D_{\text{BS}}})}, & \forall i \neq b, j \in U - \{u\},
\end{array} \right.
\]

and

\[
\tilde{f}_{b,u}^{D_{\text{BS}}} \approx f_{b,u}^{D_{\text{BS}}}((\tilde{\xi}_{\text{BS}}^{D_{\text{BS}}})), \quad \nabla g_{b,u}^{D_{\text{BS}}}((\tilde{\xi}_{\text{BS}}^{D_{\text{BS}}})), \quad \text{and} \quad \nabla^2 g_{b,u}^{D_{\text{BS}}}((\tilde{\xi}_{\text{BS}}^{D_{\text{BS}}})),
\]
where

\[ j_{l,u}^{D,n_{AP}^P} = \log_2 \left( \sum_{i=1}^{L} \sum_{j \neq l}^{\mathcal{U}} \xi_u^{n_{AP}^D} p_{i,j}^{D,n_{AP}^D} h_{i,u}^{D,n_{AP}^D} + \sigma_u^{n_{AP}^D} p_{i,u}^{D,n_{AP}^D} h_{i,u}^{D,n_{AP}^D} \right), \]  

(68)

\[ g_{l,u}^{D,n_{AP}^D} = \log_2 \left( \sum_{i=1}^{L} \sum_{j \neq l}^{\mathcal{U}} \xi_u^{n_{AP}^D} p_{i,j}^{D,n_{AP}^D} p_{i,u}^{D,n_{AP}^D} h_{i,u}^{D,n_{AP}^D} + \sigma_u^{n_{AP}^D} p_{i,u}^{D,n_{AP}^D} h_{i,u}^{D,n_{AP}^D} \right), \]  

(69)

\[ \nabla g_{l,u}^{D,n_{AP}^D}(\xi_{AP}) = \begin{cases} 
0, & \forall i = l, \\
\left( \frac{\xi_u^{n_{AP}^D} p_{i,j}^{D,n_{AP}^D} p_{i,u}^{D,n_{AP}^D} h_{i,u}^{D,n_{AP}^D}}{(\ln 2)(\sum_{v=1}^{L} \sum_{k \neq l}^{\mathcal{U}} \xi_v^{n_{AP}^D} p_{v,k}^{D,n_{AP}^D} p_{v,u}^{D,n_{AP}^D} h_{v,u}^{D,n_{AP}^D} + \sigma_v^{n_{AP}^D})} \right), & \forall i \neq l, j \in \mathcal{U} - \{u\}. 
\end{cases} \]  

(70)

Since \( \xi_{BS} \) and \( \xi_{AP} \) are not function of uplink data rates, the concave approximated uplink data rate formulations are exactly equal to (57) and (58). Moreover, \( \rho_{HV}^u \) in (21) is transformed into the following term:

\[ P_{HV}^u = \eta \left( \sum_{i \in \mathcal{B}} \sum_{j \in \mathcal{U}} \sum_{n_{BS}}^{N_{BS}} (1 - \xi_{n_{BS}}^D) p_{i,j}^{D,n_{BS}^D} D_{i,n_{BS}^D} h_{i,u}^{D,n_{BS}^D} + \sum_{i=1}^{L} \sum_{j \neq l}^{\mathcal{U}} \sum_{n_{AP}^D}^{N_{AP}^D} (1 - \xi_{n_{AP}^D}^D) p_{i,j}^{D,n_{AP}^D} D_{i,n_{AP}^D} h_{i,u}^{D,n_{AP}^D} \right). \]  

(71)

Hence, at each iteration, we solve the following convex approximated optimization problem:

\[ \max_{\xi_{BS}^D, \rho_{AP}^U} \sum_{u \in \mathcal{U}} \sum_{b \in \mathcal{B}} \left( \sum_{n_{BS}^U}^{N_{BS}^U} U_{b,u}^{n_{BS}^U} U_{b,u}^{n_{BS}^U} + \sum_{n_{AP}^U}^{N_{AP}^U} U_{l,u}^{n_{AP}^U} U_{l,u}^{n_{AP}^U} \right) \]  

(72a)

s.t. (21), (25b)-(25d),

\[ \sum_{b \in \mathcal{B}} \sum_{n_{BS}^D}^{N_{BS}^D} \rho_{b,u}^{D,n_{BS}^D} D_{b,u}^{D,n_{BS}^D} + \sum_{l \in \mathcal{L}} \sum_{n_{AP}^D}^{N_{AP}^D} \rho_{l,u}^{D,n_{AP}^D} C_{l,u}^{D,n_{AP}^D} \geq R_{u}^\text{min}, \forall u. \]  

(72b)

**Proposition 5**: The proposed SCA algorithm with the D.C. approximation method for solving the optimization problem (62) converges to a sub-optimal \( \xi \).

**Proof.** Please refer to Appendix E

\[ \square \]

**IV. COMPUTATIONAL COMPLEXITY**

In this section, we investigate the computational complexity of the iterative algorithms proposed for the FDD and TDD schemes. Due to the similarity between the optimization problems (25) and (26), we only focus on the FDD scheme to avoid replications. Using Algorithm 1, the
optimization problem (25) is solved in two main steps: 1) joint transmit power and subcarrier allocation; 2) joint uplink transmission power and subcarrier with the PS ratio allocation. The subcarrier assignment in (33) is solved by using the NOMAD optimization software which employs the geometric programming (GP) with the interior point method (IPM) [22]. The number of iterations required for solving the subcarrier assignment problem (33) is given by

\[ C_{\text{Subcarrier}} = \frac{\log(T_{\text{Subcarrier}}/t_0\tau_0)}{\log(\varpi)}, \]  

(73)

where \( T_{\text{Subcarrier}} = BLU(N_{\text{BS}}^D N_{\text{AP}}^U + N_{\text{BS}}^U N_{\text{AP}}^D + N_{\text{BS}}^D N_{\text{AP}}^U + N_{\text{BS}}^U N_{\text{AP}}^D) + B(N_{\text{BS}}^D + N_{\text{BS}}^U + 1) + L(N_{\text{AP}}^D + N_{\text{AP}}^U + 1) + 2U \) is the total number of constraints in (33), \( \varpi \) represents the accuracy updating parameter of the IPM, \( 0 \leq \tau_0 \ll 1 \) denotes the stopping criterion for IPM, and \( t_0 \) is the initial point for approximating the accuracy of IPM [22]. In addition, the number of constraints in (59) is obtained by

\[ C_\text{Power} = \frac{\log(T_{\text{Power}}/t_0\tau_0)}{\log(\varpi)}. \]  

(74)

Hence, the number of iterations required to solve (59) is on the order of [16], [26], [27].

Accordingly, the computational complexity of solving (32) in Step 3 of Algorithm 1 is on the order of \( C_{\text{Joint}} = C_{\text{Subcarrier}} + C_{\text{Power}} \). On the other hand, the computational complexity of solving (61) is on the order of

\[ C_{\text{PS,subcarrier}} = \frac{\log(T_{\text{PS,subcarrier}}/t_0\tau_0)}{\log(\varpi)}, \]  

(76)

where \( T_{\text{PS,subcarrier}} = BLU(N_{\text{BS}}^U N_{\text{AP}}^U + N_{\text{BS}}^D N_{\text{AP}}^U + N_{\text{BS}}^D N_{\text{AP}}^U) + B N_{\text{BS}}^U + L N_{\text{AP}}^U + U \) and the complexity of solving (62) is given by

\[ C_{\text{PS,Power}} = \frac{\log(T_{\text{PS,Power}}/t_0\tau_0)}{\log(\varpi)}, \]  

(77)

where \( T_{\text{PS,Power}} = 2U \). Therefore, the computational complexity of solving (60) is on the order of \( C_{\text{PS}} = C_{\text{PS,subcarrier}} + C_{\text{PS,Power}} \). The total complexity of solving the main optimization problem (25) is on the order of \( C_{\text{tot}} = C_{\text{Joint}} + C_{\text{PS}} \). In order to compute the computational complexity of solving (26) by using Alg. 1, we set \( N_{\text{BS}}^D = N_{\text{BS}}^U, N_{\text{BS}}^D = N_{\text{BS}}^U, N_{\text{AP}}^D = N_{\text{AP}}, N_{\text{AP}}^U = N_{\text{AP}} \), and then, compute it by using (73)-(77). Since the number of downlink and uplink subcarriers in the TDD scheme is more than that of the FDD scheme, the computational complexity of solving (26) is more than (25) for the same number of \( N_{\text{BS}} \) and \( N_{\text{AP}} \). The computational complexity of the proposed iterative algorithms for the FDD and TDD schemes are summarized in Table I.
TABLE I: The COMPUTATIONAL COMPLEXITY OF THE PROPOSED ITERATIVE ALGORITHMS

| Iterative Algorithm | Joint Uplink and Downlink RRA | Joint PS Ratio and Uplink RRA |
|---------------------|-------------------------------|-------------------------------|
| FDD Scheme          | $C_{\text{subcarrier}} + C_{\text{Power}}$ |                              |
| TDD Scheme          | $\log((4B_{\text{LU}} N_{\text{BS}} N_{\text{AP}} + B (2 N_{\text{BS}} + 1) + L (2 N_{\text{AP}} + 1) + 2 U)/\theta_{\text{b}}^2)/\log(\omega)$ | $\log((3 B_{\text{LU}} N_{\text{BS}} N_{\text{AP}} + B N_{\text{BS}} + L N_{\text{AP}} + U)/\theta_{\text{b}}^2)/\log(\omega) + \log((3 B_{\text{LU}} N_{\text{BS}} N_{\text{AP}} + B N_{\text{BS}} + L N_{\text{AP}} + U)/\theta_{\text{b}}^2)/\log(\omega)$ |

V. SIMULATION RESULTS

In this section, we provide numerical results to evaluate the performance of the proposed iterative algorithms. We assume that 30 MUs are uniformly spread in the coverage area of the macro-cell with radius 120 m. We also assume that 3 FBSs and 3 APs are located in the network. Furthermore, we assume that our downlink and uplink channels are composed of fading and pathloss. The fading of wireless channels are assumed to be independent and identically distributed (i.i.d.) with Rayleigh distribution meaning that the channel power gains are exponentially distributed with the mean value 1. The pathloss exponent of the pathloss model is also set to 2. In the sequel, we suppose that each subcarrier has a total bandwidth of $W_S = 39.0625$ KHz. In the FDD scheme, we assume that both the number of downlink and uplink subcarriers of BSs and APs are set to be 128 and 64, respectively. Hence, we have $N_{\text{BS}}^D = N_{\text{BS}}^U = 128$ and $N_{\text{AP}}^D = N_{\text{AP}}^U = 64$. For the TDD scheme, we assume that $N_{\text{BS}} = 256$ and $N_{\text{AP}} = 128$. We also note that in the TDD scheme, we set $\tau_D = 0.4$ and $\tau_U = 0.6$.

The power spectral density (PSD) of AWGN noise is also assumed to be $-174$ dBm/Hz. The minimum downlink data rate for each MU is assumed to be $R_{\text{min}}^u = 4$ bps/Hz. We set the maximum allowable transmit power of MBS, each FBS $b$ and each AP $l$ to $P_{0,\text{BS,max}} = 10$ Watts, $P_{0,\text{BS,max}} = 0.5$ Watts and $P_{0,\text{AP,max}} = 0.2$ Watts, respectively. The conversion efficiency of the network is also assumed to be $\eta = 0.4$. The system parameters are summarized in Table II.

A. Convergence of The Proposed Iterative Algorithm

Fig. 3 shows the convergence of the proposed iterative algorithms in terms of uplink sum data rate of MUs versus the number of iterations for the FDD and TDD schemes. It can be seen that the proposed iterative algorithms for the FDD and TDD schemes coverage to stable values in maximum 10 and 15 iterations, respectively. This simulation ensures us that the proposed
TABLE II: SYSTEM PARAMETERS

| Parameter                          | Value  |
|------------------------------------|--------|
| Number of FBSs                     | $B = 3$|
| Number of APs                      | $L = 3$|
| Maximum distance of MBS            | 120 m  |
| Number of MUs                      | $U = 30$|
| Channel power gain distribution    | mean $= 1$|
| PSD of AWGN noise ($N_0$)          | $-174$ dBm/Hz |
| $N_{BS}$                           | 256    |
| $N_{AP}$                           | 128    |
| $N_{BS}^D, N_{BS}^U$               | 128    |
| $N_{AP}^D, N_{AP}^U$               | 64     |
| $W_S$                              | 39.0625 KHz |
| Path loss exponent                 | 2      |
| $\tau_D$                          | 0.4    |
| $\tau_U$                          | 0.6    |
| $R_{\text{min}}^u$                 | 4 bps/Hz |
| $P_{BS,\text{max}}^0$             | 10 Watts |
| $P_{BS,\text{max}}^b, \forall b \geq 1$ | 0.5 Watts |
| $P_{AP,\text{max}}^l$             | 0.2 Watts |
| Conversion efficiency $\eta$       | 0.4    |

approaches are applicable in multi-user HetNets. The dash lines refer to the upper-bound solution for the FDD and TDD schemes after the proposed iterative algorithms converge. We also note that after only 8 iterations, the solution of the iterative algorithms achieve to over 90% of the upper-bound values for the FDD and TDD schemes. Accordingly, the maximum number of main iterations for the FDD and TDD schemes are set to be 8 to evaluate the performance of the proposed iterative algorithms in the following subsections.

B. Uplink Sum Data Rate of MUs and Average Harvested Power of Each MU versus Maximum Allowable Transmit Power of BSs and APs

In Fig. 4, the effect of the maximum allowable transmit power of MBS and APs on average harvested power of each MU and uplink sum data rate of MUs are investigated. Fig. 4(a) shows the average harvested power of each MU in terms of the maximum allowable transmit power of MBS, $P_{BS,\text{max}}^0$, with different values of maximum allowable transmit power of each AP $l$, $P_{AP,\text{max}}^l$, for the FDD scheme. As expected, increase in the maximum allowable transmit power
Fig. 3: The convergence in terms of uplink sum data rate of MUs over the number of main iterations \( t \).

of MBS or APs would result in an increasing in average harvested power of each MU. In other words, increasing \( P_{0,\text{max}}^\text{BS} \) and/or \( P_{l,\text{max}}^\text{AP} \) increase the received powers at MUs and by optimizing the PS ratios, the downlink data rate of each MU is equal to the minimum required data rate and more received power is split for EH, and subsequently, the average harvested power of each MU increases. Similarly, it can be shown that increasing \( P_{0,\text{max}}^\text{BS} \) or \( P_{l,\text{max}}^\text{AP} \) increases the average harvested power of each MU in the TDD scheme. Moreover, we can easily show that the results in above can be obtained by increasing \( P_b^\text{BS,\text{max}}, \forall b \in B \), for both the FDD and TDD schemes. On the other hand, increasing average harvested power of each MU extends the feasible region of constraint (21) in (25), and constraint (26q) in (26), and hence, the total uplink transmit power of MUs increases and subsequently, the uplink sum data rate of MUs increases, for both the FDD and TDD schemes. Therefore, it is obvious that increasing \( P_b^\text{BS,\text{max}}, \forall b \in B \), and/or \( P_l^\text{AP,\text{max}} \) increase the uplink sum data rate of MUs. This conclusion is shown in Fig. 4(b) in terms of \( P_0^\text{BS,\text{max}} \).

C. Uplink Sum Data Rate of MUs and Average Harvested Power of Each MU versus Number of MUs

We investigate the effect of the total number of MUs on average harvested power of each MU and uplink sum data rate of MUs in Fig. 5 for both the FDD and TDD schemes. When the total number of MUs (energy receivers) increases, more received power at MUs are split for ID to satisfy the minimum required data rate constraint (17) for the FDD scheme and constraint (26n).
(a) The average harvested power of each MU in the FDD scheme over the maximum allowable transmit power of MBS for different values of $P_{AP,max}$. Figure 4: The average harvested power of each MU and uplink sum data rate of MUs versus the maximum allowable transmit power of MBS and each AP $l$.

for the TDD scheme. Therefore, as shown in Fig. 5(a), by increasing the total number of MUs, the average harvested power of each MU decreases. Besides, decreasing the average harvested power of each MU decreases the uplink sum data rate of MUs. Furthermore, increasing the total number of MUs, increases the uplink sum data rate of MUs. As shwon in Fig. 5(b), increasing $U$ for small number of MUs, increases the uplink sum data rate of MUs whereas increasing $U$ for the larger number of MUs decreases the uplink sum data rate of MUs, because of difficulty of satisfying the minimum required downlink data rate constraints for MUs in both FDD and TDD schemes.

D. Uplink Sum Data Rate of MUs and Average Harvested Power of Each MU versus Minimum Required Data Rate of Each MU

Fig. 6 shows the effect of minimum required data rate of MUs on the average harvested power of each MU and the uplink sum data rate of MUs. In Fig. 6(a), it can be seen that increasing the minimum required data rate of MUs shrinks the feasible region of constraint (17) for the FDD scheme and constraint (26n) for the TDD scheme and therefore, more received power can be split for ID and subsequently, the amount of average harvested power of each MU decreases. On the other hand, with decreasing the average harvested power of each MU, the uplink sum data
(a) The average harvested power of each MU versus the total number of MUs for the FDD and TDD schemes.

(b) The uplink sum data rate of MUs versus the total number of MUs for the FDD and TDD schemes.

Fig. 5: The average harvested power of each MU and uplink sum data rate of MUs versus the total number of MUs, $U$, for the FDD and TDD schemes. We set $P_{BS,\text{max}} = 10$ Watts, $P_{BS,\text{max}}^b = 0.5$ Watts and $P_{AP,\text{max}} = 0.2$ Watts.

---

(a) The average harvested power of each MU versus the minimum required data rate of each MU for the FDD and TDD schemes.

(b) The uplink sum data rate of MUs versus the minimum required data rate of each MU for the FDD and TDD schemes.

Fig. 6: The average harvested power of each MU and uplink sum data rate of MUs versus the minimum required data rate of each MU, $R_{\text{min}}^u$, for the FDD and TDD schemes.

rate of MUs decreases. This result is shown in Fig. 6(b). We note that in the proposed iterative algorithms, the output downlink data rate of MUs is equal to their minimum required data rates. Hence, with increasing $R_{\text{min}}^u$, the downlink sum data rate of MUs increases.
E. Effect of Data Offloading on Uplink Sum Data Rate of MUs

Consider a scenario in which APs are turned off and all MUs are assigned to BSs. We evaluate the performance of the data offloading technique by comparing the prior scenario with our system including of 3 APs for the FDD and TDD schemes in terms of uplink sum data rate of MUs over the maximum allowable transmit power of MBS in Fig. 7. It can be seen that MUs in the scenario with APs can choose APs or BSs to assign. Hence, in some situations, MUs choose APs and therefore, the uplink sum data rate of MUs in this scenario is more than a scenario without any AP. In addition, APs work in a different frequency band from BSs and do not interfere on MUs which are associated to BSs whereas MUs which are connected to BSs can harvest the energy received from APs.

VI. CONCLUSION

In this paper, we investigated the joint uplink/downlink RRA optimization problem for a SWIPT OFDMA-based HetNet. We evaluated the performance of the considered system for two types of transmission schemes, as FDD and TDD, with utilizing the PS technique. We also formulated an optimization problem for each scheme where the objective functions are maximizing the uplink sum data rate of MUs subject to the minimum required downlink data rate of each MU, and maximum allowable transmit power of each BS, AP and MU. We supposed that the considered system can harvest the received power in downlink to use it for uplink information transmission. In the simulation results, we showed that the proposed iterative algorithm converges to a near-optimal solution in only a few iterations. The computational complexity of the proposed
iterative algorithm is calculated for each FDD and TDD schemes and we showed that the complexity of TDD scheme is more than that of the FDD scheme. Moreover, we evaluated the benefits of the utilized data offloading and EH techniques which are considered for our system for the FDD and TDD schemes. We concluded that utilizing the TDD scheme is more efficient and increases the uplink sum data rate of MUs, compared to the FDD scheme. In the future works, we can evaluate the performance of the PS technique with considering the insertion loss at the receiver’s circuit, as well as the circuit power consumption of MUs.

APPENDIX A
PROOF OF PROPOSITION 1

After finding \( (p_{t_1,s}, \rho_{t_1,s}) \) at step \( s \) of iteration \( t_1 \) for a fixed \( \zeta_{t_1-1} \), we have \( R^U(\zeta_{t_1-1}, \rho_{t_1-1}, p_{t_1-1}) \leq R^U(\zeta_{t_1-1}, \rho_{t_1,s}, p_{t_1,s}) \). This is due to the fact that solving the joint subcarrier and transmission power allocation subproblem improves the objective function which is proved in Proposition 2. Subsequently, for given \( (p^D_{BS,t_1,s}, p^D_{AP,t_1,s}, \rho^D_{BS,t_1,s}, \rho^D_{AP,t_1,s}) \), we have

\[
R^U(\zeta_{t_1-1}, \rho_{t_1,s}, p_{t_1,s}) \leq R^U(\zeta_{t_1}, p^U_{BS,t_1,s+1}, p^U_{AP,t_1,s+1}, \rho^U_{BS,t_1,s+1}, \rho^U_{AP,t_1,s+1}, p^D_{BS,t_1,s}, p^D_{AP,t_1,s}, \rho^D_{BS,t_1,s}, \rho^D_{AP,t_1,s}),
\]

which is proved in Proposition 4. Accordingly, we conclude that

\[
\cdots \leq R^U(\zeta_{t_1-1}, \rho_{t_1-1}, p_{t_1-1}) \leq R^U(\zeta_{t_1-1}, \rho_{t_1,s}, p_{t_1,s}) \leq \cdots \leq R^U(\zeta_{opt}, \rho_{opt}, p_{opt}),
\]

where \( (\zeta_{opt}, \rho_{opt}, p_{opt}) \) is the output of Alg. Hence, after each iteration \( t_1 \) the value \( |R^U(\zeta_{opt}, \rho_{opt}, p_{opt}) - R^U(\zeta_{t_1}, \rho_{t_1}, p_{t_1})| \) decreases and guarantees the convergence. Moreover, we note that \( R^U(\zeta_{opt}, \rho_{opt}, p_{opt}) \) has a finite value, because of the limitation of transmit powers and bandwidth.

APPENDIX B
PROOF OF PROPOSITION 2

After finding \( \rho_{t_1} \) for a fixed \( p_{t_1-1} \), we have \( R^U(\rho_{t_1-1}, p_{t_1-1}) \leq R^U(\rho_{t_1}, p_{t_1-1}) \), due to the fact that solving the subcarrier allocation problem \( (33) \) using the optimization software NOMAD,
improves the objective function. Subsequently, for the given \( \mathbf{p}_{t_1} \), we have \( R^U(\mathbf{p}_{t_1}, \mathbf{p}_{t_1-1}) \leq R^U(\mathbf{p}_{t_1}, \mathbf{p}_{t_1}) \) which is proved in Proposition 3. Hence, similar to Appendix A, we have

\[
\cdots \leq R^U(\mathbf{p}_{t-1}, \mathbf{p}_{t-1}) \leq R^U(\mathbf{p}_{t_1}, \mathbf{p}_{t_1-1}) \leq R^U(\mathbf{p}_{t_1}, \mathbf{p}_{t_1}) \leq \cdots \leq R^U(\mathbf{p}_{opt}, \mathbf{p}_{opt}),
\]

which means after each iteration, the value \( |R^U(\mathbf{p}_{opt}, \mathbf{p}_{opt}) - R^U(\mathbf{p}_{t_1}, \mathbf{p}_{t_1})| \) decreases and the proposed algorithm converges to a sub-optimal solution.

**APPENDIX C**

**PROOF OF PROPOSITION 3**

The terms \( g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2}) \) and \( g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2}) \) are approximated to their first order approximations and the functions \( \nabla g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2}) \) and \( \nabla g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2}) \) are the supergradients of concave approximated functions \( g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2}) \) and \( g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2}) \), respectively [25]. Therefore, we have the following inequalities as:

\[
g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2}) \leq g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2-1}) + \nabla g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2-1})(P_{BS}^{D,t_2} - P_{BS}^{D,t_2-1}), \tag{78}
\]

\[
g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2}) \leq g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2-1}) + \nabla g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2-1})(P_{AP}^{D,t_2} - P_{AP}^{D,t_2-1}). \tag{79}
\]

The data rate functions (35) and (38) are approximated with concave functions (55) and (56), respectively. Hence, at the conclusion of each iteration \( t_2 \), it must be true that

\[
\sum_{b \in B} \sum_{n_{BS}^D = 1}^{N_{BS}^D} P_{b,u}^{D,n_{BS}^D} \left( f_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2}) - f_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2-1}) - \nabla g_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2-1})(P_{BS}^{D,t_2} - P_{BS}^{D,t_2-1}) \right) + \\
\sum_{l \in L} \sum_{n_{AP}^D = 1}^{N_{AP}^D} P_{l,u}^{D,n_{AP}^D} \left( f_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2}) - f_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2-1}) - \nabla g_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2-1})(P_{AP}^{D,t_2} - P_{AP}^{D,t_2-1}) \right) \geq R_u^{\min}, \quad \forall u \in \mathcal{U}. \tag{80}
\]

According to (78)-(80), we can easily show that

\[
\sum_{b \in B} \sum_{n_{BS}^D = 1}^{N_{BS}^D} P_{b,u}^{D,n_{BS}^D} \left( f_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2}) - f_{b,u}^{D,n_{BS}^D}(P_{BS}^{D,t_2}) \right) + \sum_{l \in L} \sum_{n_{AP}^D = 1}^{N_{AP}^D} P_{l,u}^{D,n_{AP}^D} \left( f_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2}) - f_{l,u}^{D,n_{AP}^D}(P_{AP}^{D,t_2}) \right) \geq R_u^{\min}, \quad \forall u \in \mathcal{U}, \tag{81}
\]

which means the convex approximated optimization problem (59) remains within the feasible region of (34), in each iteration.
On the other hand, we notice that \( g_{b,u}^U(p_{BS}) \) and \( g_{l,u}^U(p_{AP}) \) are approximated to their first order approximations, and \( \nabla g_{b,u}^U(p_{BS}) \) and \( \nabla g_{l,u}^U(p_{AP}) \) are the supergradients of concave approximated functions \( g_{b,u}^U(p_{BS}) \) and \( g_{l,u}^U(p_{AP}) \), respectively. The following inequalities can thus be concluded as:

\[
\begin{align*}
    g_{b,u}^U(p_{BS}) & \leq g_{b,u}^U(p_{BS}^{t-2}) + \nabla g_{b,u}^U(p_{BS}^{t-2})(p_{BS} - p_{BS}^{t-2}), \quad \text{(82)} \\
    g_{l,u}^U(p_{AP}) & \leq g_{l,u}^U(p_{AP}^{t-2}) + \nabla g_{l,u}^U(p_{AP}^{t-2})(p_{AP} - p_{AP}^{t-2}). \quad \text{(83)}
\end{align*}
\]

According to (82) and (83), we have

\[
\begin{align*}
    \sum_{u \in U} \sum_{b \in B} \sum_{n_{BS}^U = 1} N_{BS}^U \sum_{l \in L} f_{b,u}^U(p_{BS}) - g_{b,u}^U(p_{BS}^{t-2}) - \nabla g_{b,u}^U(p_{BS}^{t-2})(p_{BS} - p_{BS}^{t-2}) + \\
    \sum_{u \in U} \sum_{b \in B} \sum_{n_{BS}^U = 1} N_{BS}^U \sum_{l \in L} f_{l,u}^U(p_{AP}) - g_{l,u}^U(p_{AP}^{t-2}) - \nabla g_{l,u}^U(p_{AP}^{t-2})(p_{AP} - p_{AP}^{t-2}) \\
    \sum_{l=1}^L \sum_{u \in U} \sum_{n_{AP}^U = 1} N_{AP}^U \sum_{l \in L} f_{l,u}^U(p_{AP}) - g_{l,u}^U(p_{AP}^{t-2}) - \nabla g_{l,u}^U(p_{AP}^{t-2})(p_{AP} - p_{AP}^{t-2}) \geq \quad \text{(84)}
\end{align*}
\]

Since the obtained transmit powers \( p_{BS}^{t} \) and \( p_{AP}^{t} \) are the solution of the approximated optimization problem (59) for the previous iteration \( t - 1 \), we can conclude that

\[
\begin{align*}
    \sum_{u \in U} \sum_{b \in B} \sum_{n_{BS}^U = 1} N_{BS}^U \sum_{l \in L} f_{b,u}^U(p_{BS}) - g_{b,u}^U(p_{BS}^{t-2}) - \nabla g_{b,u}^U(p_{BS}^{t-2})(p_{BS} - p_{BS}^{t-2}) + \\
    \sum_{u \in U} \sum_{b \in B} \sum_{n_{BS}^U = 1} N_{BS}^U \sum_{l \in L} f_{l,u}^U(p_{AP}) - g_{l,u}^U(p_{AP}^{t-2}) - \nabla g_{l,u}^U(p_{AP}^{t-2})(p_{AP} - p_{AP}^{t-2}) \\
    \sum_{l=1}^L \sum_{u \in U} \sum_{n_{AP}^U = 1} N_{AP}^U \sum_{l \in L} f_{l,u}^U(p_{AP}) - g_{l,u}^U(p_{AP}^{t-2}) - \nabla g_{l,u}^U(p_{AP}^{t-2})(p_{AP} - p_{AP}^{t-2}) \geq \quad \text{(84)}
\end{align*}
\]
increasing the number of iterations, the proposed D.C. approximation algorithm converges to a near-optimal solution. Therefore, we have

\[ \sum_{u \in \mathcal{U}} \sum_{b \in B} \sum_{n_{BS}^U = 1} f_{b,u}^{U,n_{BS}^U}(p_{BS}^{U,t_2-1}) - g_{b,u}^{U,n_{BS}^U}(p_{BS}^{U,t_2-1}) + \sum_{l=1}^{L} \sum_{u \in \mathcal{U}} \sum_{n_{AP}^U = 1} f_{l,u}^{U,n_{AP}^U}(p_{AP}^{U,t_2-1}) - g_{l,u}^{U,n_{AP}^U}(p_{AP}^{U,t_2-1}), \]

which means that substituting \( p_{BS}^{U,t_2} \) and \( p_{AP}^{U,t_2} \) improves the objective function (34a) for the previous iteration \( t_2 - 1 \). According to (84) and (85), we have

\[ \sum_{u \in \mathcal{U}} \sum_{b \in B} \sum_{n_{BS}^U = 1} f_{b,u}^{U,n_{BS}^U}(p_{BS}^{U,t_2}) - g_{b,u}^{U,n_{BS}^U}(p_{BS}^{U,t_2}) + \sum_{l=1}^{L} \sum_{u \in \mathcal{U}} \sum_{n_{AP}^U = 1} f_{l,u}^{U,n_{AP}^U}(p_{AP}^{U,t_2}) - g_{l,u}^{U,n_{AP}^U}(p_{AP}^{U,t_2}) \geq \]

\[ \sum_{u \in \mathcal{U}} \sum_{b \in B} \sum_{n_{BS}^U = 1} f_{b,u}^{U,n_{BS}^U}(p_{BS}^{U,t_2-1}) - g_{b,u}^{U,n_{BS}^U}(p_{BS}^{U,t_2-1}) + \sum_{l=1}^{L} \sum_{u \in \mathcal{U}} \sum_{n_{AP}^U = 1} f_{l,u}^{U,n_{AP}^U}(p_{AP}^{U,t_2-1}) - g_{l,u}^{U,n_{AP}^U}(p_{AP}^{U,t_2-1}), \]

which means after each iteration \( t_2 \), the objective function (34a) is either improved or fixed in contrast to the previous iteration \( t_2 - 1 \). Since (59) is always feasible in each iteration, with increasing the number of iterations, the proposed D.C. approximation algorithm converges to a near-optimal solution.

**APPENDIX D**

**PROOF OF PROPOSITION 4**

The objective function (61a) is either improved or remains constant after solving (61) using the standard available optimization software NOMAD, in each iteration. Therefore, we have

\[ R^U(\zeta_{t_1-1}, p_{BS,t_1-1}^U, p_{AP,t_1-1}^U, \rho_{BS,t_1-1}^U, \rho_{AP,t_1-1}^U) \leq R^U(\zeta_{t_1-1}, p_{BS,t_1-1}^U, p_{AP,t_1-1}^U, \rho_{BS,t_1}^U, \rho_{AP,t_1}^U). \]

(87)

In addition, for fixed \( (\rho_{BS,t_1}^U, \rho_{AP,t_1}^U) \), we have

\[ R^U(\zeta_{t_1-1}, p_{BS,t_1-1}^U, p_{AP,t_1-1}^U, \rho_{BS,t_1}^U, \rho_{AP,t_1}^U) \leq R^U(\zeta_{t_1}, p_{BS,t_1}^U, p_{AP,t_1}^U, \rho_{BS,t_1}^U, \rho_{AP,t_1}^U), \]

(88)

which is proved in Proposition 5. Hence, we can conclude that

\[ \cdots \leq R^U(\zeta_{t_1-1}, p_{BS,t_1-1}^U, p_{AP,t_1-1}^U, \rho_{BS,t_1-1}^U, \rho_{AP,t_1-1}^U) \leq R^U(\zeta_{t_1-1}, p_{BS,t_1-1}^U, p_{AP,t_1-1}^U, \rho_{BS,t_1}^U, \rho_{AP,t_1}^U), \]

(89)

where \( (\zeta_{opt}, p_{BS,opt}^U, p_{AP,opt}^U, \rho_{BS,opt}^U, \rho_{AP,opt}^U) \) is the solution of (60) and means that after each iteration \( t_1 \), the value \( |R^U(\zeta_{opt}, p_{BS,opt}^U, p_{AP,opt}^U, \rho_{BS,opt}^U, \rho_{AP,opt}^U) - R^U(\zeta_{t_1}, p_{BS,t_1}^U, p_{AP,t_1}^U, \rho_{BS,t_1}^U, \rho_{AP,t_1}^U)| \) decreases and the proposed iterative algorithm converges to a near-optimal solution.
The terms $g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2})$ and $g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2})$ are approximated to their first order approximations, in which $\nabla g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2})$ and $\nabla g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2})$ are the supergradient of them, respectively. Similarly, we have the following inequalities as:

\[
\begin{align*}
    g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2}) & \leq g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2-1}) + \nabla g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2-1})(\xi_{BS}^{t_2} - \xi_{BS}^{t_2-1}), \\
    g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2}) & \leq g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2-1}) + \nabla g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2-1})(\xi_{AP}^{t_2} - \xi_{AP}^{t_2-1}).
\end{align*}
\]

According to (63) and (67), after each iteration $t_2$, we have

\[
\sum_{b \in B} \sum_{n_{BS}^D=1}^{N_{BS}^D} \rho_{b,u} g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2}) - g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2-1}) - \nabla g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2-1})(\xi_{BS}^{t_2} - \xi_{BS}^{t_2-1})
\]

\[
\sum_{l \in L} \sum_{n_{AP}^D=1}^{N_{AP}^D} \rho_{l,u} g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2}) - g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2-1}) - \nabla g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2-1})(\xi_{AP}^{t_2} - \xi_{AP}^{t_2-1}) \geq R_{u}^{\min}, \forall u \in U. \tag{92}
\]

Therefore, we can conclude that

\[
\sum_{b \in B} \sum_{n_{BS}^D=1}^{N_{BS}^D} \rho_{b,u} g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2}) - g_{b,u}^{D,n_{BS}^D}(\xi_{BS}^{t_2-1}) + \sum_{l \in L} \sum_{n_{AP}^D=1}^{N_{AP}^D} \rho_{l,u} g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2}) - g_{l,u}^{D,n_{AP}^D}(\xi_{AP}^{t_2-1}) \geq R_{u}^{\min}, \forall u \in U. \tag{93}
\]

which means in each iteration $t_2$, (72) remains within the feasible region of (62). Similar to Appendix C by using (82)-(86), we conclude that the objective function (62a) is either improved or remains constant after each iteration $t_2$ and the proposed algorithm converges to a near-optimal solution.

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