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Serving Federated Learning and Non-Federated Learning Users: A Massive MIMO Approach

Muhammad Farooq†, Tung T. Vu†, Hien Quoc Ngo†, Le-Nam Tran*
*School of Electrical and Electronic Engineering, University College Dublin, Ireland
†Institute of Electronics, Communications, and Information Technology (ECIT), Queen’s University Belfast, Belfast BT3 9DT, UK

Email: muhammad.farooq@ucdconnect.ie, t.vu@qub.ac.uk, hien.ngo@qub.ac.uk, nam.tran@ucd.ie

Abstract—Federated learning (FL) with its data privacy protection and communication efficiency has been considered as a promising learning framework for beyond-5G/6G systems. We consider a scenario where a group of downlink non-FL users are jointly served with a group of FL users using massive multiple-input multiple-output technology. The main challenge is how to utilise the resource to optimally serve both FL and non-FL users. We propose a communication scheme that serves the downlink of the non-FL users (UEs) and the uplink of FL UEs in each half of the frequency band. We formulate an optimization problem for optimizing transmit power to maximize the minimum effective data rates for non-FL users, while guaranteeing a quality-of-service time of each FL communication round for FL users. Then, a successive convex approximation-based algorithm is proposed to solve the formulated problem. Numerical results confirm that our proposed scheme significantly outperforms the baseline scheme.

Index Terms—Federated learning, massive MIMO, zero-forcing.

I. INTRODUCTION

Federated learning (FL) has emerged as a promising machine learning framework in future wireless networks with a wide range of real-world digital applications such as Gboard, FedVision, etc. [1]. FL is an iterative process with many communication rounds. In each communication round, a central server sends a downlink global update to the users (UEs). The UEs compute their uplink local updates using their own data sets, and then send the local updates back to the central server for further updating the global learning model. The FL process continues until a specific learning accuracy level is achieved. By not sending the raw data, the data privacy is preserved and the communication traffic is significantly reduced. On the other hand, it is anticipated that future wireless systems not only serve FL UEs but also non-FL UEs. In each FL communication round, FL UEs need both downlink and uplink, while non-FL UEs may only need one of these transmissions. This calls for a novel network design to support both groups of FL and non-FL UEs at the same time.

In the related literature, previous publications studying the implementation of FL in wireless networks can be classified into learning-oriented or communication-oriented. The former aims to improve the learning performance (e.g., test accuracy) under the presence of detrimental factors of wireless systems such as thermal noise, fading, and estimation errors [2], [3]. On the other hand, the latter focuses on enhancing the communication performance (e.g., execution time reduction, energy efficiency) [4], [5]. However, all above works consider the cases where only FL UEs are served.

Paper Contributions: Motivated by communication-oriented studies, we propose a novel network design for serving FL and downlink non-FL UEs at the same time. First, we leverage massive multiple-input multiple-output (MIMO) and assume that each FL communication round is executed in one large-scale coherence time. Here, in the downlink of each FL communication round, both FL and non-FL groups are jointly served simultaneously and in the same frequency band. However, in the uplink of each FL communication round, the uplink transmission of FL UEs and the downlink transmission of non-FL UEs requires a two-way communication. Thus, we propose to serve these two transmissions separately at each half of the frequency band. Zero-forcing (ZF) processing is then used for both downlink and uplink transmissions. Next, we formulate an optimization problem that allocates power and computing resources to maximize the minimum effective data rate of non-FL users, while ensuring a quality-of-service execution time of each FL communication round for FL UEs. A successive convex approximation algorithm is then derived to solve the formulated problem. Numerical results show that our proposed scheme outperforms the considered baseline scheme.

II. PROPOSED SCHEME AND SYSTEM MODEL

We consider a massive MIMO system [6] where a single M-antenna BS serves simultaneously two groups of single-antenna non-FL and FL UEs. Further, the non-FL UEs are assumed to receive data in the downlink.

Let $\mathcal{L} \triangleq \{1, \ldots, L\}$, and $\mathcal{K} \triangleq \{1, \ldots, K\}$ be the sets of FL UEs and non-FL UEs, respectively. The FL framework of the FL group has the following four steps in each communication round [4], [7], [8].

(S1) A central server sends a global update to FL UEs.
(S2) The FL UEs compute their uplink local updates based on the global update and their local data.
(S3) The uplink local updates are sent to the central server.
(S4) The central server computes the global update using the received uplink local updates.

Here, the BS acts as the central server. The non-FL UEs are assumed to keep receiving downlink data in every step of each FL communication round of FL UEs.

A. Proposed Scheme to Serve FL and downlink non-FL UEs

We assume that each FL communication round (instead of the whole FL process) is executed in one large-scale coherence time. We then propose a synchronous scheme to support FL communication rounds. Here, all the FL UEs start each step of one FL communication round at the same time, and wait for others to start a new step. The global and local updates in Steps
(S1) and (S3) can be transmitted in one or multiple (small-scale) coherence times based on their sizes. Each coherence time in Step (S1) or (S3) includes channel estimation and downlink or uplink transmission.

The non-FL group is served along with the FL group as follows. In step (S1), the downlink of both non-FL and FL groups are served at the same time and frequency band. In step (S2), the BS only serves non-FL UEs in the downlink. Then, in step (S3), owing to the half-duplex operation at the BS, the downlink of non-FL UEs and the uplink of FL UEs are served simultaneously but separately in each half of the frequency band.

**B. Detailed System Model of Proposed Scheme**

1) Step (S1): In this step, the BS sends the global update to FL UEs and the downlink data to non-FL UEs. To do this, the BS fist needs to acquire the channels via uplink training, and then uses these channel estimates to send the payload data (i.e., the global update or downlink data) to the UEs.

**Channel estimation:** For each coherence block of length $\tau_c$, the BS estimates the channels by using uplink pilots received from all the UEs with a time-division-duplexing (TDD) protocol. Let $\sqrt{p_t}\varphi_k \sim CN(d,p,1)$, $\|\varphi_k\|^2 = \tau_d,p$ be the dedicated pilot symbols assigned to FL UE $k$, and $\sqrt{p_t}\varphi_k \sim CN(r,p,1)$, $\|\varphi_k\|^2 = \tau_p,r$ be the pilot sequence assigned to non-FL UE $k$, where $\rho_p$ is the normal transmit power of each pilot symbol, and $\tau_d,p,\tau_p,r \geq L + K$ are the length of pilot sequences. We assume the pilots of non-FL UEs and FL UEs are pairwise orthogonal to avoid pilot contamination, i.e., $\varphi_k^H \varphi_k = 0, \forall \ell, \forall k, \varphi_k^H \varphi_k = 0, \forall \ell, \neq \ell$ and $\varphi_k^H \bar{\varphi}_k = 0, \forall \ell, k \neq \ell$.

Let $G_d = [g_{d,1}, \ldots, g_{d,L}] \in \mathbb{C}^{M \times L}$ and $H_1 = [h_{1,1}, s, h_{1,K}] \in \mathbb{C}^{M \times K}$ be the channel matrices from the BS to the FL and non-FL groups in Step (S1), respectively. Here, $g_{d,1} = \beta_d \varphi_k$ represents the channel vector between the BS and FL UE $k$, while $h_{1,k} = \beta_c \varphi_k$ is the channel vector between the BS and non-FL UE $k$, where $\beta_d, \beta_c$ are the large-scale fading coefficients, $\varphi_k$ and $z_{1,k}$ are small-scale fading coefficients. Assuming minimum mean square error (MMSE) estimation, the channel estimate of $g_{d,1}$ can be written as $\hat{g}_{d,1} = \sigma_{d,1} z_{d,1}$, where $z_{d,1} \sim CN(0, I_M)$ and $\sigma^2_{d,1} = \frac{\rho_p \tau_d,p}{\rho_p \tau_d,p + \eta_d}$ [9]. Similarly, the estimate of $h_{1,k}$ in Step (S1) can be written as $\hat{h}_{1,k} = \sigma_{1,k} z_{1,k}$, where $z_{1,k} \sim CN(0, I_M)$ and $\sigma^2_{1,k} = \frac{\rho_p \tau_p,r}{\rho_p \tau_p,r + \eta_1}$.

**Downlink transmission for both FL and non-FL UEs:** The BS encodes the global training update intended for FL UE $k$ into symbols $s_{d,k}$, where $E\{s_{d,k}\} = 1$, $\forall k$, and encodes the downlink data for non-FL UE $k$ into symbols $s_{1,k}$, where $E\{s_{1,k}\} = 1$, $\forall k$. The data symbols are then precoded before being transmitted. Let $u_{d,k} = [s_{d,1}, \ldots, s_{d,L}]^T$, $s_1 = [s_{1,1}, \ldots, s_{1,K}]^T$. $\eta_d$ and $\eta_1,k$ denote the power control coefficient associated with UE $k$.

Then, the transmitted signal at the BS in Step (S1) is given by $x_1 = \sqrt{p_t} u_d D_1^{1/2} s_d + \sqrt{\rho_d} u_1 D_1^{1/2} s_1$, where $\eta_d \triangleq [\eta_{d,1}, \ldots, \eta_{d,L}]^T$ and $\eta_1 \triangleq [\eta_{1,1}, \ldots, \eta_{1,K}]^T$, and $D_1$ is the diagonal matrix with the elements of $x$ on its diagonal. In this paper, zero-forcing precoding is applied to precode the symbols for all the FL and non-FL UEs. Thus, the precoding vector $[u_d, u_1] = \sqrt{[(M - L - K)]} [Z H Z]^T$ [9, (3,49)], where $Z = [z_d, z_1]$, and $M \geq L + K$ is required.

The transmitted power at the BS is required to meet the average normalized power constraint, i.e., $E\{\|x_1\|^2\} \leq \rho_d$, which can be expressed as:

$$\sum_{k \in \mathcal{L}} \rho_d \eta_{d,k} + \sum_{k \in \mathcal{E}} \rho_1 \eta_{1,k} \leq 1.$$ (1)

Following [9, Sec. 3.3.2], the achievable rate for FL UE $k$ is given by $R_{d,k}(\eta_{d,k}, \gamma_{d,k}) = \frac{1}{\gamma_{d,k}(\eta_{d,k}, \gamma_{d,k})} \log_2 (1 + \gamma_{d,k}(\eta_{d,k}, \gamma_{d,k}))$, where $B$ is the bandwidth, and $\gamma_{d,k}(\eta_{d,k}, \gamma_{d,k}) = \frac{\rho_p \eta_{d,k}}{\rho_p \eta_{d,k} + \rho_d \eta_{d,k} + \eta_{d,k} t_{d,k}^2}$ is the effective signal-to-interference-plus-noise ratio (SINR). Since all the FL UEs start and end a step synchronously, it is practically meaningful to define the effective achievable rate (bps) of each FL UE to be the minimum rate of the FL group, i.e., $R_d(\eta_d, \gamma_d) = \min_{k \in \mathcal{L}} R_{d,k}(\eta_{d,k}, \gamma_{d,k})$. Similarly, the achievable rate of non-FL UE $k$ is expressed as $R_{1,k}(\eta_{1,k}, \gamma_{1,k}) = \frac{1}{\gamma_{1,k}(\eta_{1,k}, \gamma_{1,k})} \log_2 (1 + \gamma_{1,k}(\eta_{1,k}, \gamma_{1,k}))$. Where the effective $\gamma_{1,k}(\eta_{1,k}, \gamma_{1,k})$ is given by [9, Sec. 3.3.2]:

$$\gamma_{1,k}(\eta_{1,k}, \gamma_{1,k}) = \frac{\rho_p \eta_{1,k}}{\rho_p \eta_{1,k} + \frac{1}{1 + \rho_p (h_{1,k} - \sigma_{1,k}^2) + (h_{1,k} - \sigma_{1,k}^2) \sum_{k \in \mathcal{L}} \eta_{d,k} \gamma_{d,k}}}$$

**Downlink delay of the FL group:** Let $S_d$ (bits) be the data size of the global training update of the FL group. The transmission time from the BS to FL UE $\ell \in \mathcal{L}$ is given by $t_d(\eta_d, \gamma_d) = \frac{S_d}{\sum_{k \in \mathcal{L}} \rho_1 \eta_{1,k}}$.

**Amount of downlink data received at the non-FL UEs:** The amount of data received at non-FL UE $k \in \mathcal{K}$ in step (S1) is $D_{1,k}(\eta_{d,k}, \eta_{1,k}) = R_{1,k}(\eta_{d,k}, \eta_{1,k}) \eta_{1,k}(\eta_{d,k}, \eta_{1,k})$.

2) Step (S2): After receiving the global update, each FL UE $\ell$ computes its local training update on its local dataset, while each non-FL UE $k$ keeps receiving data from the BS.

**Local computation:** After receiving the global update, each FL UE executes $N_c$ local computing rounds over its data set to compute its local update. Let $c_{0}$ (cycles/sample) be the number of processing cycles for FL UE $\ell$ to process one data sample [4]. Denote by $D_k$ (samples) and $f_k$ (cycles/sample) the size of the local data set and the computing frequency of FL UE $\ell$, respectively. To provide synchronization in this step, we choose $f_k$ such that $f_k = \frac{D_k}{D_{c,k}}$, where $D = \max_{\ell \in \mathcal{L}} D_{c,k}$, $c_{0} = \max_{\ell \in \mathcal{L}} c_{0}$, and $f$ is a frequency control coefficient. The computation time is thus the same for all the FL UEs, denoted by $t_c(\ell)$, which is given by $t_c(\ell) = f_c t_c(\ell) = \frac{S_d}{\sum_{k \in \mathcal{L}} \rho_1 \eta_{1,k}}$, $\forall \ell \in \mathcal{L}$ [4, 7].

**Channel estimation for non-FL UEs:** The channel estimation for the non-FL UEs in step (S2) is performed similarly as shown in step (S1) (i.e., based on MMSE estimation). Consequently, the estimate of $h_{2,k}$ (i.e., the channel between the BS and non-FL UE $k$) can be written as $\hat{h}_{2,k} = \sigma_{2,k} z_{2,k}$, where $z_{2,k} \sim CN(0, I_M)$ and $\sigma^2_{2,k} = \frac{\rho_p \tau_p,r}{\rho_p \tau_p,r + \eta_2}$, where $\tau_2,p \geq K$ is the length of pilot sequence. Let $Z_2 = [z_{2,1}, \ldots, z_{2,K}]$. 
Amount of downlink data received at the non-FL group: Let \( \mathbf{c}_2 \triangleq \begin{bmatrix} c_2,1, & \ldots, & c_2,K \end{bmatrix}^T \) be the power control coefficients for non-FL UEs in Step (S2). The average normalized power constraint at the BS can be expressed as
\[
\sum_{k \in K} c_{2,k} \leq 1. 
\]  
(2)

Since there is no interference from the FL UEs to non-FL UEs in this step, the achievable downlink rate (bps) of non-FL UE \( k, \forall k \in K \), is thus given by \( R_{2,k}(\mathbf{c}_2) = \frac{r}{r_2} B \log_2 (1 + \gamma_{2,k}(\mathbf{c}_2)) \), where a ZF precoder vector \( u_{2,k} = \sqrt{(M-K)} \mathbf{z}_2 (\mathbf{z}_2^H \mathbf{z}_2)^{-1} \mathbf{e}_{2,k} \) is applied for each non-FL UE \( k \in K \) at the BS, and \( \gamma_{2,k}(\mathbf{c}_2) = \frac{\rho_2 \mathbf{c}_{2,k}(M-K) \mathbf{e}_{2,k}^H \mathbf{z}_2^2}{1 + \rho_2 \mathbf{c}_{2,k}(M-K) \mathbf{e}_{2,k}^H \mathbf{z}_2^2} \). Thus, the amount of downlink data received at non-FL UE \( k \) in step (S2) is
\[
D_{2,k}(\mathbf{c}_2, f) = R_{2,k}(\mathbf{c}_2) t_{C}(f) . 
\]
3) Step (S3): In this step, the local updates of the FL UEs are transmitted to the BS in the uplink, while downlink data are kept being sent from the BS to the non-FL UEs. The uplink transmission of the FL UEs and the downlink transmission of non-FL UEs are executed in two separate halves of the frequency band.

Channel estimation: Similar to the channel estimation in Steps (S1) and (S2), the channel \( g_{u,t} \) between the BS and the FL-UEs in Step (S3) has an estimate \( \hat{g}_{u,t} = \sigma_{u,t} u_{z,t} \), where \( u_{z,t} \sim \mathcal{CN}(0, I_M) \) and \( \sigma_{u,t}^2 = \frac{\rho_3 \tau_{u,t} \eta_3^2}{\rho_3 \tau_{u,t} \eta_3^2 + 1} \). Here, \( \tau_{u,t} \geq L + K \) is the length of pilot sequence. The channel \( h_{3,k} \), between the BS and non-FL-UE \( k \) in Step (S3) has an estimate \( \hat{h}_{3,k} = \sigma_{3,k} z_{3,k} \), where \( z_{3,k} \sim \mathcal{CN}(0, I_M) \) and \( \sigma_{3,k}^2 = \frac{\rho_3 \tau_{3,k} \eta_{3,k}^2}{\rho_3 \tau_{3,k} \eta_{3,k}^2 + 1} \). Here, \( \tau_{3,k} \geq L + K \) is the length of pilot sequence. Let \( \mathbf{z}_u \triangleq [\mathbf{z}_u,1, \ldots, \mathbf{z}_u,L] \).

Uplink transmission of FL UEs: After computing the local update, FL UE \( \ell \) encodes this update into symbol \( s_{u,t} \), where \( \mathbb{E}\{|s_{u,t}|^2\} = 1 \), and sends baseband signal \( x_{u,t} = \sqrt{\rho_u} s_{u,t} \) to the BS, where \( \eta_{u,t} \) is the power control coefficient and \( \rho_u \) is the normalized uplink transmit power constraint, i.e., \( \mathbb{E}\{|x_{u,t}|^2\} = \rho_u \). Thus, we have the constraint:
\[
\eta_{u,t} \leq 1, \forall t \in \mathcal{L}. 
\]  
(3)

Since the FL and non-FL groups are served in two separate halves of the frequency band, there is no interference among FL and non-FL groups. Thus, the achievable rate for FL UE \( \ell \) is given by [9, Sec. 3.3.2]:
\[
R_{u,\ell}(\eta_{u}) = \frac{r}{r_2} B \log_2 \left( 1 + \frac{\gamma_{u,\ell}(\eta_{u})}{\rho_u} \right), 
\]
where the ZF precoding vector applied for FL UE \( \ell \) is \( u_{z,t} = \sqrt{(M-L)} \mathbf{z}_u (\mathbf{z}_u^H \mathbf{z}_u)^{-1} \mathbf{e}_{u,t} \) and \( \gamma_{u,\ell}(\eta_{u}) = \frac{\rho_u \tau_{u,\ell} \eta_{u}^2}{\rho_u \tau_{u,\ell} \eta_{u}^2 + 1} \). For synchronization, we choose the rates of FL UEs to be the same as the minimum achievable rates in the FL group, i.e., \( R_u(\eta_u) = \min_{t \in \mathcal{L}} R_u(\eta_u) \).

Uplink delay of FL UEs: Denote by \( S_u(t) \) (bits) the data size of the local training update of the FL group. The transmission time from FL UE \( \ell \) to the BS is the same and given by
\[
t_u(\eta_u) = \frac{S_u(t)}{R_u(\eta_u)}. 
\]

Downlink transmission for Non-FL UEs: Denote by \( \mathbf{c}_3 \) the power control coefficient of non-FL UE \( k \) and \( \mathbf{c}_3 \triangleq \begin{bmatrix} c_3,1, & \ldots, & c_3,K \end{bmatrix}^T \). A ZF precoding matrix \( \mathbf{z}_3 = \sqrt{(M-K)} \mathbf{z}_3 (\mathbf{z}_3^H \mathbf{z}_3)^{-1} \) is applied for non-FL UEs. The transmitted signal from the BS to the non-FL UEs is given as \( x_3 = \sqrt{\rho_d} \mathbf{U}_3 \mathbf{D}_3^{1/2} \mathbf{s}_3 \), where \( \mathbf{s}_3 \triangleq [s_{3,1}, \ldots, s_{3,K}]^T \) and \( \mathbb{E}\{|x_3|^2\} = 1 \). The transmitted power at the BS is constrained as \( \mathbb{E}\{|x_3|^2\} \leq \rho_d \), which can be expressed as:
\[
\sum_{k \in K} c_{3,k} \leq 1. 
\]  
(4)

The achievable downlink rate for non-FL UE \( k, \forall k \in K \), is
\[
R_{3,k}(\mathbf{c}_3) = \frac{r}{r_3} B \log_2 \left( 1 + \gamma_{3,k}(\mathbf{c}_3) \right), \quad \text{where} \quad \gamma_{3,k}(\mathbf{c}_3) = \frac{\rho_d \mathbf{c}_{3,k}(M-K) \mathbf{e}_{3,k}^H \mathbf{z}_3^2}{1 + \rho_d \mathbf{c}_{3,k}(M-K) \mathbf{e}_{3,k}^H \mathbf{z}_3^2}. 
\]

Amount of downlink data received at the non-FL group: The amount of downlink data received at non-FL UE \( k \), \( \forall k \in K \), in Step (S3) is \( D_{3,k}(\eta_u, \mathbf{c}_3) = R_{3,k}(\mathbf{c}_3) t_u(\eta_u) \).

4) Step (S4): After receiving all the local update, the BS computes its global update. Since the computational capability of the central server is much more powerful than that of the UEs, the delay of computing the global update is negligible.

III. PROBLEM FORMULATION AND SOLUTION

A. Problem Formulation

In this section, we aim to maximize the minimum effective downlink rates of non-FL UEs while guaranteeing the quality of service (QoS) of the execution time of one FL communication round for FL UEs. Here, an effective downlink rate is defined as the ratio of the total received data of a non-FL UE and the corresponding transmission time (i.e., the total time of steps (S1)-(S3) of that FL UE). The considered problem can be formulated as
\[
\max_{\mathbf{x}} \min_{k \in K} \frac{D_{1,k}(\eta_k, \mathbf{c}_1) + D_{2,k}(\mathbf{c}_2) + D_{3,k}(\eta_k, \mathbf{c}_3)}{t_u(\eta_k, \mathbf{c}_1) + t_c(f) + t_u(\eta_k)} \quad \text{s.t.} \quad (1), (2), (3), (4), (5a), (5b), (5c), (5d), (6a), (6b), (6c), (6d), (7a), (7b), (7c), (7d)
\]

B. Solution

In the following, we propose a solution to (5) based on successive convex approximation (SCA) technique. First, we equivalently rewrite problem (5) into a more tractable form as
\[
\max_{\mathbf{x}} \frac{t}{t_Q} \quad \text{s.t.} \quad (1), (2), (3), (4), (5b), (5c), (6d), (6b), (6c), (6d), (7a), (7b), (7c), (7d)
\]

where \( x = \{x, t_Q\} \), and \( t_Q \) are newly introduced additional variables. We further rewrite (6a) as
\[
\max_{\mathbf{x}} \frac{t}{t_Q} \quad \text{s.t.} \quad (1), (2), (3), (4), (5b), (5c), (6d), (6b), (6c), (6d), (7a), (7b), (7c), (7d)
\]
To deal with these constraints, we apply the SCA method, \( R_d, \rho, \rho_n, \eta, L, K \), etc., (7e) with \( \eta \in \mathbb{R} \), where \( c \) is the prior factor, and \( x \) and \( y \) are the numerator and denominator of SINR. The convex lower bounds are found by

\[
\log(1 + \frac{x}{y}) \geq \log(1 + \frac{x_1}{y_1}) + \frac{2x_1 - 2y_1}{y_1(y_1 + 2x_1)} - \frac{(x_1^2 - y_1^2)}{(y_1(y_1 + 2x_1))},
\]

where \( x, y > 0 \), \( [10, 76] \). Therefore, \( R_d, \rho, \rho_n, \eta, L, K \), etc., (7e) have the following upper bounds \( R_d, \rho, \rho_n, \eta, L, K \), which are given by (18) and (19), respectively (see the top of the next page). Therefore, constraints (7b) can be approximated by the following convex constraints

\[
\hat{R}_d, \rho, \rho_n, \eta, L, K \leq \hat{R}_d; \hat{R}_a, \rho, \rho_n, \eta, L, K \leq \hat{R}_a, \forall \ell.
\]

(20)

**IV. NUMERICAL EXAMPLES**

1) **Parameter Setting**: We consider a \( D \times D \) m\(^2\) area where the BS is at the centre, while \( L \) FL UEs and \( K \) non-FL UEs are randomly distributed. The large-scale fading coefficients are modeled in the same manner as \([12, Eq. (46)]: \beta_k [dB] = -148.13 - 36.7 \log_{10} \left( \frac{d_k}{1000} \right) + z_k, \) where \( d_k \geq 35 \text{ m} \) is the distance between UE \( k \) and the BS, \( z_k \) is a shadow fading coefficient which is modeled using a log-normal distribution having zero mean and 7 dB standard deviation. We set \( N_0 = -92 \text{ dBm}, t_{\text{QoS}} = 3 \text{ s}, B = 20 \text{ MHz}, \rho_u = 0.2 \text{ W}, \tau_{\text{d}} = \tau_{\text{up}} = 20, \tau_{\text{SU}} = \tau_{\text{SU}} = 20, \tau_c = 200, \min f = 0, \max f = 5 \times 10^6 \text{ cycles/s}, D = \max d = 1.6 \times 10^5 \text{ samples}, c_t = c_{\text{max}} = 20 \text{ cycles/sample}, N_c = 20, S_0 = S_u = 16 \times 10^6 \text{ bits or 16Mb}.

2) **Results and Discussions**: Since there are no other existing works that study massive MIMO networks for supporting both FL and non-FL groups, we compare our proposed scheme with a baseline scheme denoted as BL. In BL, equal power allocation is adopted for both FL and non-FL UEs in step (S1), i.e., \( \eta_{d,k} = \eta_{u,k} = 1, \forall \ell, k \). The same is applied to non-FL UEs in step (S2) and (S3), i.e., \( \eta_{d,k} = \eta_{u,k} = 1, \forall \ell, k \). In addition, in step (S3), each FL UE uses full power, i.e., \( \eta_{d,k} = \eta_{u,k} = 1, \forall \ell, k \).

In Figs. 1 and 2, we compare the minimum effective rate of the non-FL UEs (in Mbps) achieved by the proposed scheme and BL. As seen, the proposed scheme offers better performance than the baseline scheme. The figures not only demonstrate a significant advantage of a joint allocation of power and computing frequency over BL, which is heuristic, but also show the benefit of using massive MIMO. Specifically, thanks to massive MIMO technology, the data rate of each

\[
\begin{align*}
\text{Algorithm 1 Algorithm for solving (5):} \\
1: & \text{Input: Set } n = 0 \text{ and choose initial point } x^{(0)} \in F \\
2: & \text{repeat} \\
3: & \text{Set } n = n + 1 \\
4: & \text{Solve (21) to get } x^* \\
5: & \text{Set } x^{(n)} = x^* \\
6: & \text{until convergence}
\end{align*}
\]
Developed an algorithm to allocate transmit power and computing resources among MIMO networks to serve FL and non-FL groups. Based on the BL baseline even provides a worse performance than that of the proposed scheme, and hence, is skipped in this paper due to space limitation.

V. CONCLUSION

We have proposed a communication scheme using massive MIMO networks to serve FL and non-FL groups. Based on the successive convex approximation technique, we have developed an algorithm to allocate transmit power and computing resources among the groups to maximize the minimum effective rate of non-FL UEs while guaranteeing a quality-of-service execution time for each FL communication round of FL UEs. Numerical results have shown that the proposed scheme significantly improves the minimum effective rate of non-FL UEs compared to a baseline heuristic scheme.

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