Effect of Downlink Energy Transfer Scheduling on SDMA and TDMA Uplink Transmission

Ibrahim Pehlivan and Sinem Coleri

***Abstract*—The high cost and power consumption of digital beamforming, as a result of the high number of RF chains, has overshadowed its performance on multi-antenna wireless powered communication networks (WPCNs). This setback forced researchers to low-cost alternatives such as hybrid beamforming, which decreases the number of expensive RF chains by utilizing cheaper phase shifters. This cost-cutting, however, comes with reduced control over beamforming weights and compromise performance. To circumvent this deficiency, scheduling of energy harvesting (SEH), utilizing the degree of freedom in the time domain, has been proposed. In SEH, the downlink slot is subdivided into multiple variable-length subslots with different beamforming weights. In this paper, we examine the effect of SEH on the optimization of minimum length scheduling for space division multiple access (SDMA) uplink transmission compared to time division multiple access (TDMA) uplink transmission. Via simulations, we demonstrate that SDMA benefits more from the additional degree of freedom provided by the usage of SEH for any number of nodes. However, SDMA yields inferior delay performance compared to TDMA as the number of nodes increases, which restricts the application of SDMA with SEH, making it impractical.**

***Index Terms*—SDMA, TDMA, RF energy harvesting, WPCN, hybrid beamforming, scheduling.**

I. Introduction

Energy harvesting wireless networks have recently proliferated due to the significant development in wireless communication technologies, low power circuit design, and power storage units. Among different energy sources for harvesting, RF energy harvesting is preferred when the application requires controllable and predictable energy transfer with a dedicated energy source to the nodes at long range [1]. One of the application areas of RF energy harvesting is wireless powered communication networks (WPCN), where an access point (AP) serves as both an energy transmitter and an information receiver. In the downlink, AP replenishes nodes with RF energy transmission; and in the uplink, nodes transmit their information to the AP with the harvested energy [2].

The energy transfer performance of the WPCN can be significantly enhanced by using beamforming techniques over multiple antennas at the AP [2], [3]. Digital beamforming, which operates with a separate RF chain for each antenna, has been extensively studied in the literature. [4] studies the optimization of the digital beamforming weights and time duration for maximum sum-throughput of a spatial division multiple access (SDMA) based WPCN, where multiple beamforming weights are used within a single time slot, in both downlink and uplink transmission. [5] optimizes the downlink covariance matrix, uplink transmit time and power to maximize energy efficiency, throughput per energy consumption, of an uplink time division multiple access (TDMA), where time slot is partitioned and each partition is assigned to a single node, and uplink SDMA based WPCN, where nodes transmit their information concurrently. They demonstrate that TDMA outperforms SDMA when there is no minimum throughput requirement on the information transmission of the nodes. For energy transfer, articles [4], [5] send energy to the nodes simultaneously, whereas in [6] single beams are transmitted sequentially with time-sharing to mitigate interference to coexisting information networks. [6] demonstrates that sending single, sequential beams can have equivalent energy transfer performance with reduced interference to coexisting networks. In [7], authors investigate different beamforming schemes to maximize the transferred energy: beam-splitting and time-sharing. In beam-splitting (BS), AP sends a single beam, corresponding to the Pareto optimal point for all nodes during the entire time slot, whereas in time-sharing (TS), AP sends single beams aiming at each node in the network sequentially during the time slot. They show that BS is a superior scheme with real-time experiments. Unlike [4], [5], articles [6], [7] employ time domain; but not for additional degree of freedom, only to provide equivalent, or inferior but easily implementable alternative.

Digital beamforming, however, results in high cost and energy consumption as it requires high number of RF chains, equal to the number of antennas. Fewer RF chains, which are distributed to a much higher number of antennas with low-cost phase shifters, can be utilized in hybrid beamforming [8], [9]. This cost-saving, however, results in reduced control over beamforming weights and induces significant performance loss [10]. Recently, scheduling of energy harvesting (SEH) has been introduced to utilize the additional degree of freedom in the time domain to compensate RF chain scarcity [11]. SEH subdivides the downlink into multiple, variable-length subslots and assigns different beamforming weights to each subslot. Although the effectiveness of SEH on the delay performance of a WPCN with TDMA information transmission in the uplink has been illustrated [12], the effect of SEH for different multiple access schemes such as SDMA remains an open problem.

In this paper, we investigate the effect of SEH on the delay performance of a WPCN for different uplink multiple access schemes, namely SDMA and TDMA, for the first time in the

Ibrahim Pehlivan and Sinem Coleri are with the department of Electrical and Electronics Engineering, Koc University, Istanbul, Turkey, email: {ipehlivan, scoleri}@ku.edu.tr. This work is supported by Scientific and Technological Research Council of Turkey Grant #117E241.

literature. We first formulate the non-convex optimization problem. We then convert it to the equivalent rank-constrained semi-definite program and utilize smart rank reduction algorithms. With comprehensive simulations, we report the effect of SEH for both uplink SDMA and TDMA schemes.

II. System Model and Assumptions

WPCN comprises an access point (AP) containing M antennas and unlimited access to a power supply, and N nodes equipped with a single antenna where each node solely relies on the harvested energy from AP to replenish and operate. As a communication protocol, a half-duplex dynamic time-division duplex (TDD) is used. Each time frame is partitioned into two subframes, uplink and downlink. The downlink subframe is subdivided into S subslots with variable duration $t_s^{dl},\ s \in [1, S]$, for wireless energy transfer from the AP to the nodes. In the uplink, nodes transmit their information to the AP. In TDMA, nodes transmit their information sequentially in their allocated time slots, i.e. t_n^{ul} allocated to node n for $n \in [1, N]$; whereas in SDMA, all nodes transmit their information simultaneously for t_n^{u}. Channels between AP and nodes are block fading; therefore, the channel gain vector between the AP and node n is fixed during the time frame, equal to $\mathbf{h_n} \in \mathbb{C}^{\mathbf{M}}$ for $n \in [1, N]$ [4], [13] for both downlink and uplink.

The AP is assumed to employ digital beamforming for the uplink reception and hybrid beamforming in the downlink transmission to simplify the problem in this step. In hybrid beamforming, AP has L RF chains where $L \leq M$ [14] and each RF chain l is connected to a group of antennas $G_l = \{(l-1)K + 1, (l-1)K + 2, ..., lK\}$, phase shifter group for $l \in [1, L]$, with $K = \frac{M}{L}$ RF phase shifters, where K is an integer. Since each antenna in a phase shifter group, G_l, is connected to the same RF chain, l, with only a phase shifter, they have the same magnitude and have only phase differences introduced by the phase shifters. Let us denote the transmit beamforming vectors at time slot s of the AP by $\mathbf{v_s} \in \mathbb{C}^{\mathbf{M}}$. Then, for each RF chain l, antennas in the phase shifter group G_l satisfies $|\mathbf{v_s}(j)| = |\mathbf{v_s}(i)|, \quad i, j \in G_l$. Uplink receive combining vector with digital beamforming architecture of the AP dedicated to a node n is defined by $\mathbf{q_n} \in \mathbb{C}^{\mathbf{M}}$ with unit norm $\|\mathbf{q_n}\| = 1$ for both SDMA and TDMA cases.

In the downlink energy transmission, the output of the AP at time slot s is given by $\mathbf{x_s}^{\mathbf{dl}} = \mathbf{v_s} y_s^{dl}$, where $y_s^{dl} \in \mathbb{C}$ is the information carrying signal. Since no information is transferred in the downlink, y_s^{dl} can be any signal with certain restrictions on its power spectral density. We assume that y_s^{dl} is a random process such that $\mathbb{E}(\|y_s^{dl}\|^2) = 1$. Maximum allowed transmit power of the AP is denoted by P_{dl}. Since energy beamforming vector $\mathbf{v_s}$ at time slot s must adhere to power limitations, it satisfies $\mathbb{E}(\mathbf{x_s^{dl}}^{\mathbf{H}}\mathbf{x_s^{dl}}) = \|\mathbf{v_s}\|^2 = \mathbf{v_s^H v_s} \leq P_{dl}$. The harvested energy by node n at time slot s is given by $\psi t_s^{dl} \mid \mathbf{h_n^H v_s} \mid^2$, where $0 < \psi \leq 1$ is the energy harvesting coefficient [4], [13]. For both staying operational and transmit information, nodes solely rely on the harvested energy, hence only a fraction $0 < \eta \leq 1$ of the harvested energy is allocated for transmission [15]. Then available energy for transmission E_n^{avail} of the node n is defined by $E_n^{avail} = \eta E_n^{harv} = \eta \sum_{s=1}^{S} \psi t_s^{dl} \mid \mathbf{h_n^H v_s} \mid^2$.

In the uplink transmission, the output of node n is given by $x_n{}^{ul} = \sqrt{P_n} y_n^{ul}$, where $y_n^{ul} \in \mathbb{C}$ is the information carrying signal, P_n is the transmit power with $P_n \leq P_{ul}$, and P_{ul} is the maximum allowed uplink transmit power. y_n^{ul} is assumed to be independent symmetric complex gaussian random variable with unit variance and zero mean, $y_n^{ul} \sim \mathcal{CN}(0, 1)$. Each node n must acquire enough energy to stay operational; therefore, following equation must hold: $\overline{\psi} E_n^{avail} = \overline{\psi}\eta \sum_{s=1}^{S} \psi t_s^{dl} \mid \mathbf{h_n^H v_s} \mid^2 \geq P_n t_n^{ul}$ where $0 < \overline{\psi} \leq 1$ is the energy conversion efficiency.

Each node n is assumed to transmit Ω_n amount of data in the uplink. In TDMA, nodes transmit their data sequentially without any interference, whereas in SDMA, nodes transmit simultenously resulting in interference. In TDMA, decoded signal by the AP is given by $r_n = \mathbf{q_n^H h_n x_n{}^{ul}} + \mathbf{q_n^H n}$, where $\mathbf{n} \in \mathbb{C}^M$ is the additive white gaussian noise with $\mathbf{n} \sim \mathcal{CN}(0, \mathbf{I}\sigma^2)$. Since there is no intereference between nodes, channel capacity C^n for node n can be written as $C^n = \mathrm{W} log_2(1 + \frac{P_n \mid \mathbf{h_n^H q_n} \mid^2}{\sigma^2})$, where W is the bandwidth. In SDMA, received signal at AP can be written as $\sum_{n=1}^{N} \mathbf{h_n} x_n^{ul} + \mathbf{n}$ and decoded signal for node n can be written as $r_n = \mathbf{q_n^H h_n x_n{}^{ul}} + \mathbf{q_n^H n}$. As a result of interference between nodes, channel capacity can be calculated as $C^n = \mathrm{W} log_2(1 + \frac{P_n \mid \mathbf{h_n^H q_n} \mid^2}{\sum_{j \neq n} P_j \mid \mathbf{h_j^H q_n} \mid^2 + \sigma^2})$.

III. Optimization Problem formulation

The optimization problem minimizes the total downlink energy and uplink information transmission time for SDMA and TDMA cases for hybrid beamforming receiver architecture in the AP.

A. SDMA

minimize

$$\sum_{s=1}^{S} t_s^{dl} + t^{ul} \tag{1a}$$

subject to

$$\overline{\psi}\eta \sum_{s=1}^{S} \psi \mid \mathbf{h_n^H w_s} \mid^2 \geq P_n t^{ul}, \quad n = 1, \cdots, N \tag{1b}$$

$$\mathbf{w_s^H w_s} \leq P_{dl} t_s^{dl}, \quad s = 1, \cdots, S \tag{1c}$$

$$P_n \leq P_{ul}, \quad n = 1, \cdots, N \tag{1d}$$

$$t^{ul} \mathrm{W} \ln(1 + \frac{P_n \mid \mathbf{h_n^H q_n} \mid^2}{\sum_{j \neq n} P_j \mid \mathbf{h_j^H q_n} \mid^2 + \sigma^2}) \geq \Omega_n, \quad n = 1, \cdots, N \tag{1e}$$

$$\mid \mathbf{w_s}(j) \mid = \mid \mathbf{w_s}(i) \mid, \quad i, j \in G_l \tag{1f}$$

$$\|\mathbf{q_n}\| = 1, \quad n = 1, \cdots, N \tag{1g}$$

variables

$$t_s^{dl}, t^{ul}, P_n \in \mathbb{R}_+,\ \mathbf{w_s},\ \mathbf{q_n} \in \mathbb{C}^M, \quad n = 1, \cdots, N, \quad s = 1, \cdots, S \tag{1h}$$

where $\mathbf{w_s}$ is defined as the time weighted energy beamforming vector equal to $\mathbf{w_s} := \sqrt{t_s^{dl}}\mathbf{v_s}$ for $t_s^{dl} > 0$, $s \in [1, S]$ to eliminate the coupling of variables t_s^{dl} and $\mathbf{v_s}$.

Eqn. (1a) is the objective function, minimization of the uplink and downlink transmission time. Eqn. (1b) guarantees that required energy for operation is harvested for each node. The maximum transmit power limits for downlink energy and uplink information transmission are enforced by Eqns. (1c) and (1d), respectively. Eqn. (1e) guarantees the minimum data transfer for each node. Eqn. (1f) enforces the hybrid beamforming architecture.

To address the non-convexity of the constraint (1e), we utilize zero forcing at the receiver. For each node n, $\mathbf{q_n} = \mathbf{h_n}$ is projected onto the null space of the matrix $\mathbf{B} = [\mathbf{h_1}, \mathbf{h_2}, \ldots, \mathbf{h_{n-1}}, \mathbf{h_{n+1}}, \ldots, \mathbf{h_N}]^H$ to ensure orthogonality among receive combining vectors [9]. Let us denote the projection of $\mathbf{q_n}$ on $\mathbf{B}$ by $\overline{\mathbf{q_n}}$ where $||\overline{\mathbf{q_n}}|| = 1$. Then the constraint at Eqn. (1b) can be written as:

$$t^{ul}\text{W} \ln(1 + \frac{P_n \mid \mathbf{h_n^H}\overline{\mathbf{q_n}} \mid^2}{\sigma^2}) \geq \Omega_n, \quad \text{for} \quad ||\overline{\mathbf{q_n}}|| = 1.$$

Then, after defining a new variable E_n, energy, for node n as $E_n := P_n t^{ul}$; we can eliminate the coupling of variables P_n and t^{ul}. We eliminate the interference and effectively change the problem as a TDMA problem with predefined transmission gain, $\mid \mathbf{h_n^H}\overline{\mathbf{q_n}} \mid^2$. Hence, this problem is a special case of the TDMA problem in [12] where authors minimize the delay while optimizing hybrid beamforming weights with SEH, similar to problem in Eqn. (2). Therefore, the same solution strategies can be implemented [12] .

B. TDMA

Similarly, the optimization problem for TDMA can be written as [12]:

minimize

$$\sum_{s=1}^{S} t_s^{dl} + \sum_{n=1}^{N} t_n^{ul} \tag{2a}$$

subject to

$$\overline{\psi}\eta \sum_{s=1}^{S} \psi \mid \mathbf{h_n^H w_s} \mid^2 \geq E_n, \quad n = 1, \cdots, N \tag{2b}$$

$$\mathbf{w_s^H w_s} \leq P_{dl} t_s^{dl}, \quad s = 1, \cdots, S \tag{2c}$$

$$E_n \leq P_{ul} t^{ul}, \quad n = 1, \cdots, N \tag{2d}$$

$$t_n^{ul}\text{W} \ln(1 + \frac{E_n \mid \mathbf{h_n^H q_n} \mid^2}{t^{ul}\sigma^2}) \geq \Omega_n, \quad n = 1, \cdots, N \tag{2e}$$

$$\mid \mathbf{w_s}(j) \mid = \mid \mathbf{w_s}(i) \mid, \quad i, j \in G_l \tag{2f}$$

$$||\mathbf{q_n}|| = 1, \quad n = 1, \cdots, N \tag{2g}$$

variables

$$t_s^{dl}, t_n^{ul}, E_n \in \mathbb{R}_+, \ \mathbf{w_s}, \ \mathbf{q_n} \in \mathbb{C}^M, \quad n = 1, \cdots, N, \quad s = 1, \cdots, S \tag{2h}$$

where energy, E_n, for node n is defined by $E_n := P_n t^{ul}$. This problem is a special case of the problem in [12], with single antenna nodes. We can further simplify this problem by using the following: Since $\mathbf{q_n}$ is independent of other variables and $\mid \mathbf{h_n^H q_n} \mid^2$ needs to be maximized in the optimal solution; $\mathbf{q_n}$ is equal to $\mathbf{h_n}$ according to the maximum ratio combining principle [12], [16].

IV. Solution Methods

Problems in Eqns. (1) and (2) are the special cases of the TDMA problem in [12]. Therefore, we utilize the Project and Alternate algorithm (PA) to solve these problems [12]. First, we convert them to the equivalent semidefinite programming problems with additional rank constraints. Then, we iteratively obtain rank one solutions. In this section, we show the PA algorithm for SDMA case; TDMA follows the same procedures but is omitted for page restrictions.

A. Semidefinite Programming Problem

Problem in Eqn. (1) can be converted to the equivalent semidefinite problem (SDP) with additional rank constraints. Observe that $\mid \mathbf{h_n^H q_n} \mid^2 = \mathbf{Tr}(\mathbf{q_n^H h_n h_n^H q_n}) = \mathbf{Tr}(\mathbf{h_n h_n^H q_n q_n^H})$. We can add rank constraints, define a new variable $\mathbf{W_s} = \mathbf{w_s w_s^H}$ and rewrite $\mathbf{H_n} = \mathbf{h_n h_n^H}$ to obtain following equivalent SDP [12], [17].

minimize

$$\sum_{s=1}^{S} t_s^{dl} + t^{ul} \tag{3a}$$

subject to

$$\overline{\psi}\eta \sum_{s=1}^{S} \psi \mathbf{Tr}(\mathbf{H_n W_s}) \geq E_n, \quad n = 1, \cdots, N \tag{3b}$$

$$\mathbf{Tr}(\mathbf{W_s}) \leq P_{dl} t_s^{dl}, \quad s = 1, \cdots, S \tag{3c}$$

$$E_n \leq P_{ul} t^{ul}, \quad n = 1, \cdots, N \tag{3d}$$

$$t^{ul}\text{W} \ln(1 + \frac{E_n \mid \mathbf{h_n^H}\overline{\mathbf{q_n}} \mid^2}{\sigma^2 t^{ul}}) \geq \Omega_n, \quad n = 1, \cdots, N \tag{3e}$$

$$\mid \mathbf{W_s}(j, j) \mid = \mid \mathbf{W_s}(i, i) \mid, \quad i, j \in G_l \tag{3f}$$

$$rank(\mathbf{W_s}) = 1, \quad s = 1, \cdots, S \tag{3g}$$

variables

$$t_s^{dl}, t^{ul}, E_n \in \mathbb{R}_+, \ \mathbf{W_s}, \in \mathbb{C}^{M \times M}, \quad n = 1, \cdots, N, \quad s = 1, \cdots, S \tag{3h}$$

This problem is non-convex due to rank constraints in Eqn. (3g). We continue with the Project and Alternate (PA) algorithm.

B. The Project and Alternate algorithm

In the Project and Alternate algorithm (PA), first, the rank constraint is rewritten as an equivalent non-convex constraint and moved to the objective function as a penalty. Then, this

Table I
Simulation Parameters

M	64	R	5	η	0.75
P_{dl}	30 dBm	P_{ul}	10 dBm	f	28 Ghz
$\psi = \overline{\psi}$	0.5	σ^2	10^{-9}	β	100 MHz
Ω_n	10 Knats	σ_z	1.7	α	1.2

problem is solved iteratively to minimize the penalty and to obtain a rank one solution [10]. In each iteration, the solution is projected to a rank one matrix to provide stability and performance [12].

It is proven that for every non-zero hermitian positive semidefinite matrix $\mathbf{W_s}$, $\text{Tr}(\mathbf{W_s^2}) \leq \text{Tr}(\mathbf{W_s})^2$; and $\text{Tr}(\mathbf{W_s^2}) = \text{Tr}(\mathbf{W_s})^2$ if and only if $rank(\mathbf{W_s}) = 1$ [10]. Therefore, rank constraint in Eqn. (3g) can be replaced with the equivalent constraint:

$$\text{Tr}(\mathbf{W_s})^2 - \text{Tr}(\mathbf{W_s}^2) \leq 0, \quad s = 1, \cdots, S$$

Although it is still non-convex, this constraint can be moved to the objective function as a *penalty* as $\sum_{s=1}^{S} \xi_n(\text{Tr}(\mathbf{W_s})\text{Tr}(\mathbf{W_s}) - \text{Tr}(\mathbf{W_s}\mathbf{W_s}))$ where ξ_n is the weight of the *penalty* of the time slot s. Then, rank 1 solution of the problem in Eqn. (3) can be obtained iteratively, where at q-th step, the following problem is solved [10], [12]:

$$\begin{aligned} \min \quad & \sum_{s=1}^{S} t_s^{dl} + t^{ul} \\ & + \sum_{s=1}^{S} \xi_s(\text{Tr}(\mathbf{\Theta_s}^{(q)})\text{Tr}(\mathbf{W_s}) - \text{Tr}(\mathbf{\Theta_s}^{(q)}\mathbf{W_s})) \qquad (4a) \\ \text{s.t.} \quad & (3b - 3h) \end{aligned}$$

where $\mathbf{\Theta_s}^{(q)}$ is defined as $\mathbf{\Theta_s}^{(q)} = \vartheta_\mathbf{1}\vartheta_\mathbf{1}^\mathbf{H}$ and $\vartheta_\mathbf{1}$ is the primal eigenvector of the solution $\mathbf{W_s}^{(q-1)}$. This rank one projection improves the performance and stability [12].

V. Performance analysis

In this section, we report the delay performance gain introduced by SEH for different number of RF chains in the AP, number of nodes and uplink multiple access schemes, TDMA and SDMA. In the scheduled case, S is set to $S = 5$, and, for the non-scheduled case, $S = 1$. Semidefinite relaxation, rank relaxed version of the problem in Eqn. (3), is included to assess optimality and used as a lower bound to time delay, and denoted by SDR-TDMA and SDR-SDMA for TDMA and SDMA uplink transmission, respectively.

Nodes are distributed randomly on a sphere of radius 5 meter for 50 independent network topologies. CVX in MATLAB [18], [19] with the solver SDPT3 [20] is used to solve the optimization problems with the simulation parameters listed in Table I.

In the AP, 64 antennas have circular-shape configuration with spacing of $\lambda/2$, where λ is the wavelength of the carrier frequency. Rayleigh fading is selected as an attenuation model with mean path loss value determined by a log-distance model: $PL(d) = PL(d_0) + 10\alpha \log(d/d_0) + Z$, where d is the distance between the node and AP, $PL(d)$ is the path loss at distance d in decibels, $PL(d_0)$ is the path loss at reference distance $d_0 = 1$ m, α is the path loss exponent and Z is a Gaussian random variable with zero mean and standard deviation σ_z. The channel parameters are $PL(d_0) = 61.39$ dB, $\alpha = 1.2$ and $\sigma_z = 1.7$ dB at 28 GHz frequency band for line of sight (LOS) transmission [21].

Fig. 1 illustrates the normalized total uplink and downlink transmission time, total delay, of uplink TDMA and SDMA schemes for the different number of nodes with 1 RF chain at the AP. SDMA outperforms TDMA for up to 5 nodes as it enables concurrent transmission. However, TDMA outperforms SDMA for the number of nodes greater than 5 due to the increase in the interference between nodes. Both TDMA and SDMA are in close proximity of the SDR bound as a restriction on the number of nodes results in reduced complexity and, therefore, limited gain from SEH for both TDMA and SDMA.

Fig. 2 shows the normalized total delay of uplink TDMA and SDMA schemes for the different number of RF chains at the AP for 4 nodes. SDMA dominates TDMA for any number of RF chains as a result of low interference and simultaneous transmission. This shows the advantage and practicality of SDMA for WPCNs with 4 nodes, and any hybrid beamforming configuration.

Fig. 3 shows the total delay normalized by the semidefinite relaxation bound, denoted by Ψ, for the different number of nodes with 1 RF chain at the AP. Ψ gives the distance of the solutions to the lower bound. Up to 4 nodes, both scheduled and non-scheduled solutions appear to be very close to the lower bound, and as the number of nodes increases, non-scheduled solutions diverge from the lower bound faster than the scheduled solutions for both TDMA and SDMA, showing the increased importance of SEH regardless of the scheme.

Scheduling gain, which is defined as the percentage gain of the scheduled solution with respect to the non-scheduled solution, is observed to be higher for the SDMA, between $[0.05, 2.83]\%$ compared to TDMA, between $[0.05, 2.67]\%$. Hence, SDMA benefits from SEH more than TDMA regardless of the number of nodes, indicating the increased necessity for an additional degree of freedom.

VI. Conclusion

We examine the effect of SEH on the total delay of a WPCN for SDMA and TDMA uplink multiple access schemes. We optimize the hybrid beamforming vectors and transmission time in the downlink, and transmit power and time for the uplink to minimize the total delay. Via extensive simulations, we observe that uplink SDMA benefits more from SEH compared to TDMA. However, due to increasing interference between nodes, SDMA is impractical and inferior to TDMA for the high number of nodes where SEH provides a significant gain.

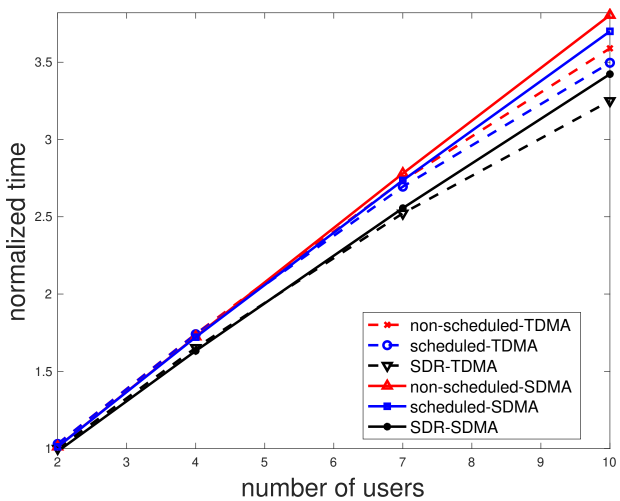

Figure 1. Normalized time for different number of nodes and 1 RF chain at the AP.

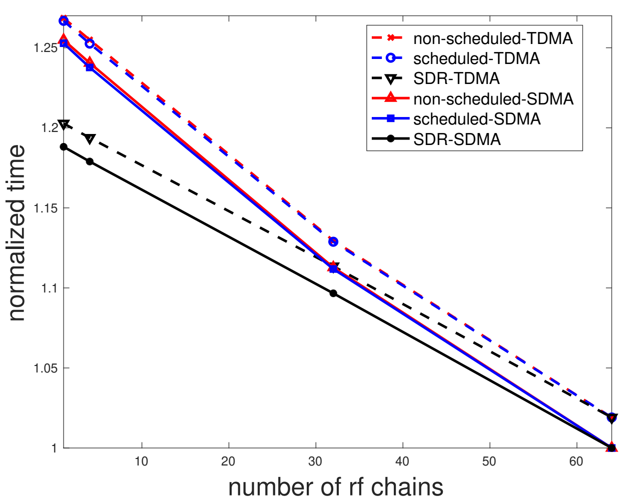

Figure 2. Normalized time for different number of RF chains in a 4 node network.

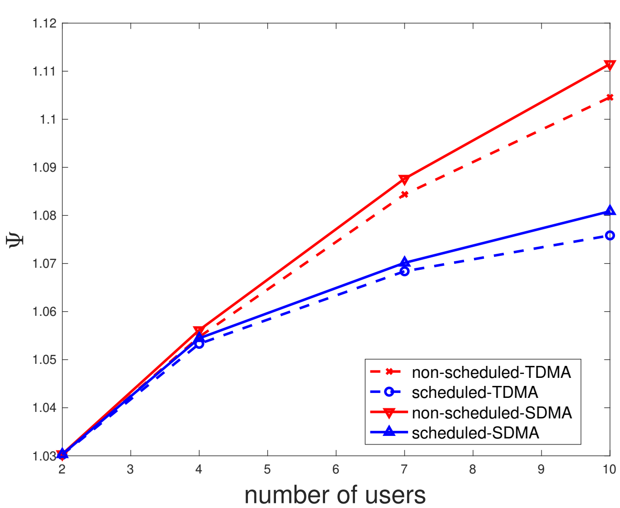

Figure 3. Ψ for different number of nodes and 1 RF chain at the AP.

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